Donald R. Woods

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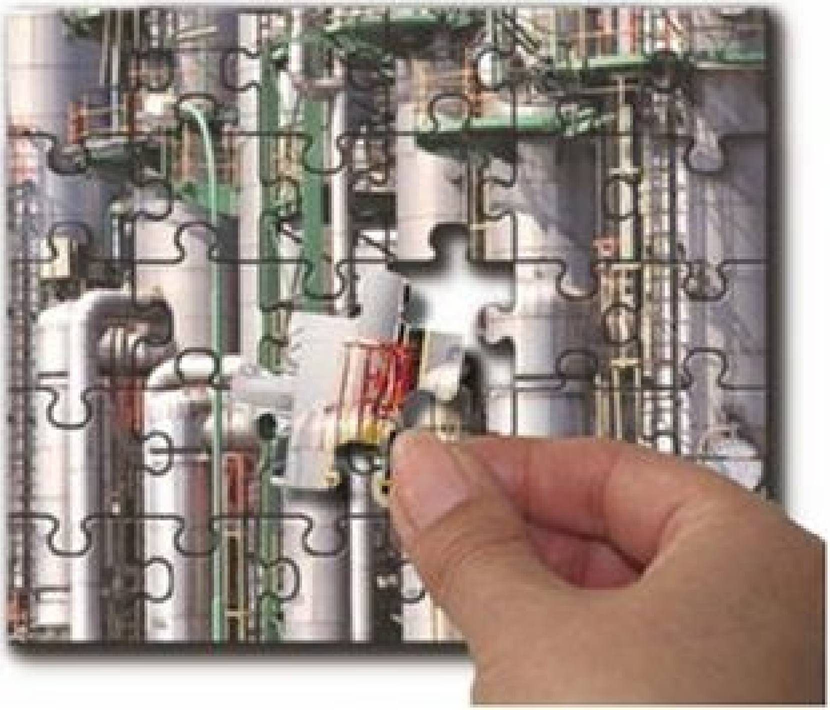
Rules of Thumb in Engineering Practice



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Rules of Thumb in Engineering Practice

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Preface

Brewster's Dictionary of Phrase and Fable defines a rule of thumb as "a rough guestimate measure, practice or experience, as distinct from theory, in allusion to the use of the thumb for rough measurements. The first joint of the adult thumb measures almost exactly 1 inch (2.5 cm)".

Engineers need such rules of thumb to guide decisions, set goals, check results and to help answer such questions as:

- When might I use something?
- How do I obtain an approximate answer?
- How might I obtain an approximate estimate of the cost?
- What is reasonable operating know-how?
- What might I do if something goes wrong?

Some believe that providing a collection of rules of thumb is dangerous – dangerous because engineers might forsake the fundamentals and place too much emphasis on order-of-magnitude estimates. However, I have found for problem solving in industry – for design, for process improvement and for trouble shooting – rules of thumb are not dangerous; they are essential. From research on *problem solving*, for example, we realize that skilled problem solvers create a rich internal representation of the problem. During the creation of that representation, problem solvers ask many *What if*? questions. They solve a simplified version of the problem. They approximate. Rules of thumb are needed to do this well. As we problem solve, research has found that we monitor our thought processes frequently; we check and double check often. To do this well requires us to have a rich set of rules of thumb. When we obtain an answer to a problem, skilled problem solvers check that the answer sounds reasonable and that it answers the initial problem. We use rules of thumb to do this. Rules of thumb are needed by working professionals.

This book is unique in its consistency in terminology and units, in its extensive cross referencing, in the range of process equipment considered, in the depth and breadth of coverage for each piece of equipment, in the coding of the source of the rule of thumb, in its synthesis of the information into convenient and easy-to-use formats and because it considers issues not usually considered in books

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about rules of thumb: career skills, how to function effectively and the people side of engineering.

This book is unique in its *consistency in terminology and units*. Tower or column? motionless mixer or static mixer? tray or plate?- these are just some of the terms that are used interchangeably when discussing process equipment. In this book consistent use of terms has been applied. The SI units of measurement are used throughout the text.

This book is unique in its *extensive cross referencing*. Some pieces of equipment are used for many different purposes. For example, fluidized beds are selected, sized and operated as heat exchangers, dryers, reactors, coaters and agglomerators. The details are given for each specific application with cross referencing to lead to other uses and rules of thumb. This cross referencing is included in each pertinent section and in the lengthy index.

This book is unique in the *range of process equipment* considered. Books on rules of thumb often focus on the familiar equipment: centrifugal pumps, shell and tube exchangers, and distillation columns, few consider solids processing equipment; and solid–solid separators are rarely discussed. In this book I have tried to consider an extremely broad range of over 350 types of equipment, especially some of the lesser-known equipment, such as prilling, flakers, electrostatic separators, magnetic separators, foam fractionation, expellers, zone refiners and multiple hearth furnaces.

This book is unique in the *depth and breadth of coverage* for each piece of equipment. Wherever possible, for each piece of equipment I have tried to include five dimensions important for the practising engineer: the area of application (or when to use a particular type of equipment); guidelines for sizing; an approximate capital cost including hard-to-locate installation factors; principles of good practice and approaches for trouble shooting. More specifically:

- *Area of Application*: how or when to select: when would you use this piece of equipment? What is the usual available size range?
- *Guidelines:* how to size: rules of thumb and short cut sizing for estimating the size of the equipment. In general these work within a factor of ten but usually a factor of four.
- *Capital Cost Guidelines*: Costs should be included with any rules of thumb because costs are such vital information to engineering practice. But these are guidelines – not data! The cost estimates given here are ball park ideas. The guideline FOB cost is in US $ for CEPCI = 1000. The L+M* factors are included because few published data are available. Some of these may be shown as a range, for example, 2.3–3. This means that values have been reported in this range and no recommended value is available at this time. The L+M* factor includes the FOB cost for carbon steel and excludes taxes, freight, delivery, duties and instruments, unless instruments are part of the package. The * is added to remind us that the instrumentation material and labor costs have been excluded, whereas most L+M values published in the 60s,

70s and 80s included the instrumentation material and labor costs. The alloy corrections are given so that L+M for carbon steel can be reduced appropriately for the alloy used in the equipment. For some unit operations the equipment is built of concrete or is a lagoon. For such equipment the reported cost is the Physical Module, PM cost, or the FOB plus L+M* plus instruments plus taxes and duties. The cost excludes offsite, home office expense, field expense and contractor's fees and contingencies.

- *Good Practice*: suggestions for good operability and suggestions for sustainability, waste minimization, safety and environmental concerns.
- *Trouble Shooting*: the symptom is given "*Temperature > design*" followed by a prioritized list of possible causes separated by "/". Sometimes it is convenient to identify a cause and list, in turn, the sub-causes until the root cause is listed. For example, [fouling]* might be listed as a "cause" but what causes the fouling? Fouling is not the *root cause*. Possible root causes are given in a separate listing under *[Fouling]**. Such documentation is required because (i) we need to keep looking for causes until we find one that we can measure or change, and (ii) sometimes, with extruders, for example, the cause is because the *temperature is too hot or too cold*. We need guidance as to what is really the cause when the temperature is too hot and what is really the root cause when the temperature is too cold.

This book is unique because it attempts to *code the source* of the rule of thumb. This is important because not all rules of thumb arise from the same source. Some are a generalization of fundamentals, for example, the friction factor for turbulent flow is about 0.005; 1 kg of steam evaporates about 5 kg of organic. Such rules of thumb will not change over time. Some are based on safety considerations; these may change as we learn more about hazards and safe operation. Some are developed from an economic analysis, but as the relative costs change then the rule of thumb will change. For example, the "economic velocity" for pumping liquids is about 1 m s^{-1}; but this will change as the relative costs of power, labor and materials change. Some rules of thumb are based on insurance policies, or the law. Such heuristics will change as policies and laws change. For example, in 1961 in the UK the insurance costs for a polymerizer to which live steam was attached were much, much higher than if hot water was attached directly to the vessel. So rules of thumb about good practice were developed in that industry to account for this. Coding is needed to remind us of the basis of the rule of thumb.

This book is unique in its *synthesis of the information*. This is not a convenient reproduction of material taken from different sources. Information from different sources is compared and contrasted, gaps are filled, and the information is presented in forms useful to the sizing, selecting and operation of the equipment. For example, sizing maps, given for pumps, heat exchangers, columns and reactors, illustrate pictorially how different factors affect the decisions. For filtering centrifuges, articles often describe which filtering centrifuge to select to handle slurries described by such qualitative terms as “fast filtering”, “medium filtering” and so on. But the quantitative design parameters for filtering centrifuges are the cake build-up rate, the intrinsic permeability and the particle size. Table 5.2, for example, relates “qualitative terms” to the “quantitative design parameters”. A similar synthesis and clarification is done, in Table 5.3, relating “qualitative” measures of filtration to such quantitative design parameters as rate of cake formation, filtrate rate, and cake resistance. The *density-weighted velocity* is important in sizing tray columns, KO pots, absorbers and demisters. Table 4.1 synthesizes and summarizes the values for these different applications. Corrosion, foam formation, stable emulsion formation and fouling are concerns that affect the successful operation of many different types of equipment. These concerns are addressed consistently, where needed, throughout the book. Interfacial and surface engineering aspects are included in the descriptions of pertinent unit operations. The selection criteria for reactors are synthesized in the series of tables in Chapter 6. Data are given for estimating the residence times in different reactors and for different types of reactions.

This book is unique because it considers *issues not usually considered* in books about rules of thumb. Most books and articles about rules of thumb focus on processing equipment but effective engineers also need to communicate, work effectively in teams, solve problems and lead. Rules of thumb are summarized for “systems” thinking and for “career skills” such as problem solving, creativity, leadership, entrepreneurship and e-business.

This book uses a format similar to my other books: *Process Design and Engineering Practice* and *Successful Trouble Shooting for Process Engineers* and the section on Design that I coauthored in Marcel Dekker’s “Handbook for Chemical Engineers”

Another *uniqueness* is the information on residence times for reactions. Data from industrial reactors were used to create Figs. 6.5 to 6.7. These show how the residence time for reaction varies with temperature, phase and the heat of reaction. To my knowledge, this is the first time such an analysis has been presented in the open literature. Other detailed information is given on how the type of reaction can be used to estimate the residence time.

Unique also is the extensive analysis of dispersed phase systems, whether these are gas bubbles in liquids, sprays, a liquid–liquid dispersion or a liquid–solid system. Characteristics of different contactors for such systems are summarized in Tables 1.1 to 1.3 and Figs. 1.1 and 1.2.

To aid in retrieving information, an extensive index is given.

Chapter 1 gives rules of thumb for physical and thermal properties, corrosion and process control; for engineering decisions related to batch versus continuous processing, the characteristics of heterogeneous phase contacting, economics, problem solving, goal setting, decision making, thermal pinch, systems thinking, process design, process improvement, trouble shooting and environmental and safety issues. Rules of thumb are included about communication, listening, interpersonal skills, team work, performance review, leadership, intrepreneurship, entrepreneurship, e-business and self management. The section on heterogeneous phase contacting includes figures and tables that compare area/volume, oxygen transfer rates and other key characteristics of a wide range of contacting devices for gas–liquid, liquid–liquid and particulate systems.

Chapter 2 considers equipment for transportation: gases, liquids, fluid mixtures and solids

Chapter 3 addresses energy exchange equipment. This includes drives, motors and turbines as well as equipment for thermal energy exchange.

Chapter 4 describes equipment to separate homogeneous phases; these range from evaporators and distillation to membrane processes.

Chapter 5 focuses on equipment for the separation of heterogeneous phases. The chapter starts with a convenient general selection guide. More specific guides are given for liquid–solid separations, Section 5.5, and for solid–solid separations, Section 5.18.

Chapter 6 starts with criteria for the selection of a reactor configuration. Data are given for sizing reactors. Then the details are given for over 30 reactor configurations.

Chapter 7 considers mixing (of gases, liquids, mixtures and solids).

Chapter 8 explores size reduction operations, such as foams, sprayers, emulsification, crushing and grinding and cell disintegration.

Chapter 9 summarizes key information about equipment to increase or change the size of drops, bubbles and particles: demisters, coalescers, flocculators, spray dryers, fluidized beds, agglomeration, pelletizing, extrusion, flakers, prilling and coating.

Chapter 10 considers process and storage vessels, bins and hoppers and bagging machines.

This book is a synthesis and summary of experience I have gained since 1955. In the seven companies for whom I worked before coming to McMaster University, I learned much from the late Don Ormston and Ted Tyler of Distiller's Company Ltd., Saltend, UK; Stan Chodkiewicz, Polysar, Sarnia, J.Mike F. Drake, British Geon Ltd., Barry, South Wales; Chuck Watson and the late Ed Crosby from the University of Wisconsin; the late Reg Clark, Queen's University helped me immensely. They started me on my search for and synthesis of sound estimating procedures and guidelines for good judgment. I have received ongoing help from my colleagues at McMaster. In particular, the late R.B. Anderson, Archie Hamielec, Terry Hoffman, Cam Crowe, Joe Wright, Jim Dickson, Phil Wood, Les Shemilt, Marios Tsezos, Neil Bayes, Malcolm Baird, John Vlachopoulos, Raja Ghosh, the late Keith Murphy, Jack Norman, Tom Marlin, Bob Pelton, John Brash, Brian Ives, Gord Irons, W.K. Lu, Carlos Filipe and Doug Keller. Others who willingly shared their expertise and contributed to this book include Ken Hester, Rio Algom; Bob McAndrew and Glen Dobby, University of Toronto; G.S. Peter Castle and Maurice Bergougnou, University of Western Ontario;

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Don Woods, Waterdown, January 2006

1
Rules of Thumb

Rules of thumb are numerical values and suggestions that are reasonable to assume based on experience. They are based on the application of fundamentals and practical experience. They do not replace fundamentals but rather they enrich the correct use of fundamentals to solve problems. Rules of thumb:

- help us judge the reasonableness of answers;
- allow us to assess quickly which assumptions apply;
- are used to guide our better understanding of complex systems and situations; and
- allow us to supply rapid order-of-magnitude estimates.

Rules of thumb important for process design and engineering practice include those about

- the chemical process equipment,
- the context in which the equipment functions (properties of materials, corrosion, process control, batch versus continuous and economics),
- the thinking process used as engineers design and practice their skills (problem solving, goal setting, decision making, thermal pinch, "systems' thinking, process design, process improvement, trouble shooting and health-safety-environment issues),
- the people part of engineering (communication, listening, interpersonal skills and team work) and
- the context in which engineers function (performance review, leadership, intrepreneurship, entrepreneurship and e-business).

In this book, the focus is on rules of thumb about process equipment. Chapters 2 to 10 provide details of equipment for transportation, energy exchange, separations, heterogeneous separations, reactions, mixing, size reduction, size enlargement and process vessels, respectively.

In this chapter, we give an overview, in Section 1.1, of how the rules of thumb are presented in the rest of the book. Then, we emphasize the contexts in which engineers work: the context for the process (Sections 1.2 to 1.7), the thinking used (Sections 1.8 to 1.16), the people dimension of our practice (Sections 1.17 to 1.20)

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and the organizational context in which we work (Sections 1.21 to 1.25). Finally, suggestions about mentoring and self management are given in Section 1.26. Consider each in turn.

1.1
Rules of Thumb about Process Equipment

The rest of this book, Chapters 2 to 10, considers rules of thumb for different types of equipment. Here we give an overview of how the information is organized and presented. Rules of thumb are based on different types of experience. These different types of experience include (together with their code):

- generalized physical, thermal, environmental and safety properties of solids, liquids or gases (P),
- generalized fundamental concepts (F),
- generalized operating conditions: transfer coefficients, efficiencies (O),
- generalized manufacturers limitations (M),
- generalized natural or legal constraints: wind load, size of equipment shipped through rail tunnels (N)
- economic optimization: approach temperature, minimum reflux ratio ($),
- generalized engineering judgement: max temperature for cooling water, operating location for pumps (J)
- hazard or safety consideration (H).

The rules of thumb are organized by prime function and within each function are listed the usual types of equipment. Each piece of equipment is assigned a code because some equipment is multifunctional. For example, a fluidized bed is primarily a method of mixing a gas–solid mixture. However, it is also used as a dryer, a heat exchanger, a reactor and an agglomerator.

For each piece of equipment are listed the following:

- *Area of Application*

How to select: when would you use this piece of equipment? What is the usual available size range?

- *Guidelines*

How to size: rules of thumb and short cut sizing for estimating the size of the equipment. In general these work within a factor of ten but usually a factor of four.

- *Capital Cost Guidelines*

Costs should be included with any rules of thumb because costs are such vital information to engineering practice. But these are guidelines – not data! The cost estimates are ball park ideas. The guideline FOB cost is in US $ for a value of the *Chemical Engineering Index (1957–59 = 100),* CEPCI Index = 1000. The value of *CEPCI* Index for the year 2003 was 395.6 so that the costs reported here are more than double the value in 2003. Costs are usually correlated in terms of a base cost multiplied by a ratio of sizes raised to the power "n". $\text{Cost}_2 = \text{Cost}_{\text{ref}} (\text{size}_2/\text{size}_{\text{ref}})^n$. The cost is usually the FOB cost although sometimes it is the field erected cost. The size should be a "cost-dependent" parameter that is characteristic of the specific type of equipment. The size parameter that provides the least accurate estimate is the *flow* or *capacity.* In this book, sometimes several different parameters are given; use the size parameter *flow* or *capacity* as a last resort.

Although the FOB cost of equipment is of interest, usually we want to know the cost of a fully installed and functioning unit. The "bare module", BM, method is used in this book. In the BM method, the FOB cost is multiplied by factors that account for all the concrete, piping, electrical, insulation, painting, supports needed in a space about 1 m out from the sides of the equipment. This whole space is called a module. The module is sized so that by putting together a series of cost modules for the equipment in the process we will account for all the costs required to make the process work. For each module we define a factor, L+M*, that represents the labor and material costs for all the ancillary materials. Some of these may be shown as a range, for example, 2.3–3. This means that for the installation of a single piece of equipment (say, one pump), the higher value should be used; the lower value is used when there are many pumps installed in the particular process. The L+M* factor includes the free-on-board the supplier, FOB, cost for carbon steel and excludes taxes, freight, delivery, duties and instruments unless instruments are part of the package. The * is added to remind us that the instrumentation material and labor costs have been excluded, (whereas most L+M values published in the 60s, 70s and 80s included the instrumentation material and labor costs). The alloy corrections are given so that L+M* for carbon steel can be reduced appropriately for the alloy used in the equipment. For some unit operations the equipment is built of concrete or is a lagoon. For such equipment the reported cost is the Physical Module, PM cost, that represents the FOB plus L+M* plus instruments plus taxes and duties. The cost excludes offsite, home office expense, field expense and contractor's fees and contingencies. Rules of thumb to account for the other cost items are given in Section 1.7. The costs are given in Appendix D.

- *Good Practice*

Suggestions may be given for good operability, and suggestions for sustainability, waste minimization, safety and environmental concerns.

- *Trouble Shooting*

For many units, likely causes of malfunction are given under "trouble shooting". For trouble shooting, the symptom is given "*Temperature > design*" followed by a prioritized list of possible causes separated by "/". Sometimes it is convenient to identify a cause and list, in turn, the sub causes. An example is [fouling]* which then has a separate listing under *[Fouling]**. This is used when elaboration about the "cause" is needed to identify a cause that we can actually correct. For example, the cause might be "fouling" but what do we change to prevent the fouling? What causes the fouling?

1.2
Rules of Thumb about the Context for a Chemical Process: Physical and Thermal Properties

Here are 17 rules of thumb:

1. Vapor pressure doubles every 20 °C.
2. The latent heat of vaporization of steam is five times that of most organics.
3. If two liquids are immiscible, the infinite dilution activity coefficient is > 8.
4. 10 % salt in water doubles the activity coefficient of a dissolved organic.
5. Infinite dilution is essentially < 1000 ppm of dissolved organic.
6. Freezing temperature may be suppressed 1 °C for every 1.5 mol % impurity present.
7. A ratio of impurity concentration between a solid/liquid phase > 0.2 is probably due to solid solution.
8. Dissolving 2–20 % organic solute usually reduces the interfacial tension.
9. The Prandtl number for gases is approximately 1; for liquids 1 to 3.
10. The thermal conductivity of hydrogen = 10 × value for most organic vapors.
11. For distillation, the condenser cooling water usage is 15 L/kg of steam to the reboiler.
12. Polymer melts can be classified based on their viscosity: *low viscosity melts* for polyacylamide; polyethylene, polypropylene and polystyrene; *medium viscosity melts* for ABS, cellulose acetate, POM and styrene butadiene; and *high viscosity melts* for polycarbonate, polymethylmethacrylate, polypropylene oxide and polyvinyl chloride.
13. Surface tension for most organics (and for organic-water surfaces) at 25 °C = 15–40 mN/m and decreases almost linearly to 0 at the critical temperature. The surface tension decreases with temperature as approximately –0.1 mN/m °C. For water the surface tension at 25 °C is 72 mN/m.

14. The variation in surface tension with surface concentration of surface active materials is about 2.5 mN m/mol.
15. The surface concentration of a surfactant A, $\Gamma_A = \beta\, c_A$ where the latter is the bulk concentration of A and $\beta = 2 \times 10^{-5}$ m for octanol water with the value of β increasing by a factor of 3 for every CH_2 added to the hydrocarbon chain.
16. The Hamaker constant for liquid surfaces is about 10^{-20} J and is relatively independent of temperature.
17. The disjoining pressure for films is negligible for fluid films > 0.1 μm thick.

1.3
Rules of Thumb about the Context for a Chemical Process: Corrosion

1. The strength of materials depends totally on the environment in which the materials function and not on the handbook values.
2. All engineering solids are reactive chemicals – they corrode.
3. The eight usual forms of materials failure by corrosion (and the frequency of failure due to this form of corrosion) are: (i) uniform corrosion: uniform deterioration of the material (32 %); (ii) stress corrosion: simultaneous presence of stress and corrosive media (24 %); (iii) pitting: stagnant areas with high halide concentration (16 %); (iv) intergranular corrosion: most often found in stainless steels in heated areas (14 %); (v) erosion: sensitive to high flowrates, local turbulence with particles or entrained gas bubbles; for flowing gas–solids systems the rate of erosion increase linearly with velocity and depends on abrasiveness of particles (9 %); (vi) crevice corrosion: concentration cells occur in stagnant areas (2 %); (vii) selective leaching or dealloying: removal of one species from a metallic alloy (1 %) and (viii) galvanic corrosion: dissimilar metals coupled in the presence of a solution with electrolyte (negligible).
4. Stress corrosion (the second form of corrosion) can start from perfectly smooth surfaces, in dilute environments with material stresses well below the yield stress.
5. $>$ 70 % of stress corrosion cracking is related to residual – not applied – stresses.
6. The penetration of stress corrosion cracking as a function of time depends on the alloy composition, structure, pH, environmental species present, stress, electrochemical potential and temperature.

- *Trouble Shooting*

"High concentration of metals (Fe, Cr, Ni, Cu) in solution": [corrosion]*/contaminants from upstream processing.

"Ultrasonic monitoring shows thin walls for pipes, internals or vessels": faulty ultrasonic instrument/[corrosion]*/faulty design. *"Failure of supports, internals, vessels":* [corrosion]*/faulty design/unexpected stress or load.

"Leaks": [corrosion]*/faulty installation/faulty gasket/faulty alignment.

[Corrosion]:* [corrosive environment]*/inadequate stress relief for metals/wrong metals chosen/liquid flows at velocities > critical velocity for the system; for **amine** circuits: > 1 m/s for carbon steel and > 2.5 m/s for stainless steel/large step changes in diameter of pipes/short radii of curvature/flange or gasket material projects into the pipe/[cavitation in pumps]*/improper location of control valves.

[Corrosive environment]:* temperature too hot; **for amine solution:** > 125 °C/high dissolved oxygen content in liquid/liquid concentration differs from design; **for steam:** trace amounts of condensate or condensate level in condensers > expected; **for 316 stainless steel:** trace amount of sodium chloride; **for sulfuric acid:** trace amounts of water diluting concentrated acid to < 90 %; **for amine absorption:** total acid gas loadings > 0.35 mol acid gas/mol MEA, > 0.40 mol acid gas/mol DEA, > 0.45 mol acid gas/mol MDEA; makeup water exceeds specifications; **for amine absorption** units exceeds: 100 ppm TDS, 50 ppm total hardness as calcium ion, 2 ppm chloride, 3 ppm sodium, 3 ppm potassium and 10 ppm dissolved iron; **for sour water scrubbers:** cyanides present/pH change/acid carryover from upstream units/high concentration of halide or electrolyte/presence of heat stable salts/bubbles present/particulates present/invert soluble precipitates with resulting underlying corrosion/sequence of alternating oxidation–reduction conditions.

*[Cavitation in pumps]**: pump rpm too fast/suction resistance too high/clogged suction line/suction pressure too low/liquid flowrate higher than design/entrained gas/no vortex breaker.

1.4
Rules of Thumb about the Context for a Chemical Process: Process Control

(based on communication from T.E. Marlin, McMaster University, 2001)

- *Area of Application*

For all processes, provide the four levels of control: (i) the basic control system, (ii) an alarm system, (iii) a safety interlock system, SIS, and (iv) a relief system.

- *Guidelines*

Sensors: What to measure? Variables are measured by sensors to achieve the following objectives, in hierarchical sequence:

safety/environmental protection/equipment protection, *for example this could include redundant temperature sensing and alarms on reactors and reboilers handling* *corrosive chemicals such as HF*/smooth operation/product quality/profit/monitoring/diagnosis and trouble shooting. Identify the objective and select a pertinent variable. Direct measurement of the variable is preferred. If direct measurement is impractical, select an inferential or calculated variable. *For example, temperature can infer conversion and composition.*

Variables must be measured that might quickly deviate from the acceptable range such as (i) non-self-regulating variables, example *level*, (ii) unstable variables, example *some temperatures in reactors* and (iii) sensitive variables that vary quickly in response to small disturbances, example *pressure in a closed vessel*.

How to measure? Select a sensor to balance accuracy and reproducibility, to cover the range of normal and typical disturbed operations and that provides minimum interference with the process operation and costs. *For example, prefer a low pressure loss flow sensor when compression costs are high*. Use a second sensor for extremely large ranges due to startup, large disturbances or different product specifications. The sensors should be consistent with the process environment, *for example, for flow measurements the instrument should be located downstream of sufficient straight pipe to stabilize the flow patterns reaching the instrument, at least 10 diameters upstream and 5 diameters downstream of straight pipe*. The sensors should be located to assist operators in performing their tasks and engineers in monitoring and diagnosing performance.

Sensors for control: should compensate for known nonlinearities before the measurement is used for monitoring or control. Prefer sensors that do not need calibration.

Specifics:

Temperature: prefer resistance temperature detectors, RTD. Prefer narrow span transmitters instead of thermocouples. Expected error: thermocouples, ±0.5 % of full scale or 0.3–3 °C; RTD, ±0.2–0.5 % of full scale; thermistor, ±0.5 % of full scale or 0.2–1 °C.

Pressure: expected error: Bourdon gauge, ±0.1–2 % of full scale; pressure transmitter, ±1 % full scale; linear variable differential transmitter, ±0.5 % full scale.

Differential pressure: prefer precision-filled diaphragm seals or remote heads for Δp because signal depends, in part, on the density of the fluid in the sensing lines.

Flow: prefer coriolis, vortex or magnetic flow meters over orifice or venturi. Keep fluid velocity > 0.3 m s^{-1}. Expected error: orifice meter, ±1–5 % of full scale; coriolis, ±0.2 % of full scale; magnetic, ±0.5–1 % of full scale; venturi, ±0.25–3 % of full scale.

Level: prefer tuning fork, radar or nuclear or consider radio frequency admittance if the composition changes. Expected error: nuclear, ±1–2 %; ultrasonic, ±3 %; vibrating probe, ±1 cm.

Composition: expected error: relative humidity, ±2–3 %; pH, ±0.005–0.05 pH units; dissolved oxygen, ±1–5 %; oxygen, ±3 %; TOC, ±2–10 %; gas chromatograph, ±0.5–1 %.

Manipulated variables and final elements: The manipulated variable, usually flowrate, has a causal effect on a key controlled variable, can be manipulated by an automated final element, provides fast feedback dynamics, has the capacity to compensate for expected disturbances and can be adjusted without unduly upsetting other parts of the plant. The final element, usually a valve, has a causal effect on the controlled variable. The number of *final elements* should be equal to or greater than the number of measured variables to be controlled *and* we must provide an independent means for controlling every variable.

Final elements must provide the desired capacity with the required precision of flow throttling over the desired range, *usually 10–95 % of maximum flow.* The valve characteristic should provide a linear closed-loop gain *except* use a linear or quick-opening characteristics for valves that are normally closed but that must open quickly. Select the valve failure position for safety. The valve body should satisfy such requirements as required flow at 0 % stem position, plugging, pressure drop or flashing. The non-ideal final element behavior such as friction and deadband should be small, as required by each application. Control valves should have manual bypass and block valves to allow temporary valve maintenance when short process interruptions are not acceptable, however, the bypass should never compromise the SIS systems. The gain on a control valve should be > 0.5. Avoid using the lower 10 % and the upper 5, 20 or 35 % of the valve stroke. Generally select a control valve body one size less than the line size. Allow sufficient Δp across the control valve when selecting pumps (Section 2.3), compressors (Section 2.1), steam lines (Section 3.13) or flow because of Δp (Section 2.7).

For pump selection: allow the greater value of 33 % of the dynamic loss or 100 kPa.

For compressor selection: allow the greater value of 5 % of the absolute suction pressure or 50 % of the dynamic loss.

For steam lines: allow the greater value of 10 % of the absolute pressure at the steam drum or 35 kPa.

For pipe sizing with flow caused only by Δp: allow the greater value of 10 % of the pressure of the lower terminal vessel or 50 % of the dynamic loss.

For the throttling valve on the bypass for manual control, a tapered plug valve is recommended (especially for steam or erosive fluids).

Specifics

Include the same length of upstream straight run piping before control valves as is recommended for orifices. This is particularly important for rotary valves.

Globe valves: permissible stroke range: 10–90 %; sliding stem gives highest sensitivity and the actuator stem feedback position more closely represents the final element position but not for fouling or solids.

Rotary ball valves: permissible stroke range: 20–80 %. Δp across the valve is small but account for the pipe reducers needed for installation. Sensitive to the need for upstream straight pipes.

Rotary butterfly valves: permissible stroke range: 25–65 %.

Signal transmission: Use sensor-matched transmitters. All measurements used for control should be transmitted using high level 4–20 mA transmission.

Feedback controller: Match the type to the process requirements:
Manual: when close regulation of the variable near its desired value is not required and when knowledge is required that is not available in the control computer.
On/off: when the system responds slowly to disturbances and close regulation of the variable is not required.
Regulator: a self-contained P-only regulator offers low-cost and reliable control of noncritical variables that can be permitted to deviate for long periods from their set points.
PID: the proportional-integral-derivative algorithm is used for most single-loop applications.

PID control: Always determine the form of the PID algorithm being used. Select the PID modes:

P – always; *I* – when the controlled variable should return to its set point; *D* – for processes that are undamped, unstable or have a very large ratio of dead time/time constant.

Tuning: typical values are $\mathbf{K_c = 0.8/K_p}$, $\mathbf{T_I = 0.75\ (\theta + \tau)}$ and $\mathbf{T_d = 0.0}$. The proportional band ($100/K_c$) and the reset time ($1/T_I$) can be calculated from these. When fine tuning, observe the behavior of both the controlled and manipulated variables. Always use an implementation that includes anti-reset windup protection for when the manipulated variable encounters a constraint. Use an implementation that includes initialization that starts automatic control smoothly from the last manual condition. The digital execution period should be fast with respect to the feedback dynamics, with $\Delta t \leq 0.05\ (\theta + \tau)$ where possible.

Filtering: For control variables: when filtering is needed, use a first-order filter to reduce the effects of high frequency noise. Do not excessively filter measurements unless absolutely necessary. The filter time constant (τ_f) should be $< <$ feedback dynamics.

For monitoring variables: use filters to reduce the noise at frequencies higher than the effects being observed. Recall that "averaging" is a filter that is often performed by the DCS historian features.

Loop pairing: Where options exist, pair the most important variables with manipulated variables that have fast feedback dynamics and large capacity. Select pairings that give good integrity. For example, select direct loop designs in which controllers will function when other controllers are not functioning. Usually avoid nested loops (a condition when some controllers will not function when other controllers are in manual or have their outputs saturated) that do not have individual causal relationships. Select loop pairings that require little adjustment to controller tuning when the controllers switch from manual to automatic.

Tune the most important loops aggressively and the less important, loosely (when interaction is unfavorable).

DCS structure: All safety and basic regulatory controls should be highly reliable and executed in the lowest level digital processes with direct input and output wiring contact signals with the process. Should the LAN fail, the control system should provide means for the personnel to operate the process, possibly through displays and adjustable parameters at the digital processor. The system should provide redundancy (with automatic switching) for key elements such as processors, power supplied and LANs. The operator consoles should provide sufficient access to displays and adjustments for off-normal operations like startup and disturbances.

Implementation hierarchy: Implement process control in a hierarchy based on frequency of decision making. First level is protection (safety, environment and equipment), the second level is smooth operation and stability (through control of flows, temperature, pressures and levels and through alarms). The third level is product quality. The fourth level is profitability. The final level is for monitoring and diagnosis.

- *Good Practice*

Mount probes and flow meters in vertical lines to prevent solids accumulation. Provide insertion lengths at least ten times the diameter for thermowells.

- *Trouble Shooting*

"Instrument readings do not make sense": transmitter range specified incorrectly/range not set to specification/measured variable $>$ 100% of range/reported range does not include static conditions/flashing or two-phase flow through flowmeter or control valve/installed incorrectly/wrong sensor/air leaks/plugged purge lines/purge liquid boiling in purge line/wrong controller tuning.

Sensors: Most sensor faults are due to improper selection, incorrect installation or adverse environmental conditions. *"Wrong signal":* fouled or abraded sensors/bubbles or solid in fluid/sensing lines plugged or dry/electrical interference or grounding/sensor deformed/process fluid flow $<$ design or laminar instead of turbulent flow/contamination via leaky gaskets or O rings/wrong materials of construction/unwanted moisture interferes with measurement or signal/high connection or wiring resistance/nozzle flappers plugged or fouled/incorrect calibration. *"Wrong input":* sensor at wrong location/insufficient upstream straight pipe for velocity measurement/feedback linkages shift or have excessive play/variations in pressure, temperature or composition of the process fluid.

Control valves: *"Leaks":* erosion/[corrosion]*/gaskets, packing or bolts at temperatures, pressures and fluids that differ from design. *"Cannot control low flowrate":* miscalibration/buildup of rust, scale, dirt. *"Cannot stop flow":* miscalibration/damaged seat or plug. *"Excessive flow":* excessive Δp. *"Slow response":* restricted air to actuator/dirty air filters. *"Noise":* [cavitation]*/compressible flow. *"Poor valve action:"* dirt in instrument air/sticky valve stem/packing gland too tight/faulty valve positioner. *"Equipment suddenly underperforms":* bypass partially or fully open.

Transmitters: *"Erratic or fluctuating output":* vibrations/improper orientation/loose connections.

1.5
Rules of Thumb about the Context for a Chemical Process: Batch versus Continuous

1. Batch if < 0.1 kg/s product.
2. Batch if it is difficult to scale up process: design data missing.
3. Batch for multiproduct.

1.6
Rules of Thumb about the Context for a Chemical Process: Heterogenous Phase contacting

Often two phases are needed in process equipment. It is convenient to summarize here some of the key characteristics of such two-phase systems. Here we consider gas–liquid, GL, liquid–liquid, LL, and particulate systems.

1.6.1
GL Systems

GL contactors are used for direct contact heat exchange, Sections 3.7, 3.8 and 3.9; for distillation, Section 4.2; absorption, Section 4.8; stripping, Section 4.9; gas scrubbers, Section 5.2; for a wide variety of reactors. For such contactors it may be useful to know the following:

1. the usual superficial gas velocity.
2. the mass transfer coefficient for the gas phase, for the liquid phase, mm s^{-1}; or the mass transfer coefficient times the area, l/s.
3. the surface area per unit volume.
4. the liquid holdup $(1-\varepsilon)$.
5. for the liquid phase, the bulk/film volume ratio = relative volume of bulk liquid to the mass transfer film at the sur-

face, δ^+. For example, for a dry foam that consists mainly of film then $\delta^+ = 1$; whereas for bubbles rising in a bubble column $\delta^+ = 4000$ to 10 000. This parameter is important for reactor design with GL reactions.

6. the Sherwood number, Sh, for mass transfer, typically 10–25.
7. the oxygen transfer rate, OTR, for air–water systems. Typical air flow is 15–50 $\mathrm{Ndm^3/s^1\ m^3}$ liquid . The symbol [ ] means that this value was calculated from other data given in the table.

Table 1.1 summarizes such values. The values given are general; for specific applications they will differ. For example, the area/volume for bubble columns varies depending on the direction of flow. The relationship between the bubble area, bubble diameter, gas concentration in the liquid phase and the power input are given in Figs. 1.1 and 1.2.

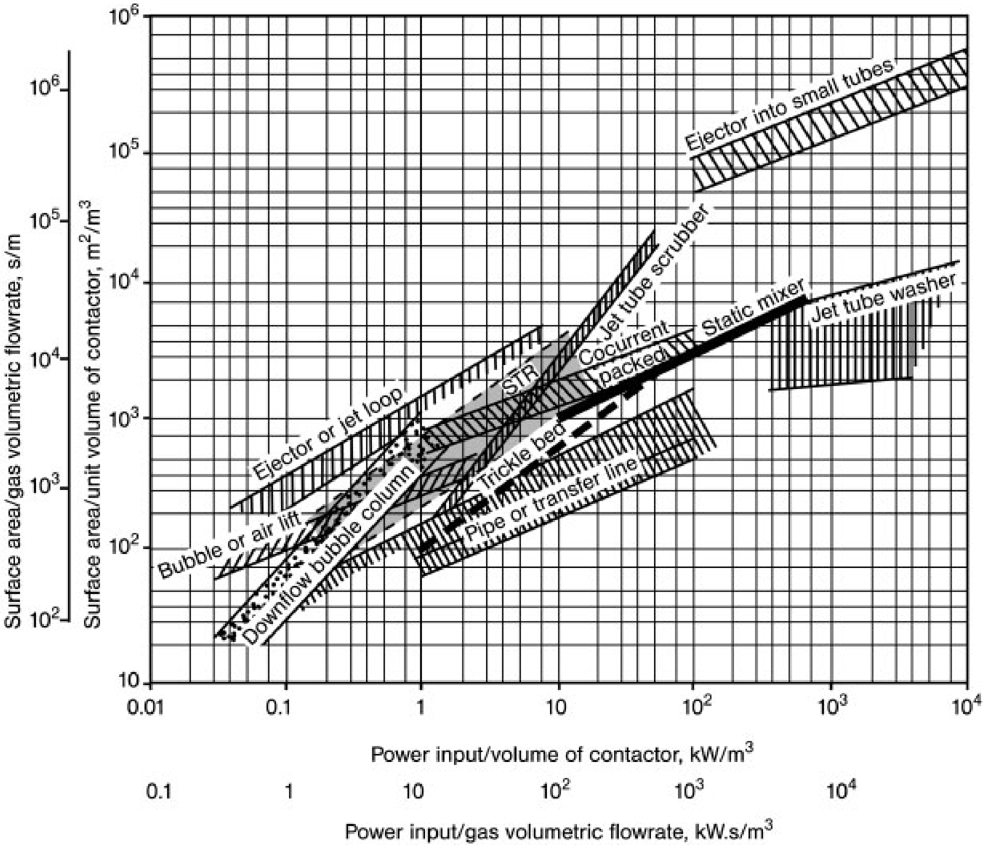

Figure 1.1 Surface area versus power input for gas–liquid contactors.

Table 1.1 Some characteristics of GL contactors.

	Gas vel. m/s	k_G; mol/s m^2 MPa (mm/s)	k_L, mm/s	k_L a, 1/s	a, m^2/m^3	L holdup (1–ε)	Bulk/ film vol. ratio, δ^+	Sh	OTR		
									g O$_2$ s^{-1} kW^{-1}	mol O$_2$ s^{-1} m^{-3}	g O$_2$ s^{-1} m^{-3}
Pipe contactor, gas injection into liquid flowing in tube; vertical tube.	0.01–0.5	5–80	0.2–0.5	0.02–1	50–2000	0.05–0.95					0.28
Pipe contactor, horizontal and coiled tube		5–40	0.1–1	0.005–0.7	50–700	0.05–0.95					
Pipe contactor, gas into liquid via ejector into a tube					40000–500000						
Static mixer in tube	1–2			0.1–3	1000–7000				0.9		
Bubble column, with gas sparged at bottom; counter current. H/D > 10	0.01–0.3	5–20 (10–50)	0.1–0.6	0.005–0.25 (0.05–0.15)	20–1000 but usually 50–700	0.6–0.98	4000–10^4	400–1000 (10^3–10^4)	0.2–0.66	0.03–0.045	[0.9–1.3]
Bubble column, cocurrent. H/D > 10					50–400						
Bubble column, with gas diffuser at bottom; H/D > 10				0.0008					0.45		

Table 1.1 Continued.

	Gas vel. m/s	**k_G; mol/s m^2 MPa (mm/s)**	**k_L, mm/s**	**k_L a, 1/s**	**a, m^2/m^3**	**L holdup ($1-\varepsilon$)**	**Bulk/ film vol. ratio, δ^+**	**Sh**	**OTR**		
									g O_2 s^{-1} kW^{-1}	**mol O_2 s^{-1} m^{-3}**	**g O_2 s^{-1} m^{-3}**
Bubble column, with diffuser plus turbine H/D > 10				0.005–0.08	200–600				0.2–0.66 [0.95]	0.06–0.12	1.6–3.3 [2.5–2.9]
Bubble column, packed[a]	0.01–0.2	5–20	0.1–0.4	0.005–0.12	100–300	0.5–0.7					
Bubble column, air lift, internal loop	0.2–0.8			0.05–0.15	300–1000	0.7			0.3–1.2	0.03–0.3	2.8 [3.3]
Bubble column, air lift, external loop				0.01–0.06							
Bubble column, air lift, via jet loop (jet nozzle reactor)			0.4	0.2–1.2	200–5000 usually 1000–2000	0.7			0.5–1.7 [0.55]	0.08–0.1	2.8 [2.5–3.2]
Spray, gravity	0.5–3	5–20 (10–50)	0.07–0.15	0.0007–0.015	10–150	0.05; 0.02–0.2	2–10	10–25			
Spray, Venturi scrubber	0.7–1	(10–30)	0.7		1000–7000	< 0.3					
Spray, plunging jet				0.2–1.2					0.25–0.9 [1.3]		3.3
Spray, circulating nozzle loop									0.6 [0.14]		0.8

Table 1.1 Continued.

	Gas vel. m/s	k_G; mol/s m^2 MPa (mm/s)	k_L, mm/s	$k_L\,a$, 1/s	a, m^2/m^3	L holdup (1–ε)	Bulk/ film vol. ratio, δ^+	Sh	OTR		
									g O_2 s^{-1} kW^{-1}	mol O_2 s^{-1} m^{-3}	g O_2 s^{-1} m^{-3}
Tray column, without downcomers	0.5–3		0.10–0.40		100–200	0.15–0.7	40–100	200–600			
Tray column, sieve, with downcomers	0.3–2.5	5–60 (20–200)	0.10–0.50	0.01–0.4	75–500; usually 100–200	0.15–0.7			1–1.1 [0.92]		2.8
Tray column, bubble cap, with downcomers		5–20	0.1–0.5	0.01–0.2	100–400	0.1–0.95					
Packed[a] **column**, random, countercurrent	1–2.2	0.3–20 (10–50)	0.06–0.2	0.0004–0.07 (0.01–0.8)	20–350	0.05–0.15	10–100 (10–40)	10–100	[0.27]		0.14
Packed column, cocurrent		1–30	0.04–0.6	0.0004–1	400–3000	0.02–0.95					
Packed, trickling filter					45–115						
Packed, structured					100–300	0.02					
Thin film, gravity	2		0.04–0.12		3–100	0.01–0.15	10–200	10–50	0.55	[0.025]	0.8
Thin film, trickle bed	> 0.01				100–3500	0.05–0.25					
STR, gas sparged into stirred tank	0.001–0.02	(10–50)	0.03–0.5	0.003–0.8 (0.05–0.2)	50–4000 usually 300–600	0.2–0.95 usually > 0.7	150–800 (10^3–10^4)	100–500	0.3–0.66 [1.5]	0.06–0.12 [0.03–0.1]	1.6–3.3 [2.5–2.9]

Table 1.1 Continued.

	Gas vel. m/s	k_G; mol/s m^2 MPa (mm/s)	k_L, mm/s	k_L a, 1/s	a, m^2/m^3	L holdup (1–)	Bulk/ film vol. ratio, δ^+	Sh	OTR		
									g O_2 s^{-1} kW^{-1}	mol O_2 s^{-1} m^{-3}	g O_2 s^{-1} m^{-3}
STR, tubular impeller									0.4		
STR, turbine									0.55–0.7		
STR, propeller									0.2–0.3		
STR, gassing tube									[0.7]		4.1

[a] Characteristics of packing are given in Table 1.2.

Table 1.2 Illustrative characteristics of packing.

		a, m^2/m^3	Void volume for gas, ε
Structured packing		100–300; usually 250	0.98
Raschig ring	ceramic	190–770	0.62–0.68
	metal	370	0.9
Saddle	ceramic	250–540	0.65–0.72
	plastic	80–120	0.9
Ring, slotted	ceramic	50–260	0.78–0.85
	metal	90–350	0.9–0.95
Tellerette		190	0.93
Intallox		120–620	0.78–0.8
Uniform spheres		depends on size	0.33–0.4

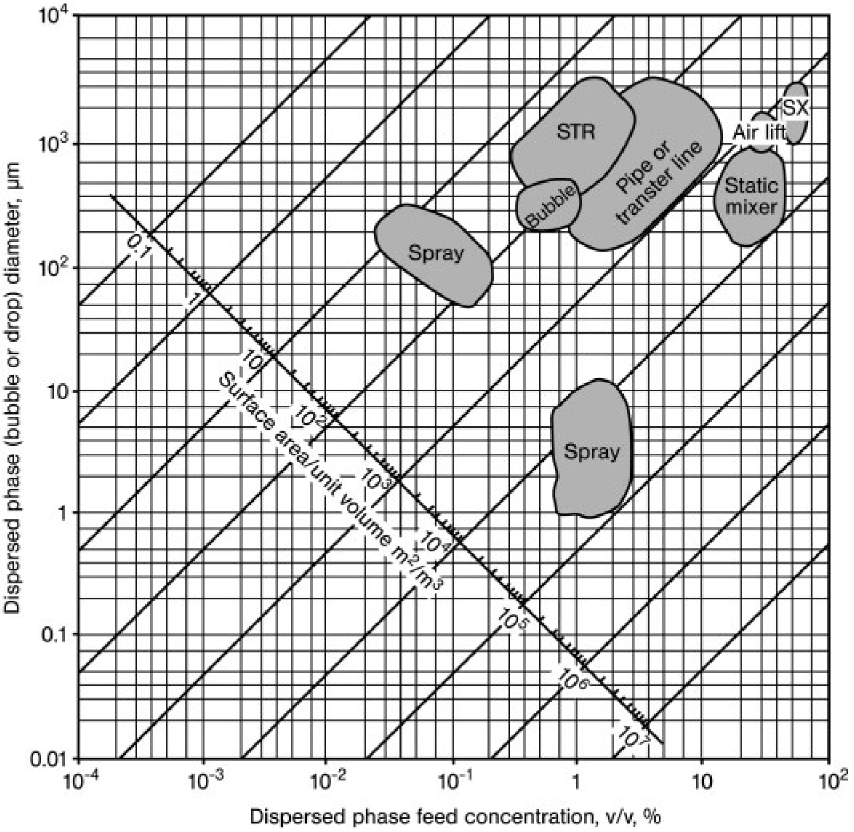

Figure 1.2 Surface area per unit volume for dispersed systems.

Figure 1.1 shows the surface area generated as a function of power input per unit volume of “contactor” for a number of different GL contactors. Also shown in Fig. 1.1 is the surface area/gas volumetric flowrate as a function of the power per gas volumetric flowrate. Thus, the lowest values for an ejector or jet loop column correspond to a, the surface area/gas volumetric flowrate, = 1000 s/m and a power per gas volumetric flowrate = 1 kW s/m^3.

1.6.2
LL Systems

LL contactors are used for direct contact heat exchange, Section 3.6; for solvent extraction, Section 4.10; for a wide variety of reactors; and for mixing, size decrease and size increase. For such contactors it is useful to know the following:

1. flow characteristics of the continuous and discontinuous phases: plug flow PF versus mixed flow MF or partial mixed flow PMF.
2. the residence time of the continuous phase.
3. the mass transfer coefficients.
4. holdup of the dispersed phase.

Table 1.3 summarizes this information.

Figure 1.2 shows the surface area as a function of the diameter of the dispersed phase bubbles, drops or particles and concentration. Also shown are illustrative regions for different contexts.

1.6.3
GLS Systems

For gas–liquid plus solids systems, the solids could be solid catalyst, inert solid or microorganisms. Most of the GL contacting systems given in Table 1.2 and Fig. 1.1 can handle the additional solid (although for Fig. 1.1, for GLS systems where a solid is suspended, about the same power input is needed for STR and cocurrent packed columns but about 1.2 to 2 times the power input is needed for suspension bubble columns). For GLS systems, additional contacting devices include fluidization, trickle beds and monolithic contactors. The diameter of catalytic or inert solid is usually about 1–200 μm. The amount of particulate catalyst or microorganisms in a reactor is 0.001–0.01 m^3 catalyst/m^3 reactor volume. For catalytic systems, the mass transfer coefficient across the liquid film to the solid, k_{La}, is as follows: bubble contactors: 0.25 1/s; jet loop and plunging jet: 0.1–1 1/s; trickling filter 0.06 l/s; sparged STR and fluidized bed: 0.1–0.5 1/s[1].

For GLS systems for bioapplications, the solid is a microorganism. Some conditions are given in Table 6.9. The biofilm areas for fluidized and trickle beds are 2000m^2/m^3 vessel and 200m^2/m^3 vessel, respectively.

Table 1.3 Characteristics of LL contactors.

	Continuous phase	Disconti-nuous phase	Residence time of continuous phase	Superficial velocity, mm/s		k_L, mm/s	a, m^2/m^3	Dispersed phase hold-up	Power input, kW/m^3
				dispersed	both				
Static mixer	PF	PF	limited			0.001–0.10	100–20000	0.05–0.2	
Spray column, gravity	MF		limited	3–8		0.001–0.10	7–75	0.05–0.1	
Gravity RTL					0.3–0.55	0.01–0.02			
Karr pulsed column; reciprocating plate					8–11	0.01–0.02			
Tray, sieve column					7.5–16	0.01–0.02			
Tray, pulsed sieve				2–20	3–4	0.01–0.02	75–3000		
Packed, random	PF	PF	limited	1–20	3–8	0.001–0.025	7–75	0.05–0.1	
Packed pulsed					3–4	0.01–0.02			
Stagewise packed with stirrer, Scheibel					3–4	0.01–0.02			
Thin film, gravity				0.02–0.8		0.01–0.02	5–120		
RDC					4–8	0.01–0.02			
STR with agitator	MF	PMF	wide variable	0.15–4		0.003–0.025	400–3500	0.01–0.5	0.2–3
Multistage STR				2–20		0.001–0.01	100–2500		
Inert gas agitation	MF	PMF	wide variable			0.001–0.003	1000–10000	0.05–0.3	

1.6.4

Particulate Systems

For particulate systems, the key characteristics are the surface area per unit volume (as shown in Fig. 1.2), the diameter of the particles (related to a commonly used method called Mesh size), the void volumes for a packed bed of particles and parameters to measure dry particle flowability.

Particle characterization includes measures of the size of particles and the flowability of dry powders. Size is frequently expressed as **Mesh size** (US Std is similar to Tyler). Mesh 325 = 44 µm; 270 = 53 µm; 230 = 63 µm; 200 = 74 µm; 170 = 88 µm; 140 = 105 µm; 120 = 125 µm; 100 = 149 µm; 80 = 177 µm; 70 = 240 µm; 60 = 250 µm; 50 = 297 µm; 40 = 420 µm; 30 = 590 µm; 20 = 840 µm; 18 = 1000 µm; 14 = 1410 µm; 12 = 1680 µm; 10 = 2000 µm; 8 = 2380 µm; 4 = 4760 µm.

Void volume between particles. For particulate systems it is useful to know the void space, or interstitial volume, ε, in particulate systems. For a loose pack of uniform spheres, $\varepsilon = 0.45$; for a tight pack of uniform spheres, $\varepsilon = 0.33$; for fresh catalyst bed $\varepsilon = 0.42$ decreasing to 0.38 as the bed ages; for uniform tower packing with sphericity of 0.4, $\varepsilon = 0.66$. The void volume decreases as the particle distribution deviates from uniformity. For example, for a log normal distribution with a geometric standard deviation of 3, then for a tight pack of spheres $\varepsilon = 0.18$.

For the flowability, use the Johanson indices to characterize dry particles: (see also related topics conveying solids, Section 2.6, storage bins, Section 10.3, mixing, Section 7.4) These indices are:

Arching index [m], **AI**, = diameter of the circular exit hole from a hopper that will ensure that an arch collapses in a conical bin or circular mixer, values range 0–1.2 m.

Ratholing index [m], **RI**, = diameter of the circular exit hole from a hopper that will ensure rathole failure and cleanout in a funnel-flow bin or mixer, values range from 0–9 m. (If **RI** > 3 then likely “lumps”.)

Hopper Index [degrees], **HI** = the recommended conical half-angle (measured from the vertical) to ensure flow at the walls. Usually add 3° to account for variability. Values range 14–33° with 304 s/s.

Flow ratio index [kg/s], **FRI** = maximum solids flowrate expected after deaearation of a powder in a bin. (Measures consistency: small **FRI** for fine, highly compressible particles; large **FRI** for particles > 400 µm, incompressible, very permeable.) Values range 0–90 kg/s.

Bin density index [Mg/m^3], **BDI** = bulk specific mass expected in a container full of solids or, in a mixer, when mixer stops and solid is allowed to deaerate. Values 0.3–1.6 Mg/m^3.

Feed density index [Mg/m^3], **FDI** = bulk specific mass at the conical hopper or mixer’s discharge outlet. Values are 1–60% $<$ **BDI.**

Chute index [degrees], **CI**, = recommended chute angle (with the horizontal) at points of solids impact. Values = angle of slide. values = 20–90°. High values suggest particles stick to sides of mixer or bins.

Rough wall angle of slide [degrees], **RAS** = angle (relative to the horizontal) that causes continual sliding on a solid on an 80-grit sandpaper surface with a pressure of 140 kPa-gauge. Values 20–35°. Approximately equal to the angle of repose.

Adhesion angle index [degrees], **AAI** = difference between angle of slide (with horizontal) after an impact pressure of 7 MPa or (**CI** –10°) and the angle of slide without impact pressure.

Spring back index [%], **SBI** = percentage of solids that spring back after consolidation.

From these definitions, we can quantify terms commonly used to describe particles.

Free flowing particles: **AI** < 0.06 m; **RI** < 0.3 m.

Moderately free flowing: **AI** < 0.18 m and mixtures of particles whose angle of repose or **RAS** differ by $> 4°$.

Moderately cohesive: 0.15 m $<$ **AI** < 0.3 m; **RI** < 1 m; **FRI** > 0.225 kg/s and mixtures of particles whose angle of reposes or **RAS** differ by $< 3°$.

1.7
Rules of Thumb about the Context for a Chemical Process: Economics

The rules of thumb refer to capital cost estimation, operating cost estimation, financial attractiveness and financial reports.

1. Total fixed *capital cost estimation*, total fixed capital investment = 3 to 10 (4 to 5 usual) × FOB major pieces of equipment. The factor decreases as more alloys are used in the process.
2. For capital cost estimation: for carbon steel fabrication: L+M factors are in the range 1.5 to 3 with corresponding L/M ratios of 0.15 to 0.65 with 0.4 being usual. The factor decreases for alloys.
3. For capital cost estimation: FOB equipment cost increases with size^n where n is usually 0.6 to 0.7. When $n = 1$ there is no capital cost advantage to building larger; increase size or capacity by duplicating equipment.
4. For capital cost estimates:

(FOB × L+M*) + installed instruments + buildings required within the battery limits = L+M cost.

L+M cost + taxes, freight and insurance at 15–25 % FOB cost = physical module cost, PM.

PM + offsites + indirects for home office and field expenses at 10–45 % of L+M with small values for large projects = bare module or BM cost.

BM cost + contractors fees (3–5 % BM) + contingency for unexpected delays (10–15 % BM) + design contingency for changes in scope during construction (10–30 % BM) = fixed capital investment or total module, TM, cost.

To the fixed capital investment might be added, as needed:

- (i) royalties and licenses.
- (ii) land (1–2 % TM).
- (iii) spare parts (1–2 % TM).
- (iv) legal fees (1 % TM).
- (v) working capital: for year-round commodities (15–20 % TM); for seasonal commodities (25–40 % TM). For specialties and pharmaceuticals (15–40 % of sales).
- (vi) startup expenses (15–40 % TM).

5. *Operating cost:* for 1 laborer/shift, 4.2 laborers are needed.
6. Operating cost: selling price = 1.3 to 3 × raw material cost with usual value of 2.
7. For *financial attractiveness:* risk-free interest: 6 to 18 % depending on the industry, usually 6 %; additional incremental interest for risk: low risk = add 1 to 5 % to the risk-free value; medium = add 5 to 20 %; high = add 20 to 100 %.
8. For financial attractiveness: Discounted Cash Flow, DCF, and payback time are approximately related as follows: DCF = 100 % $\approx$ 1 year payback time; 50 % $\approx$ 2 years; 33 % $\approx$ 3 years; 16 % $\approx$ 5 years.
9. For *financial reports:* current ratio: 1.5 to 2; cash ratio: 1; debt to assets: 0.35; times interest earned: 7 to 8; inventory sales: 7 to 9; average collection period: 45 days; fixed assets turnover: 2 to 3; total assets turnover: 1 to 2; profit margin on sales: 5 to 8 %.

1.8
Rules of Thumb about the Thinking Process: Problem Solving and Creativity

Here are 18 rules-of-thumb about the process of problem solving:

1. *Be able to describe your thought processes as you solve problems.*
2. *Know the systematic stages for each cycle of the problem solving process.* (i) **Engage** with the problem or dilemma, listen, read carefully and manage your distress well. Say “I want to and I can!” (ii) **Analyze** the data available and classify it: the “goal, the givens, the system, the constraints and the criteria”. (iii) **Explore:** build up a rich visual/mental picture of the problem and its environment; through simplifying assumptions and rules of thumb explore the problem to see what is really important; identify the *real* problem. (iv) **Plan** your approach to solving the problem. (v) **Carry out**

the plan and (vi) **Check** the accuracy and pertinence of your answer. Did it answer the problem? satisfy the criteria? Reflect on the problem solving process used to discover new insights about problem solving. Elaborate on the answer and the problem situation to discover answers to other problems, to extend the solution to other situations and to relate this problem experience to other technical problems you have solved in the past. This systematic approach is **not** sequential. Skilled problem solvers bounce back and forth between the stages. A typical approach would be engage, analyze, engage, explore, engage, explore, analyze, engage, explore, plan, engage and so on.

3. *Focus on accuracy* instead of speed.
4. *Actively write things down.* Make charts, draw diagrams, write down goals, list measurable criteria and record ideas in brainstorming.
5. *Monitor and reflect.* Mentally keep track of the problem solving process and monitor about once per minute. Typical monitoring thoughts are "*Have I finished this stage? What have I discovered so far? Why am I doing this: if I calculate* this, *what will* this *tell me? What do I do next? Should I reread the problem statement? Should I recheck the criteria?*" Typical reflections that look back on the process and attitudes used are: "*This didn't work, so what have I learned? Am I focusing on accuracy or am I letting the time pressures push me to make mistakes? Am I managing my stress? I can do this! Am I monitoring the process?* "
6. *Be organized and systematic.*
7. *Define the "real" problem by creating a rich perspective of the problem.* During the **Explore** stage, see the problem from many different points of view. Be willing to spend at least half the total available time exploring the problem. Ask many *what if* questions. Try to bound the problem space. Identify the *real* problem, by asking a series of *why?* questions to generalize the situation. This **Explore** activity of identifying the *real* problem is the heart of the problem solving process. Rules of thumb are used extensively during this activity.
8. *Be flexible.*
9. *Use your creativity effectively.* Defer judgment; be succinct; list 50 ideas in 5 minutes; create a risk-free environment; encourage free and forced association of ideas; piggy back on previous ideas; use **triggers,** such as those listed below, to maintain the flow of ideas; don't be discouraged, in the last two minutes of a ten minute brainstorming session, over 85 % of the ideas are not practical. But, spend time identi-

fying the treasures among the 15 %; use impractical and ridiculous ideas as "stepping stones" to innovative, practical options. Some **triggers** include: function, physical uses, chemical uses, personal uses, interpersonal uses, aesthetic uses, mathematical or symbolic properties, SCAMPER checklist (an acronym for Substitute, Combine, Adapt, Modify, minimize, and maximize, Put to other uses, Eliminate, and Reverse), wildest fantasy, how nature does it, *what if?* in the extremes, boundary exploration, functional analogy, appearance analogy, morphology, symbolic replacement, juxtaposition, personal analogy, reversal, book title, letter-word-sentence and famous paintings.

10. *Critically assess the knowledge and data used.* Too often we *hope that the data* are applicable. A colleague, in designing a petrochemical plant, was unable to locate the physical properties of the organics. He decided to assume they were the same as water and hope that they would work out. Just a short time spent in critical assessment of this assumption would have saved six months of wasted work. Too often we accept data from the published literature; yet about 8 % of data published are mistakes. "The temperature into the hydrodealkylation reactor is > 1150 °C" states one reference. This should read > 1150 °F. A major handbook published an incorrect value of the heat of vaporization through several editions. Check the data coming from computer programs and simulations. Check the physical property package estimates.
11. *See challenges and failure as opportunities for new perspectives.*
12. *Spend time where it benefits you the most.* Use Pareto's principle (80 % of the results can be found from 20 % of the effort). Find the key 20 %.
13. *Be an effective decision maker.* Express the goal as *results* to be achieved rather than as *actions* to be taken. Make decisions based on written criteria that are explicit and measurable. Distinguish between *must* criteria (the process must have an internal rate of return of 35 %) and *want* criteria (the process might have the potential to be licensed). Reject options that do not meet the *must* criteria. Use a rating system to score the *want* criteria.
14. *Be willing to risk.*
15. *Manage stress well.* Solving problems is stressful. When we initially encounter a problem we experience distress because of the uncertainty. Such stress tends to immobilize us. When we successfully solve a problem we experience the joy and exhilaration of stress (that distracts us from checking and

double checking that our answer is the best). A certain level of stress motivates us. Excessive stress makes us make mistakes. Data suggest that operators with confidence and training working under high stress make 1 mistake in 10 actions. Operators with confidence and training who receive feedback about their actions and are under low stress make 1 mistake in 1000 actions. Although these data refer to plant operators, the same trends can be extended to suggest how stress, lack of reflection and feedback might interfere with engineering practice. High stress would be a rating of over 450 on the Holmes–Rahe scale (Holmes–Rahe, 1967).

Ten suggested approaches to managing stress include: worry only about things over which you have control, include physical exercise as part of your routine, have hobbies and destimulating activities in which you can lose yourself, plan ahead, avoid negative self talk, rename the events that are stressful to you, build a support system, be decisive, put the situation into perspective and use role models of others who have succeeded.

16. *Manage your time well.* Covey (1989) offers excellent suggestions on time management. Identify problems and decisions according to their importance and urgency. Shift the important situations to being nonurgent. Learn to say "No".
17. *Understand your strengths, limitations and preferred style.*
18. *For problems involving people, use the 85/15 rule.* 85 % of the problems occur because of rules and regulations; 15 % of the problems are because of people.

1.9
Rules of Thumb about the Thinking Process: Goal Setting

Here are nine guidelines for setting goals:

1. We function better if we have goals about what we want to achieve, to prevent from happening and to preserve.
2. Carefully define specific goals; do not accept vague ideas of what you want to achieve, prevent or preserve.
3. Clearly differentiate between symptom, cause, issues, solutions and goals.
4. Know when your goal has been achieved by writing out measurable criteria when you create your goal.
5. Be willing to spend at least half the allotted time in defining the real goal. Be unwilling to impulsively replace a goal with an immediate answer.
6. Use eleven characteristics to describe goals: (i) are written; (ii) are in the context of **here and now**, and **now and then**;

(iii) are problems/goals and not symptoms; (iv) have owners; (v) have stakeholders (people affected by your goals); (vi) have three parts: goals, criteria and resources and these form an achievable, consistent set. (vii) are written in observable and unambiguous terms; (viii) have criteria that are written in measurable terms; (ix) are expressed as "results" and not actions; (x) are achievable in that the resources of time, talent and money are actually available; (xi) are flexible in that they can be changed when conditions change.

7. Use an approach, such as the *Why? Why? Why?* approach, to create the **here and now** context and provide the big picture in which the goal resides. Flexibly identify the **real** problem.
8. Put the goal in the context of **now and then** to ensure that it meets your overall long-term mission and vision.
9. List a range of stakeholders and classify them as being family, friends, fence-sitters, fighters, factions or foes. Rate how each is affected by your achievement of your goal.

1.10
Rules of Thumb about the Thinking Process: Decision Making

1. Consider what you want to achieve, avoid and preserve. Focus on the results you want to achieve and not the actions. Use the guidelines in Section 1.9 to create goals.
2. Generate many options to achieve the goals.
3. Decisions are made based on published, measurable criteria.
4. Criteria can usually be classified into "Must" and "Want". The Must criteria must be satisfied for the option to be viable.

1.11
Rules of Thumb about the Thinking Process: Thermal Pinch

1. Always add heat at the lowest possible temperature level; always remove heat at the highest possible temperature level.
2. Above the pinch, supply heat; below the pinch reject heat.
3. Do not transfer heat across the pinch.

1.12
Rules of Thumb about the Thinking Process: “Systems” Thinking

Three elements contribute to system thinking: physical, chemical, thermal and information dimension; the financial dimension and the people dimension.

- *Physical, Chemical, Thermal and Information Dimension*

Each chemical process is a system in which individual pieces of equipment are hooked together to function effectively and efficiently to convert feedstocks into products.

1. Startup and shutdown: can the system be started up? Were cold startup conditions considered? What happens to the air inside all vessels? What happens to the liquid and vapor inside all vessels when we shut down? Were all the vessels and lines cleaned correctly? dirt removed? rust removed? liquid puddles removed? was junk left in the lines or vessels?
2. Failure occurs: how does the system respond when corrosion, cycling, leaks, catalyst breakdown occur? power failure? barrier failure?
3. Interaction with the environment: weather, elevations, leaks, environmental impact. See related topic Section 1.16.
4. Material carry over and impact on downstream and upstream operations: fouling, foaming, corrosion, cycling, leaks, recycle, and stable emulsion formation.
5. Information carry over and interaction: cycling.

- *Trouble Shooting*

In trouble shooting “systems”, some common issues include: solvent losses somewhere in the system; fouling; foaming or stable emulsion formation that causes equipment malfunction and carry over; corrosion; and/or recycle causing a buildup of species that may not be removed from the system without adequate bleeds or blowdown. Although, in this book, many of these are considered for specific pieces of equipment, we include a generic consideration of some of these here. In this listing, the concept or symptom is shown in parentheses and italics, for example, *“Foaming”*, followed by possible causes separated by/. If the cause is not a root cause, then it is represented in square bracket plus an *, [foam-promoting systems]*. These intermediate causes are then listed alphabetically .

“Corrosion” or corrosion products: see Section 1.3.

“Foaming”: [foam-promoting systems]*/[foam-promoting contaminants]*/[gas velocity too fast]*/[liquid residence time too low in GL separator]*/antifoam addition faulty (wrong type or incorrect rate of addition)/mechanical foam breaker not rotating/baffle foam breaker incorrectly designed or damaged/overhead disengaging space insufficient height/[liquid environment wrong]*.

"Fouling": velocity too slow/[particulate fouling]* for example, rust, corrosion products from upstream, scale from upstream units, oil, grease, mud or silt/[precipitation fouling]* for example sodium sulfate, calcium sulfate, lignin/[biological fouling]* species present such as algae and fungi/[chemical reaction fouling]*, example coke formation and polymerization fouling/[flocculation fouling]* or destabilization of colloids, for example asphaltenes or waxes from hydrocarbons/corrosion products for this unit, see Section 1.3/[solidification fouling]* or incrustation such as the freezing on a solid layer on the surface or crystallization/[condensation fouling]* such as vaporization of sulfur.

"Solvent loss": [physical losses]*/[entrainment]*/[solubility]*/[vaporization]*/[degradation]*/[solvent loss elsewhere]*/**for glycol dehydration** typical losses = 0.015 mL m^{-3} gas treated.

"Stable emulsion formation": contamination by naturally occurring or synthetic surfactants: example, lubricating oils/contamination by particulates: example, products of [corrosion, see Section 1.3]*, amphoteric precipitates of aluminum or iron/pH far from the zpc/contamination by polymers/temperature change/decrease in electrolyte concentration/the dispersed phase does not preferentially wet the materials of construction/coalescence-promoter malfunctioning/improper cleaning during shutdown/[rag buildup]*/[Marangoni effects]*.

[Amine concentration too high or too low]:* if too high, lack of equilibrium driving force/if too low, insufficient moles of amine for the feed concentrations.

[Biological fouling]:* temperature, pH and nutrients promote growth of algae and fungi/biomaterials present.

[Chemical reaction fouling]:* high temperature causing cracking/high wall temperatures/stagnant regions near the wall or velocity too slow < 1 m/s reactant droplets preferentially wet the solid surface/addition of "fouling suppressant" insufficient, for PVC polymerization oxalic acid or its salt or ammonium or alkali metal borate/pH change.

[Column operation faulty]:* plugged tray or packing/poor distribution for packing/liquid flowrate < minimum required for loading/[gas velocity too fast]*/collapsed trays or packing/plugged or broken distributors/[foaming]*/solvent – stripper overhead temperature too low. See also Section 4.2.

[Condensation fouling]:* wall temperature too cold/contamination in the vapor.

[Degradation]:* chemical reaction: for **amine:** reacts with CO_2 and O_2; forms stable salts: for **glycol:** reacts with O_2/thermal decomposition: for **amine:** surface temperatures > 175 °C; for **glycol:** surface temperatures > 205 °C.

[Electrokinetic effects]:* hydrocarbon liquid velocity too high/conductivity too low/pipes not grounded.

[Entrainment: GL]:* demister plugged, missing, collapsed, incorrectly designed/[flooding]*/[foaming]*/inlet liquid line or distributor undersized or plugged/poor distribution for packing/liquid flowrate < minimum required for loading/[gas velocity too fast]*/solvent feed temperature > specifications/[column operation faulty]*/tray spacing < design. See also GL separators Section 5.1.

[Entrainment: L-L]:* fluid velocity too high; example > 10 L/s^1 m^2/liquid distributor orifice velocity > design; **for amine:** for amine > 0.8 m s^{-1}; for hydrocarbon

> 0.4 m/s[1]/faulty location of exit nozzles/interface level wrong location/faulty control of interface/no vortex breaker/exit fluid velocities > design/insufficient residence time/[stable emulsion formation]*. See also decanters, Section 5.3.

[Flocculation fouling]:* pH at the zpc/low concentration of electrolyte/colloids present/[electrokinetic effects]*.

[Foam-promoting contaminants: soluble]:* naturally occurring or synthetic polymers/naturally occurring or synthetic organics > C10; example lube oils, asphaltenes/naturally-occurring or synthetic surfactants; **for amine systems:** the surface active contaminants include condensed hydrocarbons, organic acids, water contaminants, amine degradation products/faulty cleaning before startup; surfactants left in vessels.

[Foam-promoting contaminants: solid]:* [corrosion products, see Section 1.3]*; for **amine systems:** iron sulfides; amine salts formed from organic acids + hydrocarbons/faulty cleanup before startup; rust left in vessel/dust/dirt/particulates.

[Foam-promoting systems]:* those that foam naturally: methyl ethyl ketone, aerobic fermentation, textile dyeing foam more readily than > amine and glycol absorption systems and latex stripping > amine, glycol and Sulfolane strippers > slightly foam promoting: fluorine systems such as freon, BF_3/systems operating close to the critical temperature and pressure/surface tension positive system/[Marangoni effects]*.

[Flooding]:* see Section 4.2.

[Gas velocity too fast]:* temperature too hot/design error/[foaming]*/vessel diameter too small for gas flow/column pressure < design/trays or packing damaged or plugged giving excessive vapor velocity/upstream flash separator passing liquids: feed contaminated with excessive volatile species/stripping gas fed to column too high/input stripping gas flowmeter error/design error.

[Inaccurate sensing of the interface]:* instrument fault/plugged site glass.

[Liquid environment wrong]:* pH far from the zpc/electrolyte concentration too low.

[Liquid residence time too low in gas liquid separator]:* interface height decreases/[inaccurate sensing of interface]*/turbulence in the liquid phase/flowrate > expected/sludge settles and reduces effective height of phase/inlet conditions faulty.

[Marangoni effects]:* nonequilibrated phases/local mass transfer leads to local changes in surface tension and hence stable interfacial movement.

[Particulate fouling]:* filter not working or not present/contaminant in feed/upset upstream/erosion.

*[Physical losses]**: leak to atmosphere/purges for sampling/sampling/heat exchanger leak/pump seal flushes/filter changes/leaks in piping, fitting, valve stems, gaskets and pumps.

[Precipitation fouling giving scale or sludge*]*:* soluble species present in feed/temperature high for invertly soluble/temperature too low for incrustation or crystal formation.

[Rag buildup]:* collection of material at the interface: naturally-occurring or synthetic surfactants: example, lubricating oils/particulates: example, products of [corrosion, see Section 1.3]*, amphoteric precipitates of aluminum/naturally occurring or synthetic polymers.

[Solidification fouling]:* wall temperature too cold/missing insulation/cold spots on wall/sublimation.

[Solubility losses]:* liquid-liquid systems: system pressure < design/**for amine:** concentrations > 40 % w/w/system temperatures too high.

[Solvent contaminated]:* carryover from upstream equipment; example oil from compressor; brines, corrosion inhibitors, sand, [corrosion products, see Section 1.3]*/oxygen leaks into storage tank/inadequate corrosion control, example low pH causing corrosion/degradation via overheating, ex hot spots in reboiler tubes or fire tubes/ineffective filters/ineffective cleaning before startup/for amine absorbers: corrosion products/FeS/chemicals used to treat well.

[Solvent loss elsewhere]:* upstream units, for example **for glycol dehydration:** glycol dumped with hydrocarbons separated in upstream flash drum/loss in downstream solvent stripper.

[Solvent stripping inadequate]:* not enough steam in stripper/incorrect pressure in stripper/[foaming]*/[solvent contaminated]*/contaminated feed: **for amine strippers:** other sulfur species causing high partial pressure/leak in the feed preheater contaminating feed with stripped solvent.

[Vaporization losses]:* system pressure < design/for **amine:** concentrations > 40 % w/w/system temperatures too high.

- *The Financial Dimension*

The operation is a financial system: profit and attractive returns on investment occur because revenues brought in exceed payments for equipment, personnel, feedstocks and operating supplies. Processes are built and operate because the return on financial investment relative to the risk exceeds other investment opportunities of similar risk. See related topic Section 1.7.

- *The People Dimension*

The corporation is a system of people in which the specialized knowledge, skills and attitudes of individuals are used and rewarded. See related sections on performance review Section 1.21 and leadership, Section 1.22.

1.13
Rules of Thumb about the Thinking Process: Design

The six general guidelines are:

1. Decide batch versus continuous; Section 1.5.
2. Set goals, see suggestions in Section 1.9 about how to do this.
3. Preliminary scouting of reactor configuration and conditions.
4. Explore mass recycle.
5. Explore separations. Try to avoid adding separation agents.
6. Explore energy integration. Use the principles of thermal pinch, Section 1.11.

1.14
Rules of Thumb about the Thinking Process: Process Improvement

See also Section 1.15.

Ten prioritized suggestions are listed.

1. Change control: change set points, tighten control variations of key variables.
2. Better inventory control and reduction of fugitive emissions.
3. Identify realistic needs for process units.
4. Optimize the reactor/separation system.
5. Optimize cycle time; improve control.
6. Debottleneck by relocation.
7. Debottleneck by redesign and/or equipment replacement.
8. Manage the recycle of heat and mass networks; use pinch technology.
9. Substitute reagents, catalysts, solvents, additives.
10. If waste byproducts are formed reversibly, recycle to extinction.

1.15
Rules of Thumb about the Thinking Process: Trouble Shooting

From experience, the typical faults are given for first-time startup, for ongoing processes and for different types of equipment. Also listed are mistakes commonly made by operators.

1. For *first time startup*, the faults encountered are usually:
   75 % mechanical electrical failures such as leaks, broken agitators, plugged lines, frozen lines, air leaks in seals
   20 % faulty design or poor fabrication, such as unexpected corrosion, overloaded motors, excessive pressure drop, flooded towers
   5 % faulty or inadequate initial data
2. For *ongoing processes*, the faults encountered are usually:
   80 % fluid dynamical for ambient temperature operations
   70 % materials failure for high temperature operations
3. *Frequency of failures* based on type of equipment:
   17 % heat exchangers
   16 % rotating equipment: pumps, compressors, mixers
   14 % vessels
   12 % towers
   10 % piping
   8 % tanks
   8 % reactors
   7 % furnaces

4. *Mistakes operators* make are usually:
   90 % no action taken when some kind of action is needed.
   5 % took corrective action but moved in the wrong direction, for example, knew the temperature should be changed but increased it instead of decreased it.
   5 % took corrective action on the wrong variable, for example, changed the temperature when the composition should have been changed.
   The most likely operator error is misreading technical instructions.

1.16
Rules of Thumb about the Thinking Process: Environment, Waste Minimization, Safety

Eight suggestions are:

1. Consider issues of safety, waste minimization, environmental concerns and health hazards together. Consult http://webbook.nist.gov and http://toxnet.nlm.nih.gov. Use HAZOP.
2. Identify the target or goal.
3. Eliminate the source: eliminate, substitute, recycle. Try to avoid adding agents.
4. Minimize the source: intensify, substitute, attenuate.
5. Minimize the impact.
6. Isolate the source.
7. Isolate the impact.
8. For safety, the calculated reaction temperature to form stable products (CART) is a better predictor of hazard than H_{react}. See also Section **6.1**, reactors.

1.17
Rules of Thumb about the People Part of Engineering: Communication

About the Product

1. Audience, audience, audience.
2. If the message isn't communicated, it's the speaker's or writer's fault.
3. Include advance organizers.
4. Include transitions.
5. Always give a summary.
6. Five criteria are audience, content, organization, style and format.

About the Process

1. Use an audience-based and not writer-based approach. The content addresses questions the audience wants answered (instead of incorrectly dumping the information the writer knows on the subject with the length of the topic being proportional to the time spent researching the topic); the organization is hierarchical instead of incorrectly using chronological or historical.
2. Effective communication is linked with clear thinking and problem solving skills.
3. There is not a universally-applicable template that fits all communications; each communication must answer the questions of the audience.
4. Confusion is welcome because it forces the writer to check and rethink his/her thinking.
5. Let the ideas flow rather than trying to polish the first and only sentence created.
6. When revising, be willing to rethink and rework the whole structure if it doesn't meet the needs of the audience, instead of incorrectly working only on polishing the grammar and style.
7. Develop a coherent written plan.
8. Spend most of the time planning and revising.
9. Be willing to discard sections already written instead of incorrectly hoping to use anything written somewhere.

1.18

Rules of Thumb about the People Part of Engineering: Listening

1. Focus attention on the talker.
2. Avoid distracting behavior.
3. Show respect and frequently acknowledge through appropriate body language and "ahums" and reflecting statements.
4. The process can be modeled as Sensing, Interpreting, Evaluating and Responding or SIER. That is, we sense the message, we internally interpret what is being communicated; we evaluate the message in the context of the situation, our feelings, needs and goals and we select how to respond.
5. Sensing the message is complex because about 55 % of the message is communicated by body language, 38 % by tone and 7 % by the words.
6. Listening is about four times slower than thinking.

7. About 80 % of our waking hours are spent in verbal communication; with about half of that spent listening.
8. Untrained listeners understand and retain between 25–50 % of a conversation.
9. Only about 5 % self-assess themselves as being highly skilled listeners.
10. Attend: posture is inclined forward and open, facing squarely approximately 1 m apart; no distracting behavior and eye contact is called "soft focus" (contrasted with looking away or staring).
11. Tracking/following: provides minimal encouragement (for example, *"Tell me more", "sure.." "Oh..", " Then.."*) and infrequent questions (for example, prefer "*What?"* questions to "*Why?*") and attentive silence.
12. Reflecting is responding with a concise restatement of the content and feelings expressed in the listener's own words. That is, include the content and feelings of what was said, express it in the listener's own words without adding new ideas or leaving out ideas. Some example approaches include saying "*As I understand it..*" or "*Are you saying that..*" Reflecting is usually used when someone is very emotional, or when you see differences developing between you and the other person, when there is disagreement, when the talker seems to be confused or when the talker needs encouragement that his/her contribution is valuable.

1.19
Rules of Thumb about the People Part of Engineering: People Skills

Nine suggestions are given.

1. Become aware of your own uniqueness and personal style, and how this might differ from the style of others
2. Honor the seven fundamental rights of individuals, RIGHTS. **R**, to be Respected; **I**, Inform or to have an opinion and express it; **G**, have Goals and needs; **H**, have feelings and express them; **T**, trouble and make mistakes and be forgiven, **S**, select your response to the expectations of others and claim these rights and honor these in others.
3. Avoid the four behaviors that destroy relationships: Contempt, Criticism, Defensiveness and Withdrawal/stonewalling
4. Trust is the glue that holds relationships together.
5. Build trust by *keeping* commitments to yourself and others; *clarifying* expectations that you have of yourself and of others;

showing personal integrity, honesty and loyalty to others, especially when they are not present; *apologizing* promptly and sincerely when you know you are wrong; *honoring* the fundamental RIGHTS listed above and avoiding the destroyers (listed above in point 3); *listening and understanding* another's perspective; *being truthful*; and *accepting others* "warts and all".

6. Destroy trust by the reverse of the Builders of trust listed above, and by selectively listening, reading and using material out of context; not accepting experience of others as being valid; making changes that affect others without consultation; blind-siding by playing the broken record until you've eventually worn them out or subtly make changes in the context/issues/wording gradually so that they are unaware of what is happening until it is too late.
7. The *12: 1 rule* applies to rebuilding relationships. 12 positive experiences are needed to overcome 1 negative experience.
8. To improve and grow we need feedback about performance. Give feedback to others to encourage and help them; not for you to get your kicks and put them down. Focus on five strengths for every two areas to improve on.
9. Be skilled at responding assertively. *"When you... I feel.. adjust by..."*

1.20
Rules of Thumb about the People Part of Engineering: Team and Group Skills

A team is more than a collection of individuals. In a collection of individuals each has a personal goal, trusts self, rarely exposes personal skills, decisions are usually not made and conflict is ignored. In a team, all unanimously accept the goals, each is clear about role, trust and involvement are high, personal unique skills are used effectively, decisions are made by unanimity and the team has methods for handling conflict. Our meetings and teamwork improve when we strive for the characteristics of teams. Some target behaviors of teams are:

1. Have a purpose for each team and each meeting. Set and follow agendas to get the task done.
2. No agenda; no meeting! If a meeting must be held without a circulated agenda, then spend the first five minutes creating the agenda.
3. The team must have the correct membership and resources to achieve the goal.
4. The team should be empowered and accountable to achieve the goal.

5. Both Task (getting the job done) and Morale (feeling good about the group work and about how you have interacted with the other group members) are important.
6. Have a chairperson whose role is to facilitate the team process: thinks through the tasks to be done, decides on the need for a team meeting, identifies the time and place for the meeting, sets and circulates an agenda, facilitates the meeting and start and stops the meeting on time.
7. Chairperson and leadership are different; different people may become leaders at different times.
8. Group evolution tends to follow a pattern described by such descriptors as *"forming, storming, norming and performing"*.
8. Establish group norms of behavior early. Agree on terminology and procedures for problem solving, for brainstorming, for decision-making, the role of the chair in decision-making, *for example, vote or no vote;* roles, minutes and records of decisions, *for example, format, details, who prepares them, are they circulated? use for subsequent meetings*; how to handle conflict and level of intervention; combating "group think"; how to handle emergencies and criteria and procedures for asking a member of the group to resign.
9. Each has a clear idea of roles and of group norms.
10. When groups are functioning effectively, about 70 % of the time is spent on the task; 15 % on morale building activities and 15 % of task process activities.
11. The products from groups or teams are improved when members have different "styles".
12. The quality of decisions, product, task is improved if group members offer different perspectives, disagree and seem to introduce conflict into the process. The trick is to manage the apparent conflict well.
13. Use Sanderson's 20 minute rule. After 20 minutes either make a decision or identify the key information that is missing and arrange to obtain that information for the next meeting.
14. Document decisions and record **Actions** with "what", "who" and "when". *Example:* "Decide to compare two optional control strategies" **Action:** JBM by March 30.
15. Systematically assess the quality of the teamwork and set goals for improvement. Table 1.4 is an example form for such an assessment.

Table 1.4 Assessment of group activity.

Purpose of meeting: ____________________
Date of meeting: ____________________
Chairperson: ____________________
Agenda circulated ahead of time, yes ☐
Meeting started on time, yes ☐;.
Meeting ended on time, yes ☐
start delayed ____ min.

- As a group, by consensus, agree on a rating for Task and Morale.

Task: Problem defined, many issues and hypotheses explored, criteria listed and the issues prioritized. Refrained from early closure. Task carried out and looked back at the result to assess it. Group agreement as to goals. Process was active with monitoring. Completed task on time. The accuracy in the group's answer matched the time available. Group avoided contributing excessive information.

None of these behaviors		Few of these behaviors but major omissions		Most features demonstrated		All of these behaviors
☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7

Morale: Group relaxed; enjoyed working together. They gave emotional support to each other and were able to express disagreement or disappointment directly. Seven fundamental rights preserved. Members are enthusiastic and involved.

None of these behaviors		Few of these behaviors but major omissions		Most features demonstrated		All of these behaviors
☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7

- Individual Contribution to Task and Morale: Each, in turn, takes 30 seconds to describe his/her contribution to the group. This is not for discussion.

____
____
____
____

- As a group, by consensus, list the five strengths and the two areas to work on.

Group Strengths	Group Areas to work on
____________________	____________________
____________________	____________________
____________________	
____________________	
____________________	

from D.R. Woods (1995)

- *Trouble Shooting*

Trouble shooting teams

Use Table 1.4 after each meeting, set goals and celebrate achievement. Use the framework developed by Francis and Young (1979) for growth; consult Fisher et al. (1995) for more short-term ideas.

Trouble shooting team meetings

These are organized by symptom with possible corrective responses suggested for chair {C} and member {M}.

1. Problems with purpose and chairperson.

“No apparent purpose for the meeting”: {C} don’t have a meeting. {M} question the purpose of the meeting. See also Agenda and timing problems.

2. Agenda and timing problems:

“No agenda”: {M}: phone {C} and ask for agenda. Invoke “no agenda, no attendance.”/at meeting: “Perhaps the first thing we should do is to create an agenda.”/ After 5 minutes, “We seem to be lost. Could we draw up an agenda and follow that?”

“Meeting drags on and on”: {C} should have circulated an agenda with times for each item and used the 20 minute rule/{M} “Perhaps we can follow the agenda.”/{M} indicate to {C} ahead of time the amount of time you have available for the meeting and then leave at that time.

“Get off the track”: {M} seek direction, purpose, summary of progress: “Now where are we?” “Would someone want to summarize what we have done so far?” “Let’s check on the purpose of this meeting and see our progress.”/see also Behavior problems: “*Subgroups interrupting and talking”*.

“Group gets bogged down”: state problem/summarize/seek agenda clarification/ invoke 20 min rule.

“Decisions made just at the end of the meeting”: state frustration/suggest tabling/ suggest future corrective way to handle. See also Agenda and chairperson problems.

3. Behavior and participation problems

“People come into a meeting cold:” {C or M} suggest reconvene meeting when all are prepared.

“Late arrivals”: {C} start meeting on time and continue with the agenda through the disruption of the retardee/{M} “I realize that not everyone is here but I suggest that we start. It looks like a long agenda to get through.”

“Some people do all the talking and some remain silent”: wrong membership/encourage quiet ones to contribute/ask each, in turn, to summarize his/her point of view/ask a “safe” question of the silent ones/privately check with the silent ones and reevaluate whether they need to attend./ask open ended questions/ use nominal group.

"Sub groups interrupting and talking": identify problem/suggest discussing one issue at a time and add subgroup's issues to agenda/be silent until the side conversation stops. "Thank you."/Interrupt the side conversation.
"Indecisive members, continual question asker": ask for their ideas early/redirect questions he/she asks back to him/her.

4. Conflict or apparent conflict
"Conflict because of differing views:" restate the importance and value of everyone's opinions/attempt to bring conflict into the open/summarize different views/focus on different performance or opinions and not personalities/remind of fundamental RIGHTS.
"Conflict over facts:" stop the argument, identify problem as you see it and check that that is a problem/identify facts we need clarified and probable expert.
"Conflict over values, goals, criteria, process or norms:" stop discussion, identify problem as you see it and check that that is a problem/use problem solving.
"Resistance to new ideas, we tried that before, it won't work, over my dead body, we don't have the resources": surface the resistance/honor the resistance/invoke consequence of no decision or of repeating what we've always done before/use consensus building techniques/reflect on the home turf of the objector and the impact the decision might have on them; explore if this might be brought to the group as an issue to address/root cause of most resistance is fear of change, apathy, vested interests, not invented here, negativism, overwhelmed by the enormity of proposal.

1.21
Rules of Thumb about the Context in Which We Function: Performance Review

Assessment is a judgment of the degree to which a goal has been achieved, using measurable criteria or metrics and based on agreed-upon forms of evidence.

1. Assessment is about performance not personal value or worth.
2. Assessment is based on evidence and not gut feelings.
3. Assessment is done in the context of published, observable and unambiguous goals.
4. Assessment is done in the context of published measurable criteria related to the goals.
5. Assessment is done based on agreed-upon forms of evidence.
6. Assessment should be a combination of continual and periodic and based on many different forms of evidence.

- *Trouble shooting*

"Failure to reach agreement": gut feelings used instead of evidence/evidence inadequate and or poorly presented/assessor uses this as an opportunity to "get even" or to show power.
"Frustration and anger": goals not published and or ambiguous/no published criteria/no agreed-upon forms/inconsistency between the goals and the forms of evidence/no attempt to help employee set personal goals for the next time period.
"Inadequate or inappropriate forms of evidence": misunderstanding of principles of assessment/no forms of evidence agreed-upon for some of the goals or target behaviors.

1.22
Rules of Thumb about the Context in Which We Function: Leadership

1. Know yourself: discover your unique styles; build trust by meeting commitments and keeping your word; know your many roles; know your personal goals, vision and mission; know your style of networking; strike the balance between being part of the system while retaining a position of authority; know how to support subordinates empowered to do tasks.
2. Know the environment. don't just do things right; do the right things. Know the strengths to be preserved; the areas to work on to improve and the areas to avoid.
3. Challenge the process: search for opportunities by confronting and challenging the status quo; experiment and take risks; learn from mistakes and successes.
4. Inspire a shared vision: create a vision of the future, communicate that vision to others and attract others to common purposes. We tend to under-communicate by a factor of 10.
5. Enable others to act: foster teamwork; strengthen others and share power and information.
6. Publish the vision, the goals, the milestones and measures/yardsticks/criteria to measure achievement.
7. Model the way: set by example; walk the talk; build commitment to action and understand the grieving process that some will experience as change occurs.
8. Encourage the heart: recognize contributions, link rewards with performances and celebrate accomplishment.
9. Consolidate gains and anchor the new approaches in the culture.

A leader has internal motivation, is authentic and promotes trust, brings out the best in people, seeks and learns from feedback, is curious and is a good listener.

1.23
Rules of Thumb about the Context in Which We Function: Intrepreneurship
(based on Valikangas, 2003 and Cooper, 1987)

Innovation within the corporation:

1. Create the motivation first: want to bring new products to the market. This is a high risk but vital activity.
2. Ensure management commitment: concrete, consistent and explicit.
3. Set concrete and achievable goals with resources to support.
4. Create the infrastructure: a process (and reward system) to identify winners, develop a plan and market the new product. A major cause of failure of new products is marketing: underestimating the competition, and overestimating the potential.
5. Build into the process elements to manage risk: if the uncertainty is high, keep the stakes low, reduce uncertainty by using an incremental decision process, buy information to reduce the uncertainty, don't be afraid to stop one project when it now looks unattractive.
6. Cultivate innovation routines and name your innovation ambassadors. Often select a person to lead who has a Kirton KAI inventory (Kirton, 1976) value of about 100 to 110, midway between the adaptors 85–100 and the innovators 110–130.
7. Evaluate progress effectively, purposefully and regularly.
8. Focus on quality first.

1.24
Rules of Thumb about the Context in Which We Function: Entrepreneurship

Creating your own company:

1. Need technology, creativity, courage and business know-how.
2. Kondratieff wave of world-wide prosperity with highs 1860, 1920, 1960.
3. Major innovation cycles 6 years; next major high 2035.
4. Cost of invention, R&D 5–10 %.
   Conception and product design 10–20 %.
   Fabrication & process development 40–60 %.
   Fine tuning and manufacturing 5–10 %.
   Market launch 10–25 %.
5. Business plan, business plan, business plan.
6. Use the rules of thumb for intrapreneurship that are pertinent.

7. It takes 15 years between a company's inception and a viable product entering the market.
8. One in ten brilliant start-up ideas is successful financially; nine are not.
9. The startup idea should be patented.
10. The startup company should have an address, a board, a CEO, a business plan and a bank account.

For more see Doyle (1983) and Curran (1991).

1.25
Rules of Thumb about the Context in Which We Function: e-Business

e-Business uses the same business and marketing principles, combined with ideas related to change management and building consumer trust.

1. Start small.
2. Write out your goals and focus on the goals.
3. Develop consumer trust by knowing your product and customers, through careful design of the consumer–vendor interface.
4. Astutely select the informational content: create value, be credible, be transparent, show company values and the real people behind the company by providing names and photographs, describe the company's achievements, address security concerns up-front, provide reassurance in case of fraud, give a privacy policy and let consumers be in control of their data.
5. Continue to build trust after the purchase by giving different means of contact, by handling customer inquiries efficiently, and by giving feedback about the order. Provide great after sales service.
6. Take your best people on developing e-business and take care of them.
7. Spend at least 10 % of the advertising budget on on-line advertising.

1.26
Rules of Thumb about Mentoring and Self-management

Whether it is managing yourself or giving advice as a mentor to someone else, here are my personal suggestions.

1. Complete jobs as if you were a consultant. Do them well and on time. Indeed, add a few extras.

2. Learn to say No.
3. Keep a balance in your life among physical, emotional, spiritual and intellectual.
4. Honor yourself; feel good about yourself.
5. Keep a sense of humor.
6. Be positive.
7. Be trustworthy and build trust.
8. Do things right the first time.
9. Keep good records. For example, sign and date all calculations.
10. Keep good personal files. Become an active member in professional organizations, subscribe to professional journals and set time aside to read and keep up to date.
11. Learn the company's economics.
12. Use the above ideas to learn how to cope well with the current "instant response" expectations. The e-mail and the internet have fostered a new concept of time. Many now seem to leave things to the last minute; expect instant response and incorrectly select some action, even if they know it is not the best choice. We need to re-establish that it takes time to do jobs well; we need lead times for meetings. Be patient with yourself and with others.
13. Apply the main principle of networking: "give to your network five times for any single time you want to draw on your network." (Woods and Ormerod, 1993)

1.27
Summary

The major focus of this book is on the rules of thumb for selecting, rough sizing, costing, operating and trouble shooting many different types of equipment used in chemical processes. This is **what** the book is about. The introduction and details of the organization of these rules of thumb were given in Section 1.1. Details for each major type of equipment are given in Chapters 2 to 10.

However, in selecting equipment engineers need information about the properties of materials, corrosion, process control, batch versus continuous and economics. We refer to this as the context for the chemical process and provided rules of thumb for each in Sections 1.2 to 1.7, respectively.

Rules of thumb for the thinking process used, or **how** engineers design and practice their skills, were given in Sections 1.8 to 1.16. More specifically the emphasis was on problem solving, goal setting, decision making, thermal pinch, systems thinking, process design, process improvement, trouble shooting and health-safety-environment issues, respectively.

Sections 1.17 to 1.20 summarized the rules of thumb for the people part of engineering (communication, listening, interpersonal skills and team work).

Finally, the context in which engineers function (performance review, leadership, intrepreneurship, entrepreneurship, e-business and self management) were described in Sections 1.21 to 1.26.

References

Cooper, R.G. (1987) "Winning with New Products" Gage Publishing, Agincourt, Ontario.

Covey, S.R. (1989) "The Seven Habits of Highly Effective People", Simon and Schuster, New York.

Curren, Alex (1991) "Making Ventures Succeed: Earning the Right to Succeed in Business," Curren Publishing, Oakville, Ontario.

Doyle, D.J. (1983) "Making Technology Happen", Doyletech, Kanata, Ontario.

Fisher, K. et al. (1995) "Tips for Teams", McGraw Hill, New York.

Francis, D., Young, D. (1979) "Improving Work Groups: A Practical Manual for Team Building", University Associates, San Diego.

Holmes, T.H., Rahe, R. H. (1967) "The Social Readjustment Rating Scale," J. Psychosomatic Res., Aug., 213–218.

Kirton, M. (1976) "Adaptors and Innovators: a description and measure", J. Appl. Psychol., 61, no. 5, 622–629.

Valikangas, Liisa (2003) " Manage Innovation as a Corporate Capability" Chem. Eng. Prog., Jan. pp. 64 –69.

Woods, D.R., Ormerod, S. D. (1993) "Networking: How to Enrich Your Life and Get Things Done" Pfeiffer & Co., San Diego.

2
Transportation

The fundamentals for fluid movement are that fluids move because of (i) a pressure difference; (ii) a density difference; (iii) gravity and (iv) boundary movement. These are expressed, on the macroscopic level, as Bernoulli's equation. Resisting the momentum transfer (fluid flow) is friction. We express the friction as a *friction factor* and correlate it with the Reynolds no. Centrifugal pumps are often selected to pump liquids; pumps operate on their head capacity curve showing decreasing head with increasing capacity. In this chapter we consider gas moving (pressure, and vacuum service), liquid moving, gas–liquid, liquid–solid or slurry and solid conveying. Ducts and pipes are discussed in Section 2.7. Storage, including bins and hoppers, is considered in Chapter 10.

2.1
Gas Moving: Pressure Service

- *Area of Application* (M)

Fans: 0.1–30 kPa; 1–10^5 dm^3/s.
Blowers: 10–300 kPa; 1–10^3 dm^3/s.
Rotary screw compressors: 20–2500 kPa; 10–10^4 dm^3/s.
Centrifugal compressors: 20–30 000 kPa; 200–3×10^5 dm^3/s.
Reciprocating piston compressors: 30–400 000 kPa; 5–10^4 dm^3/s. Usually economical for > 6 MPa and < 150 dm^3/s or any discharge pressure and flows < 100 dm^3/s.
Axial compressors: 20–2000 kPa; 4×10^3–10^6 dm^3/s.

- *Guidelines*

Fans: Power: up to 7.5 $kW/m^3/s$. For fan air-conditioning package units: 13.5 Ndm^3/s per m^2 of floor area. For the process area, allow 13.5 Ndm^3/s per kW for refrigeration; for office space, × 3; for stores, × 7. Allow 0.5 L/s of cooling water/kW of refrigeration. Related topic Section 3.12, refrigeration.
Blowers, centrifugal: Power: up to 125 $kW/m^3/s$.
Blowers, rotary lobe: maximum pressure ratio 2:1.

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Compressors:

adiabatic pV^k = constant

isothermal pV = constant

polytropic pV^n = constant: for uncooled internally $n > k$; for internally cooled $1 < n < k$ with $n \approx k$.

Heat capacity ratio, $k = c_p/c_v = 1.04$ for gases with molar mass > 100. The value of k increases to 1.67 as the molar mass decreases. For air = 1.4 and for such gases as ethylene, carbon dioxide, steam, sulfur dioxide, methane, ammonia = 1.2–1.3.

Temperature rise between feed 1 and exit 2:

$T_2/T_1 = (p_2/p_1)^{(n-1)/n}$

$(n - 1)/n = (k - 1)/k\ \eta_p$

η_p = polytropic efficiency

For each stage keep the exit temperature (T_2–298) < 120–150 °C. For diatomic gases, $k = 1.4$, this limits compression ratio (p_2/p_1) to 4; for triatomic gases, 6.

$\eta_p > \eta_{adiabatic}$. For uncooled compressors, polytropic, hydraulic and temperature rise efficiencies are the same and range from 0.7–0.8 with the usual value 0.72.

Rotary screw compressors: Power: 100–750 kW/m^3/s.

Centrifugal compressors: Centrifugal compressors deliver actual volumetric flows (cubic decimeters per second and performance should not be expressed as mass, mols or standard volumetric flow). Assume compression ratios equal in all stages. Maximum number of stages that can be on one shaft or fit in the "frame" = 8 minus 1 stage for each side nozzle. Compression ratio 2.5–4. The pressure coefficient = 0.5–0.65; assume 0.55. The pressure differential increases with increase in suction gas density (increased molar mass, suction pressure or decrease inlet temperature, decrease in k). Power: up to 7.5 kW/m^3/s. Efficiency of large centrifugal compressors: 76–78 %.

Centrifugal compressors operate between low volumetric flowrate "surge" conditions and high volumetric flowrate limited by the sonic velocity at the eye of the impeller. At "surge" conditions, the gas flows back through the compressor causing damage to the thrust bearings. The surge point is usually 0.33–0.5 of the normal operating capacity of the compressor. During startup the machine goes through the surge region. The point of surge is a minimum for a single impeller. The range of stable operation decreases 5 % with the addition of each impeller. High molar mass decreases the range of operation. Surge may be caused by system disturbance (especially changes in the molar mass of the feed gas) and insufficient flow.

Surge is related to power used.

When the molar mass of the inlet gas increases, the motor amps increase.

If the molar mass increases by 20 % and we control the suction drum pressure by recycling exit gas to the inlet (spill back control) the motor amps increase by 20 %; if control is by throttle of the suction line, the motor amps increase by 10 %. For every 10 % decrease in the total number of moles compressed, the amps load on the motor drive decreases by 5 %. For control valves on the suction or discharge side, allow a Δp of 5 % of the absolute suction pressure or 50 % of the dynamic loss, whichever is greater.

Reciprocating piston compressors: Compression ratios 1.2–6; select to keep outlet temperature < 150 °C. Efficiencies for reciprocating compressors 65 % for compression ratio 1.5; 75 % compression ratio 2, 80–85 % for compression ratio 3–6. Power: 70–1200 kW/m^3/s.
Axial compressors: Compression ratios of 1.2–1.5 per stage and 5–6.5 per machine. Efficiency 70 % except for liquid ring 50 %. Power: 35–950 kW/m^3/s.
In general:

Velocity: pump gas 30 to 60 m/s [$]
pump oxygen/chlorine: 20 m/s [S]
pump steam 60 m/s [$]

Pressure drop for gas flow through pipes: 1 velocity head per 45 to 50 Length/pipe diameter [$, J]
through shell & tube exchangers: 5 kPa/pass
through wet sieve tray: 0.3 to 0.65 kPa/theoretical stage
through packing tower: 0.2 to 0.75 kPa/m packing
moderate to high pressure distillation: 0.3–0.6 kPa/m
vacuum distillation: 0.08–0.16 kPa/m
absorbers: 0.15–0.5 kPa/m
through porous bed: 2 to 50 kPa (porous bed diam., mm)^3/m depth
through cyclone: 0.5 to 1.6 kPa.
through venturi scrubber: 0.5 to 6 kPa.
See other individual pieces of equipment for specifics.

- *Good Practice*

Usually driven by electric motors except for larger compressors that are driven by steam turbines (see Section 3.1).

Compressor exit gas: cool if temperature > 175 °C; include oil knock out pots and filter if the compressor is oil-lubricated. Don't let lubricating oil/mist collect or remain for a long time in the hot discharge side of the compressor. Instead of one compressor on load and a second on standby, use two compressors with each handling 60 % of load. Reduce recycle in compressor operations.

For **reciprocating** compressors, if temperature rise < theoretical temperature rise, suspect problems with compressor valves or piston rings. For reciprocating: consider downstream pulsation dampeners or accumulators to smooth out delivery volume and pressure, use variable speed drive, especially if load varies or unit may be oversized. To minimize vibrations for reciprocating equipment, the base should be 1.5 × mass of the machine.

Compressor inlet gas: consider the use of mist knockout pots.
Fans: Prefer backward bladed because they are self-limiting in power demand.
Blowers: For rotary lobe: when used for pressure pneumatic conveying install a check valve in the blower discharge.
Centrifugal. Good practice: allow safety margins of design speed 5 %, design head 10 % and design power 15 %. The sonic velocity decreases with an increase in gas molar mass.
Reciprocating piston: Good practice: design velocity through valves < 40 m/s.

- *Trouble Shooting*

Fans: "*Noise*": vortex, flow separation/loose bearings. "*Discharge pressure low*": instrument error/fans in series rotating in the same direction/operating below the stall point/density increase. "*Low flowrate*": instrument error/flow separation/pitch angle of blades too shallow/speed slow/required system discharge high.
Blowers: "*Discharge pressure high*": instrument error/restriction in downstream line/check valve jammed in closed position/dirty intake filter. "*Discharge pressure low*" : instrument error/slippage of the drive belts/relief valve stuck open/increasing air loss at the rotary valve due to larger clearance opening from wear/loss of air caused by larger lobe clearance in the blower due to wear/a leak, such as a ruptured hose, in a vacuum system/a ruptured bag in the downstream bag house.
Centrifugal: "*Surging*": insufficient flow/increased discharge pressure required by system/deposit buildup in diffuser. "*Discharge pressure low*": instrument error/compressor not up to speed/excessive inlet temperature/leak in discharge system. Provide separate anti-surge system for compressors operating in parallel; careful design of suction piping for double flow compressors.
Reciprocating piston: major faults: valves and piston rings: "*Knocking*": frame lubrication inadequate/head clearance too small/crosshead clearance too high; "*Vibration*": pipe support inadequate/loose flywheel or pulley/valve LP unloading system defective. "*Discharge pressure high*": instrument error/valve LP unloading system defective/required system discharge high. "*Discharge pressure low*": instrument error/valve LP unloading system defective/LP valve worn/system leakage. "*Discharge temperature high*": instrument error/LP valve worn/valve LP unloading system defective/required system discharge pressure high. "*Cooling water temperature high*" : instrument error/water flowrate low/fouled area/LP valve worn. "*Valve temperature high*": instrument error/required system discharge pressure high/run unloaded too long/LP valve worn. "*Cylinder temperature high*": instrument error/required system discharge pressure high/LP valve worn/wrong speed. "*Flow low*": instrument error/LP valve worn/valve LP unloading system defective/dirty suction filter.

2.2
Gas Moving: Vacuum Service

- *Area of Application*

Liquid-piston vacuum pump: down to 12 kPa absolute; 0.01 to 1000 kg/h air; see also Section 6.37.
Rotary sliding vane vacuum pump: down to 4 kPa abs.; 0.01 to 300 kg/h;
Wet reciprocating vacuum pump: down to 3 kPa abs.; 0.01 to 100 kg/h;
Dry reciprocating vacuum pump: down to 0.1 kPa abs.; 0.01 to 300 kg/h;
Mechanical vacuum pump: down to 0.01 kPa abs.; 0.01 to 40 kg/h;

Steam ejector:
1 stage: down to 5–6.7 kPa abs.; 0.01 to 100 kg/h air exhausted;
2 stage: down to 0.5–1.4 kPa abs.; 0.01 to 100 kg/h;
3 stage: down to 0.1–0.2 kPa abs.; 0.01 to 50 kg/h;
4 stage: down to 0.01–0.25 kPa.; 0.01 to 10 kg/h;
5 stage: down to 0.001–0.0025 kPa abs.; 0.01 to 8 kg/h;
6 stage: 0.0004 kPa abs.
Practical limit is 0.0004 kPa abs; usually 0.05–0.15 kPa abs.
For most steam ejector applications, direct contact condensers between stages were frequently used. For vacuum steam stripping, use shell and tube condensers with refrigerant at –8 to –12 °C upstream of the booster ejector with interstage dry condensers plus a liquid ring vacuum pump.

- *Guidelines*

Air leakage into unit: 50 kg/h.
Liquid-piston pump: 100 to 200 kW/m^3/s exhausted air.
Rotary sliding vane: 130 to 250 kW/m^3/s air exhausted.
Wet reciprocating: 2 to 50 kW/m^3/s air exhausted.
Dry reciprocating: 2 to 50 kW/m^3/s air exhausted.
Mechanical vacuum: 2 to 50 kW/m^3/s air exhausted.
Steam ejector:
1 stage: 0.002 to 10 kg steam/kg air exhausted/kPa abs.
2 stage: 100 kg steam/kg air exhausted/kPa abs.
3 stage: 1 Mg steam/kg air exhausted/kPa abs.
4 stage: 2 Mg steam/kg air exhausted/kPa abs.
5 stage: 40 Mg steam/kg air exhausted/kPa abs.
Steam ejector, general:
down to 10 kPa abs., 1 to 200 kg/h air; 1.3 kg steam/kg air exhausted/kPa abs.
down to 30 kPa abs., 1 to 20 kg/h air exhausted; 0.1 kg steam/kg air exhausted

The compression ratio of the first stage ejector is set primarily by the intercondenser cooling water temperature.

Assume the discharge pressure to atmosphere after the last stage = average barometric pressure +7 kPa. Assume motive steam = minimum steam pressure in header less 5–10 %. Pressure drop on shell side of surface condenser usually $< 5\,\%$ of absolute design operating pressure.

Related topic Section 3.9 for interstage direct contact G–L condensers, although current practice is to use surface shell and tube condensers (H).

- *Good Practice*

Liquid piston vacuum pump: cool seals with 0.03 L/s of clean cooling water at pressure at least 35 kPa greater than discharge pressure of pump.
Dry vacuum pump: size for usual discharge pressure 20–35 kPa gauge to allow for downstream discharge. Vacuum pumps run hot: 50–70 °C. Allow 30 min warmup period before putting on-line. Allow 60 min purge before shutdown. Try not to have the pump discharge into a common header. Multistage pumps

tend to run cooler than single stage. Install a check valve on the discharge. If the discharge pressure is > 35 kPa, add a positive displacement blower (designed for 6 Ndm^3/s at design conditions for the vacuum pump) with a bypass that is open for startup.

Steam ejectors: Operability of steam ejectors is very sensitive to the stability in the motive fluid (steam) pressure. Prefer vacuum pumps to steam ejectors (H). Keep diameter of pipes = diameter of inlet and discharge flanges of ejectors. As the column overhead mass flowrate increases above design, so will the column overhead pressure and vice versa. Compression ratios per ejector: 6:1 to 15:1. If inlet gas temperature < 0 °C or below the triple point of water (0.61 Pa) then add steam jacketing to cope with ice formation. Seal for the hot well: submerge > 30 cm. The volume in the hotwell between the pipe and the overflow weir should be 1.5 times the volume in the down spout sealed. Replace any nozzles or diffusers where the area is > 7 % larger than design.

- *Trouble Shooting*

Liquid piston vacuum pump: "*Noisy*": service liquid level too high/coupling misaligned. *"Capacity low"*: suction leakage/service liquid temperature too high/speed too low/seal water flowrate < design. *"power excessive"*: service liquid level too high/coupling misaligned. "*service liquid temperature high*": clogged strainer/partially closed valve/fouled heat exchanger.

Dry vacuum pump: "*Loss of vacuum*": condensation in the suction line/condensation of species from other units connected to a common exhaust header/increase in discharge pressure from restriction in downstream processing or pressure blowout in other units connected via common discharge header. "*Excessive corrosion":* for systems handling acid gas or connected to such systems via common discharge header: warmup period too short/shutdown purge too short. *"Overheating"*: low cooling water flow/fouled cooling system/inlet gas temperature > 70 °C. "*High amps.":* buildup of polymer caused by operating temperature too high/polymerizable species gain access via common discharge header.

Steam ejectors: related topic, barometric condensers, Section 3.9.

Check the last stage first and then move upstream: " *Unstable operation or loss of vacuum*": steam pressure < 95 % or > 120 % of design/steam superheated > 25 °C/wet steam/inlet cooling water temperature hot/cooling water flowrate low/condenser flooded/heat exchange surface fouled/20–30 % higher flow of non-condensibles (light end gases, air leaks or leaks from fired furnaces)/seal lost on barometric condenser/entrained air in condenser water/required discharge pressure requirement high/fluctuating water pressure. *"Water coming out of discharge"*: upstream condenser flooded.

2.3
Liquid

Overall selection and sizing factors summarized on the sizing map in Fig. 2.1. The ultimate choice is a tradeoff between the power to drive the pump and the maintenance and capital cost related to purchasing the pipe. The optimization is based on the annual operating cost of the pump–pipe system as a function of the diameter of the discharge pipe, or velocity of liquid in the discharge line optimization. This is illustrated in the lower RHS of Fig. 2.1. The analysis starts with the flowrate, the contaminants, the density and the Newtonian behavior of the liquid. The flowrate is related to the proposed liquid velocity and the diameter of the pipe. Central to all the decision making is the configuration, shown mid central in Fig. 2.1. The configuration depends on the layout of the equipment, the proximity of the pipe rack, the space available, the ergonomics and ease in maintenance, the need for and selection of instruments and control valves for process control, the length of pipe and the number and type of fittings, the vertical layout and the configuration and length of suction line. This all affects the pressure drop and the NPSH available for the pump.

The pressure drop (top LHS of Fig. 2.1) depends on the diameter, length and type of pipe and fittings, the elements for process control, the configuration, the velocity and the layout for NPSH. The latter, NPSH, depends on the vapor pressure, the temperature, the design of the vortex breaker, the NPSH required by the pump, the vertical component of the configuration. The resultant pressure drop expressed as a function of the volumetric flowrate summarizes the system needs.

The pump, shown in the lower LHS of Fig. 2.1, is selected based on the type, the rpm, the pressure the flanges can withstand, the materials of construction, seals and emissions, the coolant/lubricant and the type of drive; the housing, the rpm and the type of connection between the drive and the pump.

All these choices lead to capital and operating costs that become the objective function of the optimization, shown in the lower RHS of Fig. 2.1.

- *Area of Application* (M)

Centrifugal pumps: fluid viscosity < 300 mPa.s

end suction, single stage: 0.2 to 100 m; 0.05 to 4000 L/s; 0.05 to 0.7 kW/L/s; efficiency 40 to 60 %;

end suction, multistage: 50 to 800 m; 10 to 400 L/s; 0.2 to 10 kW/L/s; efficiency 40 to 60 %.

Peripheral pumps: 10 to 300 m; 0.1 to 2 L/s; 4 kW/L/s.

Centrifugal axial pumps: fluid viscosity < 300 mPa.s : 0.3 to 10 m; > 150 L/s; 0.1 kW/L/s.

Reciprocating pumps: fluid viscosity < 5000 mPa.s diaphragm or piston: 1 to 1000 m; < 50 L/s; 0.1 to 3 kW/L/s.

Gear pumps: fluid viscosity, usually above 10 Pa.s; 60 m; capacity depends on viscosity of liquid < 50 L/s

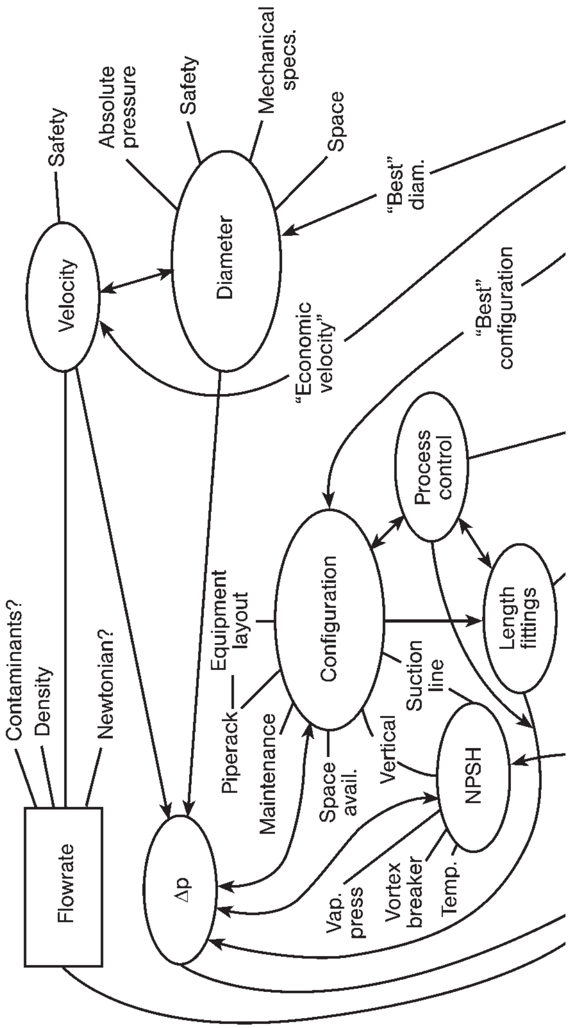
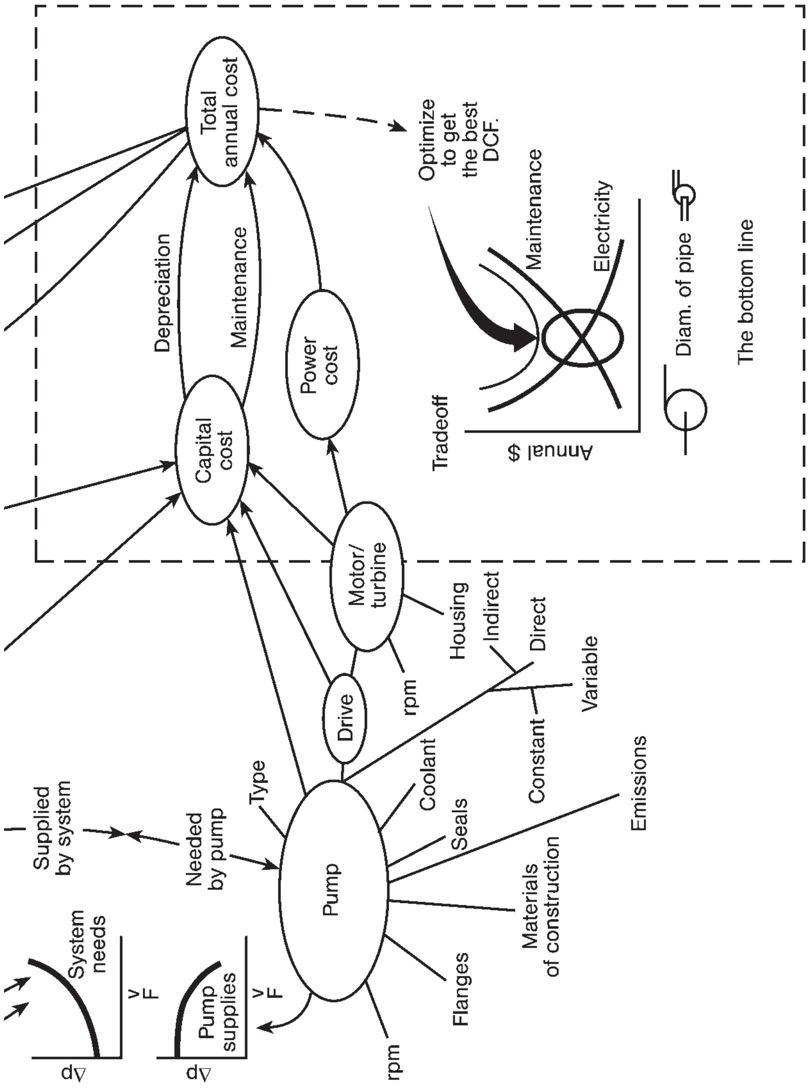


Figure 2.1 Size-map for centrifugal pumps.

Rotary screw pumps (Progressing cavity pump; moyno pump): for shear sensitive; slurries; particle diameter $<$ 5 cm., temperature $<$ 80 °C; fluid viscosity, usually above 10 Pa.s; head 0.2 to 300 m; $<$ 125 L/s; self priming; minimum foaming; pulsation-free flow. Tends to be a constant volume device.

Use centrifugal type when need to match variable flowrate with variable demand.

Use positive displacement type to supply constant flowrate relatively independent of changes in pressure; when self priming is needed, and for insensitivity to large variations in viscosity and density.



- *Guidelines*

Centrifugal: Optimum exit pipe size-selection:
pump liquids at > 1.5 m/s [\$]
hydrocarbons with low conductivity < 0.3 m/s [S]

Suction pipe of larger diameter to prevent cavitation.

NPSH requirement [m] = $\{\text{rpm}/(5400 \text{ volumetric flowrate [L/s]})\}^{1.33}$

Centrifugal pumps operate on their operating head-capacity curve. Head capacity curves are independent of the fluid although the curve drops slightly at higher capacities for higher viscosity fluids. For centrifugal pumps, the drive power required and pressure at the exit flange depend on the fluid density.

Reciprocating pumps are constant volume devices producing essentially constant "pressure."

Pressure drop for flow of liquid through pipes: 1 velocity head per 45 to 50 Length/diameter (F)

for water, 23 kPa/100 m pipe

Pressure allowance across a control valve for good operability : 20 to 50 % of the dynamic head loss or 70 to 140 kPa.

Pressure drop for flow of liquids through:
shell and tube exchanger: 70 kPa,
plate exchanger: 50 kPa,
dialysis: 50 to 10 MPa,
RO: 0.1 to 4 MPa,
Filter press: 70 kPa,
Porous bed: 0.3 to 7 kPa/m depth of bed/L/m^2 s Usual: 5 to 10 Bed Volumes per h; 1 to 10 L/m^2 s usually limit it to < 80 kPa.

Similitude for centrifugal devices: volumetric flowrate ratios = (diameter of impeller ratio) times (impeller rpm ratio); head ratios = (diameter ratio)^2 times (the impeller rpm ratio)^2; power ratio = (diameter ratio)^3 times (impeller speed ratio)^3.

Positive displacement reciprocating pumps: "head"-capacity "curve" is almost vertical: flowrate decreases only slightly with higher discharge pressure. Although we usually consider "head" for centrifugal pumps, pressure is more appropriate for positive displacement. Suction velocity < 1 m/s.

Gear pumps: power: for pressure < 20 MPa: 58 W.s/g; for pressure > 20 MPa: 120 W.s/g.

Rotary screw (moyno) pumps: shear typically 50–70 s^{-1}/100 rpm. For highly abrasive (plaster grout, emery dust slurries keep average velocity 1–1.5 m/s; mediumly abrasive (clay slurry, sludges) average velocity 1.8–3 m/s; lightly abrasive 3–4.5 m/s. Reduce rpm as capacity increases: use 1200 rpm for < 0.8 L/rev (15 L/s); < 300 rpm for > 10 L/rev (50 L/s).

- *Good Practice*

Don't let centrifugal pumps run at < 10 % of optimum design where efficiency is highest. Consider a pulsation dampener in discharge line from a reciprocating pump. Prevent flashing downstream of control valves. Control volumetric output from a positive discharge pump by a control value on a recycle line from discharge to suction. Trim the impellers for continuous turndown operation. For systems pumping edible oils include steam blowout to clear the lines.

Centrifugal pumps: head capacity curve should not be too flat if pump capacity is controlled by valve positioner. Select pump such that a larger diameter impeller could be installed later. An increase in flowrate causes an increase in required NPSH and a decrease in available NPSH.

Rotary pumps: sometimes NPSH is expressed as Net Inlet Pressure Required, NIPR, (or available NIPA), expressed as kPa absolute.

Gear pumps: Higher the viscosity, the lower the rated rpm. On the discharge install a check valve and an expansion chamber or pulsation dampener, the latter to reduce noise. For infrequent operation, operating pressure should be 20–30% $<$ rated pressure. For continual operation, operating pressure $<<$ rated pressure and rpm $<$ rated rpm. Never allow them to run dry. For startup, idle off line for about an hour.

Rotary screw (moyno) pumps: Stator has one more lobe/screw than the rotor; reduce rpm for abrasives; starting torque = 4 × initial torque. If particles are present, try to minimize the abrasion by using viscosity $>$ 5000 mPa.s. Backflow or "slip" is reduced as viscosity increases. NPSH problems are usually not important except for suction lift, pumping from a vacuum and fluid vapor pressures of $>$ 15 kPa.

- *Trouble Shooting*

Centrifugal pumps: "*No liquid delivery*": instrument error/not primed/cavitation/supply tank empty. "*Liquid flowrate low*": instrument error/[cavitation]*/non-condensibles in liquid/inlet strainer clogged. "*Intermittent operation*": [cavitation]*/not primed/non-condensibles in liquid. "*Discharge pressure low*": instrument error/non-condensibles in liquid/speed too low/wrong direction of rotation (or impeller in backwards if double suction). "*Power demand excessive*": speed too high/density liquid high/required system head lower than expected/viscosity high.

Peripheral pumps: "*No liquid delivery*": instrument error/pump suction problems/suction valve closed/impeller plugged. "*Liquid flowrate low*": instrument error/speed too low/incorrect impeller trim/loose impeller. "*Discharge pressure low*": instrument error/speed too low/incorrect impeller trim/loose impeller. "*Power demand excessive*": speed too high/improper impeller adjustment/impeller trim error.

Reciprocating pumps: "*No liquid delivery*": instrument error/excessive suction lift/[cavitation]*/non-condensibles in liquid. "*Liquid flowrate low*": instrument error/excessive suction lift/[cavitation]*/non-condensibles in liquid.

Rotary pumps: *"No flow":* instrument error/[pump not turning]*/[pump not primed]*/relief valve not adjusted correctly or dirt keeping the relief valve open/wrong direction of rotation/[cavitation]*/excessive suction lift. *"Flow $<$ design":* instrument error/rpm too low/air leak via bad seals or faulty pipe connections/[flow going elsewhere]*/[high slip]*/suction line clogged/insufficient liquid supply/[air or gas in liquid]*. *"Starts but loses prime"*: air leakage/liquid vaporizing in suction line/insufficient liquid supply. *"Noisy operation":* [cavitation]*/[air or gas in liquid]*/[mechanical noise related to pump]*/relief valve chatter/drive component noise. *"Power $>$ design":* higher viscous losses than expected/pressure $>$ design/fluid viscosity $>$ expected/fluid "sets up" or solidifies in the line or pump during shut down/fluid builds up on pump surfaces/rotating elements bind. *'Short pump service life":* [corrosion]*/abrasives present/speed and pressures $>$ design/lack of lubrication/misalignment.

Gear pumps: usually performance does not break down suddenly; gradual decrease in performance. Are particularly susceptible to cavitation and erosion. *"Low discharge pressure"*: instrument error/leakage/low drive power/faulty relief-valve setting/[internal leakage]*/[abrasion]*. *"No liquid delivery"*: instrument error/suction line clogged/drive shaft/check-valve fault. *"Low liquid delivery":* instrument error/drive power low/[internal leakage]*/[abrasion]*/[cavitation]*. *"Noisy":* entrained air in liquid/liquid doesn't drain from grooves/misaligned drive and pump shafts/faulty bearings/loose mountings/resonance because mating frequency of gears = natural frequency of gear train/rpm too high/worn parts/[cavitation]*. *"Overheating":* liquid viscosity higher than expected/liquid feed temperature too low/faults in drive system such as misaligned drive and pump shafts. *"Shaft won't rotate"*: drive system not working/material in pump not melted/temperature too low/seized pump. *"Significant oscillation in pump suction pressure":* instrument wrong/faulty control system/suction pressure set-point too low for the process. *"Pump discharge pressure oscillates":* instrument wrong/starved feed to pump/change in viscosity of feed/damaged pump internals. *"Inadequate volumetric efficiency":* decrease in viscosity/pressure in upstream process increase/worn pump.

Rotary screw (moyno) pumps: "*No liquid delivery"*: instrument error/wrong direction of rotation/insufficient suction lift/clogged inlet/air leaks on suction/faulty pressure relief valve/worn pump. *"Rapid wear":* discharge pressure too high/pump runs dry/incorrect materials of construction/speed too high for abrasives/viscosity too low for abrasives. *"Noisy"*: insufficient feed flowrate/air leak in suction/gas in feed liquid/speed too high/poor alignment. "*Excessive power"*: rpm too fast/liquid viscosity $>$ design/operating pressure $>$ design/discharge line plugged/stator expanded or swollen. "*Failure of the stator"*: bond failure (pH $>$ 10 or local hot spot)/temperature $>$ design. "*Initially OK but gradual increase in power needed":* swelling of elastomeric stator coating because of chemical attack.

[Abrasion]:* grit in liquid/[cavitation]*/pH different from design.

[Air or gas in liquid]:* [fluid vaporizes]*/air bleed missing/fluid gasifies under operating conditions/leaks in pumps or piping.

[Air lock]:* [fluid vaporizes]*/air bleed missing/fluid gasifies under operating conditions.

*[Cavitation]**: [fluid vaporizes]*/pump rpm too fast/suction resistance too high/clogged suction line/suction pressure too low/liquid flowrate higher than design/entrained gas.

[Corrosion]:* see Section 1.3.

[Flow goes elsewhere]:* relief valve faulty or jammed open/discharge flow diverted to wrong branch line.

[Fluid vaporizes]:* [NPSH supplied too small]*/fluid viscosity $>$ design/fluid temperature $>$ design/vapor pressure of fluid too high.

[High slip]:* clearance between rotors $>$ specs/worn pump/pressure $>$ design.

*[Internal leakage]**: excessive clearance between the gear and sides or end plates/[abrasion]*

[Mechanical noise related to pump]:* wrong assembly/pump distortion because of wrong piping installation/pressure $>$ rating/worn bearings/worn gears/loose gears/twisted shaft/sheared keys/worn splines.
[NPSH supplied or NIPA supplied too small]:* strainer clogged/temperature too hot/inlet line clogged/inlet line diam. too small or length too long/atmospheric pressure $<$ design.
[Pump not primed]:* valve on inlet line closed/inlet line clogged/air leaks/pump rpm too slow/liquid drains or siphons out during off-periods/check-valve missing or faulty/[air lock]*/worn rotors.
[Pump not turning]:* drive motor stopped/key sheared or missing/belt drive broken/pump shaft broken.

2.4
Gas–Liquid (Two-phase Flow)

Figure 2.2 illustrates different flow regimes for vertical cocurrent up flow, vertical countercurrent and horizontal flows. See also boilers, Section 3.3; evaporators, Section 4.1, and two-phase pipe/tube reactors, Section 6.5. Other characteristics of GL systems are given in Section 1.6.1.

- *Guidelines*

Design so that the two-phase flow is in the correct regime. Δp for two-phase flow is tricky to predict because the value depends on the flow regime, whether the individual gas and liquid flows are laminar or turbulent, on the pressure (because this affects the gas density), the mass fraction of the flow that is gas, x, and upon whether the flow is horizontal, vertical, cocurrent or countercurrent. In general the approach is that the actual pressure loss per unit length of pipe = $(\Delta p/L)_{2\phi} = \phi_G^2(\Delta p/L)_G = \phi_L^2(\Delta p/L)_L$ where the last two terms are, respectively, “corrections” to the pressure drop assuming only the gas or only the liquid are flowing in the pipe. Usually, when the mass fraction of gas, $x > 0.75$ we tend to use the former and vice versa.

The correction factors, $\phi_G{}^2$ or $\phi_L{}^2$ are usually > 1 and can be > 1000. The correlations (and approximate factors given here) apply usually for horizontal flows in the slug and bubble regime with the factors being too high for the stratified, wavy and spray flow regimes and too low for the annular flow regime.

Example values for $\phi_L{}^2$ as a function of mass fraction gas and absolute pressure are given in Table 2.1.

Thus, from Table 2.1, if the mass fraction of gas flowing in the line is about 0.2 and, if we estimated the pressure drop based on only the liquid flowrate to be 0.05 kPa, then for two-phase flow at 0.7 MPa abs we might expect the actual pressure drop to be perhaps 20 times this value or 1 kPa. If, from Fig. 2.2, we estimate that the flow regime is annular flow, then the actual pressure drop may be even larger.

Table 2.1 Correction factor, ϕ_L^2, for two-phase flow based on the liquid phase pressure drop.

Mass fraction gas	Absolute pressure, MPa abs			
	0.1	0.7	3.4	14
0.01	3.4–5	1.2–3	2	1.2
0.1	12–30	3–15	5	1.7
0.5	80–200	8–65	18	3.5

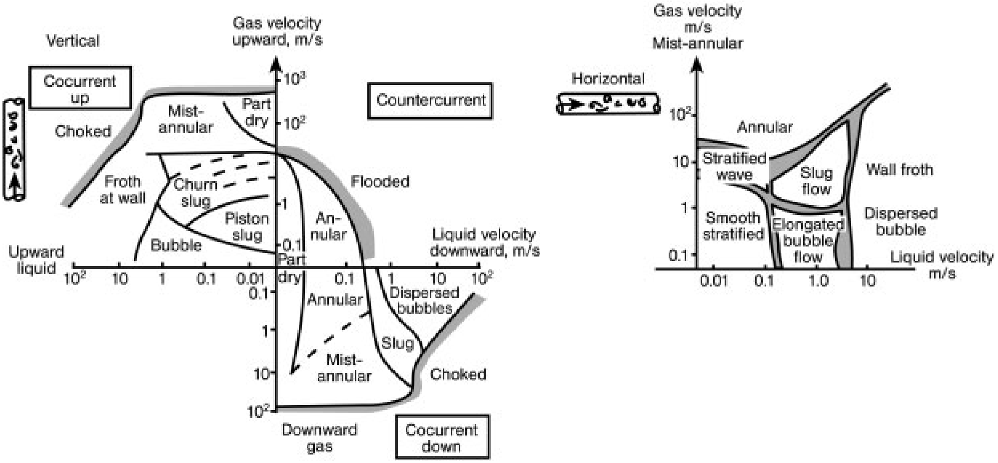


Figure 2.2 Regions for two-phase flow.

- *Good Practice*

Avoid slug flow. Avoid the use of inclined lines, use either vertical or horizontal.

Two-phase flow over a packing is given in Section 6. 17, trickle bed reactors.

2.5
Pumping Slurries: Liquid–Solid Systems

Related topic, slurry reactors, Section 6.7.

- *Area of Application* (F)

Solid concentration 25–65 % w/w; solid particle size: 20–300 μm. For finer particle size, watch for non-Newtonian behavior. For higher concentration, consider short pumping runs only; for small concentrations, beware of settling out. For larger particles, watch for settling out.

- *Guidelines*

Pumping velocity: 1 to 4 m/s, usually 1.4–1.8 m/s; 0.06 to 0.7 kW/Mg/h per km distance. Loading 0.3–1.7 kg solids/kg water. Economic tradeoff between solids loading and pumping costs. Try to use the heterogeneous flow regime and consider adjusting pH to alter stability of suspension. Minimum pipe diameter is ten times the largest diameter particle in the slurry.

- *Good Practice*

Include high pressure water purge for both forward and reverse flow at velocity > 1 m/s. Avoid dead ends and pockets. Arrange for flushing of the line with water; place nozzles on the top of the primary loop. Avoid flow restrictions, including orifices.

2.6
Solids

Choice depends on particle characteristics (size, flowability, corrosiveness, abrasiveness, handling characteristics and safety-hazard (static electrification, fumes, flammability and vertical vs. horizontal distance). Related topic Section 2.5, mixing Section 7.4 and bins for storage, Section 10.3.

Johanson's[1), 2)] definitions of terms used to characterize solid particles are given in Section 1.6.4. The important terms are **AI, RI, HI, FRI, FDI, BDI, CI, RAS** and **SBI.**

- *Area of Application* (M, F)

Belt conveyors: $< 10°$ incline; 10 to 100 m horizontal distance; capacity 3–270 kg/s. OK for most diameters of particles but not for particles that cake or are light and fluffy.
Bucket/belt elevators: usually for > 25 m vertical; 15 to 150 Mg/h; usually not for particles < 150 μm diameter particles but not for particles that cake or are light and fluffy.
Screw conveyors: 2–75 m horizontal distance; 0.3–275 kg/s. Not for particles that cake or are light and fluffy. Can be used for inclines up to 20°.
Vibratory feeder: < 20 m; 1–400 Mg/h; not for light and fluffy materials or particles < 150 μm diameter.
Apron feeder: $< 18°$ incline; 2–12 m horizontal; 10–150 Mg/h; not for particles that cake or are light and fluffy or are fine with < 150 μm diameter.
pneumatic transportation: limited by solids loading that plugs pipe.
Dilute phase: pressure: continuous: particle diameter 60 μm–0.3 cm; pressure drop < 100 kPa. Distance < 600 m. One point collection and several point delivery.

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1) J. R. Johanson, 2002, "Troubleshooting bins, hoppers, feeders", Chem. Eng. Prog. April, pp. 24–36.

2) J. R. Johanson, 2000, "Smooth out solids blending problems", Chem. Eng. Prog. April p. 21.

Dilute phase: vacuum: continuous: particle diameter 60 μm–0.3 cm; Δp pressure drop < 50 kPa. Distance < 50 m. One point delivery and several point collection. Use for hazardous solids.

Dense phase: pressure: batch: particle diameter 60 μm–0.3 cm; pressure drop 550–700 kPa. High capacity (< 10 kg/s) over long distances < 2300 m. For materials that degrade easily, are highly abrasive. Not for granular materials that have a high percentage of fines that would cause the discharge line to block.

- *Guidelines*

Caution for all: dust explosions: dust explosion potential for particle diam < 200 μm. Minimum ignition temperature > 300 °C; minimum ignition energy 10–30 mJ.

Belt conveyors: keep speeds < 1 m/s for fines; otherwise speeds in the range 2.7–4 m/s; burden thickness [cm] = 0.17 (volumetric capacity, dm^3/s)/{(Belt speed, m/s)(Belt width, m)}. Belt width 0.5–0.8 m.

Speed 0.8–2 m/s. Power: 0.02 to 0.4 kW/Mg/h per km horizontal distance.

Bucket conveyor: vertical: velocity < 1.5 m/s; for material of density 0.4 Mg/m^3 capacity < 16 kg/s; for 2 Mg/m^3 capacity < 85 kg/s or < 40 m^3/s. Power 0.15–0.35 kJ/kg or 0.013–0.023 kJ/kg.m of height.

Screw conveyors: 10–120 rpm and trough loading 15–95 % depending on the particle size, flowability, abrasiveness. Diameter 0.3–0.4 m. Power 10–20 kW/Mg/h per km horizontal distance. Can use hollow screws with heat exchange media flowing inside the screw. See Section 3.3.

Screw conveyor feeder from bottom of hopper: capacity is very sensitive to screw flight clearances for moderately incompressible solids (whose **FDI** and **BDI** differ by < 5 %). Hopper discharge active flowrate of solids limited to about one screw diameter (if hopper discharge is > 1 screw diameter there is a potential for cohesive solids to bridge and free-flowing solids to cause overload of drive).

Belt feeder from bottom of hopper: active flowing solids discharging from the hopper are on the downstream side of the belt; upstream solids in hopper may be stationary. The gap between the belt and the interface edge = 0.021 cm/cm in the direction of solids movement.

Vibrating feeder from bottom of hopper: active flowing solids discharging from the hopper are on the downstream side of the feeder; upstream solids in hopper may be stationary.

Rotary, star valve feeder: Used especially as solids feeders for dilute phase pneumatic conveying to provide an air lock and to feed solids. Seal/wear depends on Δp and abrasiveness of powder. For pressure systems keep $\Delta p < 80$ kPa; for vacuum systems $\Delta p < 40$ kPa. Provide an air vent to take the air loss away from the gravity flow of the solids and to control the filling of the star. For granular particles, prefer an offset-feed rotary valve; for cohesive particles, more difficult to handle; prefer a blow-through rotary valve. Cohesive particles will tend to seal a rotary valve and minimize air leakage. Not recommended for abrasive powders.

Pneumatic conveying: dilute phase: pressure: continuous: nominal gas velocity 5–35 m/s with usual 11–25 m/s. Solids loading 3.5–15 kg solid/kg air with usual 6–15 kg solids/kg air or 1–7 m^3 solids/m^3 air. Power 7–11 kJ/kg. Problems: about 30 % air leakage out of the system. Rotary/star valve problem/bridging: overcome with bin agitation, astute bin design and vent star valve to prevent the back flow of gas through the valve into the bin. Minimize bends. Requires a minimum of air but increasing the air velocity > minimum flow does not change the capacity; it increases the Δp. Capacity increases linearly with increase in pressure of air supplied. Reduce the pipe length by 10 %; increases capacity by 10 %. Increase the inlet pressure 10 %; increase capacity by 10 %. Pipe diameter at least 3–5 times > the maximum particle diameter. Powders become more difficulty to handle as the particle size decreases. When sizing for air flowrate, allow for air leakage across rotary valve. Caution, with friable powders, the conveying process can change the particle size distribution and hence cause receiver hopper discharge problems. An increase in gas velocity at constant solids flowrate give higher Δp.

Pneumatic conveying: dilute phase: vacuum: continuous: nominal gas velocity 20–35 m/s and must be > 15 m/s. Solids loading 2.8–11 kg solids/kg gas with usual 3–4 kg solids/kg air. Power 11–18 kJ/kg. Rate and distance sensitive. Maximum vacuum 35 to 55 kPa. When sizing for air flowrate, allow for air leakage across rotary valve. Conveying velocity increases along the pipeline as approach vacuum pump suction. An increase in gas velocity at constant solids flowrate gives higher Δp.

Pneumatic conveying: dense phase: pressure: pressure, batch; Cycle time 1–4 min; charge 10 s; convey 0.5–3 min; 20–50 batches/h. nominal gas velocity: horizontal 4.5–35 m/s with usual 6–10 m/s; vertical 1.5–27 with usual 3 m/s. Solids loading: horizontal 12–130 kg/kg air; vertical 10–800 with usual 250–400 kg solids/kg air. Blow tank < 15 m^3. Line diameter 3–10 cm. Power 3–5.5 kJ/kg. Watch for humid air and line plugging. Pressures 0.17–0.45 MPa abs.

The air supplied is split between air to fluidize and air to convey. An increase in gas velocity at constant solids flowrate gives decrease in Δp.

The longer the distance, the lower the solids loading or the more gas needed to convey.

Options include top discharge or bottom discharge.

Top discharge: can achieve the highest feed rates; flowrate must exceed the minimum for fluidization.

Bottom discharge is preferred for granular materials.

Enclosed conveyor: 0.09–9 dm^3/s; conveyor size 7.5–25 cm; travel speed 0.02–0.3 m/s.

- *Good Practice*

Use a vibratory, screw or apron feeder to unload the particles onto the conveyor. Prefer dense phase to dilute phase pneumatic conveying (H).

- *Trouble Shooting*

Bucket elevators: major difficulties are unloading and loading: jamming of materials between the buckets and the side of the boot.

Rotary/star valve: use amps as guide to solids throughput. Keep air velocity high enough to prevent plugging of the air-vent line.

Pneumatic conveying: dilute phase: for vacuum: air leakage and powder bridging in hopper are the major threats. *"No flow or flow < design":* air leaks/powder bridging in feed hopper, see Section 10.3/low solids flow because of increased air loss in rotary valve/wrong type of rotary valve used/insufficient air/line too long/vacuum pump problems, see Section 2.2. *"Pressure (vacuum) at suction to blower > design (vacuum < design)":* air leaks/failure of discharge valve to seal on the receiver. *"Erratic pressure readings":* irregular feed. *"Explosion":* moisture too low/lines not grounded. *"Does not sound "tinny" when listening with stethoscope":* material accumulated inside pipe at this location.

Pneumatic conveying: dilute phase: for pressure: use pressure at the outlet of the blower as prime indicator. *"Δp across blower > design or 2:1 ratio":* restriction in downstream conveying line/check valve jammed closed/dirty intake filter/plugged discharge silencer/increase in feed to the system/length of pipe > design. *"Δp across blower < design":* slipping v-belts/air loss at the rotary valve. *"No flow":* [plugged line]* *"No flow or flow < design":* overfed fan system/insufficient air/insufficient solids/line too long/inlet air pressure too low. *"Erratic pressure readings":* irregular feed. *"Amps on rotary valve < usual":* solids flow < design/air loss through the rotary valve/increased clearances. *"Does not sound "tinny" when listening with stethoscope":* material accumulated inside pipe at this location. *"Gradual decrease in performance":* wear on the blower caused by dusty air.

[Plugged line]:* within the first couple of metres of the beginning of the system: material feed problems/air supply problems. *[Plugged line]** after the first couple of metres: air leak with the plug occurring about 10 m downstream of leak/erosion of rotary valve causing increase in air leakage.

Pneumatic conveying: dense phase:*"No flow or flow < design"*: plugged line/malfunction of line boosters because of stuck check valve/high humidity. *"Solids fed to conveying line < design":* ratio of air to fluidize in the blow tank relative to convey is too small/fault in control system.

"Solids fed to conveying line > design": ratio of air to fluidize in the blow tank relative to convey is too large/fault in control system.*"Solids flow = 0":* top discharge and the ratio of air to fluidize to convey is too small. *"Solids flow gradually decreases":* restriction in the discharge pipe/blinding of the fluidizing membrane.

Feeder: volumetric for extruder: *"Does not run":* no power/jammed. *"Stalls":* material jam/current limit set too low. *"Erratic speed control":* controller poorly tuned/sensor malfunction/material jam. *"Feed rate variable":* particles bridging in the hopper/moisture level too high/overheated polymer (prematurely fused) feed polymer.

Feeder: screw conveyor: *"Shear pins on feeder drive break":* screw diameter < exit hole from bin. "*Motor overload on feeder drive*": screw conveyor diameter < exit hole from hopper. *"Screw feeder initially OK then motor overloads"*: screw flight spacing in the direction of sold flow decreases markedly/difference between **FDI** and **BDI** $< 5\,\%$ suggests a moderately incompressible solid whose flow is very sensitive to screw flight spacing.

Feeder from bottom of hopper: *"Feeder motor overloads immediately:"* wrong wiring/foreign material in feeder/hopper is full and solids give excessive solids pressure because of particle characterization and hopper design/**FDI** large and large **HI**. *"Feeder exit flowrate suddenly < expected"*: blockage in hopper outlet/lumps of particles forming in hopper/large **RI** and small **HI** possibly caused by temperature cycles.

"Feeder exit flowrate gradually < design:" solids builup in the feeder/large **CI**, large **AI** and **RI**/wrong materials of construction in feeder. (Often happens with vibrating feeder).

Feeder: belt feeder from the bottom of a hopper: *"Belt feeder initially starts but suddenly stops with motor overload":* gap between the belt and hopper interface edge is too small/belt sags between pulleys/large **FDI** and small % difference between **FDI** and **BDI**.

2.7
Ducts and Pipes

- *Guidelines*

Pressure drops: see Gas, Section 2.1; liquid Section 2.3. For control valves on the lines where flow is because of Δp between an upstream and downstream vessel, allow a Δp across the valve of 10 % of the pressure of the lower terminal vessel or 50 % of the dynamic loss, whichever is greater.

Velocities, see Gas, Section 2.1; and liquid, Section 2.3. Keep the velocity of compressible gases < 0.6 sonic velocity.

Sonic velocity, m/s = 1.97 $[(c_p/c_v)$ pressure, kPa, $\times$ density, kg/m$^3]^{0.5}$

Sewer pipes have maximum flowrate when liquid level is 93 % of the diameter; flowrate when full = flowrate when liquid level is 80 % of the diameter.

Schedule 40 = usual specification; schedule 80 is heavy duty.

- *Good Practice*

Use vent breaks on high points of syphon. Include high pressure water purge or blowout for pipes with slurries; include steam blowout/purge lines for pipes with edible oils, foodstuffs.

For small diameter pipes consider using schedule 80, even if schedule 40 would satisfy internal pressure requirements, to eliminate need to pipe support over short runs.

3
Energy Exchange

The fundamentals for thermal energy exchange are that heat flows from a high temperature to a low temperature. Thermal forms of energy are not always available to do work. Overall energy is conserved; often we write expressions for the mechanical energy balance (on the macroscopic level as Bernoulli's equation) and the thermal energy balance (on the macroscopic level as q = UA LMTD). The transfer of heat is resisted and we define *heat transfer coefficients*, h and U, to describe the rate of heat transfer. The heat transfer coefficients are usually correlated as the Nusselt no. which is proportional to the (Reynolds no.)$^{0.8}$ (Prandtl no.)$^{0.33}$. This equation illustrates how the heat transfer coefficient varies with flowrate and with changes in the properties of the fluids. Fluids to watch are water and hydrogen; both have extremes in thermal properties.

In this chapter in Section 3.1 we consider mechanical drives. In Sections 3.2 and 3.3 furnaces and exchangers, condensers and reboilers are considered followed by fluidized bed with coil in the bed, Section 3.4 and static mixers, Section 3.5. Direct contact systems are considered next: liquid–liquid, Section 3.6; gas–liquid cooling towers, Section 3.7; gas–liquid quenchers, Section 3.8; gas–liquid condensers, Section 3.9, and gas–gas thermal wheels, Section 3.10. Heat loss to the atmosphere is described in Section 3.11. Refrigeration, steam generation and high temperature heat transfer fluids are presented in Sections 3.12 to 3.14, respectively. Tempered heat exchange systems are considered in Section 3.15.

3.1
Drives

- *Area of Application*

Gasoline–diesel engines: 200 to 800 rpm; $>$ 80 kW ; efficiency: 28 to 38 %.

Electric motors (synchronous): $<$ 500 rpm; 35 to 500 kW; use 480 V for motors up to 115 kW; 4160 V for $>$ 115 kW.

Electric motors (induction): $>$ 500 rpm; 10 to 15 000 kW.

Steam turbine: single stage, single valve: 1000 rpm to 12 000 rpm; 50 to 1500 kW.
single valve, multistage: 1500 to 2800 kW.
multivalve, multistage: 2800 to 30 000 kW.

Rules of Thumb in Engineering Practice. Donald R. Woods

ISBN: 978-3-527-31220-7

Steam turbine generation of electricity:
Gas combustion turbine: cogeneration.

- *Guidelines*

For less than 75 kW select motor or turbine.
Gasoline–diesel engines usual application: 200 to 400 rpm; 500 to 1200 kW.
Electric motors: select synchronous for low speed; usual application for either synchronous or induction: 500 to 2100 rpm; 150 to 500 kW. Usually use Total Enclosed Fan Cooled, TEFC, enclosure. efficiency: 84 to 95 %.

Induction: available for large power requirements, relatively low efficiency, power factor is low if rpm < 500 and at starting and fractional loads.

Synchronous: high efficiency at any speed, suitable for direct coupling for < 1000 rpm. Power factor ≥ 1; constant speed without slip. Power consumption, $\text{kW} = \text{amps}\ (0.001\ V \times PF \times 0.95 \sqrt{3})$.

Power, kW	volts, V
0.1–1	110
1–75	220–440 3-phase
50–200	440–2300
175–2000	2300–4160
$>$ 2000	11 000–13 200

Steam turbines: competitive above 75 kW; condensing: 2 kg/h steam/kW with 1.8 m^2 condenser surface area per kg/h steam. Multivalve, multistage efficiency: 42 to 78 %.
Steam turbine generation of electricity: for example, via condensate-type steam turbine with simple automatic extraction and two-pole synchronous generators with a cylindrical rotor and brushless exciter system.

- *Good Practice*

Substitute variable speed drives when operation is frequently below capacity.
Engines: Use high efficiency motors when replacing or repairing existing installations.
Steam turbine: Consider extracting energy via a steam turbine for any pressure reduction in steam service. Use high pressure steam for energy; low pressure steam for heating (P, F). Don't operate with wet steam.

- *Trouble Shooting*

Engines: "*Hammering/knocking*": loose parts/seized parts. *"Pre-ignition":* fuel with unstable hydrocarbons/incorrect timing. *"Detonation":* wet fuel/incorrect timing/intake air too hot/glowing carbon on the piston/leaking valve stem/worn valve guides. *"Misfiring":* incorrect timing/faulty ignition elements/wrong gap in the spark plugs/wet fuel/spark-plug gap coated or filled with carbon or oil. *"Overheat":* lubrication failure/inadequate cooling/poor quality fuel/fuel to air ratio too lean. *"Sooty exhaust":* incorrect fuel/air–fuel ratio too rich/inadequate cooling/wrong valve adjustment. *"Valve leaking":* inadequate cooling/valve angle incorrect/wrong metallurgy. "*Piston blow-by:*" over lubrication/inadequate oil filtration/

inadequate air filtration/worn piston rings. *"Worn bearings":* misaligned crankshaft/wet fuel/unstable fuel.

Electric motor: *"Won't start":* overload trip/loose connection/grounded winding/grounded stator. *"Runs backwards":* reversed phase sequence. *"Excessive noise":* 3-phase machine single phased/unbalanced load between phases. *"Synchronous motor fails to come up to speed":* faulty power supply or overload trip/windings grounded. *"Overheat":* unbalanced load between phases/wrong line voltage/short circuit in stator winding/single phasing.

DC motors:*"Won't start":* weak field/low armature voltage/open or short circuit in armature or field. *"Runs too slow":* low armature voltage/overload/brushes ahead of neutral. *"Runs too fast":* high armature voltage/weak field/brushes behind neutral. "*Brushes sparking*": brushes worn/brushes poorly seated/incorrect brush pressure/dirty, rough or eccentric commutator/brushes off neutral/short circuited commutator/overload/excessive vibration.*"Brush chatter":* incorrect brush pressure/high mica/incorrect brush size. *"Bearings hot":* belt too tight/misalignment/shaft bent/damaged bearings.

Steam turbine: *"Turbine fails to start":* too many hand valves closed/nozzles plugged or eroded/dirt under carbon rings. "*Slow startup":* throttle valve travel restricted/steam strainer plugged/load > rating. *"Insufficient power":* throttle valve travel restricted/too many hand valves closed/oil relay governor set too low. *"Speed increases as load decreases":* throttle valve travel restricted/throttle assembly friction/valve packing friction. *"Governor not operating/excessive speed variation":* governor droop adjustment needed/governor lubrication problem/throttle valve travel restricted. *"Overspeed trip on load changes":* trip valve set too close to operating speed/throttle valve travel restricted/throttle assembly friction. *"Overspeed trip on normal speed"*: excessive vibration/dirty trip valve/trip valve set too close to operating speed. *"Leaking glands":* dirt under carbon rings/worm or broken carbon rings/scored shaft.

Steam turbine used for the generation of electricity: *"Turbine overspeeding":* [load disconnection suddenly]*/[trip throttle valve stuck]*/control valve fault//[extraction valve fault]*. *"Bearings damaged":* [turbine overspeeding]*/[lube oil]*/excessive vibration/no lube oil/bearing temperature too hot/insufficient oil because of clogged lines/flow of parasitic currents.

[Clogging]:* [lube oil]*/long time without operating.

[Electronic pin clogging]:* [lube oil]*/long time without operating.

[Extraction valve fault]:* wear on valve bearing/loss of hermetic seal.

[Load disconnection suddenly]:* operator error/automatic bus bar protection because of downstream changes in electric system.

[Lube oil]:* low pressure/oil temperature too hot/oil too old/oxidation/water contaminates oil.

[Solenoid valve malfunction]:* [electronic pin clogging]*/[clogging]*/solenoid shorted coil/faulty control signal/sensor error.

[Trip Throttle Valve stuck]:* [clogging]*/[solenoid valve malfunction]*.

Gas turbine: consists of a compressor, combustor and turbine sections.*"Combustion noise":* fouled or clogged combustor/loose or cracked lining in combustor.

"Vibration": bearing failure in compressor or turbine/blade damage in compressor or turbine/surging compressor/fouled turbine. *"Exhaust temperature > design":* combustor fouling. *"Exhaust temperature < design":* combustor clogged. *"Thermal efficiency < design":* fouled turbine/turbine blade damage/turbine nozzle distortion. *"Mass flow < design":* compressor fouling/compressor filter clogged/compressor blades damaged.

3.2
Thermal Energy: Furnaces

Multi-use including heating, boiling, reactions. Related topics distillation, Section 4.2, reactors, Section 6.5.

- *Area of Application*

250 to 1300 °C; < 30 MPa; thermal efficiency: 70 to 75 %.

- *Guidelines*

Heat flux in radiant section: 10–60 kW/m^2 based on outside tube area with fluid velocity inside tubes 0.1 to 3 m/s. Use 1.5 m/s. In the convection section: 12 kW/m^2.

Equate heat duties in the radiant and convection sections. 80 % efficiency based on net heating values.

Size radiant section to absorb 50 % of the radiant energy with 1.22 m^3 chamber per m^2 tube area.

Field fabricated for sizes above 5 MW total heat load.

Gas catalytic endothermic reaction inside tube, heat transfer coefficient $U = 0.045$ kW/m^2. K.

Flue gas temperature is usually 650–820 °C leaving the radiant section and 260–425 °C leaving the convection section. To minimize the thermal cracking inside tubes in a fired furnace, use 600 kg/s.m^2 for lube oils, crude and vacuum desulfurizer and 1200 kg/s.m^2 for delayed coker and visbreaker. Keep tube temperatures < 760 °C. Specify the highest fuel gas pressure that is consistently available.

- *Good Practice*

For fired furnaces: monitor CO and O_2 to reduce rejected energy and improve efficiency, consider the installation of economizers and air preheaters to recover additional heat from the flue gas.

For steam generation: preheat boiler feed water with available low temperature process streams, maximize the use of heat transfer surfaces by optimizing soot-blowing frequency and decoking of tubes, flash blowdown to produce low pressure steam if required.

- *Trouble Shooting*

"Gas temperature > design": instrument wrong/insufficient excess air/process side coking of tubes/leak of combustible material from process side/over-firing because of high fuel gas pressure. *"Gas temperature < design":* instrument fault/fouling/too much excess air/insufficient area/fuel gas pressure < design. For convection furnace: *"Exit process gas temperature < design":* excess air/decrease in flame temperature/damper has failed to close. *"Pressure inside furnace > design":* instrument wrong/fouling on the outside of the tubes in the convection section/exhaust fan failure. *"Faint blue-gray smoke rising from top of furnace":* fouling outside tubes in the convection section/pressure in furnace > atmospheric. *"Puffing, rhythmic explosions"*: burners short of air for short period causing minor over-firing/wind action/start up too fast. *"Tube failure":* localized overheating/burning acid gases as fuel/free caustic in water and dryout/dry out and attack by acid chloride carried over from water demineralization/breakthrough of acid into water from demineralizer. *"High fuel gas pressure":* failure of pressure regulator. *"Tube dryout":* tubeside velocity too low. *"Low furnace efficiency":* high combustion air flow/air leak into the firebox/high stack temperature/heat leaks into the system. *"Equipment suddenly begins to underperform":* fouling/bypass open. *"Temperature control problems":* missing or damaged insulation/poor tuning of controller/furnace not designed for transient state/unexpected heat of reaction effects/contaminated fuel/design error. *"Furnace tube blistering":* flame impingement/dirty or worn oil burner tips/tangential firing gun misalignment.

3.3
Thermal Energy: Fluid Heat Exchangers, Condensers and Boilers

Exothermic processes should supply all the heat requirements for the process. Related topic thermal pinch, Section 1.11. Based on the conservation of energy, the heat acquired/lost by a stream = the heat transferred to/from the stream. For sensible heat, q = mass flowrate (F) × heat capacity per unit mass ($\mathbf{c_p}$) × ΔT = heat transferred = UA MTD. This is sometimes rearranged to define a thermal heat transfer unit, THTU, = $\Delta T/\text{MTD} = UA/F\,c_p$.

- *Area of Application*

Shell and tube: –200 to 600 °C; < 30 MPa; 0.15 to 4 THTU/pass and 5 to 150 kPa/THTU; fluid viscosities < 100 mPa.s. area: 2–2000 m^2.

Fixed tube sheet limited to low thermal expansion or if $\Delta T < 30$ °C.

Usually need U-tube or floating head.

Spiral: –100 to 400 °C; < 1.8 MPa; use with sludges, slurries, high viscosity materials (especially 4×10^4 mPa s to 4×10^5 mPa.s .) > 90 % heat recovery. High heat transfer coefficients; low pressure drop. Ratio of flowrates being handled < 3.5. Not when $\Delta T_1 >> \Delta T_2$. area: 4–100 m^2.

Lamella: –200 to 500 °C; < 3 MPa. Ratio of flowrates 1 to 1.8. area: 100–10 000 m^2.

Gasket/plate: –30 to 180 °C; $<$ 2.5 MPa depending on the gasket material; areas $<$ 2000 m^2; 0.2 to 3 THTU/pass and 15 to 200 kPa/THTU; fluid viscosities $< 4 \times 10^4$ mPa.s. Holdup low, 1.5 L/m^2. Ratio of flowrates 0.7 to 1.3. Not when $\Delta T_1 >> \varDelta T_2$. area: 10–600 m^2.
Double pipe: –200 to 600 °C; $<$ 30 MPa; usually $<$ 20 m^2. use for high pressure. area: 0.3–200 m^2.
Air cooled: OK when air can be used as coolant. Low maintenance. Area: 20–2000 bare tube m^2. Finned area: bare tube area = 16:1.

Options are forced draft or induced draft. Use forced draft with louvers when temperature control is critical. Forced draft has less fan power; easy access for maintenance; easy to use hot air recirculation; but has greater susceptibility to air maldistribution and to inadvertent hot air recirculation; low potential for natural circulation; and the tubes are exposed to the elements. Induced draft: high fan power needed, not easy access for maintenance; limitation on exit air temperature; less chance of air maldistribution or unwanted hot air recirculation; better protection from the elements; process stream temperatures $<$ 175 °C.
Cubic/monolithic: corrosive liquids, acids, bases or used as catalyst/heat exchanger for reactors. Usually made of graphite or carbon that has high thermal conductivity. Area: 1–20 m^2. Ceramic monoliths are used as solid catalyst for highly exothermic gas-catalyst mass transfer-controlled reactions.
Agitated falling film: usually to concentrate slurry; see evaporation, Section 4.1.
Scraped surface, Votator: usually to condition foodstuffs, crystallize and react. Especially for viscous feed. OK for foaming, for fouling, crystal formation and suspended solids. Viscosities $>$ 2000 mPa.s. Relative to agitated film retention time of 1:1 and volume 1:1. Overall heat transfer coefficient 2 kW/m^2.°C decreasing with increasing viscosity. 3 to 12 kW/m^2. See also evaporation Section 4.1, crystallization as scraped surface crystallizer, Section 4.6 and as a reactor, Section 6.20.
Coil in tank: area: 1–30 m^2.
Jacketed: usually to exchange heat in a reactor or storage tank.
Cooling finger: added to tanks to increase the exchange area.

- *Guidelines*

Media for Heating and Cooling
Water: 18 °C to maximum outlet 50 °C with velocity $>$ 1.2 m/s
Air: 18 C to maximum outlet 50 °C
Steam: 1.7 MPa: 203 to 220 °C;
4.3 MPa 260 °C
for pressures 0.1 to 0.2 MPa:
100 °C consider ethane
50 °C consider propane, propylene
30 °C consider ammonia
0 °C consider butane
175 °C consider Dowtherm J
200 to 400 °C consider molten salt

275 °C consider Dowtherm A
310 °C consider Dowtherm G.

Heating: to increase the temperature of 1 L of water by 75 °C requires 0.12 kg steam at 200 kPa-g.

Shell and tube: (Design issues illustrated in Fig. 3.1). The heat loads, q, are identified first based on the heating/cooling media selected; the sensible, latent heat and reaction heat requirements; the pressure and temperature conditions and the flowrate capacities. This is shown top central of Fig. 3.1.The ultimate choice of area and configuration, shown at the bottom RHS, are based on an economic tradeoff with the "approach temperature". The tradeoff is between the pumping costs and the heat exchange costs. The details between the heat load and the selection are the following issues. The temperature and pressures for the system are specified, as shown in the top LHS. For the mean temperature driving force for the heat transfer, MTD, we start with the hot and cold streams the temperature profiles and the rule-of-thumb "approach temperature". These lead to the local and ultimately the overall temperature driving force. A visual plot of the temperature profile assists. Usually a variation on the LMTD is selected with corrections made to account for the configuration ultimately selected. At the LHS central the shell and tube side fluids are selected, based on pressure, materials of construction, characteristics of the fluids (corrosivity, viscosity, cleanliness) and function (condensation, boiling, heat exchange). The rate at which the heat is transferred is based on the overall heat transfer coefficient U. Trial rules-of-thumb values for U are given in this section. U depends on the configuration which dictates the individual coefficients on the shell and tube sides, the tube thickness and material of construction and on the allowance for dirt. The configuration depends on the tube and shell side fluids, temperature and pressure, materials of construction, the area required and the prevention of temperature crossover. Central to the design process is the velocity of fluids which directly affects both the pressure drop and the heat transfer coefficients. This sizing map interacts with the sizing maps for pumps, Fig. 2.1; and perhaps for distillation columns, Fig. 4.1 and for reactors, Fig. 6.1.

Use shell and tube exchangers for gas–gas and for low viscosity liquid–liquid systems (< 200 mPa.s).

Use floating head if the temperature difference between shell and tube fluids exceeds 30 °C (to minimize impact of thermal expansion).

Surface compactness: for ordinary tubes: 70–500 m^2/m^3; for finned tubes 65–3300 m^2/m^3.

Number of shell passes affected by temperature ratio $\frac{(t_{\text{hot, in}} - t_{\text{hot, out}}) + (t_{\text{cold, out}} - t_{\text{cold, in}})}{(t_{\text{hot, in}} - t_{\text{cold, in}})}$	Number of shell passes
0–0.8	1
0.8–1.1	1 or 2
1.1–1.3	2
1.3–1.4	2 or 3
1.4–1.5	3

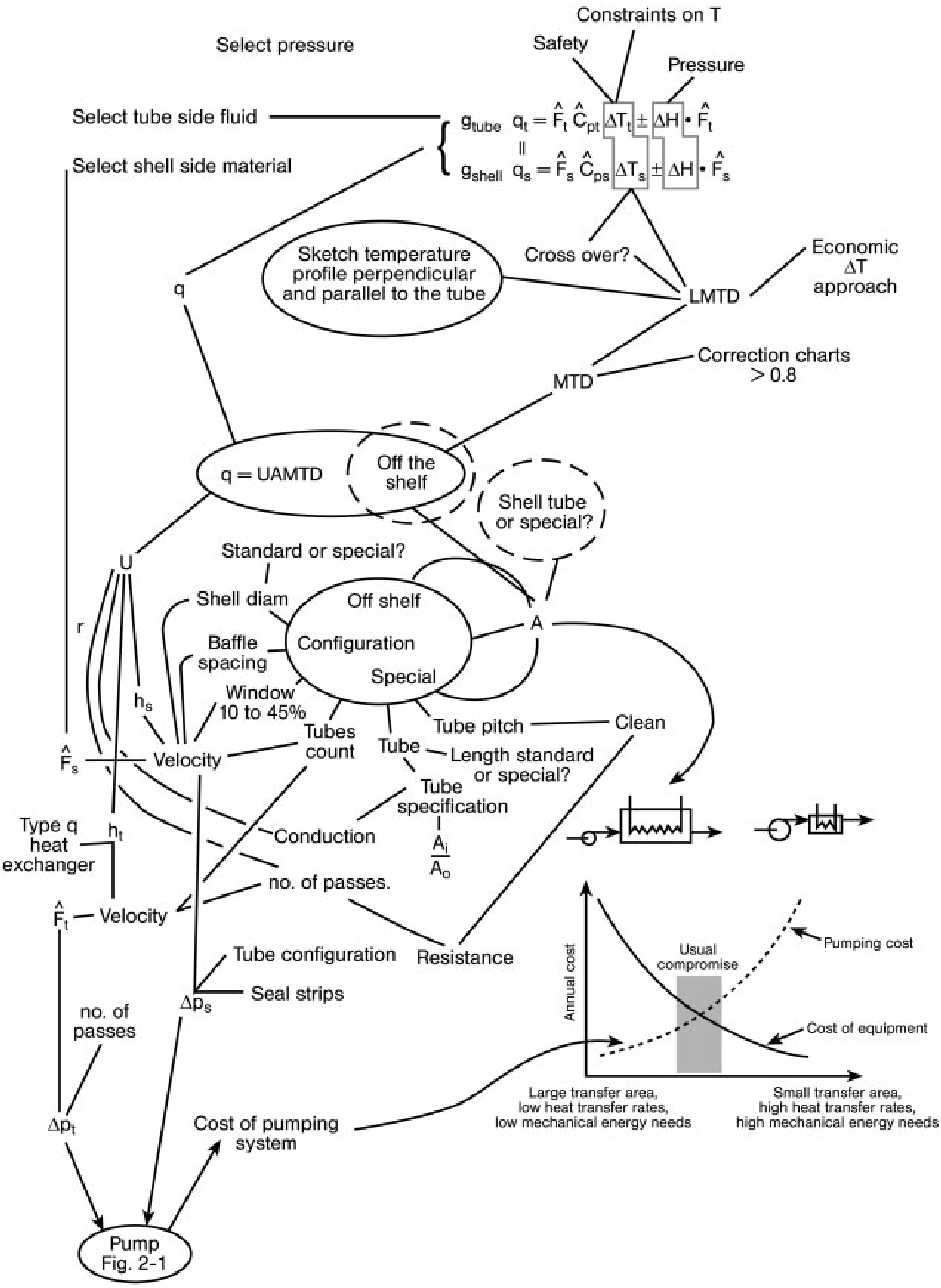

Figure 3.1 Sizing map for shell and tube heat exchangers.

Tube velocity > 1 m/s; for crude preheat exchangers tube velocity 1–2 m/s; overhead water condensers, tube velocity 1–3.5 m/s. To minimize fouling keep tubeside velocities 3–4.5 m/s, reduce the wall temperature and use single flow channels.

Nozzle velocity < 2 m/s and p, kPa = 0.75–0.9 (nozzle velocity, m/s)^2

Baffle cut $< 30\,\%$; baffle pitch: minimum should be the maximum of 5 cm or 1/5 of ID shell diameter. the maximum should be the smaller of 0.75 m or shell ID diameter.

Resistance allowances: clean water $< 50\,°\mathrm{C}$, 0.0002 m^2 K/W; silty water, 0.0006 m^2 K/W; steam, 0.0001 m^2 K/W; fuel oil, 0.0008 m^2 K/W; refrigerants, 0.0002 m^2 K/W; vegetable oils, 0.0005 m^2 K/W; amines, 0.00 035 m^2 K/W; usual hydrocarbons, 0.0003 m^2 K/W.

For shell and tube heat exchange: Numerous related topics including evaporation Section 4.1, distillation, Section 4.2, crystallization Section 4.6, freeze concentration Section 4.3, melt crystallization, Section 4.4, PFTR reactors Sections 6.5–6.12. Approach temperature 5 to 8 °C; use 0.4 THTU/pass; design so that the total pressure drop on the liquid side is about 70 kPa. Allow 4 velocity heads pressure drop for each pass in a multipass system. Put inside the tubes the more corrosive, higher pressure, dirtier, hotter and more viscous fluids. Recommended liquid velocities 1 to 1.5 m/s with maximum velocity increasing as more exotic alloys used. Use triangular pitch for all fixed tube sheet and for steam condensing on the shell side. Try $U = 0.5$ kW/m^2 °C for water/liquid; $U = 0.3$ kW/m^2 °C for hydrocarbon/hydrocarbon; $U = 0.03$ kW/m^2 °C for gas/liquid and 0.03 kW/m^2 °C for gas/gas.

Finned tubes: see Air cooled.

For shell and tube condensation: Related topics evaporation Section 4.1, distillation Section 4.2. Prefer condensation outside horizontal tubes; use vertical tubes when condensing immiscible liquids to subcool the condensate. Assume pressure drop of 0.5 of the pressure drop calculated for the vapor at the inlet conditions. Baffle spacing is 0.2 to 1 times the shell diameter with the baffle window about 25 %. Limit pressure drop for steam to 7 kPa on the shell side. $U = 0.5–0.85$ kW/m^2 °C.

For shell and tube boiling: approach temperature $< 25\,°\mathrm{C}$ to ensure nucleate boiling. Related topics evaporation Section 4.1, distillation, Section 4.2, solution crystallization Section 4.6 and reactors PFTR non-adiabatic, Sections 6.8 and 6.12.

– **kettle:** use for clean, relatively low pressure, nucleate pool boiling; not for foams. 75 to 100 % vaporized. $U = 1.1$ kW/m^2 °C.

– **vertical/horizontal thermo syphon:** use for clean, relatively low pressure, nucleate pool boiling; 5 to 25 % vaporized; Use 45 to 56 kW/m^2 heat flux for hydrocarbon and petrochemicals; 62 to 75 for aqueous and 37 to 44 for vacuum. Rarely use for vacuum or very high pressure service. $U = 1$ kW/m^2 K.

– **forced circulation:** use for vacuum or viscous/fouling fluids. sensible heat only. Tube velocity 3–4.5 m/s.

For various configurations of evaporators, see Evaporation, Section 4.1.

For steam usage see steam traps, Section 5.1.

For shell and tube gas reactor with fixed catalyst inside tubes: Related to reactor, Section 6.12.

endothermic reaction in catalytic fired tube. $U = 0.045$ kW/m^2 °C.

exothermic reaction in catalytic multitube non-adiabatic with boiling water or molten heat transfer salt or liquid: 0.05–0.12 kW/m^2 °C.

Spiral plate: for large flows and alloy construction select spiral over shell and tube. Heat transfer coefficients about double that of shell and tube; approach temperature 2.8 °C. liquid–liquid $U = 2.8$–4 kW/m^2 °C.

Surface compactness: up to 185 m^2/m^3.

Lamella/plate (Raman): approach temperature 2 °C; for liquid–liquid $U = 1.7$–2.5 kW/m^2 °C.

Surface compactness: 150–5900 m^2/m^3.

Gasket/plate: approach temperature 1–2.8 °C; heat transfer coefficients about 3–5 times higher than shell and tube. For liquid–liquid $U = 4$–4.5 kW/m^2 °C. $h = 2$ kW/m^2 °C for hydrocarbons; = 10 kW/m^2 °C for water. Surface compactness: 120–1000 m^2/m^3.

Double pipe: for heat exchange: use for < 20 m^2; attractive for the condensation of reacting gases because it provides least area per unit volume.

Air cooled: 2 fins/cm of tube length; use finned tubes on gas side to give less weight, less pressure drop but not for dirty gases on the fin side because of difficulty in cleaning: Use when the potential finned side coefficient is small (0.05–0.1 kW/m^2 °C) and when the ratio of tube side to gas side coefficient is 75–300 but not when 1–25. Use h_oA_o not area only for optimization (because heat transfer coefficient decreases as the fin area increases). Finned tubes with 15–20 m^2 total area/m^2 bare tube area. 0.4–0.6 kW/m^2 °C of bare tube; approach temperature $>$ 26 °C; fan power is 5 to 13 kW/kW thermal energy transferred or 0.15 kW/m^2 of bare tube.

Cubic/monolithic: corrosive acids and bases: liquid–liquid $U = 0.5$ to 1.1 kW/m^2 °C. For gas–catalyst heat exchange $U = 3.5$–7.5 kW/m^2 °C. Heat transfer areas up to 2200 m^2.

Monolithic catalyst for gas–solid catalytic reactions: $U = 3.5$–7.5 kW/m^2 °C and areas up to 2200 m^2.

Agitated falling film: see Evaporation, Section 4.1.

Scraped surface (often horizontal): Votator: thin liquids $U = 2.2$–4 kW/m^2 °C ; viscous films $U = 0.8$–2.3 kW/m^2 °C; crystallization $U = 0.15$–3.7 kW/m^2 °C; sulfonation $U = 0.8$–2.2 kW/m^2 °C; polymerization, $U = 1$–2.8 kW/m^2 °C. See also Evaporation Section 4.1, crystallization, Section 4.6 and reactors, Section 6.20.

Coil in tank: heating $U = 0.6$–2.5 kW/m^2 °C; cooling $U = 0.2$–1.2 kW/m^2 °C.

Jacketed: heating $U = 0.2$–1.7 kW/m^2 °C; cooling $U = 0.1$–0.6 kW/m^2 °C;

Half-round pipe on wall: cooling $U = 0.3$–0.9 kW/m^2 °C;

Cooling finger: cooling $U = 0.5$–1.2 kW/m^2 °C.

Thermal screw conveyor: see Section 2.6 but provide heat transfer fluid to the inside of hollow screws. Related to drying, Section 5.6.

- *Good Practice*

For not truly countercurrent, if the correction factor for the LMTD drops below 0.75 we run the risk of temperature crossover. Provide pressure relief to allow for systems where block valves could isolate trapped fluids. Include impingement baffles at shell inlet nozzles to prevent erosion of tubes and flow induced vibration. For air cooled systems include a trim cooler with water as coolant. Account for the larger heat exchange that occurs for clean tubes/surfaces; the design was based on reduced heat transfer coefficients that account for ultimate dirty film resistance. Ensure the air is vented. Liquids being heated should leave at the top of the exchanger to prevent the buildup of gases coming out of solution and vice versa for liquids with suspended solids or viscous fluids. Orient baffle windows to facilitate drainage. Slope condensers to remove the condensed phase. Maximum cooling water temperature is 45 °C (J). Prefer water or other nonflammable heat transfer media (H). For flammable heat transfer fluids, select operating temperature below its atmospheric boiling temperature (H). If refrigeration is required, prefer less hazardous refrigerant even if this means operating at higher pressures (H). Use pinch analysis, identify inefficient exchanges and retrofit heat exchanger networks to maximize heat recovery. Optimize cleaning schedule. Consider "on-line" mechanical cleaning where fouling is a problem. Use turbulence promoters in laminar flow and gas services and where turndown has significantly reduced the heat transfer coefficient.

Shell and tube heat exchangers: To provide lower inventory and intensify, prefer plate to shell and tube exchangers with the highest surface compactness (H).

Shell and tube reboilers: To provide lower inventory and intensify, prefer thermosyphon reboilers to kettle reboilers.

– thermosyphon: Vertical thermosyphon usually not used for vacuum or extremely high pressure service.

Plate exchanger: put regulating and control valves on the inlet lines, never on the outlet lines, to minimize pressure in the exchanger. Never allow the exchanger to be under a vacuum. Keep temperature $< 120\,°C$; pressure < 2.5 MPa.

Air cooled: induced draft preferred to forced draft to minimize hot gas recirculation. Include a water-cooled "trim cooler". Ensure the exit tubes are "flooded" so that the vapor does not bypass condenser. If extreme cold conditions are expected, allow for fan to operate in reverse to counteract the overcooling by the natural circulation of cold air.

- *Trouble Shooting*

When trouble shooting heat exchangers, usually the fault is fluid dynamical: liquids do not drain; baffles are placed so that liquid cannot go where we expect; vents are missing that prevent us from bleeding off trapped gases. Thermal expansion will occur when exchangers are brought up to temperature. This may cause a leak at the head-to-tubesheet joint if the difference between the temperature on the tubeside less the temperature of the bolts $> 50\,°C$. For systems involving steam, scrutinize the steam trapping system: ensure that traps are not flooded, that the appropriate trap has been installed, that the bypass is not left open, and that thermodynamic traps are not fed to a common header. Steam should come from a nozzle on the top of the steam main; condensate should be discharged into the top of the condensate header.

Shell and tube heat exchangers: *"Thermal underperformance on both streams (coolant exit temperature < design; hot exit > design temperature)":* instrument fault/not enough area/thermal load reduced via flowrate or change in thermal properties (e.g., less hydrogen than design)/inerts blinding tubes/[fouling]* more than expected/tube flooded with condensate (see faulty steam trap, Section 5.1) or trap in backwards or insulated inverted bucket steam trap. *"Equipment suddenly begins to underperform":* fouling/bypass open. *Temperature control problems":* missing or damaged insulation/poor tuning of controller/not designed for transient state/unexpected heat of reaction effects/contaminated feeds/design error/unexpected heat of solution effects/changes in properties of the fluids. *"Heat transfer to shell side fluid < design and Δp < design":* instrument/increase in viscosity/fluid bypasses baffles (baffle cut > 20 %, no sealing strips, excessive baffle clearance, shell side nozzles too far from tube bundle)/stratification/faulty location of exit nozzles/faulty baffling/inlet maldistribution.

"Heat transfer to tubeside < design and uneven (and uneven tube-end erosion at inlet)": maldistribution to the tubes (axial nozzle entry velocity > tube velocity, for radial nozzle entry velocity > 1.9 tube velocity).

"Heat transfer to one fluid < design and Δp = design": instrument fault/oil contamination of water.

"Thermal overperformance both fluids, and usually Δp > design on hot fluid side, perhaps charring of cold stream and freezing of hot stream": instrument fault/cocurrent piped incorrectly as countercurrent/area too large/hydrogen concentration in gas stream > design/clean tubes but design area selected on dirty service.

"Thermal overperformance one stream: cold exit temperature > expected": instrument/plugged tubes/inlet velocity < design, fouled screen on pump suction/pump problems, see Section 2.3/increased heat load.

"Poor control of outlet temperatures (±5°C)": poor tuning of control/instrument fault/oversized area combined with multipass with local changes in effective MTD with fluid velocity.

"Rapid tube failure or glass or karbate tubes break": inlet gas velocity too high and directed onto tubes/gas velocity > 5 m/s causing tube vibration/surges in cooling water/surges cause by syphon without vent break.

"Higher Δp when operating at design flows and temperatures": underdesign/design for two-phase stratified flow but slug flow occurs/gas service but the operating pressure < design.

"Leaks": erosion/corrosion/vibration/improper tube finishing/cavitation/lack of support for tube bundle/tube end fatigue.

"Noise/vibration": excessive clearance between baffles and tubes/inlet gas velocity too high and directed onto tubes/gas velocity > 5 m/s causing tube vibration/surges in cooling water/surges cause by syphon without vent break.

"Gradual reduction in heat transfer and increase in Δp": small tube leaks.

*[Fouling]**: see Section 1.12.

Shell and tube condensers: *"Condensation duty $<$ design; exit vapor temperature $>$ design, high flowrate of vapor out vent":* instrument fault/undersized condensers/change in process gas pressure/inward leakage of noncondensibles/change in feed composition/[fouling]* on the process side/vapor binding/vapor pockets/inert blanketing (usually near the condensate outlet for condensers operated flooded for pressure control)/condensate flooding, see steam traps, Section 5.1/ baffle orientation horizontal not vertical/excessive entrainment in vapor feed/ baffle window $>$ 45 %/drain line too small/leakage between the tubesheet and baffles/bowed tubesheet/condenser designed for horizontal service installed vertically.

"Condensation duty $>$ design:" excess condenser area/clean tubes/condenser designed for vertical service installed horizontally/liquid entrainment in feed.

"Condensation duty $<$ design Δp process $>$ design and excessive flow out vapor vent": undersized condenser.

"Coolant water temperature $>$ design": instrument fault/low coolant flowrate/high coolant inlet temperature/cooling tower fault/excess condenser area.

"Cooling water exit temperature $>$ design and higher steam usage in distillation column reboiler and uneven column operation": excess condenser area via overdesign or clean surfaces.

"Heat transfer drops off $>$ rate than expected and Δp increases faster than expected": fouling because of oversized kettle reboiler on distillation column or change in pH or flow regime laminar when design was turbulent or higher level of contamination in fluids or crud carry over from upstream equipment (e.g. silica from catalyst in upstream reactor) or compensation for oversize by reduced coolant flowrate.

"Loss of volatile vapor out vent , high vent gas temperature, degree of subcooling $<$ design and unusual temperature profile between vapor inlet and condensate outlet:" instrument error/underdesign.

"Loss of volatile vapor out vent, apparent undersized area for condensation of immiscible liquids": lack of subcooling of condensate/condenser installed horizontally instead of vertically.

"Fog formation": high ΔT with noncondensibles present/high ΔT with wide range of molar mass of the vapor.

"Equipment suddenly begins to underperform": fouling/bypass open. *"Temperature control problems":* missing or damaged insulation/poor tuning of controller/not designed for transient state/unexpected heat of reaction effects/contaminated feeds/design error/unexpected heat of solution effects/changes in properties of the fluids.

*[Fouling]**: see Section 1.12.

Shell and tube reboilers: general: *"Low boilup"*: [fouling on process side]*/condensate flooding, see steam trap malfunction, Section 5.1 including higher pressure in the condensate header/inadequate heat supply, steam valve closed, superheated steam/boiling point elevation of the bottoms/inert blanketing/film boiling/increase in pressure for the process side/feed richer in the higher boiling components/undersized reboiler/control system fault/for distillation, overdesigned condenser. *"Equipment suddenly begins to underperform":* fouling/bypass open. *"Temperature control problems":* missing or damaged insulation/poor tuning of controller/not designed for transient state/unexpected heat of reaction effects/contaminated feeds/design error/unexpected heat of solution effects/changes in properties of the fluids.

"Low boilup and gradual increase in steam pressure to maintain boilup:" [fouling]*/inerts in steam.

"Low boilup and gradual decrease in steam pressure to maintain boilup:" steam blowing, see steam trap malfunction, Section 5.1.

"Water contamination": leak.

"Cycling (30 s – several minutes duration) steam flow, cycling pressure on the process side and, for columns, cycling Δp and cycling level in bottoms": instrument fault/condensate in instrument sensing lines/surging/foaming in kettle & thermosyphon/liquid maldistribution/steam trap problems, see Section 5.1, with orifice Δp across trap $<$ design/temperature sensor at the feed zone in a distillation column/collapsed tray in a distillation column.

"Level high in reboiler": instrument/inlet or exit pipe nozzle too small/wrong nozzle orientation/steam trap fault, see Section 5.1/steam trap is above the reboiler.

"Breathing: puffs of vapor and entrained liquid leave reboiler:" overdesign/clean tubes when designed for fouled conditions.

*[Inadequate heat supply]**: wet steam/too great a Δp across steam valve gives wire-drawing and superheat/steam valve closed/control system fault.

– **kettle:** rarely underdesigned and not for foams. Trouble shooting: general plus the following symptoms and causes unique to this type of reboiler:

"Surging": poor liquid distribution/[fouling]*.

"Low boilup rate and gradual increase in steam": film instead of nucleate boiling/too high a ΔT/clean tubes/conservative overdesign/[fouling]*/flooding with condensate because of steam trap problems, see Section 5.1/bottom temperature elevation/increase in column pressure/feed concentration of light components $<$ design/not enough heating medium.

"Low boilup rate and decrease in steam pressure": steam trap blowing, see Section 5.1.

"Low boilup rate, pressure increase in reboiler and surges": [foaming]*/inerts/leaks/undersized reboiler/diameter of vent line too small/top tubes not covered with liquid/high liquid level that floods the vapor disengagement space/inlet feed maldistribution/inadequate vapor disengagement.

*[Fouling on the process side]**: low liquid level causing vapor-induced fouling/solids in feed that are trapped by the overflow baffle.

[Foaming]:* see Section 1.12.

– **thermosyphon:** general plus the following symptoms and causes unique to this type of reboiler:

"Low boilup": [fouling on the process side]*/insufficient steam flow/condensate flooding/low liquid level in distillation column gives low liquid circulation and increased fouling/high liquid level in distillation column (static head $>$ design) or higher density of feed liquid gives higher boiling temperature and circulation and

insufficient vaporization for vertical thermosyphon/pipe lengths < design/pipe diameter > design/process fluid in vertical thermosyphon drops below 30–40 % of the tube length. For horizontal thermosyphon, appears to be undersized but the cause is liquid feed maldistribution.

"Surges in boilup": process fluid circulation rate too low/[fouling on the process side]*/wide boiling range/overdesign.

"Cycling (30 s – several minutes duration) steam flow, cycling pressure on the process side and, for columns, cycling Δp and cycling level in bottoms": in addition to general, all natural circulation systems are prone to surging/feed contains high w/w % of high boilers/vaporization-induced fouling/contriction in the vapor line to the distillation column. For horizontal thermosyphon: maldistribution of fluid temperature and liquid.

*[Fouling]**: insufficient static head/excess friction in the pipes/on the tubeside the outlet nozzle area < total tube area/on tubeside the inlet nozzle area < 0.5 total tube area/rate of vaporization > 25 % of circulation rate/mass rate of vaporization > mass rate of circulation/natural circulation rate < 3 × vaporization rate/vaporization induced solids, and see Section 1.12 for generic fouling.

– forced circulation: operates with sensible heat mode in the tubes. General plus the following symptoms and causes unique to this type of reboiler: *"Unstable":* insufficient NPSH in pump, see Section 2.3. *"Low boilup and rapid fouling":* insufficient circulation/pump fault, see Section 2.3/plugged circulation lines.

"Low boilup": [fouling]*/circulation rate low/pump problems, see Section 2.3/no vortex breaker/excessive circulation and a wide spread in boiling temperatures in bottoms. *"Excessive vapor in flash chamber, unstable distillation column operation and apparent underdesign of overhead condenser":* overdesign.

Spiral plate exchanger: *"Heat transfer < design":* stratification caused by faulty inlet and exit nozzle location/baffling/maldistribution.

Gasket plate exchanger: *"Leaking gaskets":* temperature too high/temperature spike/pressure too high/cold fluid stopped but hot fluid continues/superheated steam/under vacuum.

Air cooled: *"Insufficient condensation":* instrument fault/maldistribution along either feed or exit headers/buildup of noncondensibles in bottom tube rows/insufficient area/ambient temperature too hot/fan not working/blades wrong pitch/baffles stuck/[fouled tubes]*/hot gas recirculation/tubes not sealed.

"Cycling": control system/vent for syphon-break is missing on exit manifold. *"Outlet temperature on tube-side is high":* undersized/[tube fouling on inside or outside]*/flow maldistribution on process or air side/hot air recirculation/air flowrate too low. *"Δp on process side high":* [fouled tube side]*/increased liquid viscosity/overcooling/vapor not condensed. *"Exit air temperature > expected":* low air flowrate/flow maldistribution on tube side/ambient air temperature > expected/unexpected hot air recirculation. *"Exit air temperature < expected":* high air flowrate/flow maldistribution on tube side/ambient air temperature < expected. *"Sluggish control":* the use of fan pitch variation as the control variable. *[Fouling]*:* see Section 1.12.

3.4

Thermal Energy: Fluidized Bed (Coils in Bed)

Fluidized beds are also used as reactors, Section 6.30; dryers, Section 5.6, and for size enlargement, Section 9.4.

- *Area of Application*

Use for heating/cooling solids. Mixing provides uniform temperature in the bed and solids increase the heat transfer coefficients 5 to 25 times that of the gas alone.

- *Guidelines*

Coils in fluidized bed: $U = 0.2–0.4$ kW/m^2 °C; bed to wall $U = 0.45–1.1$ kW/m^2 °C; solids to gas $U = 0.017–0.055$ kW/m^2 °C; thermal conductivity gas–solid thermal conductivity 0.17–42.5 kW/m K.

3.5

Thermal Energy: Static Mixers

Related topics reactors, Section 6.6; mixing, Section 7.1 and Section liquid–liquid, Section 7.2, and size reduction for liquid–liquid, Section 8.3.

- *Area of Application*

Use for viscosity liquids < 50 mPa s and liquid reactions Section 6.6. Used to cool polymer melts.

- *Guidelines:*

Cooling melts $U = 0.15–0.25$ kW/m^2 °C. Polymerization: 10 kW/m^2 °C. Internal heat transfer coefficient $h_{\text{inside}} = 3 \times$ value for fluid flowing in empty pipe of same diameter and length.

3.6

Thermal Energy: Direct Contact L–L Immiscible Liquids

Related topic: size reduction, Section 8.3.

- *Area of Application*

Exchange heat across liquid–liquid interface. Droplet diameter and area per unit volume estimated from Section 1.6.2 and Fig. 1.2.

- *Guidelines*

Volumetric overall heat transfer coefficients:
Tray, sieve: $U_v = 160$ kW/m^3 °C;
Wetted wall: $U_v = 20$ kW/m^3 °C.
Baffles: $U_v = 20$ kW/m^3 °C;
Spray tower: $U_v = 2$ to 100 kW/m^3 °C;
RDC: $U_v = 260$ kW/m^3 °C;
Pipeline: $U_v = 200$ to 1000 kW/m^3 °C.

3.7
Thermal Energy: Direct Contact G–L Cooling Towers

- *Area of Application*

Use of the latent heat of evaporation of 9 % of hot water to cool the water by removing sensible heat from hot water; size range: 60–1500 L/s.

- *Guidelines*

Volumetric heat transfer coefficients $U_v = 0.5$–15 kW/m^3 °C; gas superficial velocity 1 m/s; liquid loading 1 L/s m^2 cross sectional area.

3.8
Thermal Energy: Direct Contact G–L Quenchers

See Section 1.6.1 for area predictions.

- *Area of Application*

The quenching media can be any liquid. Gas flowrate 4–100 m^3/s.

- *Guidelines*

Tray: heat transfer coefficient, $U = 7$–20 kW/m^2 °C. of tray area; volumetric heat transfer coefficient, $U_v = 3$ kW/m^3 °C; superficial gas velocity = 1–1.6 m/s; mass loading liquid/gas = 10–20/1.
Packing: volumetric heat transfer coefficient, $U_v = 3$ kW/m^3 °C; superficial gas velocity = 1 m/s; mass loading liquid/gas = 1.5–3/1.
Spray tower: volumetric heat transfer coefficient, $U_v = 1.8$–5 kW/m^3 °C; superficial gas velocity = 1 m/s; mass loading liquid to gas = 1–50/1.
Baffles: volumetric heat transfer coefficient, $U_v = 0.5$ kW/m^3 °C; superficial gas velocity = 0.7–1 m/s; mass loading liquid to gas = 15–60/1.

3.9
Thermal Energy: Direct Contact G–L Condensers

- *Area of Application*

The condensing medium is water to condense steam or to cool gas. Use in steam ejector systems although these are being replaced by indirect condensers. Related topic vacuum service, Section 2.2. Body diameter, 0.1–2.5 m; liquid flowrate 3–700 L/s.

- *Guidelines*

Liquid loading 43–85 L/s m^2 cross-sectional area; height/diameter = 5/1. Keep temperature increase in the cooling water limited to 8.3 °C for operating pressures < 6 kPa; limited to 17 °C for operating pressures 6–25 kPa; limited to 25 °C for operating pressures > 25 kPa and keep the overall temperature < 50 °C to minimize erosion and corrosion.
Gas cooling $T = 16–18$ °C;
Steam condensation: $T = 2.75$ °C; approach temperature at both ends of the condenser = 2.75 °C.

Volumetric heat transfer coefficient $U_v = 100–150$ kW/m^3 °C but the value is very sensitive to the sensible heat load; usually about 30 kg water/kg steam condensed.

3.10
Thermal Energy: G–G Thermal Wheels and Pebble Regenerators and Regenerators

- *Area of Application*

Hot gas temperature: 180 to 950 °C or cryogenic conditions; 80 to 180 kPa absolute. Usually used to recover "waste" heat. For pebble beds, temperatures up to 1700 °C. Nominal gas flowrate to one side, 0.6–20 m^3/s.

- *Guidelines*

For air to solids: $U = 0.02$ kW/m^2 °C.; for hydrogen to solids = 0.1 kW/m^2 °C.
Pebble bed: heat transfer coefficient $U_v = 280$ kW/m^3 K volume of pebbles, contact time fractions of seconds. Surface compactness: up to 15 000 m^2/m^3.
Thermal wheel: contact time fraction of seconds; area 500–650 m^2/m^3 per wheel; gas face velocity 1–5 m/s, use 3.5 m/s; rpm 10–20.

Surface compactness: up to 6600 m^2/m^3.

3.11
Thermal Energy: Heat Loss to the Atmosphere

- *Area of Application*

Depends on the type and thickness of insulation and the external weather conditions.

- *Guidelines*

Heat transfer coefficient, uninsulated into still air $U = 0.005–0.01$ kW/m^2 °C; insulated into still air $U = 0.003$ kW/m^2 °C; Values increase as wind velocity increases: for 10 km/h multiply U by 2; for 20 km/h multiply U by 3.

Walls to wet earth, $U = 0.0015$ kW/m^2 °C; walls to dry earth, $U = 0.001$ kW/m^2 °C; floor to ground, $U = 0.0007$ kW/m^2 °C.

3.12
Thermal Energy: Refrigeration

- *Area of Application*

Mechanical vapor recompression for temperatures < 20 °C, ranging from 10 to -62 °C. Refrigeration capacity 20–5000 kW.

- *Guidelines*

About 0.2 kW compressor power/kW refrigeration.

- *Trouble Shooting*

Use the pressure–enthalpy, $p–H$, diagram for the refrigerant as a basis for trouble shooting. *"Compressor discharge pressure < design":* turbine drive problem, power limited/overloaded centrifugal compressor or valve problem for reciprocating compressor/wrong composition for the speed/not enough refrigerant/compressor fault, see Section 2.1.
"Compressor discharge pressure > design:" fouled condenser/insufficient air to the cooling tower/low flowrate of water to the condenser/air in the refrigerant/too much refrigerant, level too high.
"Compressor discharge pressure > design and condensing temperature normal": poor drainage from the condenser/non condensibles in the refrigerant/refrigerant letdown valve plugged.
"Suction pressure < design": process feedrate < design/low circulation of refrigerant/not enough refrigerant in chiller, level too low/leak causing a loss of refrigerant/compressor problems, see Section 2.1.
"Suction pressure > design": process coolant load > design/throttle valve incorrectly adjusted/low level refrigerant/compressor problems, see Section 2.1.
"Process exit temperature > design, refrigerant temperature from the chiller > design and the approach temperature = design": chiller pressure > design/not enough refrigerant/heavy ends impurities in refrigerant/level of refrigerant in chiller

< design/expansion valve plugged/restriction in refrigerant suction line/unit too small/process fluid velocity too slow/too much refrigerant in chiller causing flashing in the compressor suction.
"Process exit temperature > design, refrigerant temperature in chiller = design and approach temperature > design": fouling on refrigerant side/fouling on the process side/chiller unit too small.
"Condenser temperature > design": [fouled]* condenser. *[Fouling]*:* see Section 1.12.

3.13
Thermal Energy: Steam Generation and Distribution

See thermal energy furnaces/boilers, Section 3.2.

- *Area of Application*

Steam for power via turbines drives Section 3.1 and via vacuum ejectors, Section 2.2. Thermal heating, Section 3.3, separations via evaporators, Section 4.1, distillation, Section 4.2, dryers, Section 5.6, and blowouts of lines, Section 2.7.

- *Guidelines*

For delivery, gas velocity 60 m/s. Typical steam gauge pressures: 100–200 kPa, 120–130 °C, (comment: tends to be sluggish in response to changes in demand), 1 MPa, 185 °C; 1.7 MPa, 210 °C; 2.75 MPa, 230 °C; 4.1 MPa, 255 °C.

For a control valve in the line from the steam drum to the process, allow a Δp across the valve of 10 % of the absolute pressure at the steam drum or 35 kPa, whichever is greater.

Steam leakage: 40 g/s at 0.7 MPa through a 6 mm diameter hole. Leak rate proportional to (hole diameter)^2 × pressure.

See also steam traps to separate condensate from steam, Section 5.1. Steam generation, furnaces Section 3.2.

Steam flow through a control valve (called "wiredrawing") occurs at constant enthalpy with a resulting increase in temperature or superheat relative to the saturation temperature at the lower downstream pressure.

For gas-fired furnaces, 13.5 kg steam at 1 MPa/m^3 natural gas. Boiler rating 0.65 kW/kg/h of 1 MPa steam. 1 kg natural gas uses 17 kg air. With an economizer, each 1 % of efficiency improvement reduces the flue gas temperature by 22 °C and increases the boiler feedwater temperature by 5.5 °C. Each GJ of gas burned produced 43 kg water in the flue gas; the dew point of flue gas = 57 °C.

- *Good Practice*

Use high pressure steam for energy and low pressure steam for heating.

Take steam off the top of the steam header; put condensate into the top of the condensate return header.

- *Trouble Shooting*

"Tube failure": feed water contains impurities/for forced circulation: water circulation rate too low/vibration induced tube failure/overfiring/dry spots in tubes. *"Wet steam":* rate of steam generation > design causing inadequate demisting in the steam drum. *"Steam production < design":* fuel gas pressure < design/soot in flue gas tubes+/thermostat incorrect and burners cut out too soon/wrong type of fuel gas burner. *"Stack temperature > design":* not enough air/over-firing. + Caution: if the furnace is firing gas and producing soot, the firing is probably above the explosive limit.

3.14
High Temperature Heat Transfer Fluids

- *Area of Application*

To provide a source of heat between 200 and 450 °C. High temperature oils, alkylated aromatics, mixture of diphenyl and diphenyl oxide, di- and triaryl ethers, molten salts, liquid sodium or patented fluids can provide sensible heat or latent heat.

- *Guidelines*

for pressures 0.1 to 0.2 MPa:
175 °C consider Dowtherm J
200 to 400 °C consider molten salt
275 °C consider Dowtherm A
310 °C consider Dowtherm G

- *Good Practice*

Usually a portion of the liquid is purged and replaced with fresh makeup.

- *Trouble Shooting*

"Rapid cycling of the furnace or heating elements": [fluid velocity low]*. *"Vapor pressure increased":* [thermal cracking of fluid]*. *"Noisy pump"*: contaminants such as water/[fluid velocity low]*/[thermal cracking of fluid]*. *"Pump discharge pressure fluctuates":* contaminants such as water/[fluid velocity low]*/[thermal cracking of fluid]*. *"Startup of cold unit takes longer than usual":* [oxidation of fluid]*. *"Heater cannot achieve setpoint":* [oxidation]*/[thermal cracking]*. *"Poor control":* [control valve plugged]*/[heater cannot achieve setpoint]*/control design faulty/controller not well-tuned.

[Control valve plugged]:* [thermal cracking]*/[oxidation]*/filter plugged/filter missing/filter not working.

[Fluid velocity low]:* pump problems, see Section 2.3/filter plugged/controller not well-tuned/wrong location for filter/crud left in the lines during maintenance.

[Oxidation]:* temperature of air in expansion tank > 60 °C/for higher temperatures in expansion tank, dry inert gas blanket not used in the expansion tank.

[Thermal cracking]:* fluid velocity in the furnace or heater $<$ design.

See also trouble shooting suggestions related to gas–liquid separators, furnaces, and pumps.

3.15
Tempered Heat Exchange Systems

Coolant or heating media is circulated in a closed loop with controlled purge and addition of fresh media. The circuit may include a storage tank.

- *Area of Application*

For systems requiring more uniform temperature, to minimize local hot or cold spots; for systems that tend to foul; for systems that operate close to the freezing points; for systems with materials that thermally degrade easily. Example, batch polymerizers; condensers for fatty acids or alcohols or for maleic anhydride.

- *Guidelines*

Use a circulating pump or ejector. For a pump, the system resistance is frictional with the typical head required of about 12 m. Often select a drive at 1200 rpm.

- *Good Practice*

Consider installing a check valve (and perhaps a fail-safe-closed valve) in the return line.

4
Homogeneous Separation

The fundamentals upon which most of these processes are based include: mass is conserved; mass transfers because of bulk movement and diffusion. The rate of mass transfer is proportional to the concentration driving force of the target species and the surface area across which the transfer occurs. Phase equilibrium is a useful starting approximation but usually it is the rate at which the system moves toward equilibrium that is important. Surface phenomena effects, especially foaming and fouling, wetting and dispersed phase stability are issues to consider.

In this chapter we consider the separation of species contained in a homogeneous phase, such as a liquid or gas. The separation is based on exploiting a fundamental difference that exists between the species. Section 4.0 gives some overall guidelines. Methods that exploit differences in vapor pressures are evaporation, in Section 4.1 and distillation, in Section 4.2. Methods that exploit differences in freezing temperature and solubility are freeze concentration, Section 4.3, melt crystallization, Section 4.4; and zone refining, Section 4.5. Methods exploiting solubility are solution crystallization, Section 4.6; precipitation, Section 4.7; absorption, Section 4.8, and desorption, Section 4.9. Solvent extraction, Section 4.10, exploits differences in partition coefficient.

Methods based on exchange equilibrium and molecular geometry include adsorption of species from a gas, Section 4.11, and of species from a liquid, Section 4.12. Ion exchange, Section 4.13, exploits differences in surface activity and exchange equilibrium.

Foam fractionation, Section 4.14, uses differences in surface activity to effect the separation.

Section 4.15 describes membranes and introduces a range of membrane separation options. Molecular geometry is exploited in separations of gases via gas permeation, Section 4.16. Dialysis and electrodialysis are considered in Sections 4.17 and 4.18 respectively. Other methods to separate species in liquids are given in Section 4.19, pervaporation; Section 4.20, reverse osmosis; Section 4.21, for nanofiltration; Section 4.22, for ultrafiltration; Section 4.23, for microfiltration and Section 4.24 for chromatographic separations. Separations of larger sized species are considered “heterogeneous systems” and are considered in Chapter 5.

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Overall Guidelines

1. Keep it simple.
2. Exploit differences in properties between the key target species.
3. Consider mixing/blending of streams before considering separation.
4. Remove lightest component, most abundant, least expensive first; or remove the most difficult last.
5. Leave high specific recoveries until last.
6. Try to avoid adding an agent to achieve the separation.
7. Try to avoid extremes in operating conditions.
8. Consider shifting from homogeneous phase separation to heterogeneous phase separation.
9. Consider reaction to shift the species to another form ($).

4.1
Evaporation

Related to Crystallization, Section 4.6.

- *Area of Application*

α_{vp} = 20 to 5000. Liquid feed concentration of target solute 2 to 50 %; 1 to 40 kg/s feed rate. One product. Usually use when no solids, nonfoaming and doesn't thermally degrade although special designs can accommodate these. Can be operated as multistage with up to 3 to 10 stages.

- *Guidelines*

Dissolved solids elevate the boiling temperature between the solution and saturated vapor by 1.5 to 5.5 °C.

Temperature sensitive materials: use the Hickman decomposition hazard index, *HDHI,* expressed as the amount of time the material is kept under temperature (as measured by pressure, Pa) in units of Pa s.

External short tube, vertical exchanger, natural circulation: OK for foaming, but not for fouling, crystal formation, or suspended solids. Viscosities < 20 mPa s. Relative to agitated film retention time of 16:1 and volume 10:1. Overall heat transfer coefficient 1–1.5 kW/m^2 °C. HDHI = 10^8 to 10^9 Pa s. Area 3–1000 m^2.

External short tube, vertical exchanger, forced circulation: OK for foaming, for fouling, crystal formation and some suspended solids. Viscosities < 150 mPa s. Relative to agitated film retention time of 42:1 and volume 13:1. Overall heat transfer coefficient 0.75–3 kW/m^2 °C decreasing with increasing viscosity. Power 0.13 to 0.5 kW/m^2. HDHI = 10^7 to 10^8 Pa s. Area 3–600 m^2.

External kettle reboiler, natural circulation: Viscosities < 200 mPa s.

Internal calandria, vertical short tube: Preferred for fouling and crystal forming systems. OK for foaming, for fouling, crystal formation and some suspended solids. Viscosities < 1000 mPa s. Relative to agitated film retention time of 168:1 and volume 3:1.

Long tube, rising film: Especially for clear and relatively dilute feed, OK for foaming, but not for fouling, crystal formation or suspended solids. Viscosities 150 to 1000 mPa s. $\Delta T > 14\,°\mathrm{C}$. Select ΔT to create annular or mist-annular flow. Overall heat transfer coefficient 2 to 5 kW/m^2 °C decreasing with increasing viscosity. HDHI = 10^6 to 10^7 Pa s. Area 3–300 m^2.

Long tube falling film: Especially for heat sensitive and moderately viscous feed. Not for foaming, for fouling, crystal formation or suspended solids. Viscosities 150 to 1000 mPa s. $\Delta T > 3\,°\mathrm{C}$. Select ΔT to create annular or mist-annular flow. Outlet temperature 5–6.5 °C $<$ steam temperature. Overall heat transfer coefficient 2.5 to 5.6 kW/m^2 °C decreasing with increasing viscosity. residence time 15 to 30 s per stage. HDHI = 10^3 to 10^9 Pa s. Consider multistaging with optimum. Area 3–1000 m^2. For condenser use $U = 1.1$–1.25 kW/m^2 K.

Multistage rising or falling film evaporators: When the boiling temperature rise is large, use four to six multiple effect stages with forward feed. When the boiling temperature rise is small, use eight to ten multiple effects. For multistaging, feed forward is the most common, but feed backward is used for highly viscous liquids. In feed backward, the more concentrated solution is heated with the highest temperature steam and pumping is required between stages. The steam economy for n stages is $0.8n$ kg evaporated/kg of outside steam. Boost the interstage steam pressure with steam jet compressors (efficiency 20–30 %) or with mechanical compressors (efficiency 70–75 %).

Agitated falling film: Especially for viscous feed. OK for foaming, for fouling, crystal formation and suspended solids. Viscosities > 1000 mPa s. Relative to agitated film retention time of 1:1 and volume 1:1. Retention time about 1 to 30 s. Keep ΔT high at 27 to 50 °C to keep high heat transfer. Overall heat transfer coefficient 1–2 kW/m^2 °C decreasing with increasing viscosity although heat transfer coefficients as high as 150 kW/m^2 °C have been reported. Power 1.8 to 4 kW/m^2. HDHI = 10^4 to 10^6 Pa s. Related topic thin film reactors, Sections 6.19 and 3.3.

Scraped surface horizontal film (votator): Especially for viscous feed. OK for foaming, for fouling, crystal formation and suspended solids. Viscosities > 2000 mPa s. Relative to agitated film retention time of 1:1 and volume 1:1. Overall heat transfer coefficient 2 kW/m^2 °C decreasing with increasing viscosity. Power 3 to 12 kW/m^2. Related to scraped surface reactor, Section 6.20.

Rising and falling film: Especially for heat sensitive. OK for foaming, but not for fouling, crystal formation or suspended solids. Viscosities < 1500 mPa s. Relative to agitated film retention time of 0.5:1 and volume 0.8:1.

- *Good Practice*

Keep the pressure drop between the last effect and the inlet to the vacuum device < 3 kPa. Consider vapor recompression for conventional low-ΔT evaporators such as falling film, forced circulation and horizontal tube falling film. Vapor recom-

pression is rarely used on high-ΔT systems such as rising film, calandria and submerged tubes.
Multiple effect evaporator: Capacity of one or more effects in series is proportional to (condensing temperature of the steam supplied – temperature of the liquid boiling in the last effect) and the overall heat transfer coefficient. If foaming occurs, reduce the liquid level in the effect.
Vertical falling film evaporator: see also Absorbers, Section 4.8 and falling film reactors, Section 6.19. Always check the liquid feed distribution with water before putting on line.

- *Trouble Shooting*

"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.
Vapor recompression evaporators: *"Evaporation rate < design":* fouled heat transfer surface/uneven movement of liquid over heat transfer surface/feed property changes/excessive noncondensibles from leaks or present in feed/flooded condensate, trap malfunction, Section 5.1/feed temperature < design/water leakage into the system/lower compressor suction pressure, see also Section 2.1.
"Steam economy low": instrument fault/excessive venting especially the first, second and third effects/vapor exiting through condensate, trap problems, Section 5.1/vapor blowing into product flash tank through the liquor lines/internal afterheaters leaking/afterheater scaled so that liquor from the colder effect is not correctly preheated for the next effect/[entrainment]*/excessive vacuum/[fouling]*.
"Recovery-boiler efficiency low": [fouling]*
"Vibration": vapor velocity high through the first row of tubes.
"Vacuum problems": see vacuum, Section 2.2.
[Excessive entrainment]:* poor design of deflector/liquid level above the tubes.
*[Fouling]**: sodium sulfate precipitates especially in the first effect/lignin precipitates especially in the first and second effect/vapor sulfurization and condensation in third and fourth effects/velocity too small.
Falling film evaporator: *"Evaporation rate < design":* [liquid maldistribution]*/steam trap malfunction, see Section 5.1/steam flowrate too small.
Forced circulation evaporator: usual problems are fouling/scaling and high liquid viscosity.
*[Fouling]**: tubular velocity too small: for 5 cm diameter tubes, recommended velocities are: for viscous liquids use 3 m/s; for the finishing effect, 2–2.7 m/s; for the intermediate effects, 1.5–1.8 m/s; for the initial effects, 1.2–1.5 m/s/pump problems, see Section 2.3.
[Liquid maldistribution]:* not vertical/inadequate calming of feed/variations in weir height.
Multiple effect evaporator:
"Reduced flowrate from last stage to maintain target strength": water temperature to contact condenser too hot/insufficient condensing area/[decreased UA]*/[foaming]*.

"ΔT higher than usual before stage "x" and ΔT lower than usual after stage "x"": [decreased UA in stage "x"]*/[foaming]*
"Steam usage higher than normal": steam leak into an effect/bleed rate too high/poor trap performance.
"Cycling" (30 s – several minutes duration): instrument fault/condensate in instrument sensing lines/[foaming]*/liquid maldistribution/steam trap problems (see Section 5.1)/unsteady vacuum (see Section 2.2).
*[Decreased UA]**: inadequate condensate removal/liquid level too low in the effect/[fouling]*/inadequate removal of non-condensible gas.
*[Fouling]**: tubular velocity too small: for 5 cm diameter tubes, recommended velocities are: for viscous liquids use 3 m/s; for the finishing effect, 2–2.7 m/s; for the intermediate effects, 1.5–1.8 m/s; for the initial effects, 1.2–1.5 m/s. For more general causes see Section 1.12.
*[Foaming]**: rate of evaporation too fast/liquid downflow over foam too low. See general causes listed in Section 1.12.

4.2
Distillation

Overall selection and sizing factors are summarized in Fig. 4.1. We start in the top LH corner with the target separation. The goal is shown at the bottom RHS where the reflux ratio for the column is selected to provide the minimum annual cost. Our route will connect the target to the goal by calculating the reflux ratio (near the top RHS) and the capital and operating costs based on the operating conditions in the column (mid-LHS); the number of theoretical stages required (top RHS); the type of internals (central), the configuration (bottom LHS) and the size and cost of the equipment (the condenser, the reboiler, the piping, pumps, column and internals). We start at the top LHS: the target separation requires knowledge of the properties of the species to be separated, connected to vapor–liquid equilibrium and the unique characteristics of this separation. Sometimes an entrainer, inert gas or steam is added to facilitate the separation.

Based on the vapor–liquid equilibrium data and the complexity of the separation we determine the number of theoretical stages required for a variety of reflux ratios (top RHS). The target separation, the species, the heating and cooling media dictate the operating window of temperature and pressure (mid-LHS).

The central decision is the type of internals: tray, packing or structured packing. The choice depends on the flowrates, the characteristics of the fluids, the operating temperature and pressure, the allowable pressure drop across the column, the materials of construction and the fouling and corrosivity of the system.

The choice of internals dictates the column height and diameter (lower central).

The operating and capital costs of all the components are ultimately a choice of the reflux ratio selected. The reflux ratio that yields the minimum cost is selected (bottom RHS).

Fundamentals: use simplified McCabe–Thiele diagram to help understand what is going on and especially for trouble shooting.

In many mass transfer operations two different concepts are used frequently: the **theoretical stage** or the **transfer unit**. To size tray contactors, we usually use "the **theoretical stage**". The theoretical stage is the amount of contacting needed for the exit streams to leave with equilibrium concentrations. To determine the total height of "contacting" we estimate the number of theoretical stages, NTS and then multiply by the height of a theoretical stage, HETS (some authors call this HETP). For distillation, HETS = tray spacing/tray efficiency. Since the tray spacing is usually 0.6 m and the tray efficiency is usually 60 %, HETS = 1 m. In general, HETS for trays is in the range 0.6–1.2 m.

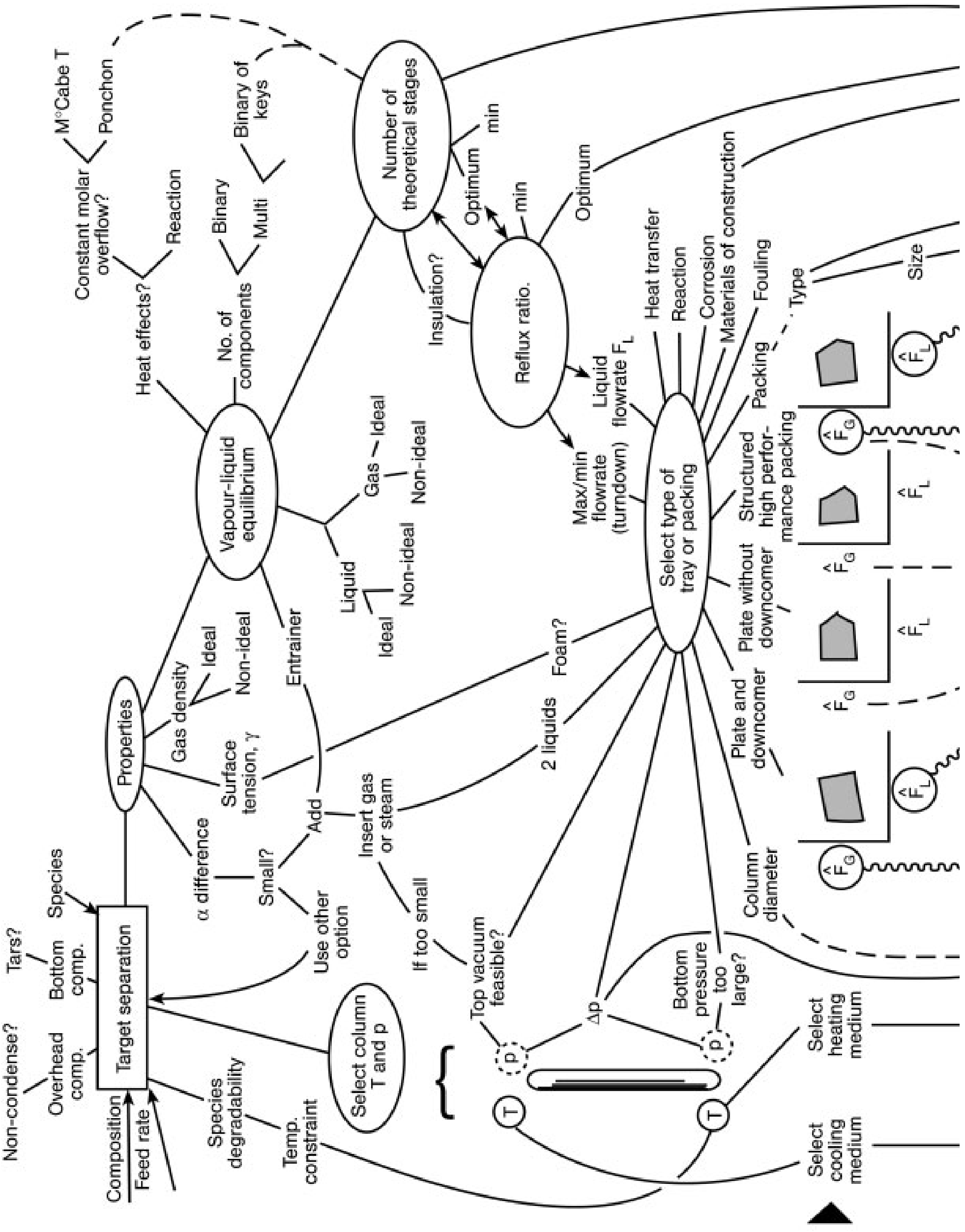
To size continuous contactors, (such as packed columns, bubble columns, solvent extraction devices), we usually use the concept of **transfer unit**. The transfer unit is defined as the amount of contacting necessary for one phase to receive an enrichment equal to the average driving force in that phase. To calculate the number of transfer units needed, NTU, we need to establish the average driving force for mass transfer throughout the whole piece of equipment. This requires knowledge of the driving force at the inlet and exit of the unit. To determine the total height of "contacting" we multiply the number of transfer units NTU by the height of a transfer unit, HTU. Care is needed with the units of measurement (usually mole fractions, y and x are used) and the phase of interest since we define the transfer unit in terms of that phase of interest. Thus, we have the NTU based on the overall gas phase mass transfer, $\mathrm{NTU_{OG}}$, or we can define the transfer unit in terms of the liquid phase, $\mathrm{NTU_{OL}}$.

Is there any relationship between theoretical stage and transfer units? Yes. In general, if the operating and equilibrium lines diverge with increasing concentrations, then NTU > NTS and vice versa. However, for distillation, the lines diverge in the column below the feed and the lines converge above the feed. The net result is that as an approximation NTU = NTS and HETS = HTU. (Such simplifications do not apply for absorption, stripping and other mass transfer operations. Details are given in Sections 4.8, and 4.9.)

- *Area of Application*

Liquid feed concentration 15 to 80 % w/w; $\alpha_{vp} > 1.2$; with materials not temperature sensitive, negligible solids, non-foaming, 99+ % purity possible for both product streams. Maximum column diameter 12 m or feedrate = 300 kg/s; maximum height 35 m. Details of gas–liquid contacting, in general, are given in Section 1.6. This method of contacting gases with liquids via trays or packing is also used for gas absorption, Section 4.8; gas desorption or stripping, Section 4.9; gas–liquid separations, Section 5.1; and reactions, Sections 6.15 and 6.16.

Configurations include ordinary, vacuum, molecular (small capacity and very high vacuum < 3.5 kPa, usually for material with molar mass 250 to 1200), cryogenic (operating at temperatures < –100 °C), steam stripping (steam provides direct heating or "inert" steam is added to provide very high "vacuum" when used with organics that are immiscible with water), extractive (solvent is added to the


Non-condense?
Overhead comp.
Tars?
Bottom comp.
Species
Target separation
Composition
Feed rate
Species degradability
Temp. constraint
Select column T and p
α difference
Small?
Use other option
Add
Insert gas or steam
If too small
Top vacuum feasible?
Properties
Gas density
Ideal
Non-ideal
Surface tension, γ
Entrainer
2 liquids
Foam?
Vapour-liquid equilibrium
Heat effects?
Constant molar overflow?
Reaction
M^cCabe T
Ponchon
No. of components
Binary
Multi
Binary of keys
Liquid
Ideal
Non-ideal
Gas
Ideal
Non-ideal
Number of theoretical stages
Optimum
min
Insulation?
Reflux ratio.
min
Optimum
Liquid flowrate F_L
Max/min flowrate (turndown)
Select type of tray or packing
Heat transfer
Reaction
Corrosion
Materials of construction
Fouling
Packing
Type
Size
Structured high performance packing
Plate without downcomer
Plate and downcomer
Column diameter
T
p
Δp
p
T
Bottom pressure too large?
Select heating medium
Select cooling medium
F̂_G
F̂_L
F̂_G
F̂_L
F̂_G
F̂_L
F̂_G
F̂_L

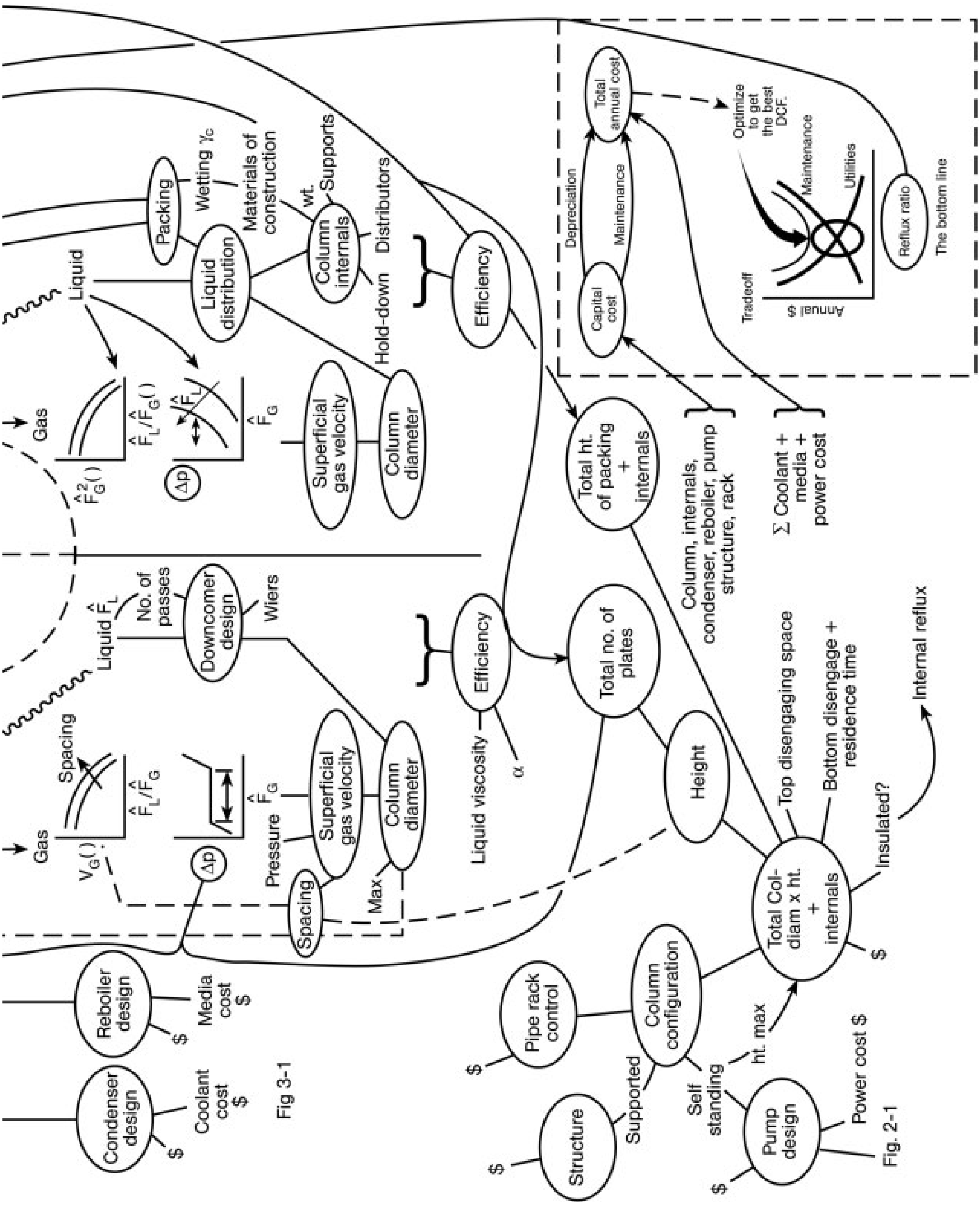


Figure 4.1 Sizing map for distillation.

top of the column), azeotropic distillation (solvent is added to the feed to the column), HIGEE (unique spinning tray design) and reactive (reaction and distillation are combined, for example for selective catalytic hydrogenation of C4 to C6, Section 6.35). The operation can be batch or continuous.

The internals are usually trays, random packing or structured packing.

- *Guidelines*

Distillation is usually the first choice for homogeneous separation ($).

The issues for sizing distillation columns, and the types of internals, are summarized in Fig. 4.1.

Prefer to remove the most valuable as distillate ($,C).

Prefer to remove components one by one as overhead ($,C).

Prefer separations that give equimolar splits ($).

Set the column pressure to try to use water as the coolant and steam as the energy source ($).

Overhead concentrations 95–99 % mol (J).

In selecting the internals: for ordinary distillation at $<$ 100 kPa, select (i) structured packing, (ii) random packing. For distillation at 0.1–0.4 MPa, use foaming, fouling and $ as criteria. For distillation at $>$ 0.4 MPa select (i) trays.

Qualitatively:

Trays: high pressure drop/HETS, high liquid holdup, low liquid/vapor ratio, can handle some fouling, high liquid loads, use care if foams, relatively high HETS, $ low.

Random packing: medium pressure drop/HETS, medium liquid holdup, wide range in liquid/vapor ratio, not for fouling, high vapor loads, OK for foams, medium HETS, $ medium. Use for columns $<$ 1 m diameter; OK for viscous liquids.

Structured packing: low pressure drop/HETS, low liquid holdup, not for fouling, high vapor loads, OK for foams, low HETS, $ high. Not for viscosities $>$ 2 mPa s, pressures $>$ 200 kPa.

A general comparison of the properties, relative to other gas–liquid contact devices is given in Table 1.1, Section 1.6.1.

- If **trays** are selected, then calculate the number of theoretical stages, NTS, required.

Tray options: *valve*: usually cheaper than sieve, use for large diameter columns at moderate to high pressures, moderate turndown ratio. Usually about 120 to 140 valves per active m^2.

sieve: use for large diameter columns at moderate to high pressures, moderate turndown ratio, residence time for sieve tray plus downcomer 2–20 s. Δp/HETS = 0.4–1 kPa; HETS = 0.6–1.2 m.

bubble cap: use for columns with small liquid flowrate, high turndown ratio, heat transfer needed internally. Residence time 20–30 s.

Downcomer: unaerated liquid velocity 0.5 m/s; head loss via underflow clearance $<$ 0.3 kPa. Allow 3 s liquid residence time and extend to 6 s for foaming systems. Weir overflow velocity = 5–20 L/s m of outlet weir.

• If **packings** are selected, then calculate the number of transfer units, NTU, required or number of theoretical stages (NTS).

– *conventional random dumped packings*: Pall rings, Tellerettes, raschig rings, beryl or intalox saddles, lessing rings. Prefer Pall rings and Tellerettes; if ceramic, use saddles. Usually use 5 cm diameter slotted rings for vapor flowrates > 950 dm^3/s; use 2.5 cm or smaller for vapor flowrates < 230 dm^3/s. Δp/HETS = 0.15–0.3 kPa. Δp/m of packing = 0.08–0.65 kPa/m or 0.32–0.65 kPa/m for moderate to high pressure distillation and 0.08–0.16 kPa/m for vacuum operation. HETS: HETS = 0.4–1.5 m; HETS 0.45–0.8 m for small diameter columns; 0.60–1.1m for $>$ 1 m diameter.

– *high performance structured packing*: Hypac, Flexipac, Gauze, Glitsch grid, Leva film:

Δp/HETS = 0.001–0.5 kPa; very small superficial gas velocity. HETS = 0.1–0.8 m.

To estimate the NTS, number of theoretical stages:

1. Estimate minimum reflux ratio from the Underwood equation, or as an approximation if the distillate is almost pure:

$$R_{\min} = \frac{1}{(a-1)(x_{\mathrm{LK,Feed}})}$$

Select operating reflux ratio at 1.2 to 1.5 times minimum ($). For vacuum distillation, usually the reflux ratio is $>$ 10:1 especially for packed columns.

2. Estimate the minimum number of theoretical stages using the Fenske equation, or as approximations:

Douglas's, T = absolute temperature for overhead distillate, D, and for the bottoms, W.

$$N_{\mathrm{m}} = \frac{T_{\mathrm{D}} + T_{\mathrm{W}}}{3(T_{\mathrm{W}} - T_{\mathrm{D}})}$$

Latour's: x = mol fraction.

$$N_{\mathrm{m}} = 0.11\frac{T_{\mathrm{D}} + T_{\mathrm{W}}}{T_{\mathrm{W}} - T_{\mathrm{D}}}\log_{10}\left[\frac{x_{\mathrm{D}}(1-x_{\mathrm{W}})}{x_{\mathrm{W}}(1-x_{\mathrm{D}})}\right]$$

The number of theoretical trays = twice the minimum number, N_{m}.

3. For **trays:** estimate the actual number of trays using the following tray efficiencies:

– Sieve, valve, or plate trays, tray efficiency 60 % (F); pressure drop 0.7 to 1.4 kPa/tray or 0.3–0.65 kPa/theoretical stage. HETS = tray spacing/tray efficiency, usually = 0.6/0.6 = 1 m. The usual range is 0.6–1.2 m.

– Sieve, valve, or plate trays, the tray efficiency decreases as the viscosity of the liquid (at column conditions) increases; at 0.2 mPa s, tray efficiency = 60 %; at 1 mPa s, tray efficiency = 16 % (F).

4. For **trays:** estimate the column height by the number of actual trays × 0.6 m tray spacing plus 1.2 m at the top and 1.8 m at the bottom.

5. For **trays:** estimate the column diameter with trays assume acceptable superficial vapor velocity

0.3 m/s for high pressure operation
0.9 m/s for atmospheric operation
2.5 m/s for vacuum < 13 kPa.

or superficial density-weighted vapor flowrate, F factor, of 1.2 to 1.4 m/s $(\mathrm{kg/m^3})^{0.5}$ or boilup rate = 1.35 kg/s m^2. The superficial gas velocity = $F/(\text{vapor density})^{0.5}$

The superficial, density-weighted vapor velocity, "*k*", is used to size the diameter of distillation columns, absorbers, Section 4. 8, gas–liquid separators or knock out pots, Section 5.1, and face velocity to demisters, Section 9.1. For convenience, values of "*k*" are given in Table 4.1 for different applications.

L/D < 30; maximum height 55 m limited by windload.

Tray column without downcomers: superficial gas velocity 0.5–3 m/s; k_L 0.01–0.04 m/s; area/unit volume 100–200 $\mathrm{m^2/m^3}$; $k_L a$ = 1–8 1/s; liquid holdup = 0.5–0.7.

Table 4.1 Density-weighted vapor flowrate or "capacity factor", m/s, for different types of separations and contacting

Type of contacting	Value of "*k*", m/s	Value of *F* factor; m/s $(\mathrm{kg/m^3})^{0.5}$	Comment
Distillation: trays	0.025–0.06 usual 0–0.15 0.009–0.075 "typical"	1.2–1.8; 0.3–2.5	
Distillation: random packing	0.009–0.09 "typical"	0.6–3.5; 0.3–2.9	
Distillation: structured packing	0.003–0.14 "typical"	0.5–2.5; 0.12–4.4	
Absorption, trays		1.2–1.8	with allowance of 1.5 m space above top tray
Absorption, random packing	0.051	0.6–3.5	
Knock out pots	0.03 to 0.12 with the usual value 0.07–0.09.		For horizontal vessels, higher values of *k* can be used. Use smaller values of *k* when the drop size in the mist is expected to be smaller.
Demister	0.06–0.12 with usual 0.106		
	0.106		for operating pressure 0.7 MPa and "*k*" decreases by 0.003 for each increase in pressure by 0.7 MPa. Application: knock out pot + demister on suction of compressor for natural gas.

3. **For packing:** estimate the height of packing from the NTU × HTU (or NTS × HETS). For distillation HTU ≈ HETS because mass transfer resistance is in the gas phase, or $k_L/k_G > > 1$.

For conventional dumped packing: column diameter/packing diameter > 15; use 2.5 cm packing for gas flowrates about 250 dm^3/s; use 5 cm diameter packing for gas flowrates > 1000 dm^3/s;

In general HETS = 0.3 to 1.8 m; 2.5 cm Pall rings: HETS = 0.4 to 0.8 m; 5 cm Pall rings, HETS = 0.7 to 0.9 m.

Split total height into self-supported sections: plastic packings: 3 to 4.5 m max. height to prevent weight from collapsing the packing; metal packings: 6 to 7.5 m height max.

Use liquid distributors every 5 to 10 tower diameters of height with at least one every 6 m. Distributors have 30 to 50 discharge nozzles/m^2 for diameters < 1 m.

5. **For packing:** estimate the column diameter: for conventional random packing: acceptable superficial vapor velocity, expressed as a percentage of gas flooding velocity is for intalox saddles, 80 % of flooding; surface areas 50 to 700 m^2/m^3 with increasing values as the diameter decreases.

for raschig rings 60 % of flooding.

for Pall rings 90 % of flooding.

or 1.4 to 2.2 m/s or superficial gas density-weighted velocity, F, of 0.6 to 3.5 m/s $(kg/m^3)^{0.5}$.

Superficial mass ratio weighted velocity for flooding = 0.35 m/s.

The liquid loading must be sufficient to wet the packing; which is 0.015 to 4 kg/s m of wetted periphery of the packing (0.015 to 4 L/s m) or superficial liquid loading of 3 to 35 L/m^2 s . Must be at least 0.5 L/m^2 s. If there is insufficient liquid, then increase the size of packing to reduce the area per unit volume.

Flooding at the density ratio weighted superficial vapor velocity, “k”, of 0.1 m/s.

Δp for moderate to high pressure 0.3–0.6 kPa/m packing height; for vacuum 0.08–0.16 kPa/m and see Section 2.1.

HETS

packing size, cm	HETS, m
2.5	0.46 (vacuum operation, 0.67)
3.8	0.67 (vacuum operation, 0.82)
5	0.91 (vacuum operation, 1.06)

Packed column: superficial gas velocity 0.1–1 m/s; k_L 0.003–0.02 m/s; area/unit volume 20–350 m^2/m^3; $k_L a$ = 0.06–7 1/s; liquid holdup = 0.05–0.1.

If **structured packing** is selected; design for 70 to 80 % of flooding; for foaming use 40 % of flooding. Usual liquid flowrate of 0.007 to 5 L/s m^2. Usual gas density-weighted superficial velocity of 0.5 to 2.5 m/s $(kg/m^3)^{0.5}$. Δp/HETS = 0.01 to 0.05 kPa. If the $\Delta p > 1.2$ to 1.6 kPa/m, then the packing is flooded. HETS 0.12 to 0.45 m. with this increasing to 1.8 m for high liquid capacity Glitsch grid. “k” or density-weighted velocity = 0.3 m/s for flexigrid structured packing; = 0.5 m/s for structured packing.

For ***extractive distillation***, the solvent should have a boiling temperature 50 to 100 °C higher than those of the products with solubility parameters and molar volume similar to those of one product but different from the other. Related additional units include decanters, Section 5.3.1 and strippers, Section 4. 9.

For ***azeotropic distillation***, additional units include decanters (see Section 5.3.1) and strippers, Section 4.9.

For ***molecular distillation***, 0.2 to 0.5 g/s m^2 with about 4.5 m^2/unit. 80 to 90 % efficient.

For ***steam distillation***, for direct heating 25 to 120 kg/m^3. For inert steam added, flowrate calculated.

For ***HIGEE***, residence time 0.1–1 s; voidage 90–95 %; 2 m diameter max., area per volume 2000–5000 m^2/m^3. 1000 rpm; film thickness 100 μm. Overall heat transfer coefficient $U = 10$ kW/m^2 K. See also Reactive distillation, Section 6.35.

For ***batch distillation***, size based on cycle time: fill, distill, discharge bottoms, clean.

for $\alpha_{vp} = 2$, NTS = 10; reflux ratio 20:1
$\alpha_{vp} = 4$, NTS = 6; reflux ratio 12:1
$\alpha_{vp} = 10$, NTS = 3; reflux ratio 7.5:1
To convert TS to height of packing
1 TS = 1 m of > 5 cm dumped Pall rings or saddles
1 TS = 0.9 m of 4 cm dumped Pall rings or saddles
1 TS = 0.6 m of < 2.5 cm dumped Pall rings or saddles
1 TS = 0.15 m of structured mesh packing in column of diameter < 0.3 m
1 TS = 0.3 m of structured mesh packing in column of diameter > 0.3 m as the more volatile species is removed, the separation becomes progressively more difficult.

too low a reflux gives unattainable product regardless of the number of trays.

gives high purity recovery from a small concentration of a low boiling species in a single operation.

keep the reflux holdup < 10 to 15 % of the initial batch charge.

- *Good Practice*

Prefer the use of low holdup internals or HIGEE (H). Prefer a distillation sequence to minimize inventory of hazardous material (H). Select materials of construction to promote wetting: select critical surface tension of the solid to be > the surface tension of the liquid. If the surface tension of the distillate > surface tension of the bottoms (surface tension negative) prefer the use of trays to packings to minimize potential for liquid film breakup. If the surface tension of the distillate < surface tension of the bottoms (surface tension positive), the foam above trays might be unexpectedly stable.

For trays, add 10 % more trays or two trays to improve operability. Weir height: 5 cm with length 75 % of the tray diameter to provide a liquid weir overflow rate > 5 and < 20 L/s m of weir into the downcomer. Usually use 15 L/s m, For lower flows use a picket weir. Overall downcomer area should be > 5 % total tray area. For foaming liquids increase downcomer area by 50 %.The downcomer exit should be at least 1.2 cm below the top edge of the outlet weir. Include four, 6 mm diameter weep holes in each tray for shutdown drainage. For packing, water test the liquid distributor for good liquid distribution before startup.

- *Trouble Shooting*

The relationship between the symptom and the causes partly depends on the control system used. Check the auxiliaries to see if they are at fault: reboilers and condensers, see Sections 3.2 and 3.3; vacuum, see Section 2.2; pumps, see Section 2.3. For packed towers, 80 % of the causes are liquid maldistribution.

“Δp across the column $> >$ design ($>$ half the column height), reflux flowrate $> >$ usual; ΔT across column $<$ design, overhead composition contains heavies $>$ design; surges in the liquid overhead, bottoms level low or fluctuates, bottoms pressure $>$ design, higher column pressure and higher temperature profile below the flooded portion of the column the temperature profile $>$ design and “all trays below the flood are dry” and bottoms composition off spec“: [jet flooding]*.

“Δp across the column $> >$ design, reflux flowrate gradually increasing; ΔT across column $<$ design, overhead composition contains heavies $>$ design; bottoms level low or fluctuates, bottoms pressure $>$ design, and higher temperature profile below the flooded portion of the column the temperature profile $>$ design and “all trays below the flood are dry”: [downcomer flooding]*.

“Δp across the column $>$ design”: instrument fault/high boilup rate/steam flow to reboiler $>$ design.

“Δp across the column $<$ design”: instrument fault/[low boilup rate]*, see Section 3.3/dry trays/low feedrate/feed temperature too high.

“Feed flowrate $<$ design”: instrument fault/pump problems, see Section 2.3/filter plugged/column pressure $>$ design/feed location higher than design.

“Temperature of feed $>$ design”: instrument fault/preheater fouled/feed flowrate low/heating medium temperature $<$ design, see heaters, Section 3.3.

“Temperature of bottoms $<$ design”: instrument fault/[low boilup]* see Section 3.3/ loss of heating medium/steam trap plugged, see Section 5.1/feed rate to column $>$ design/feed concentration of low boilers (overheads) $>$ design/feed distributor fouled.

“Temperature of bottoms $>$ design”: instrument fault/[column pressure $>$ design]*/ high boilup/overhead condenser vent plugged/insufficient condensing, see Section 3.3.

“Temperature at top $>$ design”: instrument fault/bottom temperature $>$ design/reflux too low/distillate feed forward too high/column pressure high/[flooding]*.

“Temperature at top $>$ design and overhead composition contaminated with too many heavies”: vapor bypassing caused by excessive vapor velocities (high boilup) or not enough liquid on tray or packing, or downcomers not sealed, or sieve holes corroded larger than design and tray weeps/reflux too low/feed contains excessive heavies.

“Temperature at top $<$ design”: instrument fault/control temperature too low/[low boilup]* see Section 3.3.

“All temperatures falling simultaneously”: [low boilup]*.

"All temperatures rising simultaneously:" pressure rising.

"Overhead off spec": poor tray or packing efficiency/liquid maldistribution (weirs not level, low liquid load and backmixing/not enough trays or packing/loss of efficiency/high concentration of non-condensibles/missing tray/collapsed tray/liquid entrainment/liquid bypass and weeping/liquid or gas maldistribution/excessive inerts from upstream/buildup of trace/purge not sufficient from recycle. *"Overhead contaminated with heavies and excessive reflux rate and high boilup rate":* inadequate gas-liquid contact/insufficient liquid disengagement from vapor/presence of noncondensibles in feed. *"Overhead and bottoms off spec and decreases across column in both ΔT and Δp ":* [dry trays]*.

"Overhead and bottoms off spec": bypass open on reflux control valve. *"Overhead and bottoms off spec, decrease in ΔT across column and perhaps Δp increase and cycling of liquid in the bottoms":* [damaged tray]*. *"Level of bottoms > design":* bottoms pump failure, see Section 2.3/bottoms line plugged. and see implications for reboiler, Section 3.3. *"Level in bottoms > design" and [column pressure > design]**/high boilup/overhead condenser vent plugged. *"Level in bottoms > design and pressure increase in kettle reboiler and surges"*: foaming, inerts/leaks in kettle reboiler/undersized reboiler. See also Section 3.3. *"Bottoms off spec":* loss of tray efficiency/contamination of bottoms from pump (from light oil lubricant in bottoms pump or forced circulation reboiler)/transient vapor puff from horizontal thermosyphon reboiler, see Section 3.3. *"Distillate flow too low":* feed rate low/feed composition of overhead species low/[low boilup]*/reflux too high/overhead control temperature too low. *"Bottoms and overhead flowrates < design":* [flooding]*/excessive entrainment/[foaming]*/excessive Δp but not flooded/plugging and fouling/liquid maldistribution. *"Distillate flow too high:"* feedrate high/feed composition of overhead species high/reflux ratio too low. *"Water hammer in column":* process fluid above the tube sheet of a thermosyphon reboiler. *"Cycling of column temperatures:"* controller fault. "*Product contamination":* leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects. "*Separation performance of column decreases":* trace amounts of water/trace amounts of water trapped in column/[bumping resulting in tray damage]*.

"Cycling (30 s – several minutes duration) steam flow, cycling pressure on the process side and, for columns, cycling Δp and cycling level in bottoms": instrument fault/condensate in instrument sensing lines/surging/[foaming]* in kettle and thermosyphon/liquid maldistribution/steam trap problems, see Section 5.1, with orifice Δp across trap < design/temperature sensor at the feed zone in a distillation column/collapsed tray in a distillation column.

[Bumping resulting in tray damage]:* trace amounts of water.

[Column pressure > design]:* [high boilup]*/overhead condenser vent plugged.

[Damaged trays]:* leak of water into high molar mass process fluid/large slugs of water from leaking condensers or steam reboilers/startup with level in bottoms > design/attempt to overcome flooding by pumping out bottoms at high rate/too rapid a depressurization of column/unexpected change in phase.

*[Downcomer flooding]**: excessive liquid load/restrictions/inward leaking of vapor into downcomer/wrong feed introduction/poor design of downcomers on bottom trays/unsealed downcomers/[foaming]*.

[Dry trays}:* flooded above//insufficient reflux/low feedrate/high boilup/feed temperature too high.

*[Foaming]**: gas velocity too high/vapor velocity too high/tray spacing too small/asphaltenes present. A more generic listing of the causes of foaming is given in Section 1.12.

[Jet flooding]:* excess loading/fouled trays/plugged holes in tray/restricted transfer area/poor vapor distribution/wrong introduction of feed fluid/[foaming]*/feed temperature too cold/high boilup/entrainment of liquid because of excessive vapor velocity through the trays/water in a hydrocarbon column.

*[High boilup]**: see Section 3.3 for "Low boilup" and take the reverse.

[Low boilup]:* see Section 3.3.

[Maldistribution]:* weirs not level/low liquid load/backmixing/faulty design.

*[Premature flooding]**: internal damage/[fouling]*/change in feed composition or temperature/unexpected entrainment/[foaming]*/incorrect design for downcomers/unstable control system/level control problems/instrument error/second liquid phase in the column.

4.3
Freeze Concentration

- *Area of Application*

Liquid feed 1 to 30 % w/w solute; operates below the freezing temperature of the *solvent*.

- *Guidelines*

Do not exceed the K_{sp} of the solute. For juices, the solute concentration increases from about 10 % to 50 % when the freezing temperature is –10 °C.

4.4
Melt Crystallization

Related topic see solidify liquids to solids: flakers, belts, Section 9.12.

- *Area of Application*

Liquid concentration 60 to 90 % w/w. Operates below the freezing temperature to solidify the target *solute*. Capacity usually < 3 kg/s. Use for temperature-sensitive materials, when $\alpha_{vp} < 1.4$, when azeotropes form or for solid product. A freeze test shows > 50 % reduction in impurities.

- *Guidelines*

Design based on heat transfer. Limited by eutectic formation. Multistaging possible but usually < 10 stages.

Suspension melt crystallization: crystals and melt same temperature, design on degree of supersaturation, separation of crystals from melt depends on density difference in countercurrent operation. Scraped surface crystallizer, Section 4.6. The suspension methods have slower rates of crystal growth compared with the solid layer processes.

Solid layer or progressive freezing: crystals colder than melt, design on temperature gradient, separation of crystals from melt by gravity draining. Static crystallization at crystal growth rates of 5×10^{-7} m/s; falling film crystallization at crystal growth rates of 5×10^{-6} m/s. Reflux ratio 1.3:1. Some solid layer processes have crystal growth as high as 10^{-4} m/s. Melt flows inside tubes with coolant on the outside. Continuous units include drum flaker and chiller belts, topics Section 9.12.

4.5
Zone Refining

- *Area of Application*

Operates below the freezing temperature. Solid feed with input concentration of 20 to 70 %, but usual is 95 to 99.9 % w/w; can obtain 99.999 999 % purity. Temperatures 480 to 600 °C. Impurity must lower the freezing temperature for method to be effective. Particulate impurities must not be encapsulated by the solidification front.

- *Guidelines*

Design based on heat transfer with $\Delta T = 50$ to 100 °C from the freezing temperature and stop before the eutectic temperature. Ultra-purity of solids, low throughput at 10^{-7} to 10^{-6} kg/s. Multi-cycles might be needed to yield improved purity.

Design (velocity of freezing front)(liquid boundary layer thickness that depends on mixing)/(diffusivity of solute impurity in the liquid) = 1.

Typical velocities: semiconductors and pharmaceuticals: 10 to 70 μm/s; for organics: 0.5 to 10 μm/s.

4.6
Solution Crystallization

Related topic evaporation, Section 4.1.

- *Area of Application*

Liquid feed 20 to 60 % w/w; target solute becomes insoluble by producing supersaturation. Operates about the freezing temperature of the solute. Use for heat sensitive materials, when $\alpha_{vp} < 1.4$ or when want a solid product. Usual operation temperature 50 to 120 °C. Very high purity product with low energy usage. Never possible to obtain complete separation of the target species because other species simultaneously crystallize with the target. Use for separation or to obtain solid product or to increase the size of the particle.

- *Guidelines*

General principles:

1. The change in solubility with temperature is usually the most significant characteristic for selecting "type of crystallizer".

If the solute solubility is relatively temperature independent or inversely temperature dependent: add heat to remove the solvent (i.e., must use evaporative crystallization) or add an antisolvent to "drown out" crystals. For evaporation: 14 to 20 g vapor evaporated/s m^2 exchanger area. For the exchangers use 2.5 cm diameter tubes with fluid velocities 1.5 to 3 m/s to minimize plugging. Caution: if the vapor pressure rise $>$ 3.4 kPa/°C then potential problems with control.

If the solute solubility shows some temperature dependence, use vacuum cooling plus external heat.

If the solute solubility is strongly temperature dependent: use cooling (e.g. scraped surface) or might use vacuum cooling without external heat; that is, preheated feed followed by crystallizer.

2. Limited by K_{sp} and hydrate formation. Based on mass transfer.
3. For crystal growth, must control the creation and control of the degree of supersaturation. That is, keep the operation in the metastable region. For most products, design with $\Delta T = 1$ to 3 °C from the solubility curve or half the " maximum allowable supercooling". Mechanical mixing can reduce the width of the metastable region.
4. Prefer growth to nucleation. Seed the process because the nucleation sets the crystal habit and influences crystal size distribution. Usual size of nucleate crystals 0.1 to 10 μm. For example 10 % seed with 10 μm crystals.
5. Temperature and conditions are selected so that crystal growth rate on each surface is about 0.3 to 2.4×10^{-7} m/s (0.1–0.8 mm/h). Crystal growth kinetics increase with temperature increase. For most systems growth rates of 10^{-7} m/s occur around 30 °C, but for NaCl, for example, this rate does not occur until 70 °C. For example, at a growth rate of 10^{-7} m/s crystals grow to 2 mm in 3 h; if the rate is 10^{-9} m/s then it takes 10 days for the crystal to grow to 2 mm.
6. Overmixing usually inhibits growth. Mixing also affects crystal size distribution, CSD, because of secondary "contact nucleation" where crystals strike pump and mixer impellers, especially of concern in reactive crystallization.
7. Typical target size of crystal is 0.075 to 3 mm of square or circular shape with most being 1 to 1.5 mm.
8. Washing crystals is critical: too little and product is contaminated; too much and crystals redissolve and loss of yield.
9. Solution concentration/saturation concentration = 1.02–1.05.

10. *If fouling* is a problem then consider Flash growth type Pachuca or draft tube mixed suspension mixed product removal, MSMPR, units.

11. Five options are (i) cool: equipment configuration usually scraped surface; (ii) heat to evaporate: various configurations: batch or continuous, MSMPR (forced circulation, FC, or draft tube, DT) or classified product removal, CPR (usually a fluidized bed); (iii) combine heat plus cool "adiabatic"; (iv) salt out by adding solvent or (v) react: *If the reactants* are highly soluble but the product is relatively insoluble, generate crystals by reaction. For example, a soluble gas reacts with liquid to produce crystals (ammonium sulfate); remove heat of reaction by vaporizing the water. Configurations include Oslo CPR, forced circulation FC or draft tube, DT.

12. General heat exchange and design ideas: for cooling use 2.9 kJ/kg K plus the heat of crystallization of 75–230 kJ/kg of product crystallized. Evaporation of water takes 4.6 MJ/kg of product crystallized (for a product whose solubility is 33 %). Keep viscosity of the suspending solution < 1.8 to 2 mPa s. The viscosity of the suspension is 1.5 to 2 times that of the suspending solution.

Batch: size based on cycle time: fill, crystallize, dump, clean. Use for (i) production capacity of < 0.15 kg/s, (ii) where the target is a relatively uniform and narrow CSD (although reproducibility may be difficult between batches), (iii) very expensive materials being handled and we need to keep losses to a minimum, (iv) where the cooling range is very wide: high temperature feed but final mother liquor close to room temp, or (v) when the final liquor temperature is so low that we need very high vacuum and/or extensive vapor recompression. Batch gives a narrower CSD than continuous. Solute solubility is moderately or steeply temperature dependent. Tends to be self-cleaning. Typical product size 0.15 to 0.8 mm.

Continuous:

Forced circulation, FC most widely used (or mixed suspension, mixed product removal MSMPR; the crystalls are not classified). Feed is pumped through a heater and flashes into the gas–liquid separator. (Can omit the heater if adiabatic cooling gives crystals). Top vapor goes out, is condensed and may go to vac. pump; product is continually removed before the feed enters the exit line from the separator. Use for intermediate, flat or invert or where scaling is a problem. Use where high rates of evaporation are needed and or the solution has a relatively high viscosity. Very stable operation; long and short retention times. Typical product size 0.1–0.4 mm. Examples, NaCl, sodium sulfate, sodium carbonate monhydrate, citric acid, urea, sugar.

Draft tube baffle: DTB or draft tube, DT (either adiabatic cooling or evaporative type; also called flash growth or Pachuca) MSMPR. Mother liquor is pumped up a vertical central draft tube; liquor overflow and flows down the annulus. Limits the amount of supersaturation created per pass past the heating surface to 1 °C and therefore limits the nucleation rate to very low values. Operates with a suspension of solids that is 25–50 % apparent settled volume. Used where solute solubility is temperature independent or moderately dependent and where excess nucleation makes it difficult to achieve crystals in the size 0.6–2 mm. Minimum crystallization buildup on walls; no places with close clearances (as in Oslo).

Typical product diameter 0.3 to 3 mm. Useful for multistage cooling operations, for batch and for **reaction** crystallizers.

Oslo or fluidized suspension, CPR, classify the crystals. Mix hot feed with circulated mother liquor, ML; pump to vaporizer where solvent evaporates adiabatically; the crystals and ML drop through downcomer into fluidized chamber; large crystals are removed. The close clearances between the bottom of the downcomer and bottom of the suspension chamber can lead to plugging by crystal growth. Used where solute solubility is temperature independent or moderately dependent. Usually used for coarse crystals (ammonium sulfate) and those crystals with a fast settling rate (nickel sulfate). Can operate above the natural slurry density. Typical product diameter 0.2–3 mm. Gives increased crystal size and narrow CSD. Multistaging in series gives larger crystals and narrow CSD.

Scraped surface crystallizer: Wide range of temperatures, from –75 °C to 100 °C. Temperature drop of liquid passing through heat cooler is 1–2 °C; usually ΔT in range 5–10 °C but can be run at much higher ΔT than with a shell and tube exchanger. $U = 0.15$ to 3.7 but usually 0.15 to 0.3 $kW/m^2\,°C$. Used where solute solubility is moderately or steeply temperature dependent.; use when boiling point elevation is extremely high (e.g. NaOH) or where the temperature level is so low that need vacuum or for viscosities up to 10 000 mPa s or for solids concentrations up to 65 % w/w solids. Typical product diameter 0.1–0.8 mm. Need washout cycles. Typical rpm 15–30 rpm; higher rpm improves the heat transfer but the shear gives smaller crystals.

Direct contact refrigeration: Inject refrigerant directly in to contact the mother liquor ML. Avoids problems with surface cooling. Little fouling. Typical product diameter 0.3–3 mm. Examples, caustic dihydrate contacted with freon or propane; paraxylene with propane.

Multistaging: large flow at high temp and concentration is cooled to produce crystals and mother liquor is reconcentrated. E.g. five stage cooling potash crystals using Draft Tube. Multistaging in series gives larger crystals and narrow CSD.

Vapor recompression: vapor is compressed and used to heat the feed in the single effect forced circulation or MSMPR; use for materials having relatively low boiling point elevation and where a lot of heat is required for the evaporation. E.g. sodium sulfate, NaCl, sodium carbonate monohydrate. See also Section 4.1.

Batch vacuum crystallizer: 0.035 kg/s of dry crystals of orange juice. Equipment 2.7 m diameter × 3.6 m long cylindrical vacuum chamber with 900 kW of ammonia refrigeration. Rate: 0.5 mg water evap./s. Usually limited to crystal concentrations $< 25\,\%$ w/w crystals.

See Section 4.1 for other evaporators.

- *Good Practice*

To prevent plugging, avoid having natural sumps for suspension type crystallizers. Control the degree of supersaturation. For crystallizers operated with cooling or evaporative crystallization, the supersaturation occurs near the heat exchange surface. For antisolvent or reaction crystallizers, the key control of supersaturation is often local mixing. Differentiate among the different types of impurity to solve problems: surface contamination, agglomeration traps impurities, inclusions, polymorphism. Check that impurities are soluble for the end point conditions of crystal growth = condition of separation.

- *Trouble Shooting*

Base approach on mass and energy balances, population or number balances. Follow the population density of number versus size. Must know the type of crystals and the mode of operation.
"Yield < design": initial concentration < design.
"Impure product because of surface contamination": poor solid-liquid separation/poor washing, see Sections 5.12–5.14.
"Impure product because of agglomeration trapped impurities": wrong pH/wrong magma electrolyte concentration/wrong mixing.
"Impure product because of inclusions": supersaturation driving force too large.
"Impure product because of polymorphism": change in crystal habit during the crystallization process/isoelectric point/mixing problem.
"Crystal habit (shape and aspect ratio) differs from specs": wrong temperature during growth/impurities especially surfactants/supersaturation level too high.
"Size distribution > design": supersaturation too close to metastable limit.
"Filtration rate slow": crystals too small/large size distribution/fault with filtration, see Sections 5.13 and 5.14.
"Incrustation, fouling, deposits": cold spots/missing insulation/low suspension density/protrusions and rough areas on the process surface/local supersaturation too high/cooling surfaces too cold.
"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.
Vacuum and circulating systems:
"Crystal size too small": low suspension density/high circulation rate/solids in feed causing nucleation sites/feed flowrate > design/excessive turbulence/local cold spots/subsurface boiling/supersaturation too high or too close to the metastable limit.
"Insufficient vacuum": see Section 2.2/obstruction in vapor system/insufficient cooling water to condenser/temperature of the cooling water to the condensers > design/air leaks. For steam ejectors: steam pressure < design. For mechanical vacuum pumps: seal water flowrate < design/rpm < design.
"Liquid level in crystallizer fluctuates wildly": check out the vacuum system, see Section 2.2/low steam pressure to the steam ejectors/fluctuation in the flow of cooling water to the condensers.
"Circulation rate differs from design": see pumps, Section 2.3.
[Foaming]:* air leaks in pump packing/air in feed/air leak in flanges or valve stems. A generic listing of the causes of foaming is given in Section 1.12.

4.7
Precipitation

- *Area of Application*

Liquid feed, operates at temperatures above the freezing temperature of the solute, usually in the range 18 to 35 °C. Solute formed by reaction is insoluble, key parameter is K_{sp} of product. Provides a sharp first cut removal of solute.

For **proteins**, related topic is flocculation and coagulation, Section 9.3.

- *Guidelines*

Reactions are usually very rapid and design is based on mass transfer and mixing to distribute the reactant. For most precipitation reagents allow 5 min residence time. If secondary reagents are needed to change the oxidation state of the target species before precipitation; then example residence times are: arsenic: 30 min, hexavalent chromium or iron: 20 min.

Either pre or post pH change; allow about 0.180 kg acid or base/m^3 water.

For **proteins**, alter the hydration layer surrounding the protein by (i) electrolyte addition follow the Hoffmeister series of lyotropic ions (sulfates are preferred to phosphates because of the solubility); (ii) adding hydrophilic, non-ionic polymers, polyethylene glycol; (iii) adjusting the pH to shift to zpc (but avoid low pH); (iv) lower the dielectric permeability of the continuous phase by the addition of ethanol, methanol, acetone or isopropanol; (v) adding flocculant polyelectrolytes (alginate, pectate, carrogcenan, CMC).

4.8
Gas Absorption

The general characteristics of gas–liquid contacting are described in Section 1.6.1. Other operations that use this type of contactor include gas desorption/stripping, Section 4.9; gas–liquid separations, Section 5.1; turbulent bed contactor (TCA, TVA) contactor, Section 5.2, distillation, Section 4.2, reactors, Sections 6.13–6.16 and 6.19 and direct contact heat exchange Sections 3.7–3.9.

- *Area of Application*

$\alpha = 2000$ to 100 000 and gas feed concentration of target solute is 0.1 to 20 %; 98 % purity possible. Target species is soluble.

Select sprays, trays versus packing on efficiency.

For high concentration and solubility plus particulates use:

– **Jets, venturis scrubbers:** very soluble gas only with target species Henry's law constant $< 10^3$ kPa/mol fraction; feed gas concentration > 1 vol %. Efficiencies 50 to 85 %.

– **Turbulent bed contactor:** both gas absorption and removal of heavy, sticky particulates.

For when a large amount of absorption is needed with no need for high purity effluents: venturi scrubber with high intensity mixing (usually 1 theoretical stage). Related to Section 5.2.

For high concentration and solubility: use
– **Spray column:** target species Henry's law constant 10^3 to 10^4 kPa/mol fraction; feed gas concentration 0.3 to 4 vol %. Efficiencies 85 to 95 %.
– **Spray chamber:** target species Henry's law constant $< 10^4$ kPa/mol fraction; feed gas concentration > 1 vol %. Efficiencies 50 to 85 %.
For low concentration, range of solubility and no particulates: use
– **Countercurrent packed column:** target species Henry's law constant $< 10^7$ kPa/mol fraction; feed gas concentration < 1 vol %. Efficiencies 95+ %. vulnerable to plugging. OK for foaming and corrosive.
– **Countercurrent tray column:** target species Henry's law constant $< 10^7$ kPa/mol fraction; feed gas concentration < 1 vol %. Efficiencies 95+ %. Not for foaming, corrosive or particulates.

For adsorption plus chemical reaction consider cocurrent falling film multitube system. See also long tube falling film evaporator, Section 4.1.

For requirements of a low amount of absorption and some purity of effluent, select (i) packed, (ii) tray; packed if there is a fast absorption reaction; packed for H_2S when low liquid holdup is needed. Use trays for CO_2 when high liquid holdup is preferred.

- *Guidelines*

Fundamentals: As described in Section 4.2, the concepts of **theoretical stage** and **transfer units** are often used to size tray or packed columns, respectively. For absorption (unlike distillation), however, the NTS no longer equals NTU and HETS is not equal to HTU (unless the operating and equilibrium lines are straight and parallel).

To estimate the number of **theoretical stages** required, NTS, the Kremser–Souders–Brown equations may be used. (The Kremser equation assumes that the operating and equilibrium lines are straight, the systems are nonreacting and that the concentrations are dilute (that is < 10 %). These are reasonable assumptions for many absorptions.) The key parameter is the ratio of the product of the molar equilibrium constant "m" (as in $y = mx$) with the molar gas flowrate divided by the molar liquid flowrate, = molar stripping factor = $(mF_G)/F_L = S$.

For absorption of a species from a gas into a liquid, S < 1, and S is in the range 0.5–0.8 and usually is 0.7. For absorption with $S = 0.7$:

Number of stages corresponding to driving force ratio = $((y_{out} - mx_{in})/(y_{in} - mx_{in}))$ are

1	0.42
4	0.09
10	0.01
20	0.0003

or for the range of driving force ratio from 0.09–0.03, NTS = 4 (0.09/driving force ratio)$^{0.42}$. A molar stripping factor = 0.2 is approximately the same as ∞.

The **transfer unit approach** could also be used. For the same assumptions used for the Kremser equation (straight lines, no reaction, dilute concentrations) the Colburn equation, with a molar stripping factor = $(mF_G)/F_L = S = 0.7$, gives an estimate of the NTU required. For a molar stripping factor $S = 0.7$: the number of theoretical mass transfer units, NTU, corresponding

to driving force ratio = $((y_{out} - mx_{in})/(y_{in} - mx_{in}))$ are:

1	0.45
4	0.125
10	0.018
20	0.001

As an approximation NTU + 2 = 6 $\log_{10}(y_{in}/y_{out})$

So we have two apparently different approaches. How are they linked? For simplified, dilute, nonreacting systems where the operating and equilibrium lines are straight:

$HETS/HTU_{OG} = \ln S/(S - 1)$ and $HETS/HTU_{OL} = (S \ln S)/(S\text{-}1)$

For the usual conditions with S = 0.7 and the above relationships:

$HETS/HTU_{OG} = NTU_{OG}/NTS = 1.17$

$HETS/HTU_{OL} = NTU_{OL}/NTS = 0.84$.

To minimize the cost of recovering and recycling the solvent, contact the minimum amount of liquid with the maximum amount of gas. For **packings**, this means liquid loadings about 3 L/m^2 s with high gas flowrates of superficial density-weighted velocity *F*-factor of 3.5 m/s (kg/m^3)$^{0.5}$. Values of *F*-factor are compared with other applications in Table 4.1. Characteristics of packings are given in Table 1.2 and a comparison of the characteristics of a packed absorber with other gas–liquid contactors is given in Section 1.6.1.

Selection of the solvent: select lowest molar mass liquid whose solubility parameters are similar to those of target species in the gas. Choose a solvent in which the target species are highly soluble: $>$ 700 mg/g solvent; Henry's law constant: $< 10^3$ kPa/mol fraction; or $(HTU_G/HTU_L)(F_L/F_G)$(Pressure, kPa/Henry's constant) $>$ 20: then gas phase controls mass transfer. This is most likely for many absorptions.

If target species have medium solubility: 100 to 700 mg/g solvent; Henry's law constant: 10^3 and to 10^5 kPa/mol fraction: both liquid and gas phases control the mass transfer. These systems are usually processed in packed and tray columns.

If target species have low solubility: $<$ 50 mg/g solvent; 1/Henry's law constant: $< 8 \times 10^{-5}$ mol fraction/kPa: liquid phase controls mass transfer.

Regeneration of the absorbent by distillation or pressure-reduction desorption.

Jets, venturis: Economic NTU = 3.5; critical energy consuming phase is the gas at about 20 kJ/m^3 with liquid to gas ratio about 1.3 to 1.6 L/m^3; design on gas phase controlling. Power usage 1 to 8 kW s/m^3. Δp gas = 1.2 to 6 kPa.

Peabody absorber/impingement baffle: Economic NTU usually $<$ 5; liquid to gas ratio 0.2 to 0.7 L/m^3; superficial gas velocity 1 to 1.6 m/s. Power usage 0.5 to 2 kW s/m^3. Δp gas = 1.5 to 3.7 kPa.

Spray column: Economic NTU = 2.5; critical energy consuming phase is the liquid; gas energy 8 kJ/m^3; with liquid to gas ratio high; design on gas phase controlling. superficial gas velocity 0.05–3, usually 1 m/s. Power usage 0.03 to 0.5 kW s/m^3. Δp gas = 0.6 to 1.2 kPa. k_L =0.005–0.015 m/s; area = 20–150 m^2/m ^{3}; $k_L a$ = 0.1–2.25 1/s; liquid holdup 0.05.
Spray chamber: Economic NTU = 4; gas energy consumption 2.5 kJ/m^3 with liquid to gas ratio about 1.5 L/m^3; design on gas phase controlling. superficial gas velocity 0.9 to 1.2 m/s. Power usage 0.03 to 0.5 kW s/m^3. Δp gas = 0.5 kPa.
Countercurrent packed column: Economic NTU usually < 5; critical energy consuming phase is the gas at about 3 kJ/m^3; with liquid to gas ratio about 0.7 to 1.5 L/m^3. Liquid loading on usual packings 3 to 35 L/m^2 s; (0.007 to 5 on structured packings) molar ratio liquid to gas 1.4 to 80; superficial gas velocity 1.4 to 2.2 m/s; design on mass transfer in both gas and liquid. Power usage 0.15 to 0.6 kW s/m^3. Δp gas = 0.07 to 0.4 kPa/Theoretical Stage; HETS = 0.5 to 1 m. Superficial gas velocity 0.1–1 m/s; k_L 0.003–0.02 m/s; area/unit volume 20–350 m^2/m^3; $k_L a$ = 0.06–7 1/s; liquid holdup = 0.05–0.1.

For low liquid loadings and high gas flowrates, $\text{HTU}_G/\text{HTU}_L \approx 2$; for high liquid loading and low gas flowrates, 0.2.

Assume 99 % absorption; set molar flowrates F_L/F_G = 1.2 to 2 times the minimum. Use the Colburn equation for the design of dilute units with molar stripping factor, S, = 0.7. NTU_{OG} = 20 for 99 % recovery.

Assume HTU_{OG} = 0.6 m with maximum packing height 12 m. Superficial gas velocity 1 m/s and/or superficial density-weighted velocity F-factor of 0.6 to 3.5 m/s (kg/m^3)$^{0.5}$. Use 2.5 mm Pall rings or Tellerettes of metal or plastic.
Countercurrent tray column: Economic NTU usually < 5; liquid to gas ratio 1.5 to 18 L/m^3; superficial gas velocity 1 to 1.6 m/s and/or superficial density-weighted velocity F-factor of 1.2 to 1.8 m/s (kg/m^3)$^{0.5}$. Power usage 0.5 to 2 kW s/m^3; Δp gas = 0.7 to 1.5/tray. HETS = 0.7 m. Tray efficiencies 10 to 20 %.

Assume 99 % absorption; Use the Kremser equation for the design of dilute units with molar stripping factor, S, = 0.7. Tray spacing = 0.6 m with valve or sieve trays. See also Section 4.2 for such details as downcomer sizing.

Tray column without downcomers: superficial gas velocity 0.5–3 m/s; k_L 0.01–0.04 m/s; area/unit volume 100–200 m^2/m^3; $k_L a$ = 1–8 1/s; liquid holdup = 0.5–0.7.
For multitube cocurrent falling film: U = 0.6 kW/m^2 K.

- *Good Practice*

The more selective the absorbent the more difficult it is to regenerate the absorbent. Prefer the use of low holdup internals (H). Select materials of construction to promote wetting: select critical surface tension of the solid to be > the surface tension of the liquid. If the surface tension of the feed liquid > 2 mN/m *larger* than the surface tension of the bottom exit liquid or the absorption of the solute lowers the surface tension (surface tension negative) prefer the use of trays to packings to minimize potential for liquid film breakup. If the surface tension of the feed liquid > 2 mN/m *smaller* than surface tension of the bottom exit liquid (surface tension positive), the foam above trays might be unexpectedly stable; stable films on packing.

For amine absorption of sour gas, keep inlet amine solvent temperature at least 5 °C hotter than inlet gas temperature to minimize condensation of volatile hydrocarbons in the inlet gas stream.

- *Trouble Shooting*

"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.

"Insufficient absorption or off-specification for exit scrubbed gas": feed gas concentration off spec/feed gas temperature or pressure outside operating window: **for amine absorbers:** $> 50\,°C$ for H_2S and $< 24\,°C$ for CO_2/feed gas pressure has decreased/[solvent flowrate too low]*; **for glycol dehydration**: 12.5 to 25 L TEG per kg water removed/[solvent incorrect]*/incorrect feed tray location/[column operation faulty]*/absorber operating conditions differ from design/[absorber malfunction]*.

"Δp across absorber $>$ design": gas flowrate $>$ design/pressure $<$ design/[foaming]*/plugged trays/plugged demister pads/collapsed tray or packing.

"Δp on column fluctuating": [foaming]*

"Solvent carryover from the top of the column": [foaming]*

"Liquid level in vessel fluctuates": [foaming in column]*

"Change in absorption rate": **for amine absorption:** decrease in removal of H_2S and increase in removal of CO_2/[foaming]*.

"Overloaded liquid in downstream gaseous processing equipment": [foaming in absorber]*.

"Solvent losses high": [physical losses]*/[entrainment]*/[solubility]*/[vaporization]*/[degradation]*/[loss elsewhere]*/**for glycol dehydration** typical losses = 0.015 mL/m^3 gas treated.

for multitube cocurrent falling film absorber:

"Concentration of product acid $<$ design, inadequate absorption": liquid maldistribution/gas maldistribution.

"Low heat transfer coefficient": liquid or gas maldistribution.

"Hydraulic instability": no vent break on the syphon.

[Amine concentration too high or too low]:* if too high, lack of equilibrium driving force/if too low, insufficient moles of amine for the feed concentrations.

[Column operation faulty]:* plugged tray or packing/poor distribution for packing/liquid flowrate $<$ minimum required for loading/[gas velocity too fast]*/collapsed trays or packing/plugged or broken distributors/[foaming]*/solvent - stripper overhead temperature too low.

see also Section 4.2.

[Degradation]:* chemical reaction; for **amine:** reacts with CO_2 and O_2; forms stable salts: for **glycol:** reacts with O_2/thermal decomposition; for **amine:** surface temperatures $> 175\,°C$; for **glycol:** surface temperatures $> 205\,°C$.

[Entrainment: GL]:* demister plugged, missing, collapsed, incorrectly designed/[flooding]*/[foaming]*/inlet liquid line or distributor undersized or plugged/poor distribution for packing/liquid flowrate < minimum required for loading/[gas velocity too fast]*/solvent feed temperature > specifications/[column operation faulty]*/tray spacing < design. see also GL separators Section 5.1

[Entrainment: L–L]:* fluid velocity too high; example > 10 L/s m^2/liquid distributor orifice velocity > design; **for amine:** for amine > 0.8 m/s; for hydrocarbon > 0.4 m/s/faulty location of exit nozzles/interface level wrong location/faulty control of interface/no vortex breaker/exit fluid velocities > design/insufficient residence time/[stable emulsion formation]*. see also decanters, Section 5.3

[Foaming]:* a generic listing of causes for foaming is given in Section 1.12.

[Flooding]:* see Section 4.2.

[Gas velocity too fast]:* vessel diameter too small for gas flow/column pressure < design/trays or packing damaged or plugged giving excessive vapor velocity/temperature too hot/upstream flash separator passing liquids: feed contaminated with excessive volatile species/stripping gas fed to column too high/flowmeter error/design error.

[Liquid environment wrong]:* pH far from the zpc/electrolyte concentration too low.

*[Physical losses]**: leak to atmosphere/purges for sampling/sampling/heat exchanger leak/pump seal flushes/filter changes/piping, fitting, valve stems, gaskets, pumps.

[Solubility losses]:* liquid-liquid systems: system pressure < design/for **amine**: concentrations > 40% w/w/system temperatures too high.

[Solvent contaminated]:* carryover from upstream equipment; example oil from compressor; brines, corrosion inhibitors, sand, [corrosion products]*/oxygen leaks into storage tank/inadequate corrosion control, example low pH causing corrosion/degradation via overheating, ex hot spots in reboiler tubes or fire tubes/ineffective filters/ineffective cleaning before startup/for **amine** absorbers: corrosion products/FeS/chemicals used to treat well

[Solvent feed temperature too hot]:* fouled exchanger/undersized heat exchanger/ambient temperature too hot.

[Solvent flowrate too low]:* flowmeter or sensor error/absorber pressure > design/plugged strainer, lines or filters/low liquid level in pump feed tank/[cavitation]*/air locked pump and see Section 2.3 for trouble shooting pumps.

[Solvent incorrect]:* incorrect concentration of active ingredient: **for amine absorbers:** [amine concentration too high or too low]*; **for glycol dehydration:** solvent concentration TEG < specifications/[solvent stripping inadequate]*/[solvent feed temperature too hot]*/[solvent contaminated]*.

[Solvent loss elsewhere]:* upstream units, for example **for glycol dehydration:** glycol dumped with hydrocarbons separated in upstream flash drum/loss in downstream solvent stripper.

[Solvent stripping inadequate]:* not enough steam in stripper/incorrect pressure in stripper/[foaming]*/[contaminated solvent]*/contaminated feed: for amine strip-

pers: other sulfur species causing high partial pressure/leak in the feed preheater contaminating feed with stripped solvent.
[Vaporization losses]:* system pressure < design/for **amine:** concentrations > 40 % w/w/system temperatures too high.

4.9
Gas Desorption/Stripping

Function is to strip species from the liquid to produce a quality bottoms product: for example, a solvent ready to be recycled as in glycol dehydration, amine absorption, extractive distillation or water that has been stripped of contaminants as in Sour Water strippers; deodorize edible oils. Used to regenerate solvent for absorption or extractive or azeotropic distillation. Other equipment that is used for stripping include distillation, Section 4.2, gas–liquid separators, Section 5.1 and gas–liquid–liquid separation in flash drum, Section 5.4. The general characteristics of gas–liquid contacting are described in Section 1.6.1. Other operations that use this type of contactor include gas absorption, Section 4.8; reactors, Sections 6.13–6.16 and 6.19 and direct contact heat exchange Sections 3.7–3.9.

- *Area of Application*

α_{vp} = 2000 to 100 000 and liquid feed concentration of target solute is 0.1 to 5 %; 98 % purity possible.

- *Guidelines*

Because the target solute usually has low solubility in the liquid usually the desorption is liquid phase controlled.

For packings the goal is high liquid loadings, about 30 L/m^2 s and minimum gas flowrates.

superficial density-weighted velocity *F*-factor of 0.6 m/s (kg/m^3)$^{0.5}$.

Use Kremser or the Colburn equation for the design of dilute units with molar stripping factor, *S*, = 1.4; m = Henry's constant/total pressure. See Section 4.8. For stripping of a species from a liquid into a gas, Section 4.9, $S > 1$ and is in the range 1.15–2 and typically 1.4. For stripping with $S = 1.4$, the same result occurs although the driving force ratio is $((x_{in} - (y_{out}/m)\ )/(x_{out} - (y_{out}/m))$.

For packing, HETS = 1.83 m.

For stripping ammonia from sour water: stripping steam 1 kg/kg feed. 35 theoretical trays.

Edible oil deodorizing: high vacuum. For < 0.6 kg/s, irregular production, use batch. Requires processing time = 4 h/batch, low heat recovery. For > 0.6 kg/s continuous with processing time = 1 h. Keep liquid films thin to promote mass transfer of volatiles and use astute distribution of sparge steam.

As with absorption, Section 4.8, the numerical values for HTU do not equal HETS.

What is the relationship between the **theoretical stage** and the **transfer unit** approach?

HETS/HTU_{OG} = ln $S/(S - 1)$ and HETS/HTU_{OL} = $(S \ln S)/(S - 1)$

For the usual conditions with $S = 1.4$ and the above relationships:

HETS/HTU_{OG} = NTU_{OG}/NTS = 0.84

HETS/HTU_{OL} = NTU_{OL}/NTS = 1.17.

- *Trouble Shooting*

"Solvent or stripped liquid concentration > design": boilup rate or steam stripping rate too low/feed concentration > expected/feed contamination; **for sour water stripper:** acid in feed may be chemically bonded with NH_3 and prevent adequate stripping of NH_3/[foaming]*/leak in preheater exchanger/[column malfunction]*.

"Overhead from stripper < specifications": insufficient flowrate of stripping gas/for **glycol dehydration:** reboiler temperature < 175–200 °C or reboiler too small for required duty or fouling of reboiler tubes/[foaming]*/dirty or broken packing or plates/[fouled or scaled internals]*/[flooding]*/top pressure > design/leak in preheater exchanger/[feed concentration off specification]*.

"Overhead temperature on stripper > design": reflux flowrate too low/[flooded]*/[foaming]*/feed contaminated with light hydrocarbons.

"For sour water strippers or glycol dehydration: *Pressure at reboiler > design":* instrument error/top pressure > design/[p across column > design]*/overhead line plugged/[flooding]*/for stripper for **glycol dehydration:** slug of hydrocarbon in feed is flash vaporized at reboiler and blows liquid out of stripper.

"For sour water strippers: *odor or H_2S problems at the storage tank":* 0. 6 to 1 m layer of oil on top of water missing/oil layer exceeds 0.6 to 1 m depth/faulty inert gas operation.

"Plugging of overhead system": top temperature not within the operating window; **for sour water strippers:** temperature < 82 °C at which ammonium polysulfides form but temperatures too high give excessive water in overhead vapor causing problems for downstream operation/overhead lines not insulated/insufficient steam tracing on overhead vapor lines.

"Feed flowrate and composition to the stripper varies": [instrument error]*/sampling error/analysis error/[faulty separation in flash drum]*/[foaming in upstream absorber]*/no intermediate storage tank between the flash drum and the stripper/storage tank faulty operation or design: **for SWS:** residence time < 3 to 5 days; stratification occurs, bypassing occurs, insufficient mixing in tank/oil layer on top of water in storage tank exceeds 0.6 to 1 m depth.

[Column malfunction]:* [feed concentration off specification]*/excessive stripping gas or steam velocity/too much cooling or condensation/top temperature > design/insufficient reflux cooling/packing broken, damaged/[fouled or scaled internals]*/[foaming]*/[flooding]*. see also Section 4.2.

[Feed concentration off specification]:* [foaming in upstream absorber]*/for **glycol dehydration:** upstream flash separator passing water; for oil or hydrocarbon in feed to **SWS**": residence time for sour water in flash drum is < 20 min.

[Fouled or plugged internals]:* **for SWS:** cooling water leak/pH of feed water too basic/calcium ion concentration too high causing precipitation when temperatures in stripper exceed 122 °C/temperature $<$ 82 °C at which ammonium polysulfides form/overhead lines not insulated.
[Instrument error]:* calibration fault/sensor broken/sensor location faulty/sensor corroded/plugged instrument taps": **for sour water strippers:** water or steam purge of taps malfunctioning or local temperatures $<$ 82 °C at which ammonium polysulfides form.

4.10
Solvent Extraction, SX

Related topic size reduction, Section 8.3 and reactive extraction, Section 6.35.

- *Area of Application*

General: feed concentration 0.03 to 95 % w/w; For minerals typically 0.01 to 2 % w/w; separation factor α = partition coefficient ratio with values 2 to 500 and should be > 5; for bioprocessing of proteins > 3. Separation factor for distillation $\alpha < 1.2$.
Spray and packed columns, gravity flow (spray, plate, packed column): superficial liquid velocity, 0.001–0.02 m/s; area per unit volume 7 to 75 m^2/m^3. Product of the density difference with the interfacial tension [Mg/m^3, mN/m] > 1 and number of theoretical stages needed < 3; interfacial tension $<$ 10 mN/m.
Gravity flow (Raining bucket, RTL): Product of the density difference with the interfacial tension [Mg/m^3, mN/m] > 1 and number of theoretical stages needed < 3; handles dirty liquids and ones that tend to emulsify.
Stirred tanks; mixer settler: (including Lurgi): superficial liquid velocity, 0.00 015–0.004 m/s; area per unit volume 400 to 10 000 m^2/m^3. Product of the density difference with the interfacial tension [Mg/m^3, mN/m] > 4 and number of theoretical stages needed > 3. Usually about 1 theoretical stage per unit. Rarely build more than 5 stages; can handle high phase ratios.
Stirred or pulsed columns: superficial velocity, 0.002 to 0.02 m/s; area per unit volume 75 to 3000 m^2/m^3.
Reciprocating plate: Product of the density difference with the interfacial tension [Mg/m^3, mN/m] between 1 and 4 and number of theoretical stages needed > 2. Can handle dirty liquids.
Pulsed plate or packed: Product of the density difference with the interfacial tension [Mg/m^3, mN/m] between 1 and 4 and number of theoretical stages needed > 2. Sensitive to contamination. Difficult to pulse large columns.
Rotating disk contactor, RDC, ARD contactor; Mixco, Scheibel, Treybal, Oldshue-Rushton, Kuehni : Product of the density difference with the interfacial tension [Mg/m^3, mN/m] between 1 and 4 and number of theoretical stages needed > 2. Low HETS, can handle dirty liquids, large throughputs. Needs flow ratios 1:1. Difficulty handling low interfacial tension systems that tend to emulsify.

Centrifugal extractor: Product of the density difference with the interfacial tension [Mg/m^3, mN/m] < 1 and number of theoretical stages needed < 6. Cannot handle dirty systems or high phase ratios. For continuous differential type machines (density differences > 0.05 kg/L; drop diameter > 200 μm): 6 to 8 stages per machine. For discrete, disc type machines (density differences > 0.02 kg/L and handle drops < 200 μm) 2 to 3 stages per machine.

For bioprocessing, the solvent is usually polyethylene glycol plus electrolyte or dextron.

- *Guidelines*

Design flowrate about 50 to 90 % of flooding with the superficial velocity selected varies directly with the density difference and interfacial tension. Solvent/feed = 0.5–1/1 m (volumetric flowrates of solvent/feed) = 1.5. HETS increase slightly with increase in interfacial tension.

Gravity:

– spray: HETS increases exponentially with diameter. 10 to 20 m at 1 m diameter; superficial velocity usually 5.5 L/s m^2. $k_L = 0.001–0.01$ m/s; area = 100–1000 m^2/m^3; $k_La = 0.1–10$ 1/s; dispersed phase holdup = 0.05–0.1.

– packed: HETS increases exponentially with diameter. 2.5 m at 1 m diameter; prefer diameter < 0.6 m; superficial velocity of combined dispersed and continuous phase 3 to 8, usually 5.5 L/s m^2, 2.5 cm Pall rings. Redistribute the dispersed phase every 1.5 to 2 m. $k_L = 0.003–0.01$ m/s; area = 100–1000 m^2/m^3; $k_La = 0.3–10$ 1/s; dispersed phase holdup = 0.05–0.1.

– sieve tray: HETS increases exponentially with diameter. 1 m at 1 m diameter; usually diameter$>$ 0.6 m; superficial velocity about 5.5 L/s m^2 (although some authors cite values in the range 7.5 to 16). Efficiency inversely proportional to the interfacial tension: 40 % at 5 mN/m.

– RTL: HETS increases exponentially with diameter. 0.5 m at 1 m diameter; superficial velocity based on combined flow of both phases 0.3–0.55 although some designed at 2 L/s m^2.

Static mixer-settler: $k_L = 0.001–0.01$ m/s; area = 100–2500 m^2/m^3; $k_La = 0.1–25$ 1/s; dispersed phase holdup = 0.05–0.2.

Mixer settler: 1 theoretical stage per unit; input energy 1 kW/m^3; 2 min residence time for mixer. For settler: superficial velocity for the settler 0.5 to 7 L/s m^2 with 1.4 L/s m^2 being typical for liquid–liquid extraction. Low values for small density differences. For leaching: 0.4 L/s m^2 for liquid–liquid–solids (slimes) leaching; 0.2 L/s m^2 for slurries with 50–60 % solids in aqueous phase. Height increases with increasing total feed flowrate with 1 m height for 10 L/s. Typical drop diameter is 150 μm; extraction efficiencies about 80 %. Settler design is also described in decanters, Section 5.3.1. $k_L = 0.003–0.01$ m/s; area = 100–80 000 m^2/m^3; $k_La = 0.3–800$ 1/s; dispersed phase holdup = 0.05–0.4.

Pulsed packed column: HETS increases exponentially with diameter. 0.7 m at 1 m diameter; max. diameter 2.5 m; superficial velocity of the combined flow of continuous and discontinuous phases 5 to 6.4 with usual value of 5.5 L/s m^2.

Pulsed sieve plate column: HETS increases exponentially with diameter. 0.4 m at 1 m diameter; max. diameter 3 m; superficial velocity of the combined flow of continuous and discontinuous phases 7.5 to 16 with usual value about 5.5 L/s m^2; sieve holes 3 to 8 mm; velocities through the holes < 0.2 m/s to minimize the formation of small drops. Tray efficiencies about 20 to 30 %.
Reciprocating plate: HETS increases exponentially with diameter. 0.35 m at 1 m diameter; max. diameter 1.5 m; superficial velocity of the combined flow of continuous and discontinuous phases 8 to 11 with usual value about 11 L/s m^2.
Lurgi contactor: HETS increases exponentially with diameter. 0.7 m at 1 m diameter; diameters < 8 m; superficial velocity about 5.5 L/s m^2.
Rotating disk contactor, RDC, ARD contactor; Mixco, Scheibel, Treybal, Oldshue-Rushton, Kuehni: HETS is sensitive to rotor speed. HETS increases slightly with diameter. 0.5 m at 1 m diameter; superficial velocity about 5.5 L/s m^2 with Kuehni 9.7 L/s m^2 . Mixco, Scheibel, Treybal, Oldshue-Rushton, diameter < 2.5 m; RDC diameter < 9 m. More specific recommendations are Scheibel, HETS 0.1–0. 2 m with combined superficial velocity of 3–4 L/s m^2; RDC: HETS 0.3–0.4 m with combined superficial velocity of 4–8 L/s m^2; Kuehni: HETS 0.1–0. 2 m with combined superficial velocity of 2–3 L/s m^2. Total flow through a column = 10 L/s m^2 with a density difference of 0.2 Mg/m^3.
Centrifugal: 2 to 6 units per machine depending on the machine.

- *Good Practice*

The dispersed phase should not preferentially wet the materials of construction. If unexpected rapid coalescence occurs, suspect Marangoni effects and change the dispersed phase. Treat the buildup of the "rag" at the interfaces based on the cause: corrosion products or stabilizing particulates, surfactants, or amphoteric precipitates of aluminum or iron. Consider adjusting the pH. Solid particles tend to accumulate at the liquid-liquid interface.

For **centrifugal extractors** for bioprocessing/proteins: partition coefficient sensitive to pH, electrolyte type and concentration.

- *Trouble Shooting*

"Poor separation": level control fault/phase velocities too high/contaminant gives stable dispersion/smaller drop size than design/rag formation/temperature change/pH change/decrease in electrolyte concentration.
*[Rapid coalescence]**: wrong phase is the continuous phase/[Marangoni instabilities]*/pH at the zpc/high electrolyte concentration in the continuous phase.
For column extractors: "Decrease in extraction efficiency": agitator speed to fast/excessive backmixing/flooding.
"Flooding": agitator speed too fast/feed sparging velocity too high/drop diameter smaller than design.
"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.

[Marangoni effects]:* non-equilibrated phases/local mass transfer leads to local changes in surface tension that give stable interfacial movement. see Marangoni number, Appendix B.

Other suggestions for trouble shooting decanters are given in Section 5.3.1. More about stable emulsion formation is given in Section 1.12.

4.11
Adsorption: Gas

- *Area of Application*

Use when feed concentration of the more volatile species is small, 0.15 to 10 % and when $\alpha_{ads} > 2$; when the target species is difficult to condense.

- *Guidelines*

Select adsorbent based on pore size related to the target species.
alumina: surface area: 210 to 350 m^2/g; pore volume 0.21 cm^3/g, temperature $< 320\,°C$; superficial gas velocity 125 to 500 dm^3/dm^2 s; usually adsorb 800 kg/m^3 or 0.14 to 0.22 kg organics/kg dry solid; 0.15 kg water/kg dry solid. Lifetime: 150 cycles.
silica: surface area: 750 to 830 m^2/g; pore volume 0.4 to 0.45 cm^3/g, temperature $< 230\,°C$; superficial gas velocity 125 to 500 dm^3/dm^2 s: usually adsorb 720 kg/m^3; 0.3 to 06 kg organics/kg dry solid; 0.4 kg water/kg dry solid.
4 Å molecular sieve: surface area: 640 to 80 m^2/g; pore volume 0.27 cm^3/g, temperature $< 300\,°C$: superficial gas velocity 150 to 250 dm^3/dm^2 s; usually adsorb 480 to 720 kg/m^3; 0.05 kg nitrogen/kg dry solid; 0.22 to 0.36 kg water/kg dry solid. Lifetime: 400 cycles.
activated carbon: surface area: 1000 to 1500 m^2/g; pore volume 0.6 to 0.8 cm^3/g, temperature $< 540\,°C$: superficial gas velocity 100 to 600 dm^3/dm^2 s ; capacity depends on organic; range 0.06 to 0.2 kg organics/kg dry solid adsorbent.
For fixed bed: batch: size on cycle time: load, swing out of service, regenerate, swing back into service. Loading time: 100–3000 bed volumes (BV)/h with time based on the ratio of the adsorption isotherm to the feed concentration of the target species (usual range 50–300 corresponding to load times of 0.2–2 h). Regenerate with steam (at 3 to 5 kg steam per kg organic removed), solvent, reduced pressure, combustion or via vacuum/pressure shift. Use superficial gas velocity of 60 to 600 dm^3/dm^2 s or recommended value for the adsorbent to determine cross sectional area. Residence time 0.03 to 0.8 BV/s: (F/V) with depth > 0.33 diameter.

Heat required for thermal regeneration = 2.5 × (enthalpy to heat the adsorbent bed + enthalpy of desorption); for organics = enough to heat the system to 30–50 °C above the boiling temperature of the highest boiling component in the mixture.

- *Trouble Shooting*

"Wet gas": steam leak/leaky valves/inadequate regeneration/wrong adsorbent/adsorbent damaged by excessive regeneration temperature/adsorption cycle too long/[early breakthrough]*.
"Δp high": fine particulates in feed/breakdown of adsorbent/high gas feedrate.
"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/[corrosion]* products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.
[Corrosion]:* see Section 1.3.
[Early breakthrough]:* gas short circuiting bed/faulty regeneration/increased concentration in feed/other contaminants in feed.

4.12
Adsorption: Liquid

Related topics include ion exchange, Section 4.13.

- *Area of Application*

Prime option for dilute concentrations with a need for greater selectivity than solvent extraction can provide.

- *Guidelines*

Select adsorbent:
Activated carbon: surface area: 1000 to 1500 m^2/g; pore volume 0.6 to 0.8 cm^3/g, temperature $< 540\,°C$; loading very dependent on molar mass of target solute, solubility in the carrier liquid and pH. Example loading 0.01 kg organic molar mass 100/kg dry solid. The value varies with the molar mass$^{3.5}$. Carbon usage expressed as kg carbon required/m^3 liquid increases with increase in the TOC in the feed and depends on the type of species present. A gross approximation is that 1 kg/m^3 is required for 300 mg TOC/L with $n = 1.0$ for the range 200–30 000 TOC, mg/L.
acid treated clay: surface area: 225 to 300 m^2/g.
Fuller's earth: surface area: 130 to 250 m^2/g.
Batch:
Fixed bed: Batch: size on cycle time: load, backwash/clean, regenerate, swing onstream. Load: typical flowrate 2–3.5 BV/h with the load time based on the ratio of the adsorption isotherm to the feed concentration of the target species (usual range varies with the application: 18–100 min while for water treatment: 70–100 days). Backwash with velocity to fluidize the bed; velocity 0.8 BV/h. Time such that $< 5\,\%$ feedrate used in backwash. Usually carbon is removed and regenerated about four times per annum. Try to match the loading cycle to the regeneration cycle.

Use fixed bed if < 20 L/s and carbon usage > 180 kg/day. Superficial velocity 1 to 15 L/m^2 s; use 2.6 to 5 L/m^2 s to estimate cross-sectional area. Too low a superficial velocity (< 3 L/m^2 s) gives poor feed distribution. Use 2 to 3.5 BV/hour; to give the required residence time of 18 to 100 min. Bed depths in the range 3 to 10 m but keep the pressure drop < 75 kPa. Height/diameter 1:1 to 4:1. Maximum size is based on carbon usage < 9 Mg dry carbon per day.

Active carbon volume/area = 1.6 m^3/cross-sectional area, m^2.

Continuous:

Moving bed: Use if > 20 L/s. Related topic transfer line reactor, Section 6.7.

Fluidized bed: Use if slimes or fine particles in feed, Use superficial velocities of 8 to 14 L/m^2 s. Feed contacts bed for 30 min or 0.8 BV/h. Related topics include reactors, Section 6.30, and drying, Section 5.6.

Slurry approach*:* Use if the carbon usage is < 180 kg/day. Mix and suspend powdered adsorbent and then filter exit line. Often use up to three stages of countercurrent contacting. Used for continuous bleaching of edible oils. Batch process is simple, flexible and easy to change feedstocks. Continuous operation offers better protection against oxidation, provides shorter holdup and has the potential of heat recovery. Bleach time 25 min. Related topic transfer line reactor, Section 6.7.

Loading times and elution-regeneration times should be approximately equal.

- *Good Practice*

For edible oils, prevent contact with air. Carbon regeneration by multiple hearth furnaces, see Section 6.21.

- *Trouble Shooting*

"Early breakthrough": liquid short circuiting bed/faulty carbon regeneration/increased concentration in feed/other contaminants in feed.

"Pressure drop high": fine particulates in feed/breakdown of carbon/high liquid feedrate.

4.13
Ion Exchange

Related topics include the use of ion exchange resins as catalysts in reactors, Section 6.35, liquid–solid fixed bed reactors, Sections 6.9-6.12, and adsorption-liquid, Section 4.12.

- *Area of Application*

High valence ionic species in liquid phase with $\alpha_{IX} = \Gamma^+ (1 - c^+)/c^+ (1 - \Gamma^+) = 1.01$ to 1.04 where Γ^+ = surface concentration of cations, c^+ = bulk concentration of cations, and feed concentration 0.02% to 2% w/w.

- *Guidelines*

Select the ion exchange resin based on the pH of the environment and the valence of the target ion. For high efficiency, try to use weak electrolyte resin.

Weakly acidic cationic exchange resin, WAC, carboxylic; pH > 4; $T < 100\,°C$; hydrogen or sodium form depending on regeneration preference; loading 3.5 eq/L of resin; good selectivity; greatest affinity for alkaline earth metals in the presence of alkalinity.

Strongly acidic cationic exchange resins, SAC, sulfonic; full range of pH, $T < 120\,°C$; hydrogen or sodium forms; loading 1.9 eq/L resin; high capacity, high activity. Ionic sequence $Ba > Pb > Sr > Ca > Ni > Mn > Be > Cd^{2+} > Cu > Co > Zn > Mg$.

Weakly basic anionic resin, WBA: aromatic polyamine: pH< 7; $T < 50\,°C$; chloride(more thermally robust) or OH form; loading 1.6 eq/L resin.

Strongly basic anionic exchange resins: SBA: Type I trimethyl amine: full range of pH; chloride (more thermally stable) or OH forms; loading 0.46 to 1 eq/L resin. Ions being exchanged must have a higher valence than ions in bed from regeneration [F].

For bioseparations: proteins usually have a charge in liquid solution. The magnitude and size of the charge depends on the pH and is zero at the zpc, the pH where the charge is zero. For example, the zpc for invertase is pH = 4.24. To separate a target species, identify the zpc, select a convenient pH different from the zpc and pick the exchange resin of the opposite charge. Operate the column at this pH to load the resin. Then, stop the flow, change the pH to the zpc and elute the target species.

Batch:

Fixed bed: Batch: size on cycle time: load, backwash/rinse, elute, standby. Try to match loading with off-line time. Load: loading feedrate 5–10 BV/h with loading time depends on the ratio of exchange capacity of the resin to the feed concentration of the target species. Usual ratio 10–100 corresponding to a loading time of 1.5–15 h. Backwash with a velocity to fluidize the bed for 1–10 BV (corresponding to about 1.5 h). Eluent feedrate 1–3 BV/h for typically 8–20. Standby is typically 20 % of the backwash time. When the eluate is valuable, try to match the loading time with the backwash, eluate recovery and standby.

Feed flowrate: superficial velocity 1 to 15 L/m^2 s; use 5 L/m^2 s. Superficial velocity < 3 L/m^2 s gives poor feed distribution. 5 to 10 BV/h; too deep a bed leads to excessive pressure drop; keep below 350 kPa. add 2.5 m to height to allow for bed support and head room for backwashing. Typical bed depths 1 to 5 m; usual industrial bed cross-section 5 m^2.

Use fixed bed if < 20 L/s. Pressure, gravity, cocurrent, countercurrent, series, single bed or mixed bed. Gravity is economical where the BV > 80 m^3.

Loading times and elution-regeneration times should be approximately equal.

For WAC and WBA systems the backwash, regeneration and rinse cycle is 30 to 60 min.

Continuous:

Moving bed: Use if > 20 L/s.

Fluidized bed: Use if slimes or fine particles in feed, elution time $> >$ IX time, eluant is expensive. Use 16 to 20 Mesh resin with superficial velocities of 40 L/m^2 s. Try to operate at 50 to 200 % bed expansion. Related topics include adsorption-liquid, Section 4.12.

- *Good Practice*

Use an upstream degasser to remove carbonic acid.

- *Trouble Shooting*

Usual sources of trouble are change in ions in the feed, the multiport valves improperly seat so that feed or regenerant bypass into the effluent, clogged liquid distributors, clogged underdrains; degradation of the resin and faulty backwash. Organic fouling mainly affects anionic exchangers.
"Throughput capacity < design": instrument error/increase in feed concentration/less resin volume than design/regenerant concentration < design/regenerant volume < design, 0.5–3.5 L/s L of resin/regenerant flowrate < design/wrong regeneration ion/contamination of regenerant with high valence ions.
"In the spring, reduced flowrate through the unit demineralizing river water": high concentration of particulates, clay in spring river water.
"In the summer for a unit demineralizing water, throughput of the cationic exchanger decreases, exchange capacity for calcium and magnesium decreases but the anionic exchanger is unaffected": suspect ferric or high valency cation present in the feed.
"In the summer for a unit demineralizing river water, throughput of the anionic exchanger decreases, exchange capacity decreases but the cationic exchanger is unaffected": suspect fertilizer runoff with phosphate, carbonic acid and high sulfate anions as contamination.
"Contamination in exit liquid > design": instrument error/sampling error/on-line too long/faulty regeneration/[fouled]*/[poisoned]*/high feed concentration of target ions/feed concentration of high valence co-ions.
"Δp > design": dirt in feed/water from river in springtime/instrument error/temperature/resin void volume changes/inlet distribution system blocked/[resin degradation]* and backwashes into inlet/backwash rate too high/underbed blocked.
*[Fouling of the resin]** : iron and high valence ions/oil/mud/polyelectrolyte/calcium sulfate precipitate/silica/barium sulfate/carbonic acid/sulfate or phosphate/organics/algae and bacterial fouling. More general causes of fouling are given in Section 1.12.
*[Poison resin]**: cobalticyanide/polythionate/ferricyanides/complex humic acid/color bodies in sugar juices.
*[Resin degradation]**: ingress of oxidants/free chlorine in feed/temperature increase/[fouled]*/[poisoned]*/corrosion products/[resin fines]*.
*[Resin fines]**: thermal or physical shock/freeze/thaw.
WAC: *"Alkalinity leakage during exhaustion cycle":* inadequate regeneration.
"Hardness leakage during exhaustion cycle": regeneration fault with calcium sulfate precipitation (if sulfuric acid is the regenerant).
SAC: *"Sodium leakage":* inadequate regeneration: wrong concentration, wrong flowrate, wrong length of time.
"Hardness leakage during exhaustion cycle": regeneration fault with calcium sulfate precipitation (if sulfuric acid is the regenerant).
WBA: *"Mineral acid leakage":* under regenerated/upstream SAC malfunctioning.
"Sodium leakage, high pH and high conductivity": SAC resins contaminated the bed.

"Silica problems": series regeneration with SBA with pH falling below the isoelectric point of silica in the resin bed.
SBA: *"Increase in silica leakage":* [resin degradation]*.
"Leakage of target ions": organic [fouling]*.
"Low pH and high conductivity": organic [fouling]*.
"Increase rinse quantities": organic [fouling]*.
"Low pH (5.5), increased conductivity, increase silica leakage, increase rinse volumes, loss of throughput capacity:" organic [fouling]*.
"Product contamination": leaking valves/crud left in storage tanks/crud left in dead legs in piping/corrosion products/unexpected chemical reactions/sampling fault/analysis fault/unexpected solubility effects.

4.14
Foam Fractionation

Related topics include gas in liquid, Section 8.1.

- *Area of Application*

Solute feed concentration usually 1 ppm to 0.1 % with some applications up to 10 %. [10^{-3} to 10^{-9} mol]. The bulk/film volume ratio, $\delta^{+} = 1$.

- *Guidelines*

Surface concentration 1 to 5 μmol/m^2 bubble area. Height to diameter 5:1 to 15:1. Usual liquid feed superficial velocity 0.1 to 1 L/s m^2. Bubble diameter = 0.8 to 1 mm. Volumetric feedrate ratio of inlet gas to liquid flowrates: 4 to 7.5 dm^3 gas/L liquid. Volumetric ratio of gas in foam to overhead liquid in draining foam: 100 to 250:1. Liquid in the foam/liquid in the feed = 6 to 12 % v/v; draining foam density 0.003 Mg/m^3. Superficial gas velocity for foam drainage section 3 to 250 dm^3/s m^2. Scaleup based on constant superficial gas velocity.

- *Good Practice*

To remove ions, consider adding ionic surfactant.

4.15
Membranes and Membrane Configurations

Consider first the membranes: materials of construction, pore sizes and surface properties. Then consider options for operating membranes and the configurations for membranes: hollow fibers, tubes, flat sheets and spirals.

4.15.1
Membranes

Membranes can be made of different materials, with different pore sizes and distribution of pore sizes and with different surface characteristics.

Different materials: In general, the materials are polymers, ceramics and sintered metals. Polymers can be divided into elastomeric (or rubbery) and glassy. Usual materials for liquid systems include polyethersulfone, polysulfone, cellulose acetate, and regenerated cellulose.

Membrane pore size and pore size distribution: The pore size can be reported as the average size of the pore (e.g., 5 nm) or according to the molar mass cut-off size, MMCO (and sometimes called the molecular weight cut off, MWCO). The MMCO is measured in daltons. The standard definition for membrane performance is based on 90 % rejection. That is, a 50 kDa membrane will reject up to 90 % of molecules having a molar mass of 50 kDa. For the complete rejection of a species, select a membrane with MMCO rated at 0.2 MM of the target species; i.e. 10 kDa membrane should reject 100 % of a 50 kDa species or select a pore size one order of magnitude smaller than that of the target species.

Based on pore size, membranes are described qualitatively as being *nonporous, dense* or homogeneous (with pore sizes around 1 nm); *microporous* (with pore sizes 0.001–20 μm) and *macroporous* (with pore sizes usually 100–500 μm).

Concerning the distribution of the pore size through the membrane, there are seven classes:

Symmetric: (where the pore size is uniform through the membrane; example, polyolefins, fluoropolymers, nylons with porosity as high as 85 % throughout membrane; sintered metals with porosity 25–30 %).

1. symmetric porous with long tubular pores or isoporous,
2. symmetric microporous,
3. symmetric non-porous or dense (homogeneous).

Asymmetric: (where the pore size differs through the membrane; this gives a small surface area/volume and therefore requires larger filter for a given flowrate. Some examples include ceramics that are most porous with 30–40 % porosity in the thin, membrane layer; and polymers, porosity in thin layer 1–9 %.).

4. asymmetric microporous top layer on porous but all the same polymer.
5. asymmetric nonporous (homogeneous) top layer on porous but all the same polymer.
6. asymmetric composite: non-porous (homogeneous) layer(s) of one material (example polyamide) on top of microporous support (polysulfone).
7. asymmetric composite skinned: thin layers of one material on top and bottom of membrane with porous or microporous support membrane in between.

Surface characteristics of the membranes: Two of the key characteristics are the hydrophobicity and the surface charge. Hydrophobic surfaces (or water-hating surfaces) are those where the critical surface tensions of the membrane material < the surface tension of water. Most polymers fall into this category, for example, polysulfones, polyolefins, polyvinylidine fluoride, PVDF, and carbon. By contrast, hydrophilic surfaces are preferentially wet by water and have critical surface tensions > the surface tension of water. Steel, alumina, cellulosic (temperature < 30 °C), polyacrylic, Nylon 66, polyethersulfone, metallic oxides, and ceramic surfaces usually fall into this class. Sometimes we treat the surface of the membrane to make it hydrophilic. Sintered materials are neither hydrophilic nor phobic.

The surface charge is related to whether the pH of the liquid is higher or lower than the zpc of the surface. For a pH > zpc, the surface charge is negatively charged; and vice versa. Some example zpc values are: alumina, 9.2; carbon, 3.8; polysulfone < 4.5; teflon (PTFE), 3; and silica, 1–2.

4.15.2
Membrane Operation and Configuration

Operation: can be operated *deadend* or *cross flow* : “batch” with 100 % recycle of retentate; “continuous” with recycle ratios 15–30/1 and purge and “multistage” where the purge from one stage becomes the feed of the next. ***Dead end:*** feed enters the membrane and can only leave through the membrane as permeate. ***Cross flow:*** feed flows through the membrane and as it does, some liquid passes through the membrane to create the permeate. Use cross flow especially for compressible cakes (e.g. biosystems). ***Batch:*** process: stop feed because the membrane performance has deteriorated or because the target concentrations or volumes of permeate or retentate have been achieved. Deteriorated membrane performance can be (i) because of a buildup of particulates, biological deposits (this can be corrected by backflushing with permeate or cleaning with detergents, acids or bases) or (ii) because the membrane needs to be replaced (the life of a membrane is 1–10 years depending on the operating conditions and the type of membrane).
Configuration: Table 4.2 summarizes the characteristics of various configurations used for membranes: fine tubes or hollow fibers, channels and tubes; indicates which configuration can be made out of certain materials. For liquid systems, spiral wound (using cellulose acetate or polyamide membranes) is used extensively and hollow fibers (0.1–2 mm diameter, with polysulfone, polypropylene, nylon 6, or polyvinyl chloride membranes) are used when there are no particles present.

- *Good Practice*

Fouling is a major consideration. We can try to minimize fouling by supplying high shear at the surface, by selecting hydrophilic or hydrophobic surface properties depending on system; astutely selecting the operating conditions of temperature and pH, by coating the membrane with fouling resistant material and by op-

Table 4.2 Characteristics for various membrane configurations.

	Tubes: fine hollow fibers to tubules				Channel:					Tubes	
	RO type	**UF/microfilter**			**Flat sheet: plate/ frame**	**Flat sheet: plate/ frame**	**Spiral wound**	**Pleated sheet**	**Tubular mono-lithic elements**		
Diameter or spacing, mm	0.01–0.03	0.02–0.1	0.5	1.1	0.2–0.4 0.5–1	1.2–2.5	0.75 or 1.1			2.5–6	12–25
Length, cm		< 100			45	45					1800
Reciprocal volume, 1/cm^3	300–7500	0.9–6			0.8–30						0.001–0.0001
Holdup, L/m^2		0.33	0.12	0.3							
Flow conditions, Reynolds no.	500–3000	500–3000	laminar, 500–3000	500–3000	500–3000	turbulent	laminar, 100–1300				turbulent, Re > 10000
Velocity, m/s		0.01 –2.5	0.6–1	0.6–1	0.06–0.6		0.1–2				2–6
Velocity, m/s for cross flow				1–5		1–3	0.2–0.5				5
Feed rate/surface area, L/s m^2					0.25–0.5		0.25–0.5				1–5
Shear stress/ length, 1/cm s		10–100			80–300		80–300				500–4000
Pressure drop along the membrane, kPa		30–130			70–1000		100–140				14–20

Table 4.2 Continued.

	Tubes: fine hollow fibers to tubules				Channel:					Tubes	
	RO type	**UF/microfilter**			**Flat sheet: plate/ frame**	**Flat sheet: plate/ frame**	**Spiral wound**	**Pleated sheet**	**Tubular mono-lithic elements**		
Area per unit volume, m^2/m^3	6000	600–1200	500–1100	320–505	400–1000		650–1000				25–70
Max size/unit, m^2		1	0.05–5		0.02–0.07		8–22				0.4
Cellulosics	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no
Polysulfone		yes			yes		yes	no	no	yes	yes
Acrylics		yes		no	no		no	no	no	no	no
Fluoropolymers					yes	yes	yes	no	no	yes	yes
Ceramics		yes	yes	yes	depends				yes	yes	yes
Sintered metal									no	yes	yes

erating at *subcritical fluxes*. The critical flux is that flux (for a given set of feed concentrations, cross-flow rates, pH, temperature and ionic strength) below which fouling is negligible.

4.16
Membranes: Gas

- *Area of Application*

In general there are two applications: remove volatile organics (VOC) from air and separate permanent gases (such as nitrogen, hydrogen, carbon dioxide). Related VOC removal see Section 6.16 biofilters.

To remove organics from air, VOC: feed concentration is $> 0.1\,\%$ v/v and the air flowrate is < 480 dm^3/s. For lower concentrations use adsorption, Section 4.11; for higher flowrates use adsorption and condensation.

To separate permanent gases: feed concentration is 10 to 85 % and the flowrates range from 0.05 to 65 Nm^3/s.

$\alpha = 1.4$ to 4; gas feed concentration 5 to 75 % w/w; 75 to 90 % gas purity possible. Diameter of the target species: 0.1 to 1 nm.

- *Guidelines*

Membrane type: *asymmetric*: homogeneous or microporous; composite of a homogeneous polymer film on microporous substructure or symmetrical *homogeneous* or porous polymer film.

Driving force for the rate of separation: hydrostatic pressure concentration, partial pressure.

Membrane: nonporous membrane elastomer (example, rubbers and silicone rubbers) or glassy (example, polycarbonate, polyether imide, polyethersulfone, polyimide, polysulfone, polystyrene, polyvinyl chloride, polyvinyl fluoride and teflon.)

Pressure: > 0.7 MPa for separation of permanent gases.

Temperature 0 to 60 °C.

For VOC removal from air, use elastomeric membranes (rubbery membranes). The membrane has a 0.1 to 1 μm skin layer on a 100 to 300 μm substrate. These membranes tend to have lower selectivities, higher permeabilities and are relatively impermeable to nitrogen. VOCs preferentially partition into the membrane phase. The permeability of organics tends to be 4 to 100 times higher than that of inert gases. For these membranes the selectivity increases with increasing boiling temperature of the species. The permeability increases 10 % per °C increase in temperature. Typical permeabilities for the organics are > 200 Ndm^3 μm/s m^2 MPa.

For the separation of permanent gases, use glassy membranes with higher selectivity and lower permeability.

Typical permeance are:
- for hydrogen methane separation: 0.22 to 3.75 $Ndm^3/s\ m^2$ MPa.
- for carbon dioxide–methane separation: 0.075 to 1.5 $Ndm^3/s\ m^2$ MPa.
- for air separation: 0.003 to 1.9 $Ndm^3/s\ m^2$ MPa.

The temperature of the feed should be > 20 to 40 °C above the feed dew point.

Configuration, see Section 4.15. Usually use flat or hollow fiber.

4.17
Membranes: Dialysis

- *Area of Application*

$\alpha = c_{21}\ D_2/c_{11}\ D_1 = 6$ to 25 %; liquid feed concentration 2 to 25 % w/w; 99 % purity possible. c_2 = concentration of solute in the feed. Diameter of the target species: 0.5 to 5 nm. D = diffusivity, c = concentration.

- *Guidelines*

Driving force for the rate of separation: concentration of target species.

Membrane: symmetric microporous with 0.1 to 10 nm pore diameter. Hydraulic permeability: 10^{-3} to 8 $g/s\ m^2$ MPa. Membrane-solute permeability 0.05 to 9 m/s depending on the solute and the membrane. Dialysis transfer coefficient: 1 to 10 μm/s. Hollow fiber.

- *Good Practice*

Proteins denature at temperatures > 80 °C. Glass temperature for many polymers = 60 °C. Very high flowrates should be avoided since they can generate transmembrane pressure.

4.18
Membranes: Electrodialysis

- *Area of Application*

Diameter of the target species: 0.2–0.8 nm. Feed concentration < 20 % ionic. Feed range 0.005 to 5 %.

- *Guidelines*

Driving force for the rate of separation: electropotential.

Membrane: ion exchange, homogeneous or microporous polymer with positively or negatively charged fixed ions.

Hydraulic permeability: 10^{-3}–8 $g/s\ m^2$ MPa.

Pretreat feed until ferric < 0.3 mg/L, Mn < 0.1 mg/L, $H_2S < 0.3$ mg/L.

Temperature: > 10 and < 43 °C.

Optimum feed concentration 1000 to 5000 mg/L.

Energy about 5.5 to 9 MJ/m^3 product.

Pressure drop: horizontal stack 0.2 to 0.4 MPa; vertical stack 0.02 to 0.07 MPa.

Configuration: flat, see Section 4.15.

4.19
Membranes: Pervaporation

- *Area of Application*

$\alpha = (c_{i,3}/c_{j,3})/(c_{i,1}/c_{j,1})$ where i is the target permeate species, j is the reject; 3 = permeate and 1 = feed, separates dissolved organics = 1.3–41. Particle diameter, 0.2 nm. Target concentration 5–20 % w/w but 0.1–10 % w/w for economical. Temperature $< 120\,°C$.

- *Guidelines*

Driving force for the rate of separation: concentration gradient in the vapor pressure.

Membrane: asymmetric: homogeneous or microporous (polyacrylonitrile, cellulose acetate, polyamide, polysulfone,); composite of a homogeneous polymer film on microporous substructure (cellulose acetate, polyamide, polysulfone, polyimide, polyvinyl alcohol). Usual pore 0.1–0.2 μm.

0.1 μm PVA: water $>>$ methanol $>$ ethanol $>$ other organics

Silicone rubber: methanol $>$ ethanol$>$ aldehydes$>$ ketones$>>$ water; paraffins $>$ olefins

Cellulose esters: aromatics $>$ paraffins; olefins $>$ paraffins; dienes $>$ olefins; n-paraffins $>$ branch; low molar mass paraffins $>$ high molar mass paraffins.

Capacity/unit: feed < 1.5 kg/s.

Feed pressure: atmospheric.

Feed temperature = close to the normal boiling temperature; usually 50–100 °C.

Permeate conditions: pressure 0.5–2 kPa absolute with condenser temperatures: –20 to +30 °C.

For dehydration, use a difference in partial vapor pressure at least 1 order of magnitude; the permeate flux doubles for an increase in temperature of 10 °C.

Permeate flux: depends on membrane but in the range 0.008–5 g/s m^2.

Configuration: see Section 4.15.

Spiral wound, transverse hollow fiber.

Use *cross flow* with recycle ratio 15–30/1. Criterion: 10 % of feed volume is permeate or purity of the permeate or retentate.

Membrane life, 2–4 years.

Cycle time: usually limited by life of membrane.

4.20

Membranes: Reverse Osmosis, RO

- *Area of Application*

$\alpha = 6$ to 25; feed concentration 0.05 to 20 % w/w; with suggested economic feed concentration < 0.5 %; 99 % purity possible. Diameter of the target species: 0.2 to 0.8 nm. Must overcome a difference in osmotic pressure. The osmotic pressure coefficient in mass ratio units for different solutes = 20–80 MPa kg/kg at 25 °C. The higher the valence, the better the rejection.

- *Guidelines*

Driving force for the rate of separation: hydrostatic pressure.

Membrane: Asymmetric: homogeneous or microporous; active dense 20 to 50 μm layer of cellulose acetate with total thickness 100 μm; composite of a homogeneous polymer film on microporous substructure of polyamide or polysulfone, or asymmetric skin. Usually homogeneous.

Pressure: 1.4–10 MPa (1.4–4.2 for brackish water; 5.6–10 for seawater). Inlet pressure > twice the inlet osmotic pressure.

Temperature < 45 °C.

Capacity/unit: < 7 L/s.

For cellulose acetate membranes: $1/\Theta^{+} = A\,p/B\,\varrho = 1$–500 with usual value 300, [dimensionless].

For aromatic polyamide membranes: $1/\Theta^{+} = 0.7$–20.

A = permeate hydraulic permeability, g/s m^2 MPa.

p = total operating pressure, MPa (1.4–10 MPa).

B = target solute transport coefficient, μm/s (10^{-6}–10 μm/s).

ϱ = mass density of the feed stream.

Hydraulic permeability, A: 0.0005–8 g/s m^2 MPa (0.1–10 for cellulosic).

Permeate flux 0.001–0.1 L/s m^2 ; for cellulose acetate: 0.006–0.0075 L/s m^2 ; for hollow fiber: 0.001–0.002 L/s m^2 ; for thin film composite: 0.007–0.009 L/s m^2 . Permeate flux increases about 3 % for every 1 °C increase. Permeate flux decreases by 10 to 50 % depending on the concentration polarization. Permeate flux is reduced because of particulates and bacterial adhesion so that flux for tubular < spiral wound < hollow fiber.

Configuration: see Section 4.15.

Usually spiral wound but some use hollow fiber and tubular (used for low volume, high value commodities), pleated sheet, tubular monolithic elements, or plate and frame.

Use *cross flow* batch with 100 % recycle; continuous with recycle ratio 15–30/1 or multistage (often three stages). Criterion to backwash and clean: operate until a given concentration or volume reduction is reached in the retentate or a given purity or volume is achieved in the permeate.

Membrane life, 2–4 years.

Cycle time: pretreat to prevent scaling or buildup or operate a short cycle, 2–12 h, cleaning with dilute nonionic detergent. Degree of pretreatment: hollow fiber $>$ spiral $>$ tubular.

Reverse osmosis: 0.0029 L/s m^2 of membrane area; for waste water with concentration up to 10 000 mg/L.

- *Good Practice*

Consider pretreating hydrophobic membranes for aqueous use.

- *Trouble Shooting*

"Permeate flow $<$ design": physical fouling (incorrect/incomplete pretreatment/scaling/biofouling)/chemical fouling: (pH shift/incorrect anti-scalant dosage).
"Permeate quality degradation": failure of mechanical seal/chemical attack of membrane by pH, chlorine or biodegradation/concentration polarization/post-contamination.

4.21
Membranes: Nanofiltration

- *Area of Application*

Molar mass cut off = 200 = 0.2 kDa. The usual range is 0.01–1 kDa. Can handle fluid with significant osmotic pressure, sugars, dissociated acids and divalent salts although the latter two are better handled by RO.

- *Guidelines*

Driving force for the rate of separation: pressure.
Membrane: asymmetric thin film, aromatic polyamide, cellulose membrane; membrane usually negatively charged to reject anions.

Pressure: (between UF and RO) = 0.3–1.4 MPa.

Configuration, see Section 4.15. Usually spiral wound.

- *Trouble Shooting*

See Section 4.20.

4.22
Membranes: Ultrafiltration, UF

Related topic filters, Sections 5.13 and 5.14.

- *Area of Application*

$\alpha = \kappa_2\, D_2/\kappa_1\, D_1 = 6$ to 60; liquid feed concentration 0.04–20 % w/w; 99.9 % purity possible. κ = partition coefficient; D = diffusivity. Diameter of target species 0.8–200 nm and usually 1–10 nm; removes soluble macromolecules, colloids, salts and sugars but cannot separate dissolved salts, species with molar mass < 1000 or species exhibiting a significant osmotic pressure. Feed concentration $< 20\,\%$ dissolved organics. MMCO = 0.3–500 kDa.

- *Guidelines*

Driving force for the rate of separation: hydrostatic pressure.
Membrane: Most UF membranes are polysulfone: asymmetric microporous with thin skin 0.1 to 1 μm supported on a porous layer 50 to 250 μm. Pore size 0.001–0.2 μm. This is too porous for RO. Pore size prevents concentration polarization (limiting RO) but performance is limited by gel polarization with x_{gel} 0.2–0.4. $x_{gel} = 0.25–0.35$ for macromolecules; $x_{gel} = 0.75$ for colloids. Need to have membrane life > 1 year.

Pressure: 0.1 to 0.7 MPa. Hydraulic permeability, A: 0.8–800 g/s m^2 MPa. Feed concentration: 0.05–15 % w/w.

Temperature < 90 °C and pH 0.5–13 for polysulfone. Capacity/unit: 0.1–25 L/s.

Select diameter or channel spacing so that diameter of the target species is 0.1 of the diameter or channel spacing; except for spiral wound where, for 0.75 mm spacing the particles must be < 5–25 μm; or 0.006–0.034 diameter of spacing; for 1 mm spacing particles should be < 25–50 μm or 0.025–0.05 of the diameter or channel spacing.

Permeate flux : depends on the membrane and configuration: hollow fibers/polysulfone: 0.005–0.016 L/s m^2; spiral wound/polysulfone: 0.08–0.14 L/s m^2; tubes/polysulfone: 0.06–0.2 L/s m^2.

Liquid permeability increases 25 % for every 10 °C increase in temperature.

Power depends on target species and configuration: water treatment 1.8 kJ/L permeate; food application: 32 kJ/L permeate; electropaint: 60 kJ/L permeate. Configuration: hollow fiber 6 kJ/L; plate and frame 9 kJ/L; spiral 3–6 kJ/L; tube 15 kJ/L; or hollow fibers: 100–280 W/m^2; plate and frame: 180–280 W/m^2; spiral wound 25–120 W/m^2.

Configuration: see Section 4.15.

Usually hollow fibers provided there are no particles. Other options include spiral wound, plate and frame, and tubular (use for small flow, high value and severe fouling applications).

For laminar flow operation of hollow fiber, plate and frame and spiral wound, keep the operating pressure 0.1–0.2 MPa; for turbulent flow operation of plate and frame, spiral wound and tubes, operate at 0.5–0.7 MPa.

Use *deadend* for low concentrations of particles > 0.1 μm.

Use *cross flow* batch with 100 % retentate recycle, continuous bleed with recycle ratio 15–30/1 and multistage: when a concentrated retentate is desired or when particle diameter < 0.1 μm.

Criterion to backwash/or clean: when 90 % reduction in retentate volume is achieved; given quality or volume of permeate; the permeate flux < 15 % of initial flux; or when the viscosity of the retentate is 100–300 mPa s. This corresponds to concentrations for pigments of 30–70 %; for microorganisms of 1–10 %.

Membrane life, 2–4 years.

Cycle time: clean by backwashing with permeate every 6, 24, 170, 360, 1000 h (depending on the criteria, the membrane, operating conditions and on the amount of pretreatment), Example 8 h on and 1–2 h off to clean; or short pulses every 150–300 s so that steady state flux operation is never achieved.

Clean by steam, detergents, solvents, acids or bases. Another option to lengthen cycle time is to add solids to the feed to mechanically wear away the gel layer. The choice affects membrane life. Steam cleaning gives 50–150 cycles before membrane replacement; non-steam cleaning gives 200–500 cycles.

- *Good Practice*

For membranes that are not hydrophobic; check the isoelectric or zero point of charge point of the species in solution compared with the charge on the membrane and consider changing the pH of operation so that the surface charges are the same.

For hydrophobic membranes treating aqueous feeds, consider pretreating the membrane to make the membrane surfaces hydrophilic.

- *Trouble Shooting*

"Permeate flux < design": physical clogging (inadequate pre-screening/backwash problems/aeration/recirculation/increase in influent solids loading); chemical fouling (change in water quality/inadequate cleaning).
"Permeate quality < design": failure in mechanical seal, breakage of the membrane or hollow fibres/post contamination via regrowth/degradation of membrane by pH or chlorine.

4.23
Membranes: Microfiltration

Related topic filters, Section 5.14.

- *Area of Application*

Particulate diameter 0.05 to 800 μm and usually 0.1–10 μm; feed solids concentration < 75 %w/w; < 50 % v/v. Remove solid or gelatinous particulates by pore size in the membrane. Pore size: 0.2–1 μm with the membrane cut-off sizes in the range 0.05–10 μm.

- *Guidelines*

Driving force for the rate of separation: pressure.
Membrane: symmetric or asymmetric microporous. ceramic, sintered metals or polymers with pores 0.2–1 μm. Symmetric polymers have a porosity of 60 to 85 %; asymmetric ceramic membranes, porosity 30 to 40 %, are used for high pressure and higher temperature < 200 °C. Pressure 0.03–0.35 MPa. Pressure: 0.3–0.5 MPa for ceramic. Hydraulic permeability, *A*: 70 to 10 000 g/s m^2 MPa, capacity/unit: 0.001–1 L/s. Liquid permeate flux: 0.001–0.2 L/s m^2 with the perme-

ate flux through ceramic membranes 2–3 times higher than through symmetric polymeric or sintered metal membranes and 5–10 times higher than through asymmetric polymeric membranes because ceramic operates at higher pressure. **Configuration:** see Section 4.15.

Use tubular for feed concentrations of 10–80% w/w; spiral wound or thin channels for low concentrations with particulates $< 100\ \mu m$. For more see UF, Section 4.22.

- *Good Practice*

See UF, Section 4.22.

- *Trouble Shooting*

See Section 4.22.

4.24
Chromatography

The chromatographic separation approach is often used to describe "a method of running" an IX column or an adsorption column. These are not considered here; see Sections 4.13 and 4.11 and 4.12 respectively. Two uses of the chromatographic approach are considered here: affinity or immunosorbent (that is similar to adsorption/IX but is usually applied to bioseparations) and size exclusion or gel chromatography, SEC.

In *affinity chromatography* the feed is always liquid, the feed is a stream containing the target species, the target species complexes with ligands that are immobilized on the packing and so is "attached" to the column packing and is removed from the column by flowing an appropriate eluant through the column, in this way the operation is cyclical with bed loading, washing, eluate flow, wash and then the cycle repeats. Example, target species is an enzyme then the complexing agent might be an inhibitor; for an antibody as a target species an antigen might be the complexing agent.

In *SEC* separation, the feed may be gas or liquid, the feed is a carrier fluid to which pulses of feed containing the target species are injected, the smaller species in the injected feed usually diffuses into the pore spaces in the packing such that the exit from the bed of the low molar mass species is delayed. The larger species with the larger molar mass do not diffuse into the pores and so are carried out of the bed first by the carrier fluid. By astutely selecting the packing and the carrier a separation is obtained. If the molar mass of the target species differs from the other species in solution by a factor of > 1000, then the separation is relatively easy and is referred to as *bulk SEC*.

- *Area of Application*

The target species can be complexed with immobilized ligands then use *affinity chromatography*.

Separate species in the liquid phase whose molar masses differ by factor of 1000 via *bulk CS* (example, desalt a solution of proteins. we can separate species in the liquid phase whose molar masses differ by at least 20 % via *SEC*. Use SEC for gas phase separation if the relative volatility (based on vapor pressure of key components) α_{vp} is < 1.1. See Distillation Section 4.2.

Usually chromatography is used as the last separation because of the large volume of inert carrier fluid needed and the large size column.

- *Guidelines*

For *Bulk CS*, flowrate 500 mL/s m^2. The high molar mass target species is diluted by the carrier fluid by a factor of 1.5 to 10. Select the inert stationary solid particle packing, such as a crosslinked dextran gel, crosslinked polyacrylamide gel, agarose-based gels. The carrier fluid is usually a dilute buffer (0.02 M) to eliminate any potential ion exchange effects that might occur between the target species and the inert packing.

For *SEC*, the space velocity is 0.1 to 0.2 BV/h; flowrate 2–50 mL/s m^2 or slightly turbulent flow to prevent excessive zone spreading. The injection pulse may be 10–30 s. Feed volume = 1 to 2 % of total column volume.

Feed concentration < 8 to 10 %. Multistaging is easy with up to 500 theoretical stages. Scale up based on total liquid flowrate. HETS is a function of the packing diameter, and the local fluid maldistribution. HETS = 0.1 - 0.3 cm. Residence times in a column are in the order of 3 min.

- *Good Practice*

Ensure the packing is uniform. Include a tapered porous frit at the inlet to give uniform feed flow.

- *Trouble Shooting*

"Poor separation": [poor resolution]*/maldistribution of packing.

[Poor resolution]:* carrier concentration incorrect/wrong carrier/temperature too high/flow rate too fast.

5
Heterogeneous Separations

In heterogeneous phase separation we start with at least two phases. The chapter starts with general guidelines, Section 5.0, Sections 5.1 to 5.4 address the separation of gas from liquid, gas from solid, liquid from liquid and gas liquid liquid. Section 5.5 gives an overview of options to separate liquids from solids and the details are given in Sections 5.6 to 5.17. Section 5.18 gives an overview of options to separate solids from solids and the details are given in Sections 5.19 to 5.30.

General Guidelines

Five general guidelines are listed below and Table 5.1 gives an overall guide to specific options, classified by the type of phase to be separated.

1. Consider shifting from heterogeneous phase separation to homogeneous phase separation.
2. If possible, separate the gas phase first, then the liquid, and then solid–solid ($).

For solid-solid separation (Section 5.18):

3. Consider using dense media separation to preconcentrate before grinding to final liberation size ($).
4. Use feed assay and liberation size as criteria to guide selection of options ($).
5. Try froth flotation as a first option. Suggested heuristics are given by Woods (1994) p 5–71.

5.1
Gas–Liquid

- *Area of Application*

Liquid dispersions: rain > 100 μm; fog is between 1–100 μm.

Knockout pot: drop diameter > 100 μm; feed concentration $> 1\,\%$ liquid v/v.

Zig-zag baffled chamber: > 100 μm; $> 0.01\,\%$ v/v but keep superficial gas velocity < 1 m/s to prevent re-entrainment.

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Table 5.1 Selection guide (section number in parentheses).

Minor feed component	Major feed component		
	Solid	Immiscible liquid	Gas/vapor
solid	general (5.18) zone refine (4.5) screen (5.30) classifier (5.22–5.25) separator (5.26–5.29) flotation (5.19) electrostatic (5.20) magnetic (5.21)	settler (5.8) thickener (5.10) screen (5.7) hydrocyclone (5.9) DAF (5.16) filter (5.14) centrifuges (5.12, 5.13) ultrafiltration (4.22) microfiltration (4.23)	general (5.2)
liquid	general (5.5) dryer (5.6) screen (5.7) leach (5.15) expeller (5.17)	general options (5.3)	knockout pots zig-zag baffled chambers; wet cyclones; spray chambers, venturis, cross flow; wetted packing (5.1)
gas/ vapor		stripping (4.9)	homogeneous: membranes (4.15)

Wet cyclone: 10 to 400 μm; 4 to 60 % liquid v/v.
Spray chamber: 10 to 100 μm; 0.1 to 8 % v/v; with collection efficiency decreasing from 90 % to 50 % as mist diameter decreases.
Venturi: < 100 μm; < 0.1 % liquid v/v; with collection efficiency decreasing from 95 % as mist diameter decreases.
Mesh demister: 10 μm; 0.001 to 0.01 % liquid v/v; see size enlargement, Section 9.1.
Cross flow packed column: < 10 μm; 0.001 to 0.1 % liquid v/v;
Afterburner: < 0.8 μm; < 0.1 % liquid v/v;
Steam traps: separate condensate from steam.

Float: for continuous flow required, limited to low pressures.

Float and thermostatic: to eliminate large volumes of air, low pressures and some air elimination.

Open bucket: for pulsing or widely varying pressures; low pressures and some air elimination. Rarely chosen.

Inverted bucket: for dirty lines or dirty steam, eliminate large volumes of air, lowest initial cost/kg flowrate condensate; caution about frost, if > 2 °C subcooling occurs, then there is poorer upstream heat transfer.

Balanced pressure or thermostatic: very large capacity at relatively low cost, not for superheat that could damage bellows, provides good upstream heat transfer.

Thermal expansion: when subcooling is required.

Thermodynamic/kinetic energy/impulse: OK for freezing conditions; low cost, poor air handling, keep initial steam pressure < 1.2 MPa-g.

- *Guidelines*

If only a cost estimate is needed, then start with a cost correlation based on gas flowrate. Do not spend additional time sizing.

Knockout pot (drums and accumulators for high ratios of liquid/gas, as in distillation column overheads) use horizontal cylinder: size vapor space to provide the residence time for drops to settle out. Vapor volume between 20 to 50 % with a minimum of 0.3 m. Design vapor phase cross-sectional area to allow drops to settle in assigned length of the drum. Assume drops 0.1 to 200 μm. The maximum superficial density-weighted gas velocity, for vertical vessels is $v_{\mathrm{o\ max}} = k((\varrho_L - \varrho_G)/\varrho_G)^{0.5}$ where "k" is usually 0.13. $k_{\mathrm{horiz.}} = 1.25\ k_{\mathrm{vertical}}$.

Use superficial design value of 0.5 to 0.85 % of $v_{\max}$. (This separation superficial gas velocity is used to design/size many types of equipment: distillation columns, demisters. Table 4.1 compares values for "k" for different applications.)

Design liquid volume usually 80 % with sufficient volume for 300 s residence time to satisfy process control requirements. Typical length to diameter ratio of 3:1 to 5:1. Liquid vortex breaker.

Knockout pot (for low ratios of liquid/gas, as in demisters) use vertical cylinder. Size the same as horizontal with height of the vapor space 1.5 × diameter with 15 cm minimum above the top of the inlet nozzle and use lower value for k. For the liquid phase: maximum liquid level at least 18 cm below bottom of inlet nozzle; liquid residence time about 300 to 600 s.

The following units are sized using approaches given in Section 5.2 for **gas–solid** separations: wet cyclone, spray chamber, venturi, cross flow packed column. **Steam traps:** ball float, open bucket, inverted bucket, liquid expansion and thermodynamic. Size on condensate flowrate. The cooler the condensate, the larger the flowrate.

Float: continuous discharge, operating principle of buoyancy, OK for low loads but not high pressure. Not for water hammer. Range 0.06–5 kg/s condensate. Usually size based on 2 × usual flowrate; if handling air or wide variation in flowrates, size on 8 × usual flowrate.

Inverted bucket: intermittent discharge, operating principle = weight of the bucket, robust, OK for high pressure and corrosive condensate, use check valve before trap. Can handle some water hammer. Insulate for winter use. Range 0.05–2.3 kg/s condensate. Usually size based on 2 × usual flowrate; if handling air or wide variation in flowrates, size on 8 × usual flowrate.

Balanced pressure, thermostatic: operating principle = vapor pressure of fluid inside bellows. Not for superheated steam, corrosive condensate or waterhammer. No adjustment needed for fluctuating steam pressure. Range 0.03–0.1 kg/s condensate. Size on 2 × usual flowrate of condensate.

Thermodynamic/kinetic energy: intermittent, operating principle is Bernoulli's principle/impulse, poor air handling, larger sizes more susceptible to back pressure. Usually for steam pressure < 1.2 MPa but > 0.06 MPa. Affected by ambient temperature. Discharge pressure < 0.5 steam pressure. Range 0.06–0.3 kg/s. Size on 3–4 × usual flowrate of condensate.

Select inverted bucket traps based on condensate flowrate, pressure differential and “safety factor allowance” for variations from “usual” condensate flowrate.

- *Good Practice*

Install a demister.

- *Trouble Shooting*

Knock out pots: *“Poor separation”:* [foaming]*/insufficient residence time/feed and exit nozzles at wrong location/faulty design.
*[Foaming]**: liquid downflow velocity through the foam is too low, Turner (1999). A general set of causes is given in Section 1.12.
Steam traps: install trap below condensate exit (or with a water seal if the trap is elevated), use a strainer before all traps, use a check valve for bucket traps. Slant pipes to the trap. Use a downstream check valve for each trap discharging to a common header. Pipe diameter $\geq$ trap inlet pipe diameter. Prefer to install auxiliary trap in parallel instead of a bypass. Do not group thermodynamic traps because of their sensitivity to downstream conditions.

Float and thermostatic: usually discharges continuously, low pitched bubbling noise. High pitch noise suggests live steam is blowing.

Balanced thermostatic: leave about 0.6 m of uninsulated pipe upstream of trap. Diagnostics: when bellows placed in boiling water the expansion should be 3 mm.

Inverted bucket: use initial prime to prevent steam blowing. Prime a bucket trap when first put on-line. Diagnostics sounds: when it is functioning well: loud initially, then lower pitch bubbling and then silence. Discontinuous discharge. When steam is blowing through the trap, the sound is a steady bubbling if primed with a light load or constant rattling; or continuous high pitched whistling. Diagnostic for loss of prime: close outlet valve for several minutes, then open valve slowly and operation should return to normal. If this fails then check seat and valve.

Thermodynamic: about 6 cycles/minute.

- *Trouble Shooting*

The major faults are wrong trap, dirt, steam locking in the trap, group trapping, air binding and water hammer. Too large a trap gives sluggish response and wastes steam. Too small a trap gives poor drainage, backup of condensate. There is a ΔT across all traps. *“No condensate discharge”*: strainer or line plugged/steam off/valves plugged/no water or steam to the trap/trap clogged/wrong trap selected/worn orifice/steam pressure too high (inverted bucket)/orifice enlarged by erosion (bucket trap)/incorrect Δp across the orifice (inverted bucket)/air vent clogged (inverted bucket or thermostatic air vent on float trap)/valve seat choked (inverted bucket)/flabby or elongated bellows (thermostatic)/superheated steam caused burst joints or scale (thermostatic). *“Cold trap + no condensate discharge”*: strainer or line plugged/steam off/valves plugged/no water or steam to the trap/trap clogged. *“Hot trap + no condensate discharge”*: bypass open or leaking/trap installed at high elevation/broken syphon/vacuum in heater coils/pressure too high (inverted bucket)/orifice too large (inverted bucket)/vent hole plugged (inverted bucket)/defective trap parts (inverted bucket)/clogged orifice (thermodynamic). *"Live steam blowing, and inlet and exit temperatures are equal":* bypass open or leaking/worn trap components/scale in orifice/valve fails to seat/trap lost prime (inverted bucket)/sudden drops in pressure/[backpressure too high]* (thermodynamic)/faulty air release (float)/trap too large (thermodynamic). *"Continuous discharge when it should be discontinuous":* trap too small/dirt in trap/high pressure trap installed incorrectly for low pressure service (bucket trap)/valve seat clogged with dirt/excessive water in the steam/bellow overstressed (thermostatic)/one trap serves > one unit/strainer clogged. *"OK when discharging to the atmosphere but not when to a backpressure condensate header":* condensate line diameter too small/wrong orifice/interaction with other traps connected to a common header/condensate line partially plugged/[backpressure too high]*. *"Slow and uneven heating of upstream equipment":* trap too small/insufficient air handling capacity/short circuiting when units are group trapped. *"Inverted bucket trap loses prime:"* sudden drop in pressure/faulty seat/faulty valve. "*Upstream process cycling":* defective float/multiple sources of condensate to a single trap/trap flooded from condensate header/condensate discharged into the bottom of the condensate header/Δp across the orifice is incorrect for the orifice (inverted bucket). *"Discontinuous discharge when it should be continuous":* defective float/load too small.

*[Back pressure too high and trap is hot]**: return line too small/other traps blowing steam/obstruction in return line/bypass open/pressure in header too high.

*[Back pressure too high and trap is cold]**: obstruction in return line/excess vacuum in return line.

5.2
Gas–Solid

- *Area of Application*

"Fumes" are particles < 1 μm.

In general: use cyclones and settling basins for solids loading > 20 g/m^3. Then, select bag filters unless fumes are also present, low temperatures (< 100 °C for natural fibers; < 300 °C for synthetic glass), non-corrosive conditions and not close to the dew point. Select scrubbers if fumes present. For high temperatures consider electrostatic precipitators. Design can be "high efficiency" or "standard" with mass collection efficiency decreasing as size of target particle decreases.

Dry cyclone: dust diameter 10 to 1000 μm; feed concentration 5 to 75 g/m^3; temperature < 400 °C; gas phase Δp = 0.2 to 1.6 kPa. mass collection efficiency 50 %; power usage 0.8 to 20 kW/m^3/s.

Settling basin: dust diameter > 100 μm; feed concentration 2 to 75 g/m^3; temperature < 400 °C; gas phase Δp = 3 to 7 kPa; power usage 0.04 to 0.7 kW/m^3/s.

Bag filter: very efficient removal of small diameter and small particle loadings; dust diameter 0.5 to 70 μm; feed concentration 0.01 to 100 g/m^3; temperature

$< 100\,°C$ for natural fibers and $< 300\,°C$; gas phase $\Delta p = 0.5$ to 1 kPa; power usage 0.8 to 30 kW/m^3/s.

Wet cyclone: dust diameter 0.75 to 10 μm; feed concentration 5 to 75 g/m^3; temperature $< 100\,°C$; gas phase $\Delta p = 0.5$ to 1 kPa; power usage 0.8 to 20 kW/m^3/s.

Cross flow scrubber: dust diameter > 3 μm; feed concentration < 10 g/m^3; temperature $< 100\,°C$; gas phase $\Delta p = 0.2$ to 1.6 kPa.

Wet scrubbers: countercurrent wet packing: dust diameter 0.2 to 3 μm; feed concentration < 0.1 g/m^3; temperature $< 100\,°C$; gas phase $\Delta p = 1.25$ to 6 kPa.

Turbulent bed contactor: [see also Section 4.8 absorber] temperature $< 100\,°C$; OK for heavy sticky particles; allows high gas and liquid flowrates with high mass transfer efficiencies for gas absorption; 1 to 2 μm; 2.5 to 20 kW s/m^3.

Venturi scrubbers: dust diameter 0.02 to 3 μm; feed concentration 0.1 to 20 g/m^3; temperature $< 100\,°C$; gas phase $\Delta p = 1.25$ to 6 kPa; mass collection efficiency 99 %; power usage 3 to 40 kW/m^3/s.

Low voltage electrostatic precipitator: dust diameter 1 to 100 μm and conducting particles; feed concentration < 30 g/m^3; temperature $< 800\,°C$; gas phase $\Delta p =$ 0.02 to 0.1 kPa; power usage 0.04 to 0.7 kW/m^3/s. Mass collection efficiency 5 % increasing to 90 % as the particle size increase from 0.01 to 5 μm.

High voltage electrostatic precipitator: dust diameter 0.01 to 5 μm and conducting particles; feed concentration < 25 g/m^3; with pressures < 7 MPa and temperature $< 800\,°C$; gas phase $\Delta p = 0.02$ to 0.1 kPa; mass collection efficiency 99.5 %; power usage 0.04 to 0.7 kW/m^3/s. Gas velocity 0.3–5 m/s across the face of the collecting surface. One high voltage system/2500 m^2 collecting surface. 30–100 kV DC. High initial capital investment.

Afterburners: dust diameter < 0.1 μm; combustible; feed concentration < 0.1 g/m^3

SO_2 scrubbers (double alkali, Catox, Tyco): power usage 30 to 40 kW/m^3/s

- *Guidelines*

Start with a cost correlation based on gas flowrate.

Dry cyclone: size based on an inlet gas velocity based on the particle loading:

for particle loadings of < 7 g/m^3 use inlet gas velocity of 11 to 23 m/s to size inlet nozzle and then scale configuration from this dimension.

– loadings of 10 g/m^3 use 20 m/s
– loadings of 100 g/m^3 use 10 m/s
– loadings of 1000 g/m^3 use 5 m/s
– loadings of 10 000 g/m^3 use 1.8 m/s

Gravity settler: 5 to 7 m/s at inlet baffle; but the gas superficial velocity should be < 3 m/s to avoid re-entrainment.

Bag filter: Batch: load cycle and clean: intermittent shaking, reverse pulse, reverse blow ring or sonic cleaning. Load filter until the gas pressure drop across the filter < 1.5 kPa; then clean. Choice of fabric is critical: static charge on fabric, operating temperature, potential for fumes to absorb with moisture to deteriorate bag and need to select dust removal option to keep the Δp across the bag at 0.5 to 1.5 kPa. Felted material gives higher gas flowrate per unit area than woven, costs 3–4 times more and cannot be cleaned by shaking. Gas to cloth ratio of 25 to

150 $dm^3/s\ m^2$ but usually design on $< 75\ dm^3/s\ m^2$. Usual range for woven fabric 7.5 to 50 $dm^3/s\ m^2$; for felted fabric use 7.5–100 $dm^3/s\ m^2$; for microporous tubes use 9–20 $dm^3/s\ m^2$. Gas loading depends on density of particles, size, inlet dust concentration, type of fabric. Batchwise loading with dust removal by reverse jet or blowring is about 0.04 kW/m^2 of bag area. Bag length:diameter $< 33:1$.

Wet scrubbers: limited to lower temperatures $< 100\,°C$.

Wet cyclone: size on internal superficial gas velocity of 1 m/s; height to diameter of 3:1 and water usage of 0.4 L/m^3; water flowrate 1.3 to 2.5 L/m^2 s.

Cross flow packed scrubber: $\Delta p = 0.3$ kPa/m of width; 1 to 1.5 m width usual; water flowrate 2.7 L/m^2 s of horizontal cross-sectional packing; size on actual inlet gas flowrate to the packing face of 1 m^3/m^2 s.

Countercurrent wet packing: pressure drop 0.3 to 0.5 kPa/m of packing. Liquid loading about 0.4 L/m^3 gas or 0.6 to 1 L/s m^2; superficial gas velocity 0.5 to 1 m/s; mass loading liquid/gas = 0.7–1.5.

Turbulent bed contactor: Liquid loadings 20 L/m^2 s; superficial gas velocity based on actual inlet gas flowrate 2 to 11 $m^3/s\ m^2$ horizontal cross section; mass loading liquid/gas = 4–8. Related topics fluidized bed, drying Section 5.5; reactors, Section 6.30.

Venturi scrubbers: size on throat velocity of 15 to 150 m/s selected based on particle size to be removed with 40 m/s (and 25 kPa pressure drop) for 1 μm and 120 m/s (and 25 kPa) for 0.1 μm. Water usage is in the range 0.5 to 5 L/m^3 gas with pressure drop increasing as throat velocity increases; mass loading liquid/gas = 1.3–1.6.

Wet impingement baffle (Peabody) scrubbers: height/diameter 1.3:1 to 4.6:1; liquid loading 1 to 2 L/m^2 s of horizontal cross-sectional area; mass loading liquid/gas = 0.2–0.7.

Electrostatic precipitator: Batch process: load electrodes then clean: via wet spray or mechanical rapping. For particle conductivity between 10^{-8} and 0.01 Ω^{-1} m. Prefer negatively charged configuration. May need to adjust conditions to get particle conductivity into acceptable range.

Particles > 10 μm use 38 m^2 plate area per m^3/s gas flow, 1 μm use 100 m^2 plate area per m^3/s gas flow, 0.4 μm use 120 m^2 plate area per m^3/s gas flow.

- *Good Practice*

Bag filters: Replace a complete set of bag filters annually. Install a bypass. Limit the number of parallel rows of bags on either side of the walkway to 3–4 rows for 20 cm diameter bags and 2–3 rows for 30 cm diameter bags. For cleaning, use 0.5–0.7 kPa clean, dry air with an air:cloth ratio of 2:1 for reverse jet and 2.5:1 for shaking.

- *Trouble Shooting*

Bag filters: *"Excessive particle emissions":* cleaning too often/pressure used to clean it too high/bag breaks/gas temperature too high and particles crust on movable blowrings and tear bag. *"Δp across bags > design":* faulty cleaning/improper bag tension/excessive moisture causing blinding/poor air distribution/hopper plugged, see Section 10.3/gas velocity > design. *"Short bag life":* excessive cleaning/high inlet gas velocity/fines > design/blinding because of condensation, improper cleaning, excessive dust load or high cake density.

Dry cyclone: *"Increase in catalyst losses":* [poor separation in cyclone]*. *"Opaque flue gas from the vessel":* [poor separation in cyclone]*. *"Particulate carry over that affects operation of downstream equipment":* [poor separation in cyclone]*. *[Poor separation in cyclone]*:* [stuck or failed trickle valve]*/[plugged dipleg]*/[dipleg unsealed]*/gas velocity into cyclone too low or too high/faulty design of cyclone/solids concentration in feed too high/cyclone volute plugged/hole in cyclone body/pressure surges/[change in size of particles in feed]*.*[Plugged dipleg]*:* spalled refractory plug/level of catalyst in bed too high/Δp indicator for catalyst level faulty/Δp indicator for catalyst level OK but bed density incorrect. Air out periods with a lot of water or steam in vessel. *[Change in size of particles in the feed]*:* [generation of fines]*/[coarse particles]*. *[Generation of fines]*:* [attrition of the catalyst]*/fines in the new catalyst. *[Attrition of the particles]*:* local velocities upstream of cyclone > 60 m/s/particle too fragile. *[Dipleg unsealed]*:* solids level does not cover end of dipleg/Δp indicator for catalyst level faulty/Δp indicator for catalyst level OK but bed density incorrect.

[Stuck or failed trickle valve]:* binding of hinge rings/angle incorrect/wrong material/hinged flapper plate stuck open/flapper plate missing. *[Coarse particles (diameter > design)]*:* agglomeration of catalyst/[sintered particles]*/wrong specifications for catalyst. *[Sintered particles]*:* high temperature upstream/[temperature hot spots in the upstream reactor]*. *[Plugged grid holes]**: foreign debris entering with fresh catalyst/faulty grid design.

"Temperature hot spots in upstream reactor": [maldistribution]*/local exothermic reactions.

5.3
Liquid–Liquid

Estimation of dispersed drop size: Usual drop size 200 μm; interfacial tension 30 mN/m. Primary dispersions for drop diameters > 100 μm. Secondary dispersion if the drop diameter < 1 μm.

The fundamentals are as follows. For immiscible *liquids flowing in turbulent flow in a pipe* of diameter, D, the dispersed phase breaks up into drops with the diameter of the maximum (or 95th percentile) size drop predicted as follows: $(D_{p,95}/D) = 4\,[1/\mathrm{We}]^{0.6}$ where We = Weber number. Since most drop size distributions are geometrically distributed and since the geometric standard deviation is about 2, the geometric mass average is about 30 % of the $D_{p,95}$. Thus, the average size drop would be 300 μm if the predicted $D_{p,95} = 1000$ μm.

When drops encounter shear or turbulence different from turbulent flow in a pipe, such as flow across a valve, or a rotating impeller in a pump, then (for interfacial surface tension of 30 mN/m), the following are typical drop size distributions: from a *reciprocating pump* pumping an oil water mixture will produce a dispersion with geometric mass average = 1000 μm with geometric std. deviation of 3.5; from a *centrifugal pump,* 200 μm [3.5]; *Δp across a valve,* 400 μm [2.2]; and *in-line mixer,* 200 μm [1.75].

The general characteristics of dispersions from different sources:

static mixers, flash drums: 100–100 μm; solvent extraction units, mechanically agitated systems: 20–300 μm; high Δ*p* across a valve, steam stripper bottoms, caustic wash drums: 10–400 μm; systems with interfacial tension < 10 mN/m or containing surfactant systems or secondary coalescence: 0.1–25 μm.

- *Area of Application*

For primary dispersions.

Decanter: drop diameter > 100 μm; feed concentration > 2 % v/v. Related topics where decanters are used include three phase separation, see gas–liquid–liquid separation, see Section 5.4; solvent extraction, see Section 4.10; azeotropic and extractive distillation, see Section 4.2; liquid–liquid CSTR reactions (such as alkylation), see Section 6.29.

Hydrocyclone: drop diameter > 20 μm; feed concentration 6 to 60 % v/v. Interfacial tension must be > 10 mN/m to prevent drop breakup.

Sedimentation centrifuge: Disc type: drop diameter > 20 and < 200 μm; feed concentration 6 to 60 % v/v; suited for low surface tension, density differences > 0.02 Mg/m^3. Solids contamination < 0.1 % v/v. Use differential type for drop diameter > 200 μm; feed concentration 6 to 60 % v/v; suited for low surface tension, density differences > 0.05 Mg/m^3. Solids contamination < 0.1 % v/v.

Electrodecanter: drop diameter 9 to 500 μm; feed concentration 0.8 to 8 % v/v.

Fibrous bed coalescer: drop diameter 3 to 75 μm; feed concentration < 3 % v/v. see size enlargement Section 9.2.

API separator: drop diameter > 75 μm; feed concentration 0.015 to 3 % v/v.

Dissolved air flotation: drop diameter > 8 μm; feed concentration 0.005 to 0.015 % v/v and drop diameter < 8 μm; feed concentration 0.0075 to 0.1 % v/v. see Section 5.16.

Coagulation/flocculation: drop diameter > 8 μm; feed concentration 0.005 to 0.015 % v/v and drop diameter < 8 μm; feed concentration 0.0001 to 20 % v/v. See size enlargement, Section 9.3.

Deep bed filtration: drop diameter > 8 μm; feed concentration 0.0002 to 0.005 % v/v and drop diameter < 8 μm; feed concentration 0.002 to 0.05 % v/v. see Filters, Section 5.14.

Solvent extraction: drop diameter 0.1 to 1 μm; feed concentration 0.001 to 10 % v/v. see Section 4.10.

5.3.1
Decanter

- *Guidelines*

Ill-behaved dispersions usually drift with time; are sensitive to incoming drop-diameter distribution and to upstream energy input. Examples include most systems with kerosene-based immiscible systems.

First approximation: allow 20 min residence time or total overflow velocity of 0.35 L/s m^2.

Feed concentration $<$ *10% v/v.* Size as sedimentation-controlled provided surfactants and contamination negligible and mixture is not "ill-behaved." Use overflow total flowrate velocity of 0.5 to 3 L/s m^2 based on horizontal cross-sectional area with a usual value of 1.4 L/s m^2. This is for a horizontal cylinder with length to diameter ratios of 3.5. Allow both phases to have $>$ 20% of the diameter and no less than 0.2 m to ensure that the exit phases do not become cross-contaminated. For process control the minimum distance between the high and low levels of the interface should be 0.36 m or at least 2 min residence time.

Feed concentration $>$ *10% v/v, or contamination present or ill-behaved.* Size as coalescence- controlled. For vertical decanters, allow a total residence time that depends on density difference and interfacial surface tension. For a typical 0.5 m height of coalescent band (or a decanter of 0.7 m height), use an overflow total flowrate velocity of 1.5 $(\Delta\varrho/0.1)^{0.5}$ L/s m^2 where the density difference is in units of Mg/m^3 to determine the horizontal cross-sectional area. For horizontal configurations, use half of the vertical overflow velocity.

Surface area versus volume: for **rectangular** vessels of length, depth and width, L:D:W = 10:0.5:1 the area = 40 m^2 for a volume = 40 m^3 with $n = 0.65$ for volumes 5–40 and $n = 0.51$ for volumes 40–1500 m^3. L:D:W = 2:1:1 the area = 15 m^2 for a volume = 40 m^3 with $n = 0.65$ for volumes 1–300 m^3. Factor, L:D:W = 1:1:1, × 0.75. Where $\text{area}_1 = \text{area}_2\ (\text{volume}_1/\text{volume}_2)^n$.

Surface area versus volume: for vertical **cylindrical** vessels of length, and diameter: L:D = 5:1, the area = 3 m^2 for a volume = 30 m^3 with $n = 0.65$ for volumes 1–400 m^3. Factors, L:D = 5:1, × 1.00; L:D = 3:1, × 1.4; L:D = 1:1, × 3.2. For horizontal **cylindrical** vessels of length, and diameter: L:D = 5:1 the area at the centerline = 14 m^2 for a volume = 30 m^3 with $n = 0.49$ for volumes 2–200 m^3. Factors, L:D = 5:1, × 1.00; L:D = 3.5:1, × 0.82.

Can add parallel plates or high and low energy combination coalescer promoters (see Section 9.2).

- *Good Practice*

Contamination can interfere with the operation. Traditionally this contamination is surfactants, or particulates. The particulates can be corrosion products, amphoteric precipitates of aluminum or iron. Try changing the pH of the water to alter the surface charge on the dispersed drops. The separation capacity of a settler/decanter doubles for every 20 °C increase in temperature. Caution, if, to ease this separation, the temperature is increased, such an increase in temperature will increase the bulk phase contamination because of the increased cross-contamination by the mutual solubility.

- *Trouble Shooting*

"Entrained droplets in liquid effluent": sensor error/sampling error (immiscible drops are not being entrained)/faulty design of separator/improper cleaning of vessel after shutdown, e.g., rust left in vessel/pressure fluctuation/pressure too low causing flashing/[inaccurate sensing of interface]*/[drop doesn't settle]*/[drop settles and coalesces but is re-entrained]*/[drop settles but doesn't coalesce]*/[stable emulsion formation]*.
"Fluctuation in liquid level": no vacuum break on syphon line for bottoms/level sensor error/poorly tuned controller/surges in feed.
[Coalescer pads ineffective]:* temperature too hot/pH incorrect/fibers have the same charge as the droplets/surface tension negative system/wetting properties of fibers changed/fibers "weathered" and need to be replaced/flowrate too slow through fibers/wrong mix of fibers/prefiltering ineffective/surface tension < 1 mN/m for fluoropolymer fibers or < 20 mN/m for usual fibers/wrong design/included in decanter but should be separate horizontal coalescer promoter unit/faulty design. See Section 9.2.
[Density difference decrease]:* dilution of the dense phase/reactions that dilute the dense phase; for **sulfuric acid alkylation:** if acid strength $< 85\%$ w/w the olefins polymerize with subsequent oxidation of the polymers by sulfuric acid as a self-perpetuating continuing decrease in acid strength. Alkylate–acid separation is extremely difficult when acid concentration is 40 % w/w.
[Drop doesn't settle]:* [density difference decrease]*/[viscosity of the continuous phase increases]*/[drop size decreases]*/[residence time for settling too short]*/[phase inversion or wrong liquid is the continuous phase]*/pressure too low causing flashing and bubble formation.
[Drop settles and coalesces but is re-entrained]:* faulty location of exit nozzles for liquid phases/distance between exit nozzle and interface is < 0.2 m/overflow baffle corroded and failure/interface level at the wrong location/faulty control of interface/liquid exit velocities too high/vortex breaker missing or faulty on underflow line/no syphon break on underflow line/liquid exit velocities too high.
[Drop settles but doesn't coalesce]:* [phase inversion]*/pH far from zpc/surfactants, particulates or polymers present/electrolyte concentration in the continuous phase < expected/[coalescer pads ineffective]*/[drop size decrease]*/[secondary haze forms]*/[stable emulsion formation]*/[interfacial tension too low]*/[Marangoni effect]*.
[Drop size decrease]:* feed distributor plugged/feed velocity > expected/feed flows puncture interface/local turbulence/distributor orifice velocity > design; **for amine units:** for amine > 0.8 m/s; for hydrocarbon > 0.4 m/s/[Marangoni effects]*/upstream pump generates small drops/[secondary haze forms]*/poor design of feed distributor.
[Inaccurate sensing of the interface]:* instrument fault/plugged site glass.

[Interfacial tension too small]:* temperature too high/[surfactants present]* at interface.

[Marangoni effects]:* nonequilibrated phases/local mass transfer leads to local changes in surface tension and stability analysis yields stable interfacial movement.

[Phase inversion]:* faulty startup/walls and internals preferentially wetted by the dispersed phase.

[Rag buildup]:* collection of material at the interface: [surfactants present]*/particulates: example, products of [corrosion see Section 1.3]*, amphoteric precipitates of aluminum/naturally occurring or synthetic polymers.

[Residence time for settling too short]:* interface height of the continuous phase decreases/[inaccurate sensing of interface]*/turbulence in the continuous phase/flowrate in continuous phase $>$ expected; for example $>$ 3 L/s m^2/sludge settles and reduces effective height of continuous phase/[phase inversion]*/inlet conditions faulty.

[Secondary haze forms]:* small secondary drops are left behind when larger drop coalesces, need coalescer promoter, see Section 9.2.

[Stable emulsion formation]:* [surfactants present]*/contamination by particulates: example, products of [corrosion products. see Section 1.3]*, amphoteric precipitates of aluminum or iron/pH far from the zpc/contamination by polymers/temperature change/decrease in electrolyte concentration/the dispersed phase does not preferentially wet the materials of construction/coalescence -promoter malfunctioning/improper cleaning during shutdown/[rag buildup]*.

[Surfactants present]:* formed by reactions/enter with feed, example oils, hydrocarbons $>$ C10, asphaltenes/left over from shutdown, example soaps and detergents/enter with the water, example natural biological species, trace detergents.

*[Viscosity of the continuous phase increases]**: temperature too low, for **alkylate–acid** separation, temperature $<$ 4.4 °C/[phase inversion]*/contamination in the continuous phase/unexpected reaction in the continuous phase causing viscosity increase.

5.3.2
Hydrocyclone

Design using same principles as liquid-solid hydrocyclone, Section 5.9. For flooded underflow, the pressure drop is about 2 to 7 times greater than air-core operation.

5.3.3
Sedimentation Centrifuge

Disc type: (Westfalia, Alfa-Laval, Robatel) continuous: Centrifugal field about 10^4 g and 100 rps with residence times of 1 to 10 s. Power 3 to 10 kW s/L of feed.

Differential type: (Podbielniak; Quadronic) continuous: Centrifugal field about 500 g and 25 rps with about 10 to 75 s residence time. Power 1 kW s/L.

5.4
Gas–Liquid–Liquid Separators

- *Area of Application*

Horizontal drum: Separates gas, oil and water; as for example as an early separation of natural gas upstream of drying or to handle sour water. Typically a relatively small load of hydrocarbon. Often called a "flash drum".

Often follow the flash drum with a storage tank to allow further separation of water and hydrocarbon.

- *Guidelines*

Size of dispersed liquid phase is given in Section 5.3. Horizontal cylindrical vessel with allowance for 20 min residence time for the water phase. Keep liquid velocity < 10 L/s m^2. Carefully size the inlet distributor for the liquid so that inlet velocity is < 0.4 m/s.

If some hydrocarbon is heavier than water, then include a boot. For more, see Section 5.3.1, decanter design, and Section 5.1, horizontal knockout pots. Include a vortex breaker and demister.

For downstream buffer tank, design for 3–5 day residence time and provide gentle mixing to prevent stratification and fresh feed bypassing directly to the exit nozzle. Example horizontal cross-sectional area versus volume is given in decanters, Section 5.3.1.

- *Good Practice*

Contamination from naturally occurring or synthetic surfactants or polymers, or corrosion products from upstream processing can cause stable foam or emulsion formation.

- *Trouble Shooting*

"Entrained liquid in overhead gas": sensor error/[entrainment: GL]*. *"Incomplete separation of oil from water":* faulty design of separator/residence time of liquid phases too short/liquid velocity in the decant phases too fast/Marangoni instabilities/liquid feed velocity too fast/poor distribution of liquid feeds/faulty location of exit nozzles for liquid phases/overflow baffle corroded and failure/interface level at the wrong location/faulty control of interface/no vortex breaker at water and heavy oil exit nozzles/liquid exit velocities too high/[emulsification]*.
"Poor separation": level control fault/phase velocities too high/contaminant gives stable dispersion/smaller drop size than design/rag formation/temperature change/pH change/decrease in electrolyte concentration. See Sections 5.1 and 5.3.1 for more details.
[Entrainment: GL]:* vessel diameter too small for gas flow/no demister or demister malfunctioning/vessel pressure $<$ design/[foaming]*/inlet liquid line or distributor undersized or plugged.
[Entrainment: L–L]:* liquid velocity too high; example > 10 L/s m^2/liquid distributor orifice velocity $>$ design; **for amine:** for amine > 0.8 m/s; for hydrocarbon

$>$ 0.4 m/s/faulty location of exit nozzles/interface level wrong location/faulty control of interface/no vortex breaker/exit fluid velocities $>$ design/insufficient residence time/[stable emulsion formation]*.
[Foaming]:* see Section 1.12 for generic causes.
[Stable emulsion formation]:* see Section 1.12 for generic causes; Section 5.3.1 for more specific causes.

The dispersed phase should not preferentially wet the materials of construction. If unexpected rapid coalescence occurs, suspect Marangoni effects and change the dispersed phase. Treat the buildup of the "rag" at the interfaces based on the cause: corrosion products or stabilizing particulates, surfactants, or amphoteric precipitates of aluminum or iron. Consider adjusting the pH. Solid particles tend to accumulate at the liquid–liquid interface.
For column extractors: "*Decrease in extraction efficiency*": agitator speed to fast/excessive backmixing/[flooding]*.
*[Flooding]**: agitator speed too fast/feed sparging velocity too high/drop diameter smaller than design.

5.5
Liquid–Solid: General Selection

Effect of particle diameter and solid concentration on the choice: For particle diameter greater than 1000 μm and solid concentration $>$ 3 %, use screens, Section 5.7.

For particle diameter less than 2 cm and $>$ 5 μm and solid concentration 1 to 50 %, consider settlers, filters or centrifuges.

For particle diameter less than 300 μm and solid feed concentration 0.01 to 20 %, consider thickeners, Section 5.10.

For particle diameter greater than 20 μm and solid feed concentration greater than 50 %, consider dryers, Section 5.6.

For particle diameter 0.01 to 150 μm, consider deep bed filter, Section 5.14 or dissolved air flotation, Section 5.16.

For particle diameter 0.6 to 40 μm and solids concentration $<$ 0.1 %, consider homogeneous separation via ultrafiltration, Section 4.22.

For particle diameters from 0.8 to 20 μm consider using a filter aid to precoat on the filter medium. For example, use diatomous earth or perlite. A *fine* filter aid is 8 to 20 μm diameter to give a precoat bed of permeability 0.05 to 0.5 μm^2; a *medium* filter aid is 30 to 60 μm diameter to give a precoat bed of permeability 1 to 2 μm^2; a *coarse* filter aid is 70 to 100 μm diameter to give a precoat bed of permeability 4 to 5 μm^2.

For particle diameter less 1 μm, consider size increase via coagulation/flocculation, Section 9.3. An example coagulant is starch.
Effect of recovery on the choice: To recover liquid: in the order of preference of **filters**, Section 5.14 and **filtering centrifuges**, Section 5.13: deep bed, horizontal vacuum, pressure leaf, gravity flat table; cartridge, precoat drum and plate and

frame, or vertical basket filtering centrifuge. For high fluid viscosity use plate and frame or horizontal filtering cone centrifuge.

To recover liquid: in order of preference of **settlers**, Section 5.8, **thickeners**, Section 5.10 and **sedimentation centrifuges**, Section 5.12: clarifier, settler, washing tray thickener, reactor-clarifier, hydrocyclone, batch tubular bowl centrifuge, batch automatic (horizontal or vertical bowl, disc with intermittent nozzle discharge); continuous disc bowl centrifuge with nozzle discharge.

To recover liquid and solids: in order of preference of **filters:** expellers and presses, Section 5.17.

To recover liquid and solids: in order of preference of **settlers**, Section 5.8, **CCD,** Section 5.11 and **sedimentation centrifuges**, Section 5.12: continuous countercurrent decanter circuit CCD, horizontal solid bowl centrifuge with scroll discharge.

To recover solids: in order of preference of **filters:** Requiring good washing: pressure, vacuum, gravity table/pan, horizontal pressure or vacuum, horizontal belt, vacuum drum, cylindrical screen scroll discharge filtering centrifuge and plate and frame. Requiring good washing and the crystals break easily: gravity, vacuum table/pan; vacuum, pressure, gravity drum and plate and frame.

If the cake is compressible use low pressure < 200 kPa or vacuum rotary drum. For dry solids: consider the following **filtering centrifuges,** Section 5.13: basket, basket automatic constant speed vertical, basket automatic variable speed horizontal; continuous conical with scroll conveyor, oscillating conical screen; cylindrical screen with pusher conveyor or horizontal solid-screen scroll conveyor.

To recover solids: in order of preference of **thickeners,** Section 5.10 and **sedimentation centrifuges,** Section 5.12: thickeners, deep thickener, rake thickener and tray thickener or hydrocyclone, batch automatic solid bowl centrifuge, continuous conical bowl centrifuge, continuous contour bowl vertical or horizontal centrifuge.

5.6
Dryers

Use when the goal is solid recovery. Related topics: screens, Section 5.7, centrifugal filters, Section 5.13, and dewatering expellers, Section 5.17.

- *Area of Application*

Particle diameter 20 μm to 1 cm; feed solid concentration $> 50\,\%$ solids. Liquid contamination in exit solids 0 to 20 % v/v liquid. Use batch for < 40 g/s; use continuous for > 280 g/s. Select initially on temperature sensitivity. Prefer "adiabatic" over conduction. For temperature sensitivity the classes are: *extremely sensitive,* usual drying temperature is $< 5\,°C$; *very sensitive,* drying temperature = 5–10 °C; *sensitive,* drying temperature = 10–40 °C; *moderate,* drying temperature = 40–100 °C; *insensitive,* drying temperature = 100–150 °C. Examples of *moderately sensitive* include PVC, dyes, pharmaceuticals (typical inlet temperature = 150 °C with exit temperature → 75 °C); foods (175 → 80 °C); pigments (320 → 90 °C).

Examples of *insensitive* include sulfonates (215 → 95 °C); clay (600 → 120 °C); TiO_2 (550 → 100 °C); ceramics (300 → 120 °C).

– *Indirect conduction options:* (nonadiabatic) for temperature sensitive, very sensitive and extremely sensitive solids [$T < 40\,°C$].

Batch:

Tray/shelf: jacketed, atmos. or vacuum (conduction) batch, feed: thin or thick liquids, soft or stiff pastes, moist crumb, grains (> 150 μm) and grits (< 150 μm). Product: solid cake

Pan, agitated: atmos. or vacuum (conduction) batch, feed: thin or thick liquids, soft or stiff pastes, moist crumb, grains (> 150 μm) and grits (< 150 μm). Product: solid cake.

Rotary indirect (steam or hot fluid) atmos. or vacuum(conduction): batch feed: moist crumb, grains (> 150 μm) and grits (< 150 μm). For heat sensitive, free flowing or pasty feed. Dries in < 60 min. Product: crumb/powder.

Cone/double cone, jacketed, atmos. or vacuum (conduction): batch, feed: sticky, fine, moist crumb, grains (> 150 μm), grits (< 150 μm). Product: crumb.

Freeze, batch, atmos. or usually vacuum (conduction): batch, feed: thin or thick liquids, soft or stiff pastes, moist crumb, grains (> 150 μm), coherent sheets, discontinuous sheets.

Dielectric: feed: thin or thick liquids, soft or stiff pastes, moist crumb, grains (> 150 μm) and grits (< 150 m).

Continuous:

Drum dryer, atmos. or vacuum (conduction): feed: thin or thick liquids, soft and stiff pastes, wet paper. Dries in 2–30 s. Product: flakes, dry sheet.

Screw, jacketed, atmos. or vacuum (conduction): feed: sticky, fine, moist crumb, grains (> 150 μm), grits (< 150 μm). Product: crumb.

Conveyor, (band) jacketed, atmos, or vacuum (conduction): feed: sticky, fine, moist crumb, grains (> 150 μm), grits (< 150 μm). Product: crumb.

– *Indirect convection options:* for moderately temperature sensitive, sensitive and very sensitive solids [$5 < T < 100\,°C$]. Indirect heating means heat source temperature < 200 °C.

Batch:

Tray/shelf, **cross flow** (indirect convection): batch, feed: soft paste, preform, hard-paste, granular, fragile particles, fibrous, discontinuous sheets and shaped pieces.

Tray/shelf, through flow (indirect convection): batch, feed: preform, granular, fibrous.

Open sand bed (natural convection): batch feed of waste water sludge.

Continuous:

Spray (indirect convection): feed: thin liquids and slurries. Dries in 1–10 s. Product: 1–300 μm powder.

Flash/transported (indirect convection): feed: preformed paste, granular, fibrous solids. Dries in 0.5–3 s. Product: powder. Particle diameter < 2 mm.

Fluidized bed (indirect convection): feed: soft paste, sludge, preformed paste, granular, fibrous solids. Product: powder. Particle size 0.05–15 mm but usually 40–100 μm.

Tray/shelf continuous, (Turbo) (indirect convection): feed: soft paste, preform, granular, fibrous. Product: solid cake.

Desolventizer: feed: leached vegetable seeds contaminated with solvent (such as hexane). Product: solvent-free cake.

Tunnel/truck continuous (indirect convection): feed: grains (> 150 μm), discontinuous sheets and shaped pieces, soft paste, preform, granular, fibrous. Product: solid cake.

Belt, through flow, continuous (indirect convection): grains (> 150 μm), discontinuous sheets and shaped pieces.

Rotary, continuous (including steam tube) (indirect convection): feed: hard, granular, fibrous. Dries in < 60 min. < 50 kg/s/unit.

– *Direct convection options* (adiabatic) for temperature sensitive, moderately sensitive and insensitive solids [$10 < T < 150\,°\mathrm{C}$]. Insensitive materials include sulfonates ($215 \rightarrow 95$); clay ($600 \rightarrow 120$), titanium dioxide ($550 \rightarrow 100$); ceramics ($300 \rightarrow 135$).

Options similar to *Indirect convection* but hotter gases are used: fluidized bed, rotary kiln, bands/belts and open bed with specialized option **hopper dryer for polymer feed to extruder**.

- *Guidelines*

Indirect conduction at reduced pressure: evaporative capacity 42 to 5 g water/s m^2 as moisture goes from 0.5 to 0.015 kg water/kg dry solids.

Convection with hot gas through the bed: evaporative capacity 1.2 to 0.25 g water/s m^2 as moisture goes from 0.9 to 0.025 kg water/kg dry solids.

Convection plus radiation: evaporative capacity 0.8 to 0.15 g water/s. m^2 as moisture goes from 0.9 to 0.025 kg water/kg dry solids.

Solutions of salts: Overall heat transfer coefficient: $U = 0.12–0.35$ kW/m^2 °C.

Slurries, powders and granules: Overall heat transfer coefficient: $U = 0.03–0.23$ kW/m^2 °C.

– *Indirect conduction options:*

Batch: size on cycle time: load, dry, discharge, clean.

Tray/shelf, jacketed, batch, atmos. (conduction): evaporative capacity 0.13–0.27 g water/s m^2 tray area for crystals, 0.07 to 0.14 g water/s m^2 tray area for finely divided solids; loading 10 to 35 kg wet paste/m^2 tray area; pressure 7 to 27 kPa.

Tray/shelf, jacketed, batch, vacuum (conduction): area 1–20 m^2; evaporative capacity 0.01 to 7.7 g water/s m^2. Time 4 to 48 h. Heat transfer coefficient $U = 2–500$ W/m^2 K.

Pan, agitated, batch, atmos. (conduction): area 1.5–15 m^2; 5–12 g water evaporated/m^2; power 4 kW/m^3; heat transfer coefficient 300 W/m^2 K constant rate period; falling rate = 135 W/m^2 K and decreasing to 6–10 W/m^2 K near the end of the drying cycle; solids capacity 2.8 to 4.2 g dry solids/s m^3. The drying rate is proportional to $(\mathrm{rpm})^{0.4}$.

Pan, agitated, batch, vacuum (conduction): evaporative capacity 1.3–6.8 g/s m^2; time 7.5 to 35 h depending on the material; $U = 25–115$ W/m^2 K; area = 1.4 m^2/m^3 working volume. Power usage 4 kW/m^3.

Rotary indirect, batch, vacuum (conduction), horizontal jacketed fixed cylinder with rotating central agitator: L:D = 2 to 4:1: area 2–35 m^2; evaporative capacity 0.3 to 5 g water evaporated/s m^2 with values increasing as initial feed moisture content increases; 0.7 to 5 g organic evaporated/s m^2; working capacity = 60 % volume; power 0.5 kW/m^2 area or 15 kW/m^3 of working capacity reducing to 3 kW/m^3 at larger sizes, usually 3.8 m^2/m^3 working capacity.

Cone/double cone, jacketed, batch, vacuum (conduction): area 1–10 m^2; evaporative capacity 2.7 to 5.4 g water evaporated/s m^2 of actual surface area; power 0.5 kW/m^2 area.

Freeze, vacuum, batch (conduction): drying temperature serum, –9 to –12 °C; plasma, –20 to –25 °C; penicillin –28 to –32 °C; size vacuum pump to remove the water vapor; avoid air leaks; pressure 10 to 200 Pa or 1/4 to 1/2 the vapor pressure at the temperature; 7–8 h drying cycle; 2800 kJ/kg water sublimated.

Continuous:

Drum dryer, (conduction) range of types: single drum, twin drum dip feed or splash feed, double drum with nip feed and operating at atmospheric or vacuum. The solids output increases approximately with increase in rpm, usually in the range 8 to 10 rpm. Evaporative capacity 7–11 g water evaporated/s m^2; area 2–50 m^2; residence time: 6 to 15 s; solids capacity 5–50 kg/m^2; heat transfer coefficient 0.001–0.002 kW/m^2 °C. Single drum, power 2.5–1.3 kW/m^2 with power ratio decreasing as area increases; double drum, power 1.3–0.9 kW/m^2 with power ratio decreasing as area increases. 1.4–2.5 kg steam/kg water evaporated. For single or twin dip feed, dry solids capacity 1–5 g dry solids/s m^2 increasing slightly with increasing rpm.

Use double drum with nip feed for solutions but not for slurries because the particulates may force the drum apart, cause frequent shear pin failure and leakage from the end plates. Slurries can be dried by splash feed to single or twin drums.

Use top feed for pulpy products; use double drum immersion feed for pulps, muds, and pastes; use immersion pan for dilute products; use spray feed for dilute products that are temperature sensitive.

Applications: agar, blood, calcium carbonate, iron oxide, foodstuff: strawberry pulp, potato flakes, liver extract, seaweed, flour, starch, tomato concentrate, plant extracts; dyestuffs, PVC, metal salts.

Related topic flakers, Section 9.12.

Fourdrinier machine for paper: 37 cylinders, 1.5 m diam; velocity of paper = 4–5 m/s; residence time 31 s; heat transfer coefficient U = 0.34 kW/m^2 °C. Water/solid = 0.4; 2.8 g water evaporated/s m^2.

Screw, jacketed, atmos. (conduction): 2–30 rpm; area 4–60 m^2; volume 0.1–3 m^3. 0.03–0.5 kg water evaporated/s. Heat transfer coefficient 4–60 W/m^2 °C with 4–10 for hollow screw and 5–35 for hollow paddles; power 140 MJ/Mg.

Continuous band, vacuum. (conduction): 2.2 kg steam/kg water evaporated; solid capacity 2–5 g dry solids/s m^2 belt area; belt size $<$ 8 m^2.

Continuous band, atmospheric (conduction): evaporative capacity 0.8 g water/s m^2; dry solids output 2 g solid/s m^2; area 56 m^2.

Freeze, continuous tray: 50 mm thick bed; vacuum 13 Pa absolute: heat transfer coefficient, $U = 0.01\text{–}0.02$ kW/m^2 °C; relatively independent of stirring speed but dependent on residence time and the vacuum with the smaller values for lower absolute pressures (higher vacuum) and longer residence time. Residence time 10–200 s.
Dielectric: 315 °C
– *Indirect convection options:* for moderately temperature sensitive, sensitive and very sensitive solids [$5 < T < 100$ °C].
Batch: size on cycle time: load, dry, discharge, clean.
Tray/shelf (indirect convection) crossflow: 0.05–0.2 g water evaporated/s m^2 tray area; residence time 4–48 h; 1.5–5 m/s gas flow; steam 1.8–2 kg steam/kg water evaporated; power 8–15 kJ/kg; air temp. 50–110 °C. solids capacity < 6 g/s.
Open sand bed: (natural convection) 1000–100 000 m^2 including piping, sand/gravel beds and underground collection.
Continuous:
Spray (indirect convection): residence time 3–30 s; gas velocity 0.2 m/s; thermal efficiency 50 %; adiabatic efficiency 100 %; solid temperature = adiabatic saturation temperature; volumetric heat transfer coefficient 0.13–0.18 kW/m^{3}K; 1.8–2.7 kg steam/kg water evaporated. $\Delta p = 1.5\text{–}5$ kPa; exit air temperature 20 °C greater than exit solid temperature. Design on the amount of water evaporated with the usual range of 0.03–2.8 kg water evaporated/s. Rough size the volume of the dryer based on the ΔT between inlet and exit temperature gas and on the amount of water evaporated. At $\Delta T = 50$ °C the volume of the spray chamber = 2000 m^3/kg water/s evaporated. ΔT between inlet and exit temperature = 100 °C the volume of the spray chamber = 600 m^3/kg water/s evaporated. ΔT between inlet and exit temperature = 200 °C, the volume of the spray chamber = 250 m^3/kg water/s evaporated. ΔT between inlet and exit temperature > 200 °C with *direct heating with gas,* the volume of the spray chamber = 200 m^3/kg water/s evaporated. ΔT between inlet and exit temperature = 500 °C the volume of the spray chamber = 150 m^3/kg water/s evaporated. See Size reduction sprays: Section 8.2; spray reactor Section 6.14, heat exchange Section 3.8.
Flash/transported (indirect convection): because the contact time is very short, transported driver is ideal for temperature sensitive material: examples, foodstuffs coffee, maize gluten, maleic acid, oxalic acid, starch, proteins; for stearates, PVC, adipic acid, aluminum oxide, CMC, dicalcium phosphate, fumaric acid, melamine. The inlet gas temperatures for flash dryers range from 175 to 750 °C and the typical exit gas temperatures range from 50 to 200 °C; the exit air temperature is usually 20 °C greater than exit dry solid temperature. Gas velocity 3–30 m/s (usually 20 m/s) or 2.5 to 3 times the terminal velocity of the particles; gas requirement 1–5 Nm^3/kg solid or 1–10 kg air/kg solid; 4000–10 000 kJ/kg water evaporated. Heat transfer coefficient for gas drying: $h = 0.2$ kW/m^2 K and wall to gas/particles $U = 0.1$ kW/m^2 K. At $\Delta T = 550$ °C (the difference between inlet and exit gas temperature), the air usage/evaporation rate is 2 or 7.2 m^3/s/kg/s of water evap. At $\Delta T = 220$ °C; 4 or 14.4 m^3/s/kg/s of water evap. At ΔT about

150 °C, 6 or 21.6 m^3/s/kg/s of water evap. At ΔT about 100 °C 10 or 36 m^3/s/kg/s of water evap.

See transported slurry, transfer line reactors Section 6.7.

Fluidized bed (indirect convection), residence time 30–60 s for surface fluid vaporization; 15–30 min for internal diffusion; 3500 to 4500 kJ/kg water evaporated. Allow 1–2 m for disengagement. The dewpoint of the exit gas should be at least 10 °C less than the exit solids temperature of the bed. Gas and particles leave the bed at the same temperature. Particle–gas heat transfer coefficient U = 0.01–0.06 kW/m^2 K. Surface area 20 000–100 000 m^2/m^3 bed. For solids with medium sensitivity, such as organics, grains, PVC. Inlet temp about 80–150 °C; ΔT = 50–100 °C. Bed volume 10–60 m^3/kg water evap/s; solids residence or drying time, 400–1800 s. Mass air/mass water evaporated = 40–100; MJ/kg water evaporated = 2–10; evaporation rate = 0.002–0.5 kg water evaporated/s m^2. Solids holdup 100–500 kg solids/m^3 See fluidized bed reactors Section 6.30, heat transfer Section 3.4, size enlargement Section 9.4.

Tray/gas flow through the bed (indirect convection), 0.24–3.3 g water evaporated/s m^2 tray area; residence time 2–8.5 h; superficial air velocity 0.2–1 m/s; steam 2–6.8 kg steam/kg water evaporated. Fan power 1.6–2.5 kJ/g solids throughput; area 4–15 m^2; air temperature 9 to 100 °C; solids capacity < 6 g/s.

Continuous tray, turbo (indirect convection): Solids follow plug flow so that the product quality is very uniform with exit moisture content as low as 0.1 %. Can handle fragile solids with minimum breakage. Heat transfer coefficients: 28–55 W/m^2 K for dry solids and 65–110 W/m^2 K for wet solids. Maximum operating temperature 535–650 °C; 1–2 rpm; 10–50 trays/unit; residence time 0.25–2 h; diameter 1.25–11 m; height 1.5–18 m; area 10–1000 m^2; evaporative capacity 0.05–15 g water evaporated/s m^2 with usual values of 0.3–1.8 g water evap/s m^2. Gas velocity 0.6–2.4 m/s; solids capacity 0.003–4.25 kg/s. Fan power 8–15 kJ/kg solids handled. Power required = 5–8 kW/Mg dried solids; or 5–7 kW/Mg water evaporated. 0.08–15 kW/m^2 with usual values 0.06–0.12 kW/m^2; 0.1 kg steam/kg dry solid; energy 50–100 kJ/m^2 drying area for dry solids; 70–200 kJ/m^2 drying area for wet solids.

Desolventizer: combination of live and indirect steam; inlet solvent concentration about 30 %; capacity 2–50 kg/s; flakes 0.25–0.3 mm thick.

Toaster: hot air contacts flakes.

Tunnel/truck (indirect convection) area 10–100 m^2; evaporative capacity 0.15 to 0.77 g water evaporated/s m^2.

Rotary (indirect convection) temperature 300 °C; area 10–1000 m^2; evaporative capacity 9 g water evaporated/s m^3 or 0.5–4 g water/s m^2 of peripheral area; 5 to 10 % solids, residence time 0.1 V/volumetric feed rate; gas velocity 1–1.5 m/s; peripheral velocity 0.1–0.5 m/s. Steam heated gas temp 120–175 °C; size on volumetric heat transfer coefficient; power 0.15–0.25 kW/m^2 nominal circumferential area. L/D = 5.5/1. Assume average temperature of evaporation throughout is 3 °C above inlet wet-bulb temperature. Peripheral area/volume = 1.4–2.6 or about 2 m^2 peripheral area/m^3 dryer volume. Indirect rotary 0.5–4 g water evap/s m^2.

Rotary steam tube (indirect convection): temperature 150–180 °C; area 10–1000 m^2; evaporative capacity 0.77 g water/s m^2; gas velocity 0.3 m/s; heat transfer coefficient $U = 0.03–0.09$ kW/m^2 °C, although some sources give 2 kW/m^2 °C.

Continuous metal band: (heated by forced convection air, IR, direct steam or direct hot water): Heat transfer coefficient from impinging hot air: $U = 0.06–0.09$ kW/m^2 K; air velocity 15–25 m/s; 5–50 kg water evaporated/m^2 drying surface; 1.5–2 kg steam/kg water evaporated; power required is 20–30 kW with values relatively independent of the size.

– *Direct convection options* for temperature sensitive, moderately sensitive and insensitive solids [$10 < T < 150$ °C].

Hot gas temperature 550–800 °C.

Fluidized beds: (direct convection) moderate sensitivity, direct fired, inlet temp about 80–200 °C;

$\Delta T = 10–100$ °C. Example, fertilizer: solids residence or drying time, 300–600 s; mass air/mass water evaporated = 200; evaporation rate = 0.008–0.04 kg water evaporated/s m^2; solids holdup 120–300 kg solids/m^3.

Fluidized beds: (direct convection), relatively insensitive, solutions, crystals and melts. Inlet temp about 400–500 °C; $\Delta T = 150–300$ °C; solids residence or drying time, 30–250 s. Mass air/mass water evaporated = 10–100; evaporation rate = 0.005–0.4 kg water evaporated/s m^2. Solids holdup 10–30 kg solids/m^3.

Fluidized beds: (direct convection) direct contact, insensitive: slag, sand, coal, katex and ore. Inlet temp about 300–760 °C; $\Delta T = 200–400$ °C; solids residence or drying time, 50–2000 s. Mass air/mass water evaporated = 10–30; MJ/kg water evaporated = 2–5; evaporation rate = 0.008–4 kg water evaporated/s m^2; solids holdup 150–600 kg solids/m^3.

Continuous band/belt: gas flow through the bed: 1–10 g water evaporated/s m^2; steam 2–5 kg steam/kg water evaporated; 1.25 m/s gas velocity through the bed; area 5–25 m^2. Usually operate 10–30 % less than achievable thermal efficiency. Power = 2.5 kW/m^2.

Continuous band/belt: cross flow: < 3 mm thick bed; area: 20–100 m^2; evaporative capacity 2–13 g water evaporated/s m^2; residence time 0.2–1.3 h; steam 1.7–1.9 kg/kg water evaporated; fan power 35–1300 kJ/kg; belt drive power 0.5–1.4 kW/m^2.

Rotary cascading dryer/kiln roto-louvre (direct convection): area 10–1000 m^2; evaporative capacity 18 g water evaporated/s m^3 or 0.8–7 g water/s m^2 of peripheral area; 5 to 10 % solids, residence time 0.1 V/volumetric feedrate; gas velocity 1 to 1.5 m/s or ½ terminal velocity of particles; peripheral velocity 0.1 to 0.5 m/s, 4–5 rpm; rpm times diameter = 3–12 rpm m; L/D = 4–15/1; average temperature of evaporation throughout = 3 °C above the inlet wet-bulb temperature. Counter current exit air temperature about 100 °C; for cocurrent exit air temperature = 10–20 °C higher than the exit solid temperature; heat transfer coefficient 0.1 W/kg solids °C for coarse materials and 0.4 W/kg °C for fine. NTU = 0.5 for vegetables. NHTU (for air water) = 1.0–3.5 = ln $(T_{\text{hot gas in}} - T_{\text{wet bulb}})/(T_{\text{hot gas out}}$

– $T_{\text{wet bulb}}$); drive power 0.075–0.16 kW/m^2 nominal circumferential area for area in the range 200–2500 m^2. Related topic and reactors Section 6.23.
Open bed (direct convection): residence time: minutes; gas through bed 0.5 to 1 m/s.
Hopper dryer for polymer feed to extruder. Hot gas $< 120\,°C$.

- *Good Practice*

Consider preconcentrating liquid via falling film evaporation, Section 4.1; preforming paste into extrudate via extruders, Section 9.11; grinding solid into fine powder, Section 8.5. Operate under slight vacuum except for flammable solvents which should be operated with a slight positive pressure. See steam traps, Section 5.1, when steam is used.
For freeze drying: pressure/vacuum must be controlled accurately. Prevent thawing of the product by matching heat supplied with heat of sublimation.

- *Trouble Shooting*

Work with an overall mass and energy balance.
For drum dryer: *"Moisture content in the exit solids > design":* drum rpm too high/drum clearance too large/steam pressure < design/feed temperature < design/twin drum with dip feed is used when it should have been double drum with nip feed. **For continuous rotary steam-tube dryer:** *"Product moisture content high":* upstream batch centrifuge gives periodic wet cake. **For fluidized bed dryer:** "*Product moisture content high*": solids buildup on gas sparger in fluidized bed (caused because inlet gas temperature too hot). **For spray dryer:** "*Product wet and clumps form inside spray dryer*": insufficient gas flow/inlet gas temperature too low, instrument fault/feed solids concentration lower than design/liquid drops larger than design.
For belt dryer, flow through: *"Product does not meet specs":* air short circuiting/air seals inadequate/depth of feed varies on conveyor/apron perforations clogged/feed agglomerating/feed sticking to apron/buildup of product in dryer at sharp edges/air recirculating around fan/fan rotating in wrong direction/feeder not giving uniform thickness of wet feed/heating capacity < design.

- *For Polymer Processing*

For fixed bed-hopper to dry polymer feed for extruder (hot gas $< 120\,°C$): *"Feed material not dry":* incorrect drying temperature/solids throughput > design/instrument error/input air too moist/ambient air leaking into drying air circuit/adsorbent for drying air incorrectly regenerated/air dryer (gas adsorber) fault. See related unit adsorption: gas, Section 4.11.
Hopper dryer for polymer feed to extruder. *"Polymer pellets leaving hopper are not dry"*: incorrect drying temperature/solids throughput > design/instrument error/input drying air too moist/ambient air leaking into drying air circuit/adsorbent for drying air incorrectly regenerated/air dryer (adsorber) fault see Adsorption: gas, Section 4.11.

5.7
Screens for "Dewatering" or Liquid–Solid Separation

See also Section 5.30 for solid–solid separation.

Related topics: Filters, Section 5.14, centrifugal filters, Section 5.13 and expellers, Section 5.17.

- *Area of Application*

In general, particle diameter > 1000 μm and solid concentration > 3 %.

Special types include microscreens for > 20 μm and screen packs after extruders.

Batch:

Deep bed or granular: batch, for 0.01 to 50 μm (see Filter, Section 5.14).

Fixed bar screen; batch, grizzly (the filter cloth is made of rods and bars) removal of very coarse material of diameter > 2 to 5 cm; low concentration of solids < 15 mg/L; bars at 30 to 60° to the horizontal that can be cleaned manually or automatically.

Microscreen (rotary drum or disk): batch, removal of participles of diameter > 20 μm; 20 mg/L solids feed concentration.

Screen packs downstream of extruders

Custom designed for each polymer.

Continuous:

Fixed inclined wedge wire screen (sieve bends, DSM): removal of particles > 0.15 cm. Variable inclination from 65 to 45° to the horizontal; feed concentration 200 mg/L. For dewatering minerals, dewatering particles of diameter > 40 μm.

Vibrating screens: typical exit liquid concentration for < 8 mm particle size, 20 to 45 vol % liquid; for > 40 mm particle size, 2 to 10 % v/v liquid.

Belt, gravity: see Section 5.14.

- *Guidelines*

Batch: consider cycle time: load, clean.

Bar screen: batch: fluid velocity through the screen 0.6 to 1.2 m/s; head loss 15 to max. 75 cm. Mechanical clean.

Rotating microscreen: batch, fluid loading 3 to 6 L/s m^2 of submerged area; usually 66 % area submerged; solids loading 0.05 to 0.1 g/s m^2; headloss 7 to 14 cm to max. of 45 cm. Clean by backwash at 2 to 5 % volumetric throughput capacity.

Screen pack downstream of extruders: screen pack area directly proportional to rate of extrusion. Cycle time for the screen to blind > time between shutdowns. For example, screen pack area 0.17 m^2 s/kg and screen pack diameter 20 cm s/kg but must be custom selected for the polymer.

Continuous

Fixed inclined wedge wire screen, sieve bend : fluid loading 6.7 to 20 L/s m^2; or 10 to 40 L/s m of width; solids loading 1.4 to 4.2 g/s m^2; exit solids concentration 12 to 15 % w/w solids. For dewatering minerals, fluid capacity of 0.0015 to

0.03 L/s m^2 with larger fluid capacity for larger size particles (1 to 2 mm) and smaller the included angle of the bend. The bend in the screen is such that the oversize are continually sluiced off.

Vibrating screens: see Section 5.30.

- *Good Practice*

Batch

Screen pack downstream of extruder: Install standby screen pack with diverter valve to bring standby on line when on-line filter blinds.

- *Trouble Shooting*

"Solid contamination of product": mesh size too large/contamination downstream of screen pack. *"Gels in final product":* gels form in extruder/Δp across screen pack excessive/screen area too small/size and type of screen cannot retain gel/gels form downstream of screen pack/downstream temperature promotes gel formation. *"Δp excessive"*: filter media too fine/screen area too small/screen temperature too low/gel formation in extruder. *"Filter media pushes through back support plate in screen pack":* screens on the downstream side of the pack not coarse enough or not rigid enough/support plate holes too large.

5.8
Settlers

- *Area of Application*

Particle diameter < 2 cm; solids concentration 0.2 to 50 %.

- *Guidelines*

Upward liquid overflow rate 0.25 to 0.6 L/s m^2 with the value increasing as the feed concentration and particle diameter and density increases.

For solids concentration 0.2 to 2, use 0.4 to 1 L/s m^2, for 1 to 5, use 0.5 to 1.4 L/s m^2.

Usual depth is 4 to 5.2 m with drive for rake 0.5 to 10 kW.

Overflow rate 0.38 L/s m^2; for domestic wastewater use an overflow rate = 0.19–0.58; side depth 2.1–3.7 m. If cylindrical then use a central rake mechanism. If rectangular , use chain and flight sludge collectors.

For the relationship between cross sectional area and volume, see decanter, Section 5.3.1.

- *Trouble Shooting*

Grit chamber: *"Floating sludge"*: sludge decomposing and buoyed to the surface/ infrequent sludge removal/sludge not removed from the hoppers. *"Excessive sedimentation at the inlet":* fluid velocity too slow. *"Intermittent surging":* intermittent pumping rates/liquid maldistribution of feed. *"Sludge hard to remove from hopper":* high feed concentration of grit, clay/low velocity in the sludge withdrawal lines.

Settlers: *"Floc or particulates do not settle":* size different from design/density different from design/unanticipated turbulence or back eddies/liquid residence time too short/feed flowrate > design/incorrect design of inlet/faulty design of solids removal. *"Supernatant not clear":* [floc or particulates do not settle]*/faulty design of overflow weirs/short circuiting.

[Floc or particulates do not settele]:* floc density < design/temperature too low or fluid phase contaminated so that viscosity > design/turbulence/inlet design incorrect/shear breaks up particles/inadequate flocculation and particles to small.

5.9
Hydrocyclones

(see also Section 5.22 for solid–solid separations)

- *Area of Application*

Particle diameter 4 to 400 μm; feed solids concentration 4 to 30 % solids v/v but usual application is separating particles > 50 μm and concentrations < 10 % v/v with pressure loss of 20 to 100 kPa.

Regular hydrocyclones: particle "settling velocity" 2 μm/s to 5 mm/s and clarified liquid product of 0.1 to 70 L/s.

Miniature hydrocyclones: particle "settling velocity" 0.05 μm/s to 0.04 mm/s and clarified liquid product of 0.02 to 30 L/s.

- *Guidelines*

Determine diameter of hydrocyclone from D [cm] = 6×10^5 {Feed flowrate [L/s]/ target diameter^2 [μm^2] Δp [kPa]} {ϱ_L, density liquid [Mg/m^3], $\times$ liquid viscosity [mPa s]/$\Delta\varrho$, density difference, [Mg/m^3]}.

Typical target diameters are 5 to 100 μm and are the diameters where 50 % reports to the overflow and 50 % reports to the underflow. Typically 3 times target diameter is the diameter below which all particles in distribution are removed. The standard hydrocyclone has an inlet diameter of $0.28D$; the overflow exit diameter = $0.34D$; the vortex finder length is $0.4D$; cylindrical body of height of $0.4D$, vertical length of cone = $5D$ or cone angle about 10°. Underflow diameter adjustable to adjust the volume split between the overflow and underflow.

- *Good Practice*

Control on pressure drop.

- *Trouble Shooting*

"Underflow too dilute, underflow appears as smooth inverted cone": inlet velocity low/ inlet feed pressure low. *"Underflow appears as slow, vertical rope of coarse solids"*: underflow opening too small/feed concentration of solids higher than design. *"No discharge from the underflow":* plugged inlet/plugged underflow.
"Underflow unsteady and variable inlet pressure": air-gas in the feed.

5.10
Thickener

- *Area of Application*

Particle size 0.1 to 300 μm; try to avoid using a thickener for particle diameters > 200 μm especially if their density is > 2 Mg/m^3. Feed solids concentration 0.01 to 20 % v/v; exit liquid contamination in the solids exit 80 to 90 %v/v liquid; Deep cone thickener: exit liquid contamination in the solids exit 30 to 40 % v/v liquid.

- *Guidelines*

Downward solid flux of 0.2 to 500 g/s m^2 with low values of 0.2 to 2 for waste water treatment, pickle liquor and higher values of 40 to 70 for mineral processing. Higher flux rates by factors of 3 to 10 up to fluxes of 800 g/s m^2 can be obtained with the addition of flocculants. Fluid residence times 2–4 h; solids residence times 4–24 h.

Torque for rake [Nm] = K(thickener Diameter, m)^2 where $K = 15$ to 30 for solid flux loadings of < 2 g/s m^2, 70 to 130 for solid flux loadings of 2 to 7 g/s m^2, 150 to 300 for solid flux loadings of 7 to 23 g/s m^2 and > 300 for solid flux loadings of > 23 g/s m^2.

Operate the rake at 1–20 % of design torque at the drive head. Rake tip speed 15–25 cm/s but for appreciable amounts of particles of diameter > 200 μm, then increase tip speed to 25–40 cm/s. Power 0.06 kW/m^2.

Pump the underflow at 1–2.4 m/s. see Section 2.5.

- *Good Practice*

Consider the use of flocculants or deep cone. Flocculant dosage should be related to feed inlet concentration, see also Section 9.3. Include high pressure water purge lines for both forward and reverse flow at > 1 m/s. Raise and lower the rake once per shift. For startup, pump feed into the empty tank and recycle underflow until the design underflow densities are achieved.

- *Trouble Shooting*

“Stalled rake”: uneven central feed distribution/excessive flocculant causing island formation/underflow concentration $>$ design/unpumpable underflow/trying to maintain the underflow concentration when the feed contains fines $>$ design/ storing too many solids in the thickener/“sanding out”/particle shape differs from design. *“Plugged underflow lines”:* insufficient fines/targetting underflow concentration $>$ design/temperature change/pump problems, see Sections 2.3 and 2.5/suction velocity $<$ 0.6–2.5 m/s.

Underflow concentration of solids too low”: removal of too much underflow/flocculation problems that give islands that lead to the feed concentration rat-holing directly to underflow.

“Supernatant cloudy”: feed velocity excessive causing breakup of colloidal flocs/ changes in pH or electrolyte concentration causing floc breakup/excessive feed

turbulence/excessive vertical drops of feed/insufficient flocculant added or flocculant feedrate constant instead of proportional to solids concentration in the feed. *"Sanding out":* too high an underflow concentration/feed concentration of dense particles > 200 μm is $>$ design/power failure.

5.11
CCD: Counter Current Decantation

- *Area of Application*

When dilute liquid overflow is acceptable because high wash water ratios are used; for high temperature operation, when anticipate changes in feed materials and if the filtration rate is < 140 g/s m^2.

- *Guidelines*

Wash ratio 2–2.2 water to 1 solids. Wash ratio and the number of stages are selected for expected recovery.

- *Good Practice*

Add one more thickening stage to account for inefficiencies in mixing.

5.12
Sedimentation Centrifuges

Primarily to recover liquid although they can be used to recover solids. Incomplete separation. Gives clear supernatant.

- *Area of Application*

Liquid contamination in the exit solids: 10 to 15 % v/v liquid.
Batch:
Tubular bowl: batch, very fine particles with settling velocities 5×10^{-8} to 5×10^{-7} m/s; particle diameter 0.1–500 μm, feed concentrations 0.1–20 % v/v; $<$ 5 % w/w. Clarify low concentrations. Not for foaming.
Vertical solid bowl: batch, particle diameter > 30 μm; feed solids concentration 3 to 5 % w/w to prevent frequent cleaning.
Multi-chamber vertical solid bowl, manual batch discharge: particle settling velocity 2×10^{-6}–7×10^{-5} m/s; particle diameter 1–50 μm; feed solids concentration $<$ 4 to 5 % v/v. Very dry product and higher capacity.
High speed disc vertical solids retaining: batch, particle settling velocity 8×10^{-8}–2×10^{-7} m/s; particle diameter < 1 μm; feed concentration solids $<$ 1 % w/w; $<$ 20 % v/v.
Continuous:
High speed disc, intermittent solids ejecting: particle diameter 1–500 μm; feed concentration solids 2–6 % v/v and $<$ 5 % w/w.

High speed disc, continuous nozzle discharge: particle diameter 0.1–500 μm; feed concentration solids 5–30 % v/v; < 10 % w/w. Usually select when have a large amount of fines.
Horizontal scroll discharge: (solid bowl decanter) 10^{-6} to 5×10^{-6} m/s; particle diameter 2–5000 μm ; feed solids concentration 0.5 to 50 % v/v. Usually > 10 % v/v; only option when feed concentration > 40 % v/v solids.

- *Guidelines*

Scaled up based on liquid handling capacity.
Batch: size on cycle time: separate, remove solids, clean. Cleaning interval: hours.
Tubular bowl: batch, up to 50 000 rpm; 3×10^3–6×10^4 g; L/D = 4–8; liquid flowrates 0.03 L/s at high rpm, 0.1–10 L/s at lower rpm. Clarify low concentrations. Σ 1500–4000 m^2
Vertical solid bowl: batch, 450–3500 rpm, 900 to 1100 g; L/D = 0.8; 1.6–2.8 L/s; 70–120 cm diameter bowl; 200 to 500 g/s m^2; area 0.5 to 3 m^2; 3 to 17 kW.
Multi-chamber vertical solid bowl, batch discharge: 4500 to 8500 rpm; 3×10^3–3×10^4 g; 0.7 to 2.8 L/s; 30 to 60 cm diam. bowl. Clarification efficiency constant until bowl is full.
High speed disc vertical solid bowl: < 12 000 rpm; 3×10^3–3×10^4 g ; L/D = 1; < 28 L/s; 15 to 100 cm bowl diameter; cone 35 to 50°.
solids retaining: 5 to 20 L/s

Σ, m^2	bowl diam., cm
1000	10
10 000	20 to 30
100 000	60 to 90

Continuous:
High speed disc vertical, intermittent solids ejecting: supernatant clarification; max. 55 L/s; feed 0.01–10 v/v; poor dewatering, can handle foaming, Σ up to 270 000 m^2, cleaning interval: weeks; max. g: 5000–7500.
High speed disc vertical, continuous nozzle discharge: < 85 L/s; feed 1–30 v/v ; poor dewatering; can handle foaming, clarified supernatant; cleaning interval: weeks; max g: 6–9000; Σ up to 80 000 m^2.
Horizontal scroll discharge: 1600 to 6000 rpm; 1500–5000 g; L/D 1.5 to 3.5; 0.1 to 16 L/s;

Σ, m^2	bowl diameter, cm
200	12 to 15
1000	25 to 35
5000	50 to 70

- *Good Practice*

Because of high speeds, maintenance tends to be extensive. Capacity sensitive to density and particle size.

V-belt drive tends to isolate vibrations.

- *Trouble Shooting*

Horizontal scroll discharge decanter: *"Centrifuge won't start:"* vibration switch triggered/no power/motor or starter failure/overheated motor/[broken shear pin]*/ lubrication oil flowswitch tripped. *"Centrifuge shuts down"*: blown fuse/overload relays tripped/motor overheated/[broken shear pin]*/lube oil flowswitch tripped. *"Excessive vibration"*: broken isolators/motor on flexible mounts/motor bolts loose/flexible piping not used/misalignment/bearing failure or damaged/loss of plows/damaged conveyor hub/solid product buildup in conveyor hub/conveyor or bowl not balanced/conveyor flights worn or portion of blade missing/trunions cracked or broken/conveyor bowl cracked or broken/leaking effluent weirs/ plugged solids in the effluent hopper/not level. *"High moisture in exit solids"*: liquid dams not set alike or set incorrectly/feed temperature too low/feed rate too high/effluent hopper plugged or not vented/conveyor flights worn. *"High solids in liquid effluent"*: feed rate excessive/effluent dams set wrong/no strip installed/incorrect feed temperature.
[Shear pins breaks]:* Feed rate too high/solids concentration too high/foreign material stuck in bowl. *[Solid and screen bowl shear pins break]**: plugged discharge hopper/conveyor blades bent or rough/worn bowl strips/loose or broken trunion bolts/bowl inadequately washed/clearance too large for blade tip to bowl wall/ bowl inside rough/wrong size shear pin.

5.13
Filtering Centrifuge

Table 5.2 summarizes the characteristics of different rates of filtration for different size of particles.

Table 5.2 Characteristics of different rates of filtration.

	Fast	Medium	Slow	Very slow	Very, very slow
Intrinsic permeability, $m^4/N\ s$	$> 20 \times 10^{-10}$	$1–20 \times 10^{-10}$	$0.2–1 \times 10^{-10}$	$0.02–0.2 \times 10^{-10}$	$< 0.02 \times 10^{-10}$
For viscosity 1 mPa s, size, μm	> 50	> 15	> 4	> 1.5	< 1.5
For viscosity 60 mPa s, size, μm	> 350	> 100	> 50	> 17	< 17
Cake buildup rate, $g/s\ m^2$	> 700	70–700	7–70	0.02–7	< 0.02
Possible option	continuous pusher	peeler centrifuge	vertical basket centrifuge	multichamber vertical solid bowl sedimentation centrifuge, Section 5.12	sedimentation centrifuge, Section 5.12

- *Area of Application*

Liquid contamination in the exit solids: 4 to 13 % v/v liquid.

Batch:

Vertical basket: batch, particle diameter > 2 μm; feed solids concentration 2–50 % w/w. Minimize damage to crystals. Low capacity: 0.003–5 kg/s. Product dryness 70 % solids. Possible for sterilization between batches.

Vertical basket with bottom plough discharge: batch, particle diameter 5–500 μm; feed solids concentration 9–90 % w/w; capacity 0.1–1.25 kg/s. Product dryness 25–60 % solids. Use with free draining, medium capacity, and where need multiple rinse.

Horizontal basket, plough discharge: particle diameter 200–20 000 μm; feed solids concentration 10–70 % w/w. free – slow draining, multiple rinses, low – medium capacity: 0.5–5.5 kg/s. Product dryness 87–96 %. Keep feed consistent with high solids concentration.

Semicontinuous:

Horizontal basket, pusher discharge: particle diameter 50–5000 μm; feed solids concentration 15–70 % w/w. capacity 0.3–7 kg/s. Product dryness 85–98 %. Free draining. Main advantage is to rinse the solids.

Continuous:

Horizontal combo solid-screen, scroll discharge: particle diameter > 150 μm; feed solids concentration 10–75 % w/w. Solvent-based reactions.

Vertical or horizontal cone: slip discharge: continuous, particle diameter > 200 μm; feed solids concentration 10–80 % w/w, capacity 0.25 kg/s. Dewater crystals and free draining fibers.

Vertical cone, scroll discharge: continuous, particle diameter 200–5000 μm; feed solids concentration 5–60 % w/w. capacity 0.02–8 kg/s.

Horizontal cone oscillating/torsional vibration discharge: particle diameter < 6 mm; feed solids concentration 40–80 % w/w. capacity 7–40 kg/s.

- *Guidelines*

In general, for most centrifugal filters, the filtering area, m^2 = 1.75 (basket diameter, m)^2.

Batch: size on cycle times: accelerate to load speed, load and cake formation, accelerate to wash, wash, accelerate to full speed, spin dry, decelerate to unload speed, unload. Cake volume in the centrifuge is key. During load and cake formation the particles migrate to the periphery to form a cake, the supernatant liquid moves through the bed to the cake surface and then the liquid drains out of the interstices in the wet cake. The latter two times usually control.

Vertical basket: batch with cycle: cake formation, wash, discharge, clean. Total cycle > 10 min e.g. 180 min. Cake buildup rate 200–1000 g/s m^2; area per unit: 2.8 m^2; cake volume 0.009–0.5 m^3; cake thickness 25–150 mm with smaller thickness in smaller diameter centrifuges. 600–2100 rpm; 300–800 G. Basket diameter 0.3–1.5 m; L/D = 0.5–0.6/1. Power 3–6 kW/m^2 filter area. Temperature < 175 °C.

Vertical basket, bottom discharge: batch with cycles: accelerate to load speed, load and cake formation, accelerate to wash, wash, accelerate to full speed, spin dry, decelerate to unload speed, unload: 3–120 s. Cycle time for free draining 2–6 min; slower draining materials cycle time 20–30 min with some > 60 min. area per unit 0.4–4.5 m^2; cake volume 0.018–0.53 m^3; about 67 % of feed volume; cake thickness 50–150 mm with smaller thickness in smaller diameter centrifuges. 900–1800 rpm. Basket diameter 1–1.2 m; L/D = 0.5.

Horizontal basket, plough discharge: batch with cycles: load 7–25 s; wash 5–25 s, spin dry 12–30 s, unload cake 3–12 s; total cycle time 20 s–15 min but usually < 3 min. Cake buildup rate 500–3000 g/s m^2; area per unit, 0.1–3.8 m^2; cake volume 0.03–0.17 m^3. Bowl diam. 0.3–1.2 m. 1000–2500 rpm; < 1250 G. Power 25–40 kW/m^2 filter area.

Semibatch: particles move through the cycle continually.

Horizontal basket, pusher discharge: 20–120 cycles/min: cake formation, wash, discharge. Cake buildup rate 1000–10 000 g/s m^2; area per unit: 0.1–1.8 m^2; cake thickness < 75 mm. Basket diameter 0.2–1.2 m; 300–600 G. Power 40–60 kW/m^2 filter area or 7–15 kJ/kg “salt” (about 3000 g/s m^2). Keep feed solids concentration > 40 % w/w for optimum. Example data: adipic acid, urea 1.4 kg/s m^2; crude sodium bicarbonate 1.45 kg/s m^2; phosphate rock, 2.2 kg/s m^2; ammonium sulfate 2.36 kg/s m^2; and sodium chloride 3.1 kg/s m^2.

Continuous:

Horizontal combo solid-screen, scroll discharge: area per unit, 1.2 m^2; power 12–15 kW/m^2 filter area.

Vertical or horizontal cone: slip discharge: cake buildup rate 3000–20 000 g/s m^2; area per unit, 4 m^2; Cone angle 20–35° and > angle of repose of the solids. 2500 G. Rinsing efficiency: fair.

Vertical cone, scroll discharge: diameter 0.5–1 m. 2500–3800 rpm; 1800–2500 G. Product solids 24 %.

Horizontal cone oscillating/torsional vibration discharge: cone angle 13–18°; cycles > 20 cycles/min. 300–500 rpm; < 500 G. Diameter 0.5–1 m; L/D = 0.5–1/1. Product 92 % solids. Limited liquid handling capacity. Power 0.2 kW/Mg solids.

- *Good Practice*

Monitor pH and temperature.

- *Trouble Shooting*

Pusher: *“Machine floods”:* feed concentration < design/feedrate > design/irregular feedrate/change in size distribution or particle diameter. *“Unstable cake formation”:* feedrate > design.

5.14
Filter

Table 5.3 relates filtration rate to process operation.

For incompressible cakes, the filtration rate is directly proportional to the specific cake resistance, the pressure/vacuum and inversely proportional to the viscosity and the cake thickness.

The filtration rate is inversely proportional to the ratio of solids to filtrate while the rate of cake formation is directly related to this ratio.

For compressible cakes, the filtration rate is relatively independent of pressure. The more flocculated the solids, the more compressible will be the filter cake.

- *Area of Application*

Prefer **Batch**, when cake formation rate is $<$ 0. 01 mm/s (low concentrations of small diameter particles). OK for higher liquid viscosities and higher temperatures. Batch can be vacuum or pressure operation. Prefer vacuum operation for particle diameter $>$ 30 µm; if there is a small mass of fines ($<$ 50 % with diameter $<$ 5 µm) and bed has permeability between 0. 1–1000 (µm)^2. Prefer pressure filters for particle diameter 1–70 µm, if there is a large mass of fines (with $>$ 50 % w/w with diameter $<$ 10 µm) and bed has permeability between 0.001 and 0.1 (µm)^2.

Prefer **Continuous** for cake formation $>$ 0.01 mm/s (high concentrations of larger diameter particles); viscosity $<$ 50 mPa s. Continuous is usually gravity or vacuum operation. For gravity operation particle diameter $>$ 1 mm; and bed has permeability $>$ 1000 (µm)^2. For vacuum, usually particle diameter $>$ 30 µm and bed has permeability between 0. 1 and 1000 (µm)^2.

Table 5.3 How process operation relates to filtration rates.

	Fast	**Medium**	**Slow**	**Very slow**	**Very, very slow; clarification**
Cake formation rate, mm/s	> 1	0.12–1	0.02–0.12	0.001–0.02	< 0.001
Cake formation rate, g/s m^2	700	70–700	7–70	0.07–7	< 0.07
Filtrate rate, L/s m^2	> 3	0.3–3	0.03–0.3	0.003–0.03 rarely filter for flux < 0.01	< 0.003
Typical cake resistance, m/kg	$< 8 \times 10^8$	8×10^8–10^{10}	10^{10}–5×10^{10}	5×10^{10}–3×10^{11}	$> 3 \times 10^{11}$
	Usually prefer continuous			Usually prefer batch	
Comments	vacuum belt, screens, belts, top feed drum	tilting pan, vacuum drums or disks	continuous filters	vacuum filter, rotary vacuum, pressure filters	batch cartridge, precoat drums, deep bed

For compressible cakes, prefer mechanical compression via diaphragm plates or belt presses. Compressed volume = 0.6–0.75 volume before compression. Compression cycle 0.33–0.4 h for diaphragm plate and frame press.

Highly compressible: latex, highly flocculated materials > silica, talc, attapulgite > kaolin > > barite, diatomaceous earth > > incompressible = polystyrene, carbonyl iron.

Batch:

Leaf, pressure vertical: particle diameter 1–120 μm; feed solid concentration 0.08–0.5 % w/w. Recover liquid.

Leaf, vacuum: particle diameter 1–500 μm; feed solid concentration 0.07–2 % w/w; solids capacity < 5.5 kg/s.

Leaf, horizontal pressure: particle diameter 1–100 μm; feed solid concentration 0.003–0.05 % w/w. Recover wet solid with good washing (rank 2).

Plate, horizontal vacuum: Recover liquid (rank 1) Recover wet solid with good washing (rank 2); Liquid contamination in exit solids: 15–50 % v/v liquid. Dry solids capacity < 0.0027 kg/s.

Plate and frame: particle diameter 1–100 μm; feed solid concentration 0.003–25 % w/w. Recover liquid (rank 5); use for liquids with viscosity > 50 mPa s. Recover wet solid with good washing (rank 6); with good washing and fragile crystals (rank 3). Relatively incompressible solid bed. Liquid contamination in exit solids: 30 to 70 % v/v liquid. Solid capacity < 55 kg/s.

Diaphragm plate and frame: compressible cake.

Deep bed: particle diameter 0.01–50 μm; feed solid concentration 0.002–0.02 % w/w. Recover liquid (rank 1); 50–90 % removal efficiency. 10–300 mg/L feed solids concentration but usually < 40 mg/L. Dry solids capacity < 0.5 mg/s.

Cartridge: particle diameter 0.8–50 μm; feed solid concentration 0.003–0.02 % w/w. Recover liquid (ranks 3). Dry solids capacity, 0.0014 kg/s.

Continuous

Drum, gravity: particle diameter 40–5000 μm; feed solid concentration 0.08–0.8 % w/w. Recover wet solid with good washing and fragile crystals (rank 2).

Drum, pressure: particle diameter 5–200 μm; feed solid concentration 0.75–5 % w/w. Recover wet solid with good washing and fragile crystals (rank 2).

Drum, rotary vacuum: particle diameter 1 to 700 μm; feed solid concentration 5–60 % w/w. Recover wet solid with good washing (rank 4) Recover wet solid with good washing and relatively compressible cake (rank 1). Recover wet solid with good washing and fragile crystals (rank 2). Dry solids capacity < 50 kg/s.

Drum, precoat rotary vacuum: particle diameter 0.5–80 μm; feed solid concentration 0.02–0.1 % w/w. Recover liquid (rank 4).

Disk, rotary vacuum: Particle diameter 15–500 μm; feed fraction solids 0.02–0.70. Free flowing.

Table/pan gravity: recover liquid (rank 1) Recover wet solid with good washing (rank 1) Recover wet solid with good washing and fragile crystals (rank 1). Particle diameter 40–50 μm; feed fraction solids 0.02–0.20. Dry solids capacity, 280 kg/s.

Table/pan vacuum: Particle diameter 40–50 μm; feed fraction solids 0.02–0.20. Dry solids capacity: 280 kg/s.

Belt, gravity: Recover wet solid with good washing (rank 3); Liquid contamination in exit solids 20 to 30 % v/v liquid.

Belt, vacuum: Particle diameter 20–70 μm; feed fraction solids 0.05–0.6. Dry solids capacity: < 30 kg/s.

Belt press: dewater and handle flocculated solids.

Rotary press: dewater and handle flocculated solids. Particle size 1–50 μm; feed solids 0.1–25 % w/w. Related to extruders, Section 9.11 and expellers, Section 5.17.

Ultrafiltration: see Section 4.22. Particle diameter 0.4–200 nm; feed solids concentration < 20 % w/w.

Microfiltration: see Section 4.23. Particle diameter 0.05–800 μm; feed solids concentration < 75 % w/w.

Dissolved air flotation, DAF: see Section 5.16. Particle diameter 0.1–50 μm with typical target diameter 2 μm; feed solid concentration 0.002–0.08 % w/w; > 80 % removal efficiency.

- *Guidelines*

General porosity of cake over the usual range of pressure difference for filtration: 0.9: silica, polystyrene; 0.8–0.85: talc, zinc sulfide; 0.7: calcium carbonate; 0.6 titanium dioxide; ignition plug; 0.5 kaolin; 0.42 iron carbonyl.

Table 5.4 relates particle diameter to parameters important in filtration.

For filter press, nominal press volume within the frames = 1 m^3 corresponds to a filter area of 40 m^2 for a 5 cm cake and 80 m^2 for a 2.5 cm cake (or chamber depth).

Batch:

Usually size unit on cycle and based on volume of cake removed. Select required cake volume in batch unit. 2/3 of the cake forms in 1/3 of filtration time: consolidation of the last 1/3 of the cake during the last 2/3 of the filtration time. Typically filtration cycle stops when the filtrate flux < 0.01 L/s m^2. Cycle: filter, drain,

Table 5.4 Particle diameter and cake permeability and resistance.

Particle diameter, μm	Permeability $(\mu m)^2$	Intrinsic permeability, m^4/N s	Cake resistance, m/kg
1	10^{-3}–0.1 depending on ε	10^{-13}–10^{-10} depending on ε and liquid viscosity	10^{12}
10	0.1–10 depending on ε	10^{-12}–10^{-8} depending on ε and liquid viscosity	10^{10}
100	10–1000 depending on ε	10^{-10}–10^{-6} depending on ε and liquid viscosity	10^{8}
1000	1000–10^{5} depending on ε	2×10^{-8}–10^{-4} depending on ε and liquid viscosity	10^{6}
10000	10^{5}–10^{7} depending on ε		$< 10^{6}$

3 min, fill with wash, 2 min; wash with volume = 5 times the cake void volume; air blow; unload, 6 min.

The time required for constant flowrate filtration = double the time for constant pressure filtration to reach the same volume of filtrate.

Leaf, pressure vertical: cycle (for wet cake): filter 2–80 h; open, dump, close 0.4–4 h; cake volume/unit 0.1–2 m^3 corresponding to 5–90 m^2 filter area; leaves on 75 mm spacing. Δp 250–400 kPa. cake buildup flux: 0.001 kg/s m^2. Precoat: 0.68 kg/m^2 filter. solid flux for precoat 0.06–0.18 kg/s m^2. Filtrate flux through precoat = 0.1–1.1 L/s m^2.

Leaf, vacuum: cycle: precoat; filter 0.6–20 h; wash-clean. Cake formation rate 1.3 mm/s; solids flux 0.009–0.02 kg/s m^2 filter area. Cake thickness $<$ 10 cm. Area per unit 1.2–180 m^2; $\Delta p < 80$ kPa. Cake volume per unit: 0.1–4.5 m^3. Precoat: liquid filtrate flux for pharmaceuticals: 0.0003–0.0017 L/s m^2.

Leaf, horizontal pressure: cycle: precoat; filter 8 h; wash-clean. Availability per cycle for filtration 65 to 85 %. Cake thickness $<$ 10 cm; solids flux 0.001–0.04 kg/s m^2 of filter area; filtrate flux: 0.34–1 L/s m^2. Area per unit $<$ 280 m^2; Δp 100–700 kPa. Cake volume per unit: 0.2–4.5 m^3.

Plate, horizontal vacuum: cycle: precoat, filter, 70 h; wash-clean: 2–4 h. solids flux: 0.003 kg/s m^2 of filter area; area per unit $<$ 6 m^2; $\Delta p < 80$ kPa. Cake volume per unit: 0.06 m^3.

Plate and frame: cycle time: feed, wash, unload, clean; filtration: 10 min–24 h, usually 2–8 h; wash 10–25 min. Cake formation rate $<$ 0.7 mm/s; solids flux 0.02–0.07 kg/s m^2 of filter area; filtrate flux 0.004–0.8 L/s m^2 of filter area. Area per unit $<$ 500 m^2; Δp 400–1600 kPa. Cake thickness 2.5–5 mm. Cake volume per unit: 0.012–2 m^3 corresponding to 1 to 160 m^2 filter area for 25 mm plates; 0.024–4 m^3 for 50 mm plates.

Diaphragm plate and frame: cycle: fill, stop when about 80 % of the plate has been filled: 0.2–0.5 h; squeeze, 0.25–0.4 h; discharge, 0.33–0.4 h. Post squeeze volume/pre squeeze volume = 0.63–0.75. Cake volume 0.003–7.8 m^3. Fill at 700 kPa; squeeze at 0.85–1.5 mPa.

Deep bed: cycle: load 8 h; backwash 15 min; 93 % availability. Cake formation rate 1×10^{-5} mm/s; solids flux 0.02–0.5 g/s m^2 of filter area; filtrate flux 1.3–16.7 L/s m^2 of filter area with fluid loading decreasing as solids feed concentration increasing; the usual value is 2.7 L/s m^2. Area per unit $<$ 25 m^2; maximum depth 4.5 m. Gravity upflow or downflow with single or multiple media; pressure upflow or downflow. Use pressure units for small to medium fluid capacities where high terminal headloss is expected. Backwash at 6 L/s m^2.

Cartridge: cycle: days–months. Cake formation rate $<$ 0.000 067 mm/s; area per unit 0.3-0.7 and 1.5–15 m^2.

Continuous:

Drum, gravity: cake formation rate $>$ 3 mm/s; solids flux 0.15–0.47 kg/s m^2 of effective filter area. Actual filter area 0.7–15 m^2.

Drum, rotary vacuum: cake formation rate 0.01–17 mm/s; solids flux 0.008–0.16 kg/s m^2 of submerged filter area; filtrate flux 0.08–1 L/s m^2 of submerged filter area. Total drum area per unit 0.585 m^2; $\Delta p < 80$ kPa; rpm 0.4–1. Variety of options to remove cake:

- belt: submerged 35 %; air required 13–22 dm^3/s m^2. Thickness of cake: > 3–5 mm.
- roll: submerged 35 %; air required 13–22 dm^3/s m^2. Thickness of cake: > 1 mm.
- standard scraper: submerged 35 %; air required 13–22 dm^3/s m^2. Thickness of cake: > 6 mm.
- coil: submerged 35 %; air required 13–22 dm^3/s m^2. Thickness of cake: > 3–5 mm.
- string: submerged 35 %; air required 13–22 dm^3/s m^2. Thickness of cake: > 6 mm.

Wash ratio 1.5 water/solid. Agitate the feed pan to keep the feed solids in suspension but not interfere with cake formation. Solid flux for fine diameter minerals 0.09 kg/s m^2 of total drum area at pressure drop across the cake = 60 kPa; coarse diameter minerals 0.35 kg/s m^2 of total area at pressure drop across the cake = 10–20 kPa.

Drum, precoat rotary vacuum: submerged 35, 55, 85 %. Usually 85 %; air required 28–42 dm^3/s m^2. Thickness of cake: < 3 mm. Need low viscosity liquid. Filtrate flux: 0.004–0.07 L/s m^2. Procedure to form the precoat: use maximum drum speed. gradually increase the submergence from 5–85 %.

Disk, rotary vacuum: cake formation rate 0.01–1.6 mm/s; solids flux 0.01–0.55 kg/s m^2 of submerged filter area. Total disk area per unit 0.4–300 m^2; $\Delta p < 80$ kPa. Submergence 35 %; cake thickness > 13 mm. Air/vacuum: 8–25 dm^3/s m^2.

Table/pan gravity: cake formation rate 0.5–16 mm/s; solids flux 0.02–0.25 kg/s m^2. Total table area per unit 8–200 m^2; $\Delta p < 80$ kPa. Cake thickness > 20–25 mm. Air vacuum needed: 10–40 dm^3/s m^2.

Belt, gravity: dilute sludges with 0.5–8 % solids typically dewater in 20–80 s. Length 2.4 m. (Often combined with downstream belt press.)

Belt, vacuum: solids flux 0.08–2.2 kg/s m^2; filtrate flux 0.038–1 L/sm^2 area: for particles < 0.3 mm, 0.08–2 L/s m^2; for particles > 0.3 mm, 2–12 L/s m^2 . Area per unit 1–120 m^2; $\Delta p < 80$ kPa; cake thickness 5–100 mm, usually 12 mm. Size on the filtrate flux. Vacuum air 25 dm^3/s m^2. Velocity < 0.75 m/s. Wash ratio 1.1–1.2 water/solids; width < 3 m. 22 h continuous operation plus 2 h routine maintenance. 1 L/s of sludge/m width.

Belt press: belt width 0.5–2.6 m with areas from 6.9–35.7 m^2; belt speed 04–0.15 m/s. For feed concentrations < 5 %, usually liquid dewatering controls: liquid load 2.5–3.5 L/s m of belt width. For feed concentrations > 5 % solids throughput limiting: 0.15–0.275 kg/s m of belt width. $\Delta p < 80$ kPa.

Revolving drum: (microscreen). For waste water application with 6.7 L/s m^2 loading.

Rotary press: < 3 rpm; dewatering area: 1.25–5 m^2. Solids flux 0.003–0.127 kg/s m^2 depending on the feed solids concentration in range 0.1–6 % solids. Product 20–75 % solids. See also Sections 5.17 and 9.11.

Ultrafiltration: see Section 4.22.

Microfiltration: see Section 4.23.
Dissolved air flotation, DAF: see Section 5.16.

- *Good Practice*

Precoat: 0.75 kg/m^2 to give a precoat thickness of 1.6 mm. Rate for precoat: concentration between 0.3 and 5 % w/w and at a rate of 0.7–1.4 L/s m^2. This should give a $\Delta p = 14$ kPa. For leaf or rotary filters, maintain consistent pressure differential across cake once the cake is formed.

Consider adding body feed continuously when filtering gelatinous species.

- *Trouble Shooting*

"Poor clarity": leak/cracks in cake/partially blinded septa/cake washing too fast/flashing of filtrate/air in filter of feed liquid/changes in liquid properties/incorrect filter aid/change in temperature of pH/small diameter particles in feed than design/process upset.
"Short cycle/high pressure/low flow": flow lines too small/obstruction in outlet line/pump sucking air/pressure differential too low/wide fluctuations in feedrate/air trapped in filter/too high a filtration rate.

5.15
Leacher

- *Area of Application*

Percolation leach: particle diameter > 700 μm; liquid concentration 0.8 to 20 %; relatively fragile solid (e.g. seeds)

Immersion leach: particle diameter < 700 μm; liquid concentration < 20 %; relatively robust solids (e.g. minerals)

Combo leach: high feed concentration of solute, relatively robust solid.

Supercritical solvent: usually CO_2 for small capacity of high value products especially for temperature sensitive foods, cosmetics and pharmaceuticals.

- *Guidelines*

– Percolation leach:

High solute leach rate; solvent percolation through the bed > 3 mm/s; 3–10 L/s m^2; bed permeability > 200 μm^2; low feed concentration of solute; 0.5–0.7 kg liquid solvent carryover from stage to stage/kg inert solid; solute diffusivities of essential oils 10^{-7}–10^{-14} cm^2/s; of sugar in sugar beets 10^{-5} cm^2/s. Tend to use series of countercurrent contactors with time for diffusion and separation in each stage.
Rotating cells/baskets: capacity: 30 kg/s flaked soybeans in 10 m diameter unit; prepressed cottonseed × 0.66; unpressed cottonseed × 0.33; sugar cane × 0.33; canola × 0.33.
Buckets: 10 kg/s flaked soybeans with 40 buckets.

Belt: 10 kg/s flaked soybeans with belt 20 m long × 0.3 m wide; 2–5 kg solvent makeup/Mg oil seed feed.
Drag-chain: 10 kg/s flaked soybeans with belt 20 m long.
– Immersion leach:

Low solute leach rate. Product of residence time × concentration of leachant for acid leach = constant for a given particles diameter. Tend to have a separate leacher followed by system to separate and wash solids.
Pachuca: plus CCD, settler; particle diameter < 70 μm; solids 30–60 % w/w; agitator 0.07–0.2 kW/m^3; for CCD 1.5–2 kg liquid solvent carryover/kg inert solid.
Autoclaves: plus CCD: particle diameter < 70 μm; solids 30–60 % w/w; 0.7–1.3 kW/m^3.
– Combo leach:

Tend to use countercurrent contactors with time for diffusion and separation in each stage.
Sloped diffuser with rotating screw: 10 kg/s sugar beets in 2 m diameter.
Column with rotating screw: 10 kg/s sugar beets in 0.3 m diameter unit.
Trough-scroll: 10 kg/s sugar beets in 3 troughs.
Rotary diffuser: 10 kg/s sugar beets in 5 m diam. unit.
– Supercritical solvents:

Batch process operating at $T > 31$ °C and pressures > 7.3 MPa. Solvency is intermediate between nonpolar and weakly polar solvents. Contact times 0.1 × usual leach times.

- *Good Practice*

Rate of dissolution of solid minerals increases by factor 1.5–2 with 10 °C increase.

Supercritical carbon dioxide: manage aqueous contamination or use alloys.

5.16
Liquid–Solid: Dissolved Air Flotation, DAF

- *Area of Application*

Particle diameter 0.1 to 50 μm with typical target diameter 2 μm; feed solid concentration 0.002 to 0.08 % w/w; > 80 % removal efficiency.

- *Guidelines*

Bubble size 70 to 90 μm; air: solids 0.005 to 0.1 kg/kg; liquid loading 0.5 to 2 L/s m^2. liquid residence time 20 to 200 min with a minimum depth of 1.8 m. If feed concentration is < 400 mg/L use about 50 % recycle.

5.17
Liquid–Solid: Expeller and Hydraulic Press

- *Area of Application*

Particle diameter $>$ 1 cm; liquid concentration 10 to 60 %.

- *Guidelines*

Batch:

Hydraulic press: 30–60 MPa. Cycle: load, press, discharge.

Continuous:

Expeller:

– expelling essential oils: Fullpress capacity 0.02–5 kg/s; prepress capacity (which will be followed by leaching, Section 5.15) = 2 × full press capacity (where only expelling is used to remove the essential oils); prepressing 2.2 Mg/d cottonseed/rpm; relative capacities depend on the seed being processed: cottonseed and soybean × 1; copra, wet corn germ, canola × 0.75–0.82; flax seed, safflower × 0.62; power 100–200 kJ/kg cottonseed prepress with the value increasing with feed capacity.

– dewatering polymers; capacity 1–1.5 kg/s; power 200 increasing to 450 kJ/kg as capacity increases. Related topics: dryer, Section 5.6, screens, Section 5.7, and centrifugal filters, Section 5.13.

5.18
Solid–Solid: General Selection

To separate solids having about the same density and particle size, use flotation, electrostatic and magnetic separators. Particle diameter must be $>$ 20 μm.

To separate solids having about the same density but with a range of particle size, separate based on cut diameter and use air or liquid *classifiers* such as cyclones, hydrocyclones or spiral classifiers: Particle size 25–2000 μm; feed solids concentration 5 to 40 %. Cut diameter is the particle diameter that has equal chance to report to either the overflow or the underflow streams.

To separate solids having about the same particle size but with a different density, separate based on cut density and use *Concentrators* such as jigs, tables, sluices or Dense Media Separators, DMS. Particle diameter must be $>$ 40 μm. Concentrate before flotation if the feed assay of mineral is $<$ 0.3 %.

To separate solids having different densities and particles sizes, then use combinations, such as a screen to provide narrow size range followed by concentrators.

For minerals, the liberation size is 0.01 of the diameter of the mineral crystal.

5.19
Froth Flotation

- *Area of Application*

For systems with a narrow range of both density differences and particle size. Density ratio 1–1.3; particle diameter usually 20–50 μm although occasionally the diameter could be as large as 200 μm. Feed concentration of target solid $> 0.5\,\%$.

- *Guidelines*

Condition the solids to alter the wettability of the mineral and the gangue. The fundamental surface wettability for sulfide ores is different from oxides, silicates and salt-type minerals. pH is a critical variable.

Typical conditioning chemical additions include collector about 0.01–0.1 kg/Mg solids, frother about 0.01–0.05 kg/Mg solids, activator about 1–4 kg/Mg solids, depressant about 0.02–2 kg/Mg solids.

Allow 6 min contact for conditioning. Air: 1–1.5 m^3/m^3. Bubble size about 1000 μm. Flotation rate constant is 0.2–1 min^{-1}; sink rate constant is 0.005 min^{-1}.

Flotation cells: working volume = 80 % of nominal cell volume.

Mechanical cell: for fast float, sequential separation and relatively coarse particle diameter; 1.6–6 kW/m^3 cell volume with usual 2.6–6 kW/m^3 cell volume. Larger values used for smaller sized cells.

Pneumatic cell for relatively dilute feed concentrations and smaller particle diameters. Air blower 0.5 kW/m^3 cell volume. Typical solids throughput 0.4–0.8 kg/s m^3; feed concentration 10–40 % w/w; air escape velocity 0.02 m/s. Float times 6–20 min.

Typically three units: the rougher, cleaner and scavenger.

Rougher: feed concentration: 30 % w/w; modest amount of flotation agent; moderate agitation; relative flotation constant: 1. Usually 1–2.5 m^3 cell volume/kg; 0.8 kg/s m^3.

Cleaner: feed concentration: 10 % w/w; more flotation agent; gentle agitation; relative flotation constant: 0.5. Tails are often reground, sometimes thickened. More flotation time is required. Usually 2–6 m^3 cell volume/kg; 0.4 kg/s m^3.

Scavenger: feed concentration: 30 % w/w; much more flotation agent; intense agitation; relative flotation constant: 2. Float is often reground.

Rougher + cleaner: for single mineral that is easy to float and grade is important.

Rougher + scavenger: for single mineral that is not easy to float and both grade and recovery are important.

Rougher + scavenger + cleaner + scavenger: for highly concentrated feed that is easy to float.

- *Good Practice*

Fresh grinds are easier to float. Conditioning time is critical. Fluctuations in flowrate and solids concentration affect mainly the conditioning and not the flotation. Consider softening the water. Deslime the feed to remove particles of diameter < 20 μm.

5.20
Electrostatic

- *Area of Application*

For systems with dry particles, no slimes or organic coatings, a narrow range of both density differences and particle size and a difference in conductivity. Particle diameter 40–3000 μm: usually 80 to 1000 μm; feed concentration of target species 5 to 75 %. Good conductors have relative permittivity > 11; poor or nonconductors have relative permittivity < 10; threshold voltage to make species conducting is 1–10 kV/cm.

- *Guidelines*

Select voltage where one species conducts and the other does not.

Corona-active electrode rotary drum: handles wide range of particle diameters from 75–1000 μm; high capacity < 0.75 kg/s m of drum width; high efficiency 95 %; separates good from poor conductors. 0–40 kV DC, 0.5–1 mA/electrode; insensitive to humidity and temperature; often can recycle the middlings with recycling 10–30 % OK.

Active electrode rotary drum: trouble handling fines; capacity < 0.5 kg/s m of drum width, moderate efficiency; separates good from poor conductors or two semiconductors. 0–30 kV DC, 0.04 mA/electrode. The voltage gradient must be sufficient to charge target particles. operates best in a controlled environment.

For roughers and scavengers: set the active polarity so that the valuable minerals become conductors.

For cleaners and recleaners: set the active polarity so that the gangue and middlings become the conductors.

Collect middlings if the valuable target is trapped in the gangue; if the density of the nonconducting is heavier than the conducting and if the feed has a wide range of particle diameters.

- *Good Practice*

Consider increasing the temperature because for every 50 °C increase the conductivity often increases by a factor of 10.

5.21
Magnetic

- *Area of Application*

For systems with a narrow range of both density differences and particle size; particle diameter > 50 μm; feed concentration of target species 0.4 to 40 %.

Magnetization = product of the mass magnetic susceptibility and the magnetic field, T m^3/kg

Ferromagnetic species: magnetization > 10^{-4} T m^3/kg.

Paramagnetic species: magnetization 10^{-8} < value < 10^{-5} T m^3/kg.

Batch: cycle: load, clean.

Plate: batch: magnetization > 10^{-4} T m^3/kg; particle diameter > 6 mm; feed concentration of magnetic < 0.01 % w/w. Primarily to remove tramp ferrous metal.

Grate: batch: magnetization > 10^{-4} T m^3/kg; particle diameter < 1.8 mm; feed concentration of magnetic < 0.01 % w/w. Primarily to remove tramp ferrous metal.

WHGMS (wire, Kolm-Marston): batch: magnetization > 2 × 10^{-9} T m^3/kg; particle diameter 1–30 μm; feed concentration of magnetic < 0.05 % w/w. Solids concentration in water 20 %.

WHGMS (grooves, Jones): batch: magnetization > 2 × 10^{-9} T m^3/kg; particle diameter 200–1000 μm; feed concentration of magnetic < 50 % w/w; solids concentration in water < 50 %.

Continuous:

Pulley: magnetization > 10^{-4} T m^3/kg; particle diameter > 6 mm; feed concentration of magnetic < 0.01 % w/w. Primarily to remove tramp ferrous metal.

Belts/cross or in-line: magnetization > 10^{-4} T m^3/kg; particle diameter > 6 mm; feed concentration of magnetic 0.01–10 % w/w. Primarily to remove tramp ferrous metal.

Belts/cross HGMS: magnetization > 10^{-4} T m^3/kg; particle diameter 150–1500 μm; feed concentration of magnetic 0.5–2 % w/w. Primarily to remove tramp ferrous metal.

Wet belt: magnetization > 10^{-4} T m^3/kg; particle diameter 100–2500 μm; feed concentration of magnetic 0.3–2 % w/w.

Dry drum/LGMS: magnetization > 2 × 10^{-5} T m^3/kg; particle diameter 0.1–100 mm; feed concentration of magnetic 1.5–75 % w/w.

Dry drum high speed/MGMS: magnetization > 2 × 10^{-5} T m^3/kg; particle diameter 100 μm–30 mm; feed concentration of magnetic < 10 % w/w.

Dry rotor HGMS (induction): magnetization > 4 × 10^{-8} T m^3/kg; particle diameter 70–2000 μm; feed concentration of magnetic < 0.05 w/w.

Wet drum/LGMS: magnetization > 10^{-4} T m^3/kg; particle diameter 70 μm–6 mm; feed concentration of magnetic > 25 % w/w.

WHGMS (carousel, BoxMag, Frantz): magnetization > 2 × 10^{-9} T m^3/kg; particle diameter 200–1000 μm; feed concentration of magnetic < 50 % w/w; solids concentration in water < 50 %.

- *Guidelines*

Consider wet processing for particle diameter < 6 mm to minimize dusting and electrostatics.

For particle diameter > 150 μm prefer wet belt; < 150 μm prefer wet drum.

Match magnetic gradient to the diameter of the particles. Match the machine to the liberation size (liberation size is 0.01 of the diameter of the mineral crystal, Section 5.18).

For wet machines pump 4 Mg water/Mg solids although 90 % of the water can be recirculated.

Batch:

Plate: batch, remove tramp metal from solids moving in ducts or on conveying belt. Usually keep burden depth < 20 cm; magnetic field 0.3 T; gradient 0.04 T/cm.

Grate: batch, magnetic field 0.05 T; gradient 0.02–0.5 T/cm.

WHGMS (wires, Kolm-Marsden): batch; 100 μm wires; 10–80 kg/s per pole; 10–160 L/s m^2 gap cross sectional area; solids concentration in water 20–25 % w/w; induced magnetic field 1–2 T; gradient 1000 T/cm; 35–42 kW/pole; 1–18 kJ/kg solids for magnet and 4.5 kJ/kg pumping; solids loading before unload 0.1–0.5 Mg/m^3 of matrix.

WHGMS (grooves): batch, 0.03–0.04 kg/s; 8–12 kg/s.pole; solids in water < 40 % w/w; induced magnetic field 1–2 T; gradient 0.1–1000 T/cm, usually 10–200 T/cm; 16 kW/pole; 1.8 kJ/kg solids collected for magnet; feed < 50 %w/w solids in water.

Continuous:

Pulley: remove tramp metal from solids exiting from a conveyor belt. Usually keep burden depth < 20 cm; magnetic field 0.1–0.3; gradient 0.04 T/cm.

Belts/cross or in-line: < 1 kg/s.m width; gradient 0.1–1 T/cm; belt speed 1 to 2 m/s.

Belt with rotating disk: 0.2 kg/s m width; magnetic field 0.04–0.1 T; gradient 0.1–1000 T/cm.

Wet belt: 3 kg/s.m width; magnetic field 0.3 T; gradient 0.1–1 T/cm.

Dry drum/LGMS: 80–200 kg/s m width of drum, 60–90 dm^3/s.m width for drum diameter < 1.2 m; 25–35 rpm, peripheral speed 1–1.5 m/s; magnetic field 0.04–0.1 T; gradient 0.001–0.5 T/cm; drive power 2–5 kW/m width.

Dry drum high speed/MGMS: 0.5–20 kg/s m width, 0.8–20 dm^3/s m width with capacity decreasing as magnetization decreasing; 2.5–7 m/s with peripheral speed increasing as the number of poles increases from 6 to 44; 50–200 rpm; as particle diameter decreases, the number of poles and the rpm increases; for highest recovery operate at lower rpm; for higher incoming concentration of mags and more efficient recovery of middlings operate at higher speeds; magnetic field 0.04–0.1 T; gradient 0.001–0.5 T/cm; drive power 10 kW/m width.

Dry rotor HGMS (induction): 0.8–1 kg/s m width; induced magnetic field 1–2 T; gradient 0.001–1000 T/cm, usually 10 T/cm.

Wet drum/LGMS: 1–5 kg/s m width; 4–25 L/s m width; water velocity 0.5 m/s; drum peripheral speed 2 m/s; 20 rpm; diameter 0.75 m; magnetic field 0.04–0.1 T; gradient 0.001–0.5 T/cm; constraint is the amount of magnetic material discharged from the drum; feed < 25 % w/w solids in water; drive power 1–2 kW/m width.

WHGMS (carousel, BoxMag, Frantz): continuous 1–5 kg/s pole, 10–50 L/s m^2 gap cross sectional area; usual canister cross sectional area 0.5–3 m^2; induced magnetic field 0.1–2 T; 1–6 MJ/Mg solids collected; feed solids concentration in water 30–50 %.

- *Good Practice*

For compounds containing ferric species, consider roasting particles at 55 °C to increase magnetism.

For dry machines, keep the moisture in the feed < 0.5 %.

For high speed dry drum particle diameter in the feed < 3.2 mm use a star feeder; particle diameter > 3.2 mm use vibrator.

5.22
Hydrocyclones

For solid–solid separations; see Sections 5.5 and 5.9 for separation of liquid–solid for Guidelines.

- *Area of Application*

Cut diameter 5 to 1000 μm; capacities up to 50 kg/s per unit.

5.23
Air Classifiers

- *Area of Application*

Separate solids with similar densities based on cut diameter. Conveying fluid is a gas such as air. Contrast with hydrocylcones and spiral classifiers where the conveying fluid is liquid such as water. Particle cut diameter 30 to 1000 μm. Particle diameter > 1.5 μm. Feed concentration of target solid 4 to 60 % w/w.

- *Guidelines*

Zig-zag: cut diameter 100 to 10 000 μm; capacity 0.01 to 0.08 kg/s.
Gas centrifugal separator: cut diameter > 20 μm; capacity < 15 kg/s.
Gas cyclone: cut diameter 10 to 50 μm; capacity < 15 kg/s.
Gas gravitational inertial classifier, GIC: cut diameter 50 to 200 μm; capacity < 300 kg/s.
Gas Mikroplex spiral: cut diameter 2 to 20 μm; capacity 0.01 to 1 kg/s.
Gas Nauta-Kosakawa: cut diameter 3 to 300 μm; capacity 0.01 to 1 kg/s.
Gas classifiers for MSW: cut diameter > 100 μm with capacities up to 20 kg/s. Solids to gas ratio 2 to 8 w/w. Solids loading 2 to 4 kg/s m^2.

5.24
Rake Classifiers

Superceded by hydrocyclones. (Sections 5.22 and 5.9)

5.25
Spiral Classifiers

- *Area of Application*

Bird number (mass of solids with a ±0.1 density variation from the cut density) < 15; particle cut diameter > 50 μm but usually 1000 to 20 000 μm.

- *Guidelines*

Two types: cut diameter > 200 μm use high weir configuration; cut diameter < 200 μm use submerged spiral. Size based on the target exit overflow concentration and "limiting" particle diameter. Diameter of the limiting particle should have a settling velocity double that of the cut diameter (cut diameter is about 70 % of the limiting diameter).

Separation efficiency is 50 %; that is, use double the cross section area obtained from the settling velocity of the "limiting" particle diameter.

Capacity 2 to 250 kg/s.

Underflow solids capacity is a function of the spiral diameter and solids density; independent of the separation. Angle of inclination 16°.

High weir: 1 m^2 pool area produces about 5 kg/s dry solids in the overflow with 400 μm limiting diameter or about 280 μm cut diameter and 30 % concentration.

Submerged weir: 1 m^2 pool area produces about 0.5 kg/s dry solids in the overflow with 150 μm limiting diameter or about 100 μm cut diameter and 16 % concentration.

For both configurations, increasing the area by a factor of 10 increases the amount of overflow solids by 10 with the same cut and limiting diameters and overflow concentrations.

Rotational speed increases with the cut diameter.

- *Good Practice*

Feed concentration between 10 to 50 % w/w solids. Dilution water is the important operating variable.

5.26
Jig Concentrators

- *Area of Application*

Bird no. (mass of solids with a ±0.1 density variation from the cut density) < 15; relative density ratio 2 to 2.5 and particle diameter 2 to 10 mm. Feed concentration 1.5 to 30 % w/w.

- *Guidelines*

Loading 1 to 8 kg/s m^2 with loading increasing with increase in particle diameter. Power 1 kW/m^2 and water usage 13 L/s m^2.

- *Good Practice*

Keep feedrate constant. Add surge and storage tanks to aid control. Keep feed free from a high portion of fines.

5.27
Table Concentrators

- *Area of Application*

Bird number (mass of solids with a ±0.1 density variation from the cut density) < 15; relative density ratio > 2 to 2.5; usual particle diameter 70 to 2000 μm; only one valuable mineral. Tilting frames: density ratio 2.5 and particle diameter > 50 μm ranging to density ratio of 1.25 with particle diameter > 5 mm. Holman slimes table for < 70 μm.

- *Guidelines*

7 to 12 m^2 per unit; 6° incline; usual capacity 0.03 to 0.06 kg/s m^2. The higher the Bird no., the lower the capacity, power 0.15 kW/m^2; wash water 0.1 to 0.3 L/s m^2.

- *Good Practice*

Constant mass feedrate and constant physical properties.

5.28
Sluice Concentrators

- *Area of Application*

Bird number (mass of solids with a ±0.1 density variation from the cut density) < 15; relative density ratio > 1.8; usual particle diameter 400 to 3000 μm; only one valuable mineral.

- *Guidelines*

Humphreys and Reichert Spiral: capacity/unit: 0.25 to 1.5 kg/s to handle particle diameters 75 μm to 2 mm.

- *Good Practice*

Constant feedrate and constant diameter of heavy particles.

5.29
Dense Media Concentrators, DMS

- *Area of Application*

Systems with a narrow range of particle size but with a range in densities. Bird number (mass of solids with a ± 0.1 density variation from the cut density) 15 $>$ Bi $>$ 25; relative density ratio $>$ 1.25 to 1.5; usual particle diameter $>$ 10 mm.

- *Guidelines*

Choose media with density between desired cuts. For media with density 1.2 to 2.2 use magnetite; for 2.9 to 3.4 use ferrosilicon. Use mixtures for intermediate densities: 2.5 to 15 kg/s m^2 of pool area.

- *Good Practice*

Prescreen feed to eliminate fines and clay. Consider DMS before liberation grinding.

5.30
Screens

(see also Section 5.7 for liquid–solid separation)

Screens can be used to:

– wash or dewater, see Section 5.7.

– scalp: remove 5 % of oversize and have $>$ 50 % half size.

– screen: remove fines $<$ 425 μm.

– size or separate: choice depends on particle size: coarse $>$ 4.75 mm; intermediate size between 425 and 4750 μm and fines between 45 and 425 μm; see filters, Section 5.14, centrifugal filters, Section 5.13 and expellers, Section 5.17.

- *Area of Application*

Grizzly: particle diameter 15 to 30 cm and $>$ 30 cm; Use: primarily to scalp, screen fines.

– rod grizzly: particle diameter 8 to 30 cm. Use: primarily to scalp.

Rod deck screen: particle diameter 0.75 to 8 cm. Use: scalp, dewater and separate.

Sieve bend: particle diameter: 45 to 2000 μm; Use: dewater, separate intermediate and fines: 45 to 4750 μm.

Revolving screen: Trommel particle diameter 3 mm to 50 cm; feed solids concentration 5 to 25 %. Use: separation.

Revolving screen: centrifugal: particle diameter: 400 to 1200 μm; Use: dewater, separate intermediate diameters and use high speed for fines.

Revolving screen: probability: particle diameter < 6 mm; Use: separate intermediate and fines 45 to 4750 μm.

High speed vibrating horizontal screen (600 to 3000 rpm with low amplitude < 2.5 cm): 3 to 100 mm. Use for dense granular materials > 0.3 Mg/m^3 Use: wash, dewater, scalp, screen fines, separate coarse.

High speed vibrating inclined screen (600 to 7000 rpm with low amplitude < 2.5 cm): 200 to 100 000 μm. Use for dense granular > 0.3 Mg/m^3. Use: wash, scalp and separation of wide range of particle diameters.

Low speed oscillating screen (25 to 500 rpm with 15 to 30 mm amplitude): 74 to 12 000 μm especially for lower density solids; although some suppliers recommend this for only $> 12\,000$ μm. Use: separate.

Gyratory in plane of the screen (500 to 600 rpm; 5° inclination): fine separations particle diameter 50 to 4000 μm.

- *Guidelines*

Screen: efficiency 85 to 95 %; length/width of screen 2:1 to 1.5:1; rate of travel of solids along the screen face 0.3 to 0.5 m/s. The flux of solids passing through the screen is about: for coarse particle diameters, 2 to 5 kg/s m^2; for intermediate particle diameters 0.4 to 4 kg/s m^2; for fine particle diameters 0.08 to 0.4 kg/s m^2 with fluxes decreasing as the density decreases.

Trommels: rotational speed should be slow enough that the particles free fall (about 45 % of the transition rpm). L/D = 2:1 to 5:1; residence time 30 to 60 s with flux rates of 0.03 to 0.1 kg/s m^2.

- *Good Practice*

If damp or sticky, predry or use heater above the screen to reduce moisture to < 3 %. Avoid resonance frequencies. Usual angle of operation is 12 to 18°; for wet, inclined vibrating screen to 7 to 11°. Capacity decreases if the angle of inclination is too high. Blinding is mainly caused by material that is 1 to 1.5 times the hole size. Feed thickness should not exceed 4 × aperture size for 1.6 Mg/m^3; and not exceed 2 to 3 × aperture size for 0.8 Mg/m^3.

- *Trouble Shooting*

"Capacity decreases": angle of inclination too high/blinding.

References

Turner, J. et al., 1999 (June), *HP*, 119.

Woods, D. R., 1994, *Process Design and Engineering Practice*, Prentice Hall, Englewood Cliffs, NJ.

6
Reactors

In this chapter the focus is on reactors. First we introduce the general factors that affect the selection of the reactor. In Section 6.2 are given general guidelines. Section 6.3 considers details for different types of reactions that affect the size of the reactor. The rest of the chapter discusses some specifics about the different types of reactor. Section 6.4 considers burners. Plug flow tubular reactors, PFTR, are considered in Sections 6.5 to 6.26. Stirred tanks reactors, STR, are considered in Section 6.27 to 6.33. Finally Sections 6.34 to 6.37 explore combining reactors with other unit operations such as distillation, extrusion, membranes and vacuum pumps.

6.1
Factors Affecting the Choice of Reactor

The general selection procedure or "sizing map" for reactors is given in Fig. 6.1. In this map we start at the upper left-hand side by considering the products: issues of sustainability, the impact on the environment and the hazards associated with the product. Naturally we need to know the production capacity or flow and concentration or purity of the product. The final selection of the reactor is an optimization based on the selected design criteria and is shown in the bottom right-hand corner of Fig. 6.1. Unlike the sizing of most process equipment, where the optimization function is cost, for reactors the optimization criteria may be selectivity, yield, flexibility, ability to control, cost or health and safety. The design criterion is usually selectivity or cost but Table 6.1 provides guidelines for selecting the criterion. The design variable is usually the contact time in the reactor.

To move through the sizing process we consider various reactants, top RHS of Fig. 6.1 and select possible reaction routes from the chemistry, understand competing and unwanted side reactions, select the phases and decide if a catalyst should be used. As illustrated on the RHS of Fig. 6.1, having a catalyst introduces questions of selectivity, activity, size, porosity, life, contaminants and poisons that interfere with the catalyst's function and temperature limitations. Our choice of reaction route also sets the heat release from the reaction; highly exothermic or

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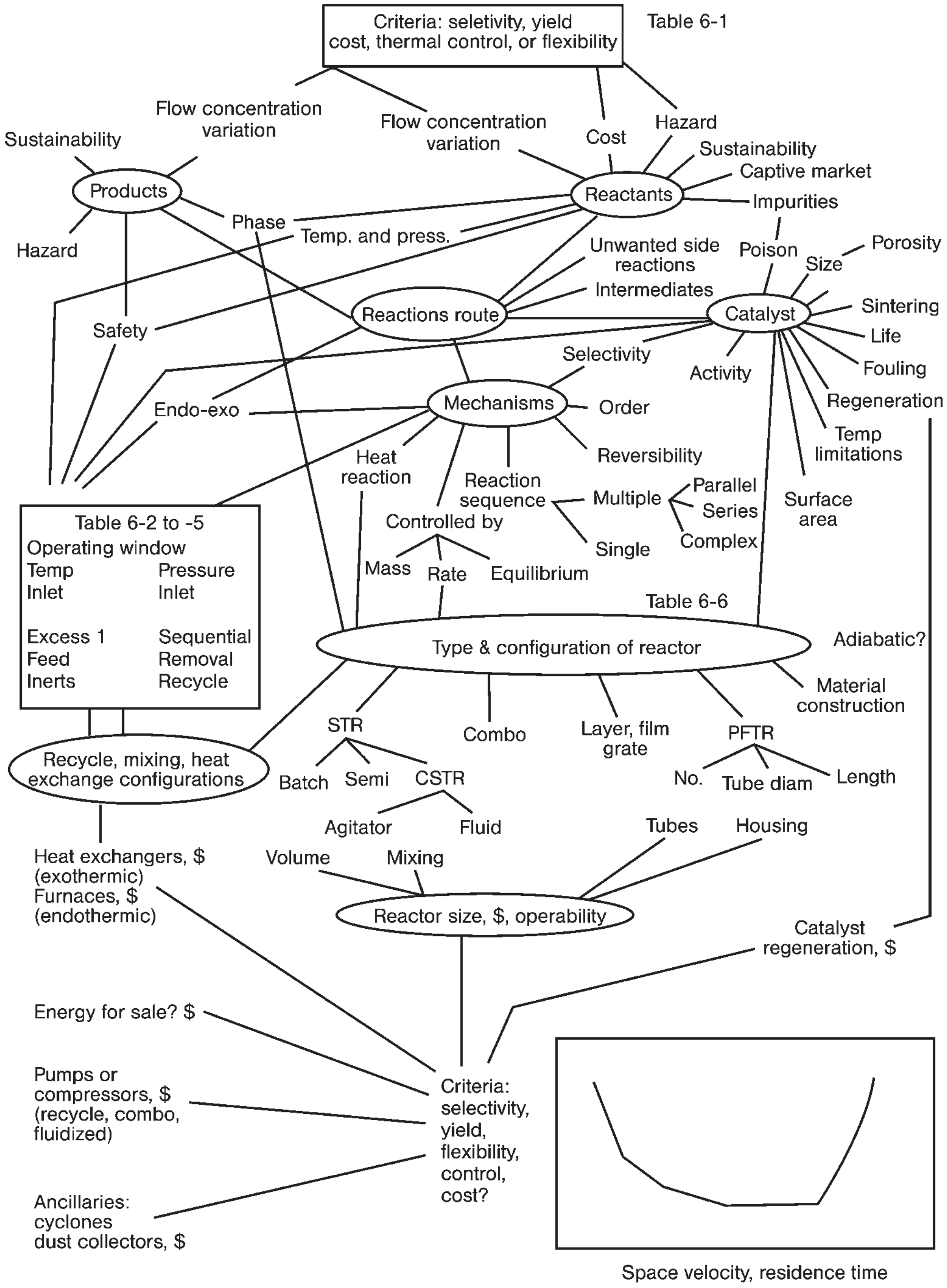

Figure 6.1 Sizing map.

Table 6.1 Criteria for selecting reactor.

Criterion to use:	**If the following issues apply:**			
	Cost of raw materials	**Ease of recovery of unreactea feed**	**Reactions**	**Variability in demand, feed-stocks, product specifications**
Selectivity	cheap	easy	multiple reactions producing byproducts	
Yield	expensive	difficult		
Flexibility				great variation
Cost			single reaction	
Thermal control			highly exothermic	
Health and safety; environmental, hazards.			Highly endothermic or exothermic reactions, see Table 6-3. Hazardous reactions: azides, peroxides, perchlorates or nitro compounds. Reactions of the type*: decomposition, nitration, oxidation, polymerization, alkylation, amination, combustion, condensation, diazotization, halogenation or hydrogenation.	

* Only *some* of the reactions in each type pose a hazard.

endothermic? Highly exothermic reactions sensitize us to the concern for reactor safety and reliability.

Thus we are led, through an iterative process, to the selection of the conditions for operating the reactor (called the operating window and shown midway on the LHS of Fig. 6.1). Start first with the chemistry of the target and unwanted competing reactions. Use Le Chatelier's principle, then equilibrium considerations and finally reaction rates – if needed – to suggest temperatures and pressures that will maximize the target reaction and minimize the unwanted reactions. Use Table 6.2 to select the use of recycle, inerts or excess reactants and temperature. The overall theme is to have the desired reaction to proceed quickly and safely. A major consideration is that many reactions are highly exo- or endothermic.

A highly endothermic reaction may extinguish the reaction before it is complete. Highly exothermic reactions require a strategy for the safe control of the heat release. Three options to control the heat release are: (i) dilute the reactants or add inerts so that the heat release is slower and more manageable, (ii) use undiluted reactants and control the rate of reaction (or mass transfer) by using lower temperatures and (iii) use undiluted reactants and control the heat removal via reactor design and process control to manage the non-adiabatic operation. Usually we select options 2 or 3. Table 6.3 lists a range of dimensionless groups that can be used to identify the amount of heat released, the speed of the reaction and the

Table 6.2 Selecting operating window with respect to temperature, inerts and recycle.

Heat of reaction	Reversible reaction?	Order of irreversible reactions	Inlet temperature	Control of temperature	
				adiabatic	**non-adiabatic**
endothermic	yes		**T** = (Max. catalyst temp. – 25 °C)	add **inerts**	Use method to add heat?
	no	Order of the target (a1) > order of the undesired (a2)		add **excess of one reactant**	
exothermic (typical of many reactions in the liquid phase)	yes			add **inerts and recyle**	Use configuration or methods to remove heat.
	no	Order of target reaction (a1) > order of the undesired (a2)	**T** = (Max. catalyst temp. – 25 °C)		

cooling capacity of the system. Consider the product of $\Delta T_{ad}{}^{+}$ with the Arrhenius number to be a measure of the heat released. If the product is > 5 to 10 for irreversible reactions, then there is the potential for a thermal runaway reaction. Considering the relative importance of the speed of the reaction and the cooling capacity: if the ratio of the Damkohler number to the modified Stanton number is < 0.1, then a batch reactor is probably safe. But if the ratio is > 1, then a batch reactor is likely to be unsafe; a semibatch operation will allow the gradual addition of the reactants to better control the heat release. The combination of Tables 6.2 and 6.3 gives starting guidelines for the range of temperature. Table 6.4 adds another perspective for the selection of the temperature.

Table 6.5 gives guidelines for selecting the pressure for the operating window. The pressure and temperature affect the strength of the material. For example, Fig. 6.2 shows the code design for pressure vessels, coded 300, 400, 600, 1500 and 2500 for carbon steel. At temperatures above 350 °C, the strength of carbon steel decreases so that carbon molybdenum steels are preferred. Also shown in this figure are the behaviors of steel alloys: austenitic steels and chrome molybdenum.

Ideally, we prefer an operating window between 20 and 250 °C and 0.1 to 1 MPa so that we can use water as a coolant and steam for heating. This window is shown in Fig. 6.2. Also plotted (as data points) are the operating conditions for a variety of commercial reactions. Many fall in the ideal target window. If a catalyst is used this adds additional temperature constraints to the constraints posed by the strength of materials. Those reactions at the higher temperatures tend to be homogeneous reactions.

Table 6.3 Parameters related to hazard and reactor safety.

	Word definition	**Equation**	**Significant value**	**So what?**
Heat of reaction, ΔH_{react}	*Highly exothermic* or highly endothermic		$>$ 150 MJ/kmol	safety concern
$\Delta T^{+}_{\text{ad.}}$ Dimensionless **Adiabatic temperature increase**, where the adiabatic temperature rise $\Delta T_{ad} = (T_{ad} - T_o)$ is divided by the inlet temperature	adiabatic temperature change accompanying complete consumption of the reactant without regard to equilibrium considerations divided by inlet temperature	= heat of reaction × mol fraction major reactant at inlet/average gaseous molar heat capacity $= (-\Delta H_{react})\ x_{\text{Ao}}/c_{\text{p}}T$ $= (-\Delta H_{react})\ c_{\text{Ao}}/\varrho_{\text{G}}\ c_{\text{p}}T$	safe if $\Delta T_{\text{ad}} < 50\,°\text{C}$	If $>$ 50 °C, explore options to design the reactor and manage the heat release.
Arrhenius number, Arr no.	activation energy divided by the ideal gas constant × absolute temperature	$E/\ RT$ where E = activation energy	typical range is 10–40, and 5–30 for gas–solid or liquid–solid reactions	Used in reaction rates and in safety analysis as part of the **Thermal Reaction no.**
Arr no. ($\Delta T^{+}_{\text{ad.}}$) **Thermal reaction number** or Excessive heat generation (some authors assign this the symbol β and others $\gamma\beta$)	adiabatic temperature increase × heat generation potential	$(E/RT)\ (\Delta T_{\text{ad}}/T)$ $(\text{Arr})\ (\Delta T^{+}_{\text{ad.}})$	range 1–50; safe if $<$ 5 to 10	If $>$ 10, explore options to design the reactor and manage the heat release.
Damkohler no. dimensionless reaction rate	rate of reaction/rate of convection	equation depends on the rate expression	Combine Da with Stanton no; Da/St.	Da/St $<$ 1 then ok to use batch; if $>$ 1 use semibatch
modified Stanton no. or cooling capacity	heat transfer ability/sensible heat sink	$UAt/V\varrho\ c_{\text{p}}$ where U = overall heat transfer coefficient, A = area t = time V = volume ϱ = density c_{p} = heat capacity		

Table 6.4 Selecting operating temperature.

Range		
Must operate so that the correct phase is present.		
Want to select temperature that minimizes the significant side reactions.		
Want to operate from 20–250 °C to minimize utility cost by using water and steam.		
For *adiabatic*	For *reversible exothermic* or some *irreversible catalytic*, optimize to select best temperature. Recall that high selectivity and high yield are usually very sensitive to temperature.	For *endothermic* reactions or *irreversible exothermic*
then the minimum is set by:	then midway is set by:	then the maximum is set by:
For gases, must be > dew point. For liquids, > freezing temperature. Prefer the minimum temperature for *exothermic* (LeChatelier, F) but the rate of reaction is reduced	For non-adiabatic gas catalytic operation, by the jacket temperature.	For liquids, < boiling temperature. and use 25 °C less than the following max. catalyst temperature, exothermic adiabatic reaction temperature, or temperature limitations of the materials of construction.

Table 6.5 Select operating pressure.

Range: usually < 100 MPa	
Must operate so that the correct phase is present.	
Want to select a pressure that minimizes significant side reactions.	
Want to operate from 0.1–1 MPa to minimize utility cost.	
Want to use the minimum possible pressure or the least vacuum	
Use the minimum	Maximum is suggested by
If *reversible* and more moles are produced as product than moles of reactants (LeChatelier, F). If the target reaction is of lower order than the undesired reactions. If large volume of gas needs to be compressed for recycle.	the maximum feed pressure of reactants. the cost of recycle. the pressure limitations of the materials of construction. the pressure drop across device or through the catalyst bed. If *reversible* and more moles as reactants than as products (Le Chatelier, F). If target reaction is of higher order than the undesired reactions. If the main reaction is slow.

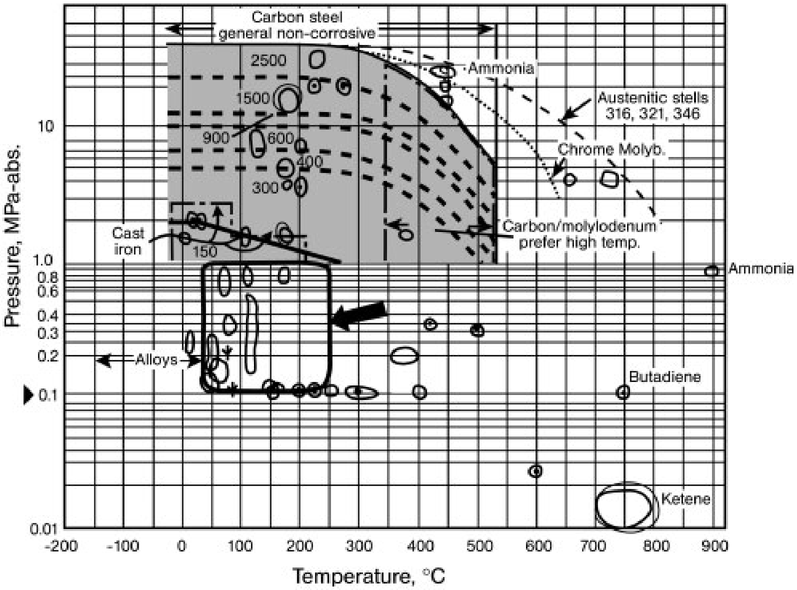

Figure 6.2 Pressure–temperature operating window.

Table 6.6 illustrates the impact of the reaction mechanism on the choice of reactor. The important parameters are the order of the reaction, the reaction rate and the activation energy, *E*. Models for the reaction rate, for an example reaction A + B = P, are of the form –rate = $k\, c_A^{a1}\, c_B^{b1}$. The activation energy, *E,* is usually represented as the Arrhenius number = E/RT and $k = \exp(\mathrm{Arr})$. In general, E = 20–30 MJ/kmol for polymerizations; 150–250 MJ/kmol for uncatalyzed gaseous decompositions. The temperature dependence of the reaction rate is directly related to the activation energy. If the reaction temperature is about 300 °C, then the reaction rate doubles for a temperature increase of 45 °C (if E = 50 MJ/kmol), an increase of 12 °C (if E = 150 MJ/kmol) and 6 °C (if E = 300 MJ/kmol).

All these factors lead to the central issue of selecting the type and configuration of the reactor (the central issue in Fig. 6.1). That choice converts into costs as we identify the processing conditions and configurations and the required ancillary equipment. If a catalyst has been selected, then the reaction cycle and the catalyst replacement/regeneration become important. If a batch or semi-batch reactor is selected, then the cycle times become issues.

Section 6.2 provides rules of thumb that help to quantify the decisions on some of the major issues illustrated on this sizing map.

Table 6.6 Selecting reactor configuration based on the type of reactions.

Type of reaction			Reactor	Operating conditions	
Single Reactions:					
Reversible; equilibrium $A \leftrightarrow P \quad c^{a}$	maximize selectivity assume 95 % equilib. conversion		ideal batch or PFTR ; series of adiabatic beds if exothermic	use excess of feed that is less hazardous and easiest to separate and remove the product stagewise	
$A + B \leftrightarrow P + \text{Waste}$				use excess of feed that is less hazardous and easiest to separate	if ν product $> \nu$ reactants add inerts
					if ν product $< \nu$ reactants no inerts to feed
$A + B \rightarrow P \quad k_1 c^{a1}$			PFTR	isothermal	
			CSTR + PFTR	adiabatic or PFTR if the reaction rate decreases monotonically with conversion	
$A \rightarrow P \quad k_1 c^{a1}$	minimize volume assume 95 % conversion		ideal batch or PFTR		
Multiple parallel (simultaneous parallel)					
$A \rightarrow P \quad k_1 c^{a1}$ $A \rightarrow W \quad k_2 c^{a2}$	$a_2 > a_1$ selectivity increases assume 95 % conversion		CSTR	keep c_A low; use large recycle, low pressure and add inerts but the rate is lower.	
	$a_2 < a_1$ selectivity decreases assume 50 % conversion		Ideal batch or PFTR	keep c_A high; no recycle, high pressure and no inerts	
$A + B \rightarrow P$ $k_1 c^{a1} c^{b1}$ $A + B \rightarrow W$ $k_2 c^{a2} c^{b2}$	$a_2 > a_1$	$b_2 > b_1$	CSTR	If $E1 > E2$ use high temperature If $E1 < E2$ use low temperature Where E = activation energy for the reaction. To maximize yield, use low temperature initially and then increase the temperature as the rate diminishes; use high initial concentration of one of the feeds.	
(continued)		$b_2 < b_1$	semi batch or cold shot PFTR	(continued)	

Table 6.6 Continued.

Type of reaction			Reactor	Operating conditions
(as previous)	$a_2 < a_1$	$b_2 > b_1$	batch PFTR; series CSTR	(as previous)
		$b_2 < b_1$	batch PFTR; series CSTR	
Multiple series or sequential (e.g. polymerization, degradation, crystallization)				
$A \rightarrow P$ $P \rightarrow W$	assume 50 % conversion		batch or PTFR	If $E1 > E2$ use high temperature
				If $E1 < E2$ use high temperature initially to produce product rapidly and then decrease temperature as product accumulates.
Mixed parallel and series				
$A \rightarrow P \quad k_1 c^{a1}$ $A \rightarrow W \quad k_2 c^{a2}$ $P \rightarrow W \; 2 \; k_3 c^{a3}$	$a_2 > a_1$		Combo CSTR + PFTR PFTR + CSTR PFTR with large recycle series of CSTR	
	$a_2 < a_1$		PTFR	
$A + B \rightarrow P \quad k_1 c^{a1} \; c^{b1}$ $P \rightarrow W1 \quad k_2 c^{a2}$ $P \rightarrow W2 \quad k_3 c^{a3}$				For $E3 > E1 > E2$ search for best intermediate feed temperature.
$A + B \rightarrow P \quad k_1 c^{a1} c^{b1}$ $A + B \rightarrow W1 \quad k_2 c^{a2} c^{b2}$ $A + B \rightarrow W2 \quad k_3 c^{a3} c^{b3}$				For $E3 > E1 > E2$ search for best intermediate feed temperature.

Table 6.6 Continued.

Type of reaction		Reactor	Operating conditions
[1] A + B $\rightarrow$ *Intermediate* $k_1\ c^{a1}\ c^{b1}$			$E1 > E2$ and $E3 > E4$ start with high temperature and reduce.
[2] A $\rightarrow$ W1 $k_2\ c^{a2}$			$E1 < E2$ and $E3 < E4$ start with low temperature and increase
[3] *Intermediate* $\rightarrow$ W 2 $k_3\ c^{a3}$			$E1 > E2$ and $E3 < E4$ use maximum possible temperature
[4] *Intermediate* $\rightarrow$ P $k_4\ c^{a4}$			$E1 < E2$ and $E3 > E4$ use lowest possible temperature
Polycondensation with no termination reaction		PFTR or batch	
Free radical	active polymer life >> residence time	PFTR or batch	difficult if the system is viscous and there is buildup on the walls that reduces the heat transfer
	active polymer life << residence time	CSTR	
Copolymers		CSTR	

6.2
General Guidelines

Here are some general rules of thumb and specific guidelines about the phase for either gas or liquid phases. Suggestions for reaction using solid catalysts and for gases reacting with solids are given in Sections 6.2.3 and 6.2.4. Bioreactors, reactions under supercritical conditions and polymerizers are discussed in Sections 6.2.5 and 6.2.7, respectively. Section 6.2.8 considers how the phases present guide the choice of reactor.

6.2.1
General Rules of Thumb for the Type of Reactor

Temperature effects: For reactions that are rate or kinetics controlled, at low temperatures and for moderate activation energies, the rate of reaction doubles for a temperature increase of 10 °C. For low activation energies or for temperatures above 500 °C, the rate doubles for a temperature increase of 25 to 35 °C. For reactions in the liquid phase that are mass transfer- not kinetically- controlled, the liquid phase mass transfer increases by two when the temperature increases by 35 °C. For gas liquid, GL, reactions that are mass transfer- not kinetically-controlled, the solubility decreases by two when the temperature increases by 35 °C and the liquid phase mass transfer increases by two when the temperature increases by 35 °C so the net effect is no change in the rate of reaction with temperature. Figure 6.3 shows how the residence time in a reactor decreases with increase in temperature, if the reaction is kinetically controlled. Other lines show how the liquid phase mass transfer coefficient, the gas solubility and the net result for some gas–liquid reactions change with temperature. A "characteristic trajectory line" is included as a reference guide for information given subsequently in Fig. 6.6.

For exothermic reactions, a temperature increase causes the equilibrium constant to decrease; vice versa for endothermic reactions (Le Chatelier, F).

It is difficult to talk about fast or slow reactions because a reaction may be slow to an organic chemist but fast to a biotechnical specialist. However, in this book I have used the following terms, expressed in units consistent with first order reactions:

Extremely fast reaction, rate > 1000 1/s		microseconds
Very fast, rate 500–1000 1/s		
Fast reaction, rate 50–500 1/s	dehydrogenation of ethyl benzene	seconds
Intermediate, reaction rate 2–50 1/s		
Slow reactions, rate 0.01–2 1/s	liquid phase chlorinations	minutes
Very slow, rate 10^{-4}–10^{-2} 1/s	bromination of xylene	
Extremely slow, rate10^{-6}–10^{-4} 1/s	polymerizations	hours
Lengthy, rate $< 10^{-6}$ 1/s	fermentations	days

To be viable, the rate of production for gaseous catalyzed reactions should be $> 3 \times 10^{-4}$ kmol/s m^3 or at 327 °C (or $RT = 9.314 \times 600$) about 1.7 1/s, that is, faster than intermediate.

For reaction rates that are not first order the units are not 1/s. As approximations these can be converted into "first order" reactions so that we can estimate the speed of the reaction in terms of the above definitions. For example, a reaction rate expressed as *mol/s g catalyst* can be converted into a "first order" rate by multiplying by the bulk density of the catalyst and by RT. Similarly, rates expressed as *mol/s m*^{3} can be converted by multiplying by RT.

Most **gas phase** and **liquid phase** reactions are kinetically controlled as opposed to being equilibrium controlled (except for the oxidation of sulfur dioxide to sulfur trioxide, the production of methanol from synthesis gas, the production of ammonia from synthesis gas, and the production of hydrogen from the water-gas shift reaction – these are equilibrium controlled).

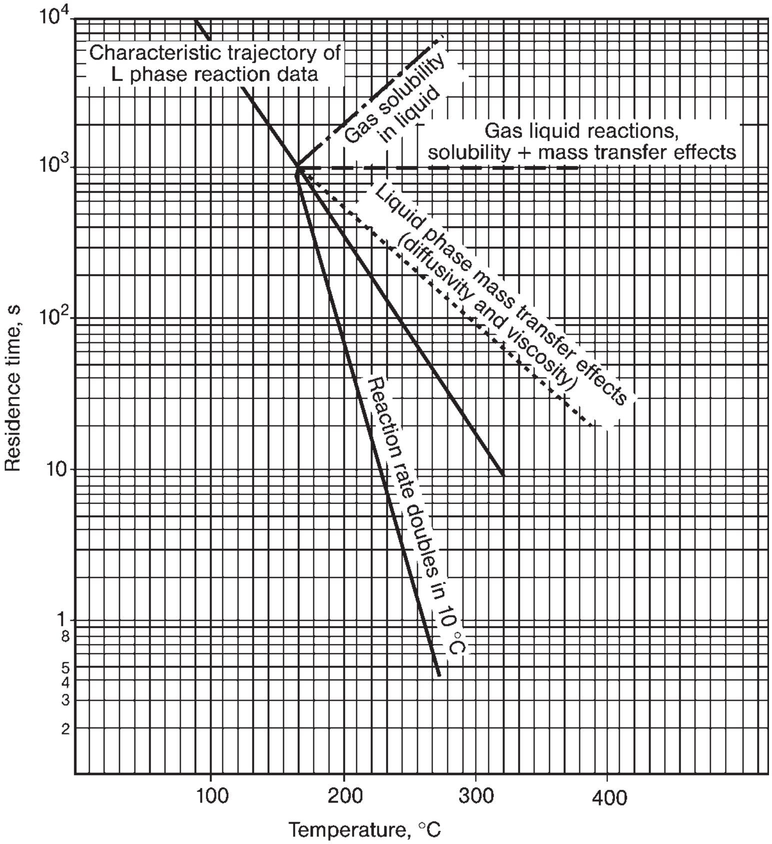

Figure 6.3 Residence time versus temperature.

Most **gas–solid** reactions are heat transfer controlled.

Most **heterogeneous catalytic gas** reactions are mass transfer controlled.

For slow reaction rates, prefer batch to continuous.

Prefer continuous to semicontinuous to batch (H).

Prefer PFTR to CSTR (H).

Prefer minimum inventory in reactor by providing better mixing, increased temperature or pressure or changing the catalyst (H).

Prefer internally heated/cooled to externally heated/cooled (H).

Consider light and ultrasound as optional forms of energy (H).

The heat of reaction can be used to identify the degree of hazard for different reactions (and, to some extent, the length of time required in the reactor). As given in Table 6.3, "highly exothermic or highly endothermic reactions" have heats of reaction > 150 MJ/kmol. Here are some examples.

- *Extremely exothermic*: direct oxidation of hydrocarbons with air; chlorinations, polymerizations of polyethylene without diluent: > 3 MJ/kg (or > 150 MJ/kmol: examples: combustion –900 MJ/kmol; hydrogenation of nitroaromatics, –560 MJ/kmol; nitro-decomposition, – 400 MJ/kmol; diazo-decomposition, –140 MJ/kmol).
- *Strongly exothermic*: nitrations, polymerization of propylene, styrene butadiene. 1.2–3 MJ/kg (nitration, –130 MJ/kmol; amination –120 MJ/kmol; sulfonation or neutralization with sulfuric acid, –105 MJ/kmol; epoxidation, –96 MJ/kmol; diazotization).
- *Moderately exothermic*: condensations or polymerization reactions of species with molar mass 60–200 = 0.6–1.2 MJ/kg.

More information is given in Tables 6.3 and 6.1.

6.2.2
Specific Guidelines for Gas Phase, Liquid Phase and Gas–Liquid Reactions

For **gas** reactions, usually use plug flow tubular reactors, PFTR, static mixers or fluidized beds.

For gaseous, fixed-bed catalytic reactions, use $L/D_p > 100$ and $D_p/D < 0.10$ to ensure good gas distribution and negligible back mixing. L = length, D = tube diameter, and D_p = diameter of the solid particle or catalyst.

For **liquid** phase reactions, usually use continuous stirred tank reactors, CSTR, unless the pressure is so high that the rotating shaft of the agitator cannot be sealed. For such high pressures consider the use of static mixers. Most liquid phase reactions are exothermic.

Prefer operating temperatures below the boiling temperature or dilute the liquid with a safe solvent (H).

For **gas–liquid** reactions, usually use aerated CSTR or bubble columns.

For **GL** reactions, whether the reaction is controlled by gas phase mass transfer, rate of mass transfer through the liquid film resistance at the surface or the reaction rate affects the configuration we select for the reactor. Two parameters that show where the reaction occurs are the Hatta number, *Ha*, and the dimensionless bulk/film volume ratio (ratio of the total liquid volume to the film volume), δ^+.

The Hatta number is the ratio of the reaction in the liquid surface/mass transfer into the bulk phase; or a modified Thiele modulus for GL systems to correct the mass transfer for chemical reaction. Because the ratio involves the reaction rate, the actual form of the Hatta number depends on the reaction kinetics. For first order reactions,

$Ha^2 = k_A\, c_A\, \delta / k_L\, (c_A - 0)$

where k_A = reaction rate/unit surface area,

δ = liquid film thickness causing resistance to mass transfer at the surface, which, for the film theory, = D/k_L

D = diffusivity of the gaseous reactant species in the liquid.

k_L = mass transfer coefficient in the liquid phase

or

$Ha = (k_A\, D)^{0.5}/k_L$

More complex expressions apply for reactions of order other than first.

The ratio of the total liquid phase to the film volume

δ^+ = bulk/film volume ratio = $(1 - \varepsilon)/a\,\delta = (1 - \varepsilon)\, k_L/a\, D$

Values of δ^+ are given for different types of reactors.

$\delta^+ = 1$ for equipment with a very dry foam so that all the liquid in the reactor is the foam film;

$10 < \delta^+ < 200$ for thin film reactors (Section 6.19)

$10 < \delta^+ < 100$ for packed columns (Section 6.16).

δ^+ is > 100 for mechanically stirred reactions (STR and CSTR, Sections 6.27 and 6.28) and for bubble columns (Section 6.13).

Values of δ^+ are given for different GL contactors in Table 1.2.

The implications of the Hatta number, and thus the δ^+ characteristic of the reactor that should be selected, are summarized in Table 6.7.

Table 6.7 Use of the Hatta number to guide in the selection of GL reactors.

Zone	***Ha***	**Speed of reaction**	**Location of reaction**	**Controlled by**	**An increase in temperature causes**	**Equipment**		
						should give	**δ^+ values**	**Example:**
1	$<< 0.3$	very slow	bulk	reaction kinetics, k_A	increase in conversion	large liquid holdup	large	bubble column; sparged STR
2	between 0.3 to 0.6		mostly in bulk	some mass transfer effects		both holdup and area		packed
3	between 0.6 and 3	inter-mediate	mostly in film	strong mass transfer effects		both holdup and area		trays
4	> 3	very fast	surface film	mass transfer, k_L	usually negligible effect	large surface area	small	spray, wetted wall, trickle bed

6.2.3
Specific Guidelines for Reactions using Catalysts

Catalysts improve the reaction rate and selectivity of reactions. They reduce the energy barrier or activation energy for reactions; uncatalyzed reactions have activation energies in the range 100 to 500 MJ/kmol whereas with most catalysts the activation energies are in the range 50 to100. The temperature effects on the reaction rate overwhelm other effects when activation energy $>$ 30–50 MJ/kmol. Catalysts can be heterogeneous, homogeneous or enzymes. Heterogeneous, solid catalysts usually consist of (i) active species from Groups VIb, VII, VIII and Ib such as elements, oxides, sulfides and carbides, (ii) supports with structural stability and high surface area (such as alumina, carbon, silica, clays with internal pore density 15 m^2/g (for α-alumina support), 2–30 m^2/g (for kieselguhr); 200 m^2/g (for γ-alumina support) and 200–800 m^2/g (for silica gel)), and (iii) promoters to enhance the activity and selectivity (such as alkali earth metals and metal oxides). Examples of the active species used for different types of reactions are given in Table 6.8.

A measure of the catalyzed reaction rate is the turnover frequency, TOF, = number of molecules reacting per second per active site. Usual values for commercial heterogeneous solid catalysts are, TOF = 0.1–1 1/s; for heterogeneous metallocene catalysts for polymerization reactions, TOF = up to 30 000 ethylene units/s; and for enzyme catalysts: TOF = 10–10 000 1/s. For catalyzed reactions, the controlling step is often the mass transfer. The density of most solid catalysts, is the density of the support and is 1.4 to 2.5 Mg/m^3 of solid (although a nonmetallic resin catalyst has a density of about 0.7). The bulk density of most beds of catalyst, ϱ_b, (that accounts for the porosity or fluid voidage, ε is in the general range 0.5–0.9 Mg/m^3 of reactor volume where $\varrho_b = (1 - \varepsilon)\,\varrho_s$.

In commercial operation, the solid catalysts usually lose their effectiveness because of (i) poisons (such as sulfur, chloride), (ii) sintering, (iii) fouling by carbon and coke, and (iv) loss of the active species via volatilization. Furthermore, the life of the catalyst depends partly on the thermal stability of the support/carrier. Poisoning is minimized by the removal of poisons from the feed stream by upstream guard units. Sintering is minimized by operating at lower temperatures. Regeneration can be used to periodically remove the coke and carbon; active species may be added.

Enzyme catalysts deactivate especially for temperatures $>$ 50 °C and inadequate control of such conditions as pH.

Table 6.8 also gives example information about the catalyst life, causes of loss in activity and regeneration options.

Table 6.9 indicates how the characteristics of the catalyst affect the type of reactor. Prefer monolithic configuration for intensification (H) with surface area/volume usually 1.5–4 times greater than traditional pellets. The monolithic configuration is excellent for mass transfer controlled reactions.

Table 6.8 Types of reactions and suggested catalysts with illustrative catalyst life and regeneration information.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Acetylation	Pd						
Acetoxidation	homogeneous						
Addition	metallic salt in solution						
Aldolization	homogeneous						
	CaO, Mg aluminate						
Alkylation	molecular sieves						
	zeolite	ethyl benzene	420–450	> 3 years			regeneration (for 24 h) of cat. every 15–30 days
	$AlCl_3$						
	sulfuric, HF acid						
	oxides of V, Mn, Fe, Cu, Mo, W						
Amination via ammonolysis	mixed oxides						
	silica alumina	aniline ex phenol, ammonia	385	1–2 months			regenerate for 20 h

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Amination via reduction	Ni, Cu & Cr oxides						
Ammoxidation	Pt Pt–Ru						
	mixed oxides, Fe, Sb, Sn	acrylonitrile ex ammonia, propylene	220	1–3 years			
	mixed metal molybdates or antimonates	acrylonitrile ex propene	450	1–3 years	volatalization, attrition		periodic addition of Mo ammonium salt as vapor
	none						
Carbonylation, hydroformylation, FT	homogeneous						
	Ni or Pd on C or Co Rh or Ni carbonyl or Fe carbonyl						
	Cu	methanol	200–300	2–8 years	slow sintering, poisons	325	
Chlorination	none						
	ferric chloride						

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Condensation	Fe/alumina [K_2O]	ammonia ex hydrogen, nitrogen	450–470	10–15 years	slow sintering, poisons	625	
	Rh/Ba/MgO or iron oxide or alkali earths or homogeneous						
Cracking, cat	Co/Mo S or Si alumina or Pd or oxides of V, Mn, Fe, Cu, Mo, W						
	zeolite	refinery oils	500–560	1–2 s	rapid coking, poisons	595	regenerate continuously in separate fluidized bed
Dehydration	Ta silica						
Dehydrochlorination	none						
	silica alumina or NaOH or metal chloride						
Dehydrogenation	none						
	Cu–Cr; Cu–Zn–bronze	2 butanone		2 years			regenerate every 2–3 months
	Ni or Pt						
	oxides of Cr, Ni, Fe	butadiene ex butene or butane	600–680	> 0.5 year			regenerate for 1 h every 1–7 days

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Dimerization	tripropylaluminum						
Disproportionation	CdI or zeolite						
	Rh/alumina	propylene from ethylene	50				regenerate every 10 days
Epoxidation	homogeneous						
Esterification	IX resin or sulfuric acid						
Ethynylation	Cu acetylide or KOH						
FT	Ni or Cu with ZnO or carbides of Fe, Mo, W						
	$Co/ZrO_2/SiO_2$	alcohols		5 years			regen. once per year.
Halogenation	none						
Hydration	homogeneous cupric chloride						
	sulfuric or phosphoric acid or Ta on silica						

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Hydrodealkylation	none						
	Cr or Mo oxides or Pt on zeolites						
Hydroformylation	Co or Ru or Rh or Co or Pd on C or Cu, Ni, Zn or Fe pentcarbonyl						
Hydrogenation	Pt or Cu on Si or Ni Cr or Pd on C or Raney Ni or Pt-Co/ C						
	Cu on ZnO	alcohols ex aldehydes	220–270	0.5–1 year	slow sinter		
	Cu-Cr oxides	furfuryl alcohol ex furfural	150–200		coke		regenerate with oxidation
	CuO/ ZnO						
	sulfided Ni	aniline ex nitrobenzene	300–475		coke		decoke via air burn at 300 with later reduction via hydrogen
	carbides of Fe, Mo, W on alumina						

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Hydrolysis	sulfuric acid						
Hydrotreat	Pd or Co Mo						
	sulfided Co–Mo/γ-alumina [Bo, P, K, SiO_2]	light distillate	300	10 year	poisons V, Ni, Fe; coke	450	regenerate in situ by burning coke about 2 times via combustion with steam–air. For poisoning, regen. externally with aqueous leach
	sulfided Ni						
Isomerization	zeolites						
	Pt	xylenes ex ethyl benzene	400–480	3–5 years			regenerate every 6–18 months
	oxides of V, Mn, Fe, Cu, Mo, W or oxides of rare earths						
Nitration	Co naphthaneate						
	mixed acids						

Table 6.8 Continued.

Type of reaction	Example catalysts	Products/ reactants	Temperature, °C	Catalyst life	Cause of decay	Max. temp., °C	Comments about regeneration
Oxidation	Cu Ag or Fe Mo						
	Ag/α-alumina [alkali metals]	ethylene oxide ex ethylene, air	200–270	1–3 years	poisons, Cl and S; some coking		regen. via periodic addition of Cs/methanol solution
	Pt Rh gauze	NO ex ammonia	800–900	0.1–0.5 years	loss of Pt, fouling		
	Pd Cd/alumina	vinyl acetate ex ethylene, acetic acid	140–180	2 years	sintering		
	V/K sulfate	sulfur trioxide ex sulfur dioxide	525	5–10 years	plugging, sintering		
	mixed oxides; metallic oxides or AgO						
	homogeneous: Mn, Cu or Co acetate						
Reforming	zeolite						
	metals, Ni/ alumina	steam reform ex methane	500–850	2–4 years	sintering, coke, sulfur poison	875	
	Pt/treated alumina		460–525	0.01–0.5 years	coking	550	frequent regeneration needed

Table 6.9 How the solid catalyst affects choice of reactor.

Conditions	Consider the following type of reactor	Constraints
Catalyst retains activity > 3 months:	fixed bed	if < 3 months use fluidized, moving, or slurry
Operating pressure high	fixed bed	if catalyst strength > 3 kg/ particle
Reaction is highly exothermic	fluidized bed	if the attrition $< 1\%$/day
Very short contact time available	monolith with low pressure drop or fluidized/loop reactors with recycle	
Enzyme catalyst	fixed bed	if immobilized
	CSTR	if pH and temperature control are vital or if mass transfer controls

6.2.4
Specific Guidelines for Gases Reacting with Solid

When the solid reacts with gas, usually heat transfer controls because these are highly exothermic or endothermic reactions. Particle size and size distribution are critical. These reactions may follow different patterns:

- for multigranule reactions the time for reaction = independent of particle diameter.
- for shrinking core without ash reactions, the time for reaction $\propto$ particle diameter (for reaction controlled), $\propto D^{1.5}$ (for fluid diffusion controlled with fluidized, fixed or moving beds), $\propto D^2$ (for fluid diffusion controlled with transported bed)
- for shrinking core plus ash, the time for reaction $\propto D_p$ (for reaction controlled), $\propto D_p$ (for fluid diffusion controlled), $\propto {D_p}^2$ (for fluid diffusion through the ash controlled).

6.2.5
Bioreactors

The two general types of bioreactors are anaerobic and aerobic: anaerobic means no oxygen is present; aerobic means oxygen must be supplied with 17 kJ of heat released/g O_2 utilized = 13 kJ/g of cell mass generated.

The three types of biotechnical products are:

1. cell biomass
2. metabolic products of cells: anaerobic: alcohols, organic acids, hydrogen, carbon dioxide; for aerobic: citrate, gluta-

mate, lactate, antibiotics, hydrocarbons and polysaccharides, yeast and single cell protein SCP
3. enzymes that can be used as catalysts.

In selecting an aerobic bioreactor, there is a tradeoff between the degree of mixing and the required rate of oxygen transfer, OTR. How this affects the type of reactor is illustrated in Table 6.10.

Some useful definitions are:
microorganism: microscopic, living organisms including prokaryotes (e.g. bacteria) and eukaryotes (fungi).
bacteria: microorganisms that are cells without a fully differentiated nucleus. May be round, rod-like, spiral or filamentous of diameter 0.5–3 μm.
fungi: microorganisms that are cells with membranes with a discrete nuclei (eukaryotes). They are saprophytic and parasitic plants that lack chlorophyll. Fungi are typically filaments that are 5-15 μm diameter and 50–500 μm long.

Table 6.10 Some bioreactions with different types of microorganisms.

Factors related to the reactor	Microorganisms			
	Bacteria	Fungi		Mixed culture
		yeasts	fungi, moulds	
Amount of biomass, kg/m^3 (volume fraction)	10–50 (0.001–0.01)	10–50	10–50	5
Biomass viscosity, mPa s	low, < 100	low, < 100	high, 100–1500	low, < 100
Oxygen consumption, g/s m^3	0.2–1	0.2–1	0.2–1	0.002–0.01
k_La, gas–liquid, 1/s	0.05–0.2	0.05–0.2	0.01	0.003
k_La, liquid–solid, 1/s	0.01–0.5	0.25 bubble	0.1–1 jet loop	
Metabolic heat production, kW/m^3	3–15	3–15	3–15	0.03–0.14
Sensitivity to shear	relatively insensitive, robust	sensitive (animal and plant cells)		fluidized
Choice of reactor configuration if fermentation requires high OTR; e.g. antibiotics, acetic acid, SCP	aerated STR; 0.1–1.7 kW/m^3	bubble reactors: jet loop or air lift		fluidized
Choice of reactor configuration if fermentation requires low OTR;	aerated STR; 0.1–1.7 kW/m^3	packed column, immersed wick, immersed column		
Example rate of growth of biomass for the production of Single cell protein, SCP, g/s m^3 of broth	1–2.5	0.5–1.2	0.3–0.5	

yeast: a fungus of the family *Saccharomycetacea* that is typically 1–50 μm in diameter.
enzyme: a protein produced by living cells that catalyzes the metabolic process.

For mixed culture microorganisms used for **biological treatment of waste water**, the general range of values used are: $BOD_u \approx 1.43 \times BOD_5$; Approximately 1.4–1.5 kg O_2/kg BOD_5.

Microorganisms use the organic substrate, characterized by BOD_5 or COD, for growth and for endogenous respiration. Illustrative reaction rate terms include, for COD at 20 °C:

Substrate concentration at which the specific growth rate is 0.5 maximum, K_s, = 25–100 mg COD/L.

Maximum specific utilization rate of the substrate, k, = 6–8 kg COD/day kg VSS.

Biomass lost to endogenous respiration per unit time per unit biomass, K_d, = 0.05–0.1 1/day.

Yield of biomass produced per unit of substrate removed, Y_T, = 0.35–0.45 mg VSS/mg COD.

6.2.6
Reactors for Supercritical Conditions

When a fluid is compressed and heated above the critical conditions (or to supercritical conditions, *sc*), the differences between gas and liquid disappear. For carbon dioxide, this occurs for temperatures above 31 °C and pressures above 7.3 MPa. For reactions (such as alkylations, aminations, hydroformylations, hydrogenations and Fischer Tropsch synthesis) occurring in supercritical fluids, the reaction rate is often increased dramatically because of improved desorption of heavy molecules; minimizing the oxygen and hydrogen solubility limitations, improved heat transfer, and improved selectivity by a catalyst by minimizing pore diffusion limitations.

6.2.7
Reactors for Polymerization

The options for polymerization reactions, the types of polymerizations and the reactor configurations are given in Table 6.11.

For suspension or emulsion polymerization, the shaft power can be estimated as follows:

Shaft kW = $16\,(D_i/107)(N/170)^3\,n$
where
N = rpm
n = number of impellers on the shaft.
D_i = diameter of impeller in cm
Motor kW = 1.3 × shaft kW

Table 6.11 Polymerization reactions.

Liquid phase reactors	Types of polymerizations	Reactor options
1. Bulk: liquid monomer with initiator in absence of diluent or solvent.	condensations, LDPE, PS, Nylon, PMMA, acrylics, polyacetals	STR (3–6 kW/m^3 mixer; tip velocity 0.2–0.3 m/s), long tubular reactors, screw extruders
2. Solution: monomer dispersed in solvent with soluble catalyst	free radical, ionic, Zeigler Nichols; thermosets, acrylics, PVAlc, PVC, polybutadiene, polypropylene, melamine phenolic resins, polyisoprene, polycarbonate, chlorinated polyesters	glass or s/s STR (2–8 kW/m^3 mixer; heat transfer area = 1–4 m^2/m^3 depending on the volume of the reactor with small area associated with large volumes).
3. Suspension with large drops 10–1000 μm of insoluble monomer and catalyst suspended in water.	free radical addition, styrenic IX resins, vinyl polymers, PVC, styrene-acrylonitrile, polypropylene	batch STR (1–6 kW/m^3 mixer; tip speed 6–9 m/s; 3-retreated blades at 46–120 rpm; heat transfer area = 1–4 m^2/m^3 depending on the volume of the reactor with small area associated with large volumes); continuous PVC
4. Emulsion: small drops 0.5–10 μm of insoluble monomer suspended in water with water-soluble catalysts in micelles	industrial polymers, synthetic rubbers, polybutadience, PVC, latex paints, adhesives, coatings, ABS, PV acetate, styrene butadiene	batch STR; 2–3 kW/m^3 mixing @ 155–230 rpm; shear number 9000–12 000; impeller diam./tank diam. = 0.25–0.3, U = 110 W/m^2 K; heat transfer area = 3.3 m^2/m^3.
Gas phase reactors		
Gaseous monomers, continuous	heterogeneous solid cat. PE, PP;	fluidized beds; horizontal with weirs & rotating paddles; helically stirred tanks.

Since polymerizations are exothermic, it is essential that the heat of reaction is removed. Since polymer and scale tend to build up on any heat exchange surfaces contacting the reactants the preference is to have jacketed reactors. The amount of internal surface area varies from 4 m^2/m^3 for 1 m^3 vessels and reduces to 1.5 m^2/m^3 for a 35 m^3 volume reactor. Cooling fingers or external coolers can be used. The overall heat transfer coefficients are in the range 60–350 W/m^2 K. In general, to account for the fouling on the walls, the internal heat transfer coefficient for polymerization reactions is about half that expected.

Table 6.12 How phase affects type of reactor.

Type of reactor	Homogeneous			Heterogeneous							Comment
	G	L	S	GL	LL	no-catalyst		catalytic			
						GS	LS	GS	LS	GLS	
6.4 Burner	**										Fast; For homogeneous endo or exothermic, gas phase reactions; short reaction times, high temperatures
6.5 PFTR pipe/empty tube for fluids (tube loop, ejector into tube)	***	**		**	**					bio	Fast; good for consecutive reactions. High temperature, large surface area, well-defined residence time. May operate under a vacuum.
6.6 PFTR: static mixer in tube or as sections in a tower	*	*		*	*			*			Large heat transfer area; intensive radial mixing with negligible backmix; narrow RTD; suitable for processes where viscosity increases.
6.7 PFTR: pipe/empty tube for transported or slurry; transfer line; moving bed in a tube								**	**	**	Very fast; good for consecutive reactions. Large transfer area; temperature can be controlled by injection; little backmix; well-defined residence time.
6.8 PFTR empty multitube (± static mixers)	*	*									Fast reactions; good for consecutive reactions. Large transfer area to remove heat from exothermic reactions; use static mixers for viscous fluids.
6.9 PFTR: fixed bed catalyst or inerts: adiabatic	* inerts							***	*	***	Fast; good for consecutive reactions. Simple and easy to design.not suitable for reactions with high exo or endothermicity $\Delta T_{\text{ad}} > 100$ °C. or that have temperature sensitivity. For fast reaction rates and unstable products, use shallow beds that give very short residence times and some axial mixing. Catalyst may be a gauze. For noncatalytic, mixing can be promoted by inerts.
6.10 PFTR: multibed adiabatic with quench or heat exchange								**			Large transfer area; used primarily for equilibrium reactions that are temperature sensitive.

6.2.8
Using the Phases to Guide in the Choice of Reactor Configuration

Table 6.12 lists the reactor configurations that have been used for different phase conditions and can be used as a guide to select the reactor configurations that might be appropriate for the target reaction under consideration.

Table 6.12 Continued.

Type of reactor	Homogeneous			Heterogeneous							Comment
	G	L	S	GL	LL	no-catalyst		catalytic			
						GS	LS	GS	LS	GLS	
6.11 PFTR: fixed bed catalytic radial flow								***			Fast; good for consecutive reactions. Use to minimize Δp.
6.12 PFTR: multi-tube fixed bed catalyst: non adiabatic						*		***	**		Fast; good for consecutive reactions. Large transfer area. Can handle exothermics.
6.13 PFTR: bubble reactor: jet loop, air lift with central or off-center draft, external loop, bubble packed				**	**					**	Slow reactions; consecutive reactions; irreversible or reversible with high equilibrium constant. Relatively isothermal, limited in range of temps and pressures. High capacity, simple design; high backmix of liquid. Liquid is usually the key component. OK for corrosive chlorinations, sulfonations, phosgenations.
6.14 PFTR: spray reactor and jet nozzle reactor: gravity spray, venturi jet, plunging jet, circulating nozzle.				**	*					**	Fast reaction, high capacity, low Δp; fines OK.
6.15 PFTR: trays, with and without downcomers				***	**					*	Intermediate reaction rates. High capacity, high conversion in both gas and liquid phases. Intensive dispersion of gas in liquid. Large number of plates gives plug flow. Some flexibility in varying liquid holdup; and exchange heat via coils on plates.

Table 6.12 Continued.

Type of reactor	Homogeneous			Heterogeneous							Comment
	G	L	S	GL	LL	no-catalyst		catalytic			
						GS	LS	GS	LS	GLS	
6.16 PFTR: packing, full column, shallow, RBC, trickle filter				**	*					**	Very fast reactions. essentially plug flow for both G and L. High capacity, high conversion in both gas and liquid phases. Difficult to control temperature, adiabatic. Conversion is often limited by equilibrium. Design like an absorber, Section 4.8.
6.17 PFTR: trickle bed									*	***	Use for very fast reactions, all reaction is in the liquid film and is mass transfer controlled.
6.18 PFTR: monolithic								*			Use when mass transfer affects selectivity or reactivity. Perhaps not for highly exothermic reactions because limited in radial heat transfer unless cross flow is used.
6.19 PFTR: thin film, including agitated thin film		*		*						*	Mass transfer controlled, fast absorption and highly exothermic reactions or highly endothermic reactions producing a volatile compound whose desorption is desirable to shift the equilibrium or prevent side reactions. Agitated for very exothermic reactions in viscous liquids.
6.20 Scraped surface		*		*			*				Very exothermic reactions in viscous liquids. OK for foaming, fouling and particles with up to 65 % w/w solids. Sulfonations and polymerizations
6.21 PFTR: multiple hearth			*			*	*				
6.22 PFTR: traveling grate			*			*					
6.23 PFTR: rotary kiln			*			*	*				

Table 6.12 Continued.

Type of reactor	Homogeneous			Heterogeneous							Comment
	G	L	S	GL	LL	no-catalyst		catalytic			
						GS	LS	GS	LS	GLS	
6.24 PFTR, shaft furnace			*			*					
6.25 PFTR, melting cyclone burner			*			*					
6.26 PFTR: series of CSTR. Cascade or multistage or multichamber tank		*		*					*	** cascade	Slow reactions, RTD similar to PFTR; can change reaction conditions along the route
6.27 STR: batch, with or without gas sparge		*		*	*		*		**	**	Slow, consecutive reactions. Moderate reaction rates, conversion in the liquid phase. Flexible.
6.28 STR: semi-batch: with and without gas sparge		*		*	*				*		Moderate reaction rates, conversion in the liquid phase, parallel reactions. fast and very exothermic reactions; flexible; and if some of the reactants may decompose, or if want gradual addition of reactants.
6.29 CSTR: mechanical mixer: with or without gas sparge		***		**	**		*		**	***	Slow to moderate reaction rates, conversion in the liquid phase; Suitable for fast, highly endo or exothermic reactions. Flexible.
6.30 STR: fluidized bed, BFB, CFB or spouted						*	*	**	*	***	Very fast reactions; When temp control is needed or when nearly isothermal needed. Poor flexibility. Some axial mixing.
6.31 TR: tank or drum reactor: ponds, lagoons	*	*								**	
6.32 Mix of CSTR, PFTR with recycle.	*	*		*			*				Slow reactions.
6.33 STR: PFTR with large recycle		*					*			*	Good backmixing and heat removal; suitable for slow reactions.
6.34 Reaction injection molding and reactive extrusion		*					*				Highly viscous.

Table 6.12 Continued.

Type of reactor	Homogeneous			Heterogeneous							Comment
	G	L	S	GL	LL	no-catalyst		catalytic			
						GS	LS	GS	LS	GLS	
6.35 Reactive distillation/ extraction/ crystallization, HIGEE		*									Reaction window = distillation window; reaction equilibrium can be shifted by removing one or more of the species from the reaction space.
6.36 Membrane reactors				*					*	*	Reaction equilibrium can be shifted by removing one or more of the species from the reaction space or reactant can be provided through the membrane
6.37 Transport-react: liquid ring pump				*							Fast reaction between a liquid and an unstable gaseous reactant (produced under vacuum).

6.3
How the Type of Reaction Affects the Size of the Reactor

In Section 6.2 we used the phases for the reaction to guide in the selection of the *type* of reactor. We consider now how the type of reaction might guide in the estimation of the *size* of the reactor. Figure 6.4 illustrates how the type and size of reactor relates to the production rate and the residence time. From the residence time we can estimate the size of the reactor or of the catalyst bed. For a continuous process, the residence time is usually based on the volume of the reactor or catalyst bed/volumetric feedrate of reactants to the reactor at inlet conditions. For a batch or semibatch process, the residence time is the length of time the batch is operated at reaction conditions.

As an aside, some authors use the term "*space velocity*": such as, the liquid hourly space velocity, LHSV, the gas hourly space velocity, GHSV, the mass hourly space velocity, WHSV, or mol-volume space velocity, mol feed/hour litre of catalyst, MvolHSV. Unfortunately, the flowrates used in space velocity data are defined at conditions different from the typical reaction conditions. Thus, LHSV is measured at 20 °C; GHSV, at 15 °C and 0.1 MPa. As an approximation, we can convert space velocity to residence time, in seconds, = 3600/(the hourly space velocity corrected to volumetric conditions using the temperature and pressure to reactor inlet conditions).

Now consider rules of thumb about residence time. As an approximation, one option might be to assume that the same residence time is required when the same net bond energy is required. Bond energy data are available. For example,

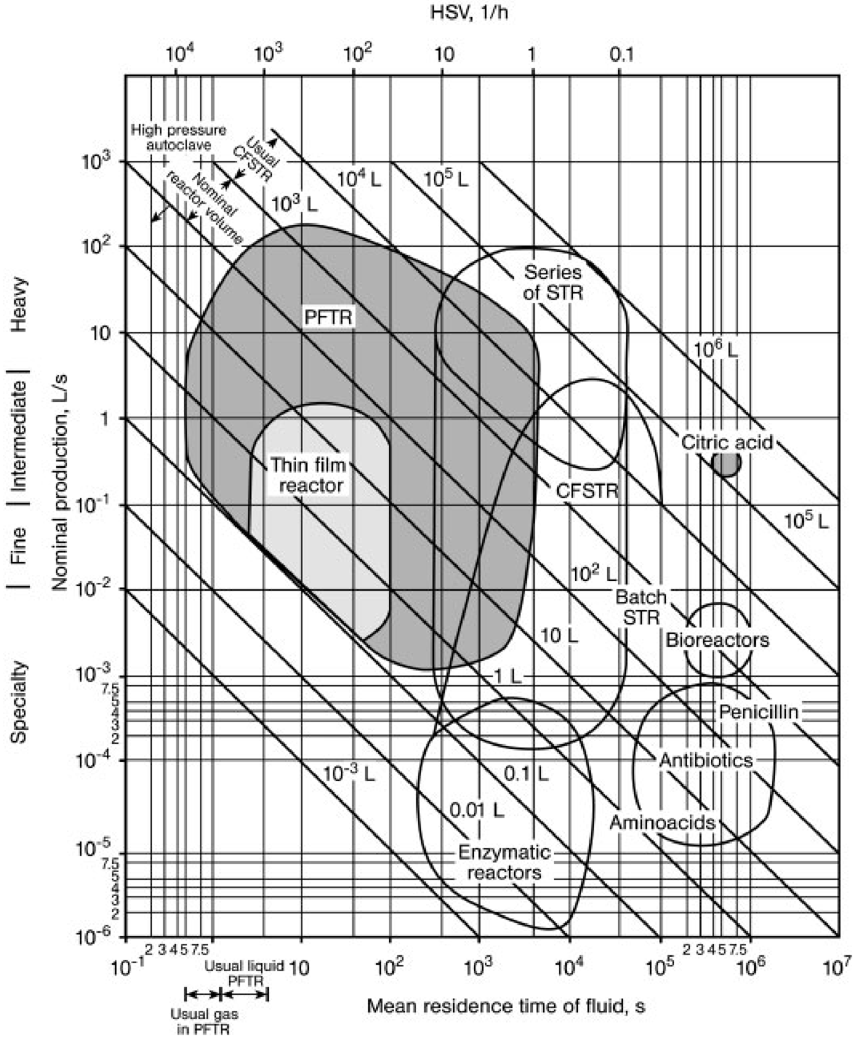

Figure 6.4 Some characteristics of fluid processing reactors.

the C–C bond in the gas phase has an average bond energy of 347 MJ/kmol. Breaking this bond requires 347 MJ/kmol, endothermically; forming the bond releases this energy exothermically.

For any given reaction (with its making and breaking of bonds), the heat of reaction can be estimated by considering the sum of the energies of the bonds broken less the sum of the bonds created. Table 6.13 summarizes typical heats of reactions, MJ/kmol, for different *types* of reactions. Also given in this table is a brief description of the reaction, and a percentage representing the number of accidents out of 100 that have occurred with this type of reaction.

Table 6.13 Example *types* of reactions.

Net forming of bonds	Net breaking of bonds
acetylation, −220 MJ/kmol	
addition, add moiety to unsaturated compound −110 to −120 MJ/kmol	
alkylation, add alkyl group, (4 %) aromatic + olefin, $AlCl_3$ −100, −120 MJ/kmol paraffin + olefin, −80 to −112 [**4**, alkali acetylides, diazoalkane + aldehyde]	**hydrodealkylation**, dealkylation in presence of H_2 −100 MJ/kmol
amination, add amino group by ammonolysis or by reduction −120 MJ/kmol	
carbonylation, add CO to olefin (oxo, hydroformylation): add CO and hydrogen to olefin, Fischer Tropsch: react CO and hydrogen to produce alkanes −165 MJ/kmol to produce alcohols, −245 MJ/kmol	
chlorination, add chlorine (6 %) −180 MJ/kmol	
condensation add moiety to saturated compound [**4**, CS_2 + aminoacetamide → pyrazoles] −30 to −90 MJ/kmol	
diazotization, −65 MJ/kmol (3 %)	**diazo decomp** −140 MJ/kmol
esterification, split off water and join acid and alcohol. (1 %) −40 MJ/kmol [**4**, carboxylic acid + diazomethane; acetylene + carboxylic acid vinylester]	**hydrolysis**, add water and cleave into two parts. −15 MJ/kmol (7 %)
epoxidation, −100 MJ/kmol	
ethynylation, acetylene adds across a carbonyl group; −230 MJ/kmol **vinylation**, add acetylene to form =	
hydration, add water to = −155 MJ/ kmol	**dehydration**, take off water, −295 MJ/kmol
hydrogenation, add hydrogen depends very much on the degree of hydrogenation −600 MJ/kmol	**dehydrogenation**, take off hydrogen +50 to +230 **reforming**, +200 to −890 MJ/kmol
isomerization, change structural arrangement $AlCl_3$ −10 to −20 MJ/kmol	
oxidation, addition of O_2 or remove H −170 to −990 MJ/kmol (1.5 %) [**4**, ozonolysis; nitrous acids; low MM peracids]	**combustion**, +600 MJ/kmol **pyrolysis**, +150 MJ/kmol **cracking**, decompose at high temperature +600 MJ/kmol
neutralization, −50 to −100 MJ/kmol (6 %)	
nitration, insert NO_2 −130 MJ/kmol (11 %)	Nitrodecomposition, −400 MJ/kmol
polymerization −55 to −95 MJ/kmol (45 %)	
	dehydrocyclization + 200 to 250 MJ/kmol
sulfation, **sulfonation**, addition of sulfate, sulfonate or sulfonic acid to aromatic −100 MJ/kmol (10 %)	desulfurization

Consistent with our concern for safety, Table 6.1 listed types of reactions that might be considered hazardous but only some specific reactions of a particular type are hazardous. For example, many condensation reactions do not pose a hazard. However, the reaction between carbon disulfide and aminoacetamide to make pyrazoles is hazardous. If a hazard rating = 0 means negligible hazard; 4 means extremely hazardous, then in Table 6.13 are listed some example 4 reactions that pose hazards. Another way of considering hazardous reactions is to identify the types of bonds that are potentially hazardous. These include vinyl, conjugated double bonds with carbon, nitrogen, and oxygen atoms (e.g., butadience, isoprene, cyclopentadiene, acrolein), adjacent double bonds (toluene diisocyanate), three membered rings (ethylene oxide), aldyhydes, isopropyl compounds, alkyl compounds, haloalkenes and dienes.

Thus, for *Option 1* to estimate residence time we might plot residence time as a function of temperature with the heat of reaction as a parameter.

Option 2 for estimating the residence time might be related to the *type* of reaction. That is, at a given temperature, all gas phase chlorinations, for example, might require the same residence time.

Now for the specifics. Rules of thumb given here for residence times are based on

- the phase: G, L, GL
- whether catalyzed or uncatalyzed
- the inlet temperature
- the heat of reaction or the *type* of reaction.

Few data have been published about the residence time of commercial reactors. Thanks to the help of many colleagues, I was able to work with 250 species and over 650 data[1]. From the data available we can provide some order-of-magnitude estimates (within a factor of ten) of the residence time used industrially.

Option 1: given the phase, assume that reactions with the same heat of reaction require the same residence time. Here we use a generic trajectory plot of residence time versus reaction temperature. We use the term trajectory because the data do not represent how the rate of reaction changes with temperature for any specific reaction. Figure 6.5 shows such data for gaseous, catalyzed reactions for three different ranges of heats of reaction: 5–100 MJ/kmol; 150–300 MJ/kmol and 600–900 MJ/kmol. For a given reaction temperature, the higher the heat of reaction, the longer the residence time required. Also shown above and below the 150–300 MJ/kmol line are lines indicating the arbitrary “factor-of-ten” region. Similar lines for the other two heats of reaction are also shown. For catalyzed gas reactions, with 44 species and 150 data, the data were within these bounds except for fluidized bed operations, for acrolein via oxidation (prediction low, data are above the line, (+), ethanol via hydration (+), cyclohexanol (–), aniline (+) and ammonia (+ +) via hydrogenation and butadiene via dehydration (++). Over 80 % of the available data are within the bands.

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[1] I would appreciate receiving residence time data for industrial processes so that I can improve this analysis. My e-mail is < woodsdr@mcmaster.ca> . Thanks.

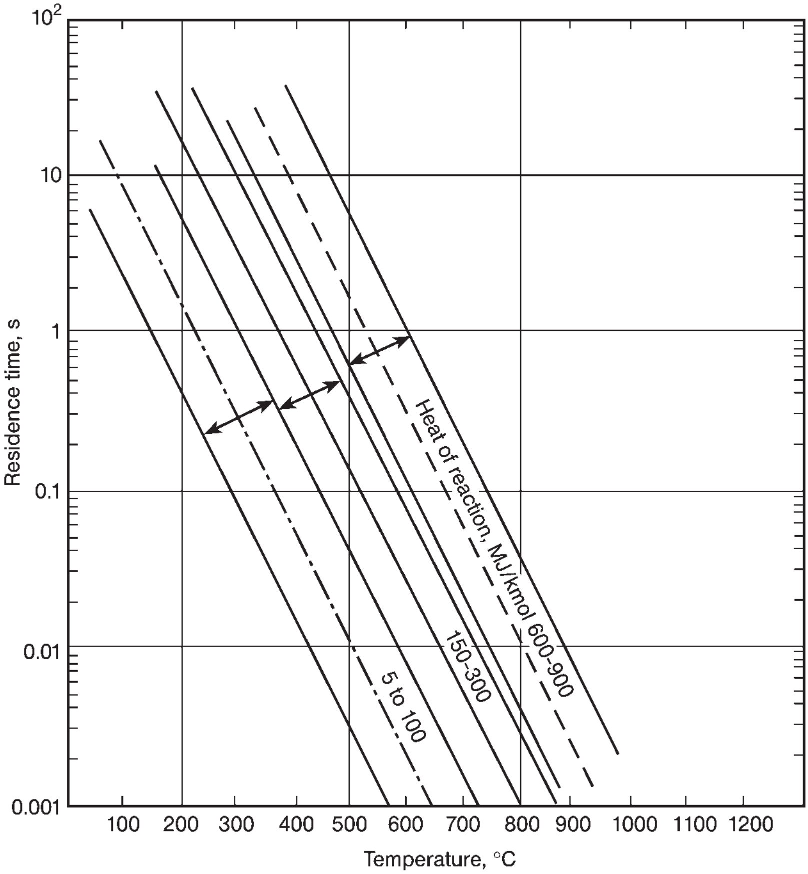

Figure 6.5 Residence time versus temperature for gaseous, catalyzed reactions with the heat of reaction as a parameter, 5–100 MJ/kmol; 150–300 MJ/kmol and 600–900 MJ/kmol with the factor-of-ten lines.

Figure 6.6 presents data for gaseous, noncatalyzed reactions (pyrolysis, thermal cracking, oxidation, 10 species and 21 data) with typical heats of reaction of 120–150 MJ/kmol. In general, noncatalyzed reactions take about 1000 times longer than the same catalyzed reaction at the same reaction temperature. Data lying outside the factor-of-ten bands are benzene (+) via hydrodealkylation and benzene (+) via hydrogenation of biphenyl (+).

For liquid reactions (192 product species, 450 data) Fig. 6.7 provides data for liquid, liquid–liquid, gas–liquid, gas–liquid–solid reactions. Over 80 % of the data lie within the factor-of-ten bands. Data lying outside the factor-of-ten bands are: acetaldehyde (–) via oxidation; acetone (++) via oxidation; adipic acid (–) via oxidation; aldol (–) via condensation; alkylate (– –) via alkylation; amino undecanoic acid (–) via hydrolysis; benzoic acid (–) via oxidation; butanol (–) via carbonylation; butene diol (–) via hydrogenation; butyl acetate (–) via alkylation; cellulose

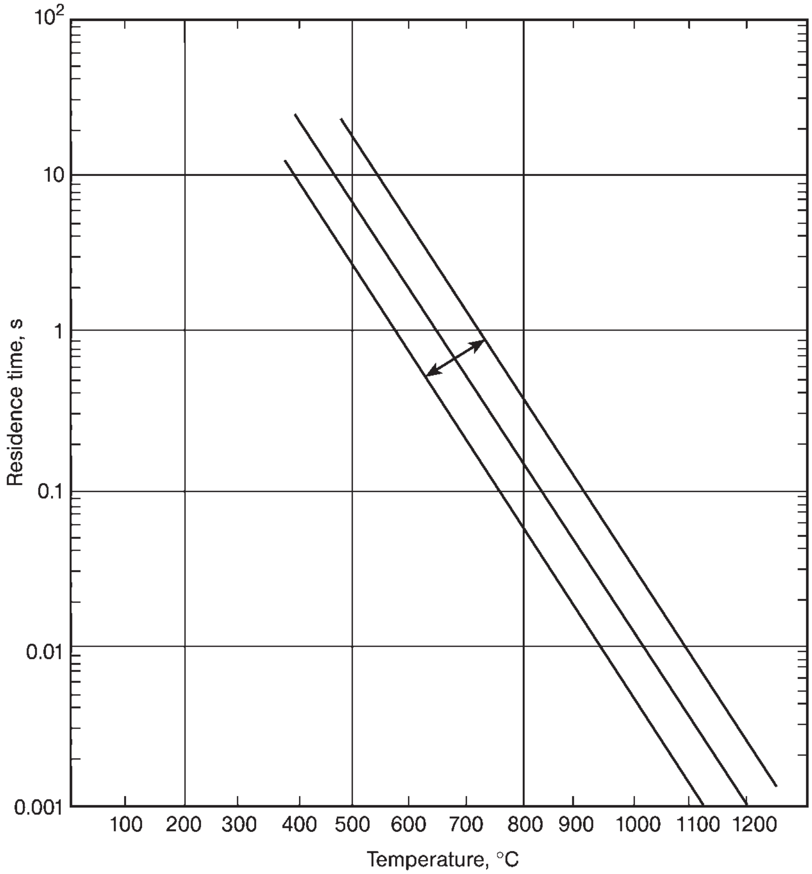

Figure 6.6 Residence time versus temperature for gaseous, uncatalyzed reactions. The factor-of-ten lines are drawn. The heat of reaction is about 120–150 MJ/kmol.

triacetate (– –) via acetylation; chloroprene (– –) via chlorination; DDT (–) via condensation; dimethyl terephthalate, (+) via esterification; dimethylaniline (+ +) via alkylation; erythritol (+) via aerobic fermentation; ethanol from corn or whey (–) via anaerobic fermentation; ethylene glycol (–) via hydration; ethyl hexanol (–) via hydrogenation; ethyl hexanol (+) via carbonylation; lactic acid from 15 % sugar, (+) via aerobic fermentation; methyl butynol (– –) via ethynylation; penicillin (+) via aerobic fermentation; polyester (++) via esterification; polyester (+ +) via condensation; polyetherpolyol (+) via addition; polyethylene, high pressure process for LDPE (– – –) via polymerization; polyethylene terephthalate (+) via polymerization; polyisoprene (–) via polymerization; polystyrene crystal and high impact (+) , via polymerization; polyurethane RIM (– – –) via polymerization; propylene oxide (+) via oxidation; SCP ex methane (–) via aerobic fermentation; sodium benzoate (– –) via neutralization; sorbitol (–) via hydrogenation; terephthalic

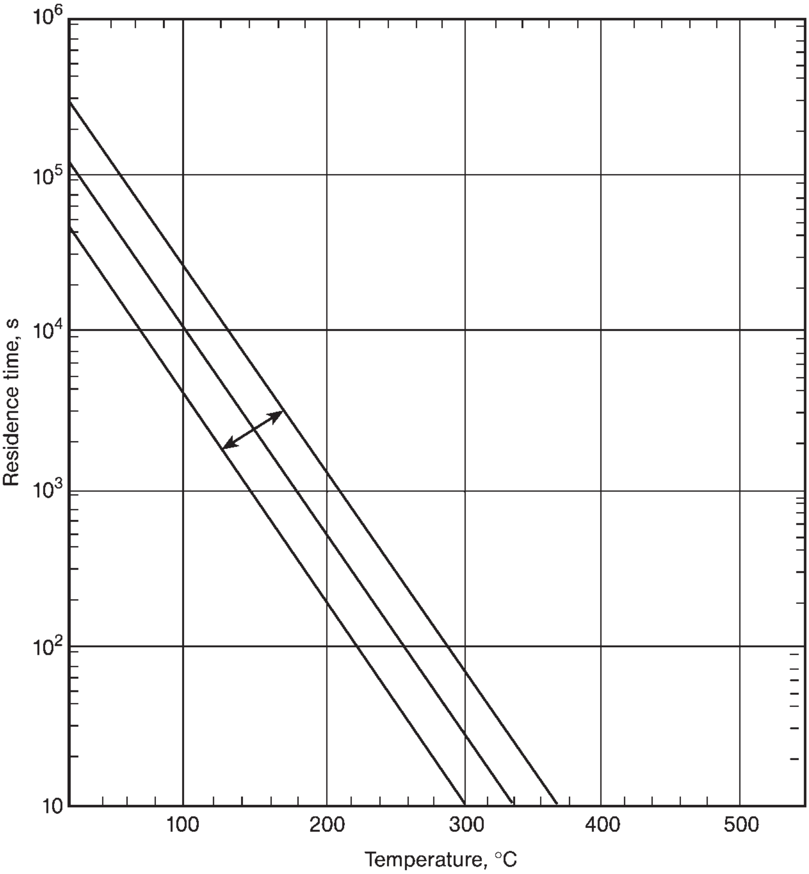

Figure 6.7 Residence time versus temperature for liquid, liquid–liquid, gas–liquid and gas–liquid–solid reactions. The factor-of-ten lines are drawn.

acid. (+) via disproportionation; terephthalic acid (+) via oxidation; toluene diisocyanate (+) via carbonylation; xylene, (+) via disproportionation.

Option 2: identify the *type* of reaction and details are given for each. Data are missing for some types of reactions. For many, the data are limited to a few data points and *option 1* may be the only possible choice because no data are given for the system of interest. These are organized according to the type of reaction:

Acetoxylation: L, catalyzed, CSTR, 80 °C, 7200 s (1 species, 1 datum).

Acetylation, **LS**, catalyzed, batch STR [–220 MJ/kmol]; 35 °C; 2000 s (2 species, 4 data) rate doubles in 15 °C for the range 20–60 °C.

Addition, **G**, solid catalyst, multitube catalyst bed/fluidized bed [–110 MJ/kmol] 180 °C, 10 s (2 species, 6 data) rate doubles in 30 °C for the range 100–225 °C.

Aldol condensation, **G**, solid catalyst, 300 °C, 25 s (1 species; 2 data) rate doubles 100 °C.

L, homogeneous catalyst, loop reactor; 20 °C, 5500 s (1 species, 1 datum)

Alkylation, **G,** solid catalyst, series of adiabatic beds, fluidized bed; 425 °C, 100 s (3 species, 9 data) rate doubles in 15 °C for the range 300–475 °C.

GL, aluminum chloride catalyst, bubble column [–115 MJ/kmol]; relatively independent of temperature for the range 50–180 °C, 1500 s (3 species, 5 data)

L, solid catalyst, multistage adiabatic, reactive distillation [–114 MJ/kmol] 200 °C, 2000 s, (cumene, phenol, 6 data) trajectory doubles in 25 °C for the range 60–260 °C.

LL, sulfuric acid catalyst, multistage CSTR [–80 to –112 MJ/kmol] 4 °C, range 300–40 000 s (alkylate, 9 data); dimethylaniline, 200 °C, 18 000–22 000 s (2 data); with HF, 25–40 °C, 300–2500 s (alkylate, 2 data).

Amination by ammonolysis, **G**, solid catalyst, fluidized bed [–650 MJ/kmol] 440 °C, 4 s (acrylontrile, 5 data) rate doubles 30 °C for the range 400–550 °C; multitube fixed catalyst bed [–650 MJ/kmol] 230 °C, 4 s (acrylonitrile, ethyl amine, 4 data) rate doubles in 25 °C for the range 150–250 °C.

Amination by reduction, **G**, fixed catalyst bed, 110 °C, 3300–6500 s. (1 species, 2 data).

Carbonylation (oxo, hydroformylation) react synthesis gas with olefin, **GL**, catalyst, fixed bed, CSTR or bubble reactor [–140 MJ/kmol] wide range; temperatures 100–200 °C, 3–40 000 s. (5 species, 15 data) no apparent trends.

Fischer Tropsch from synthesis gas to make alkanes or alcohols, **G,** catalyst, series of fixed beds, for alkanes, [–165 MJ/kmol] 350 °C, 40 s (1 species, 4 data), negligible temperature effect; for alcohols [–245 MJ/kmol] 250 °C, 20 s (1 species, 4 data), negligible temperature effect.

Chlorination, **G**, no catalyst, some catalyst, tower, fluidized bed, PFTR, multibed, multitube [–82 to –220 MJ/kmol] 400 °C, 2 s (4 species, 8 data) trajectory doubles in 60 °C for the range 150–520 °C.

GL, no catalyst, CSTR 20–90 °C, 500 000 s (chloral, 1 data);

GL, solid catalyst, STR, bubble [–100 to –185 MJ/kmol] 40–50 °C, 15–90 000 s; (2 species, 3 data) no apparent trends.

Combustion, **G**, no catalyst, plasma, burner [600 MJ/kmol] 1000–2700 °C, 0.01–0.002 s (acetylene, 10 data) no apparent trends.

Condensation, **G**, catalyst, fixed bed [–50 MJ/kmol] 400–550 °C, 45 s (ammonia, 9 data); fluidized bed [very exo] 300 °C, 0.6 s (acrolein, 1 data).

L, catalyst, pipe loop, CSTR (single and multistage), fixed bed [–45 to –100 MJ/kmol] 100 °C, 6000 s (12 species, 15 data) trajectory doubles in 20 °C for the range 15–200 °C.

Cracking thermal (Pyrolysis), **G**, no catalyst, fired tube [60 to 150 MJ/kmol] 700 °C, 0.7 s (10 species, 21 data) trajectory doubles in 50 °C for the range 400–900 °C.

Dehydration, **G**, catalyst, tubular fixed bed [–290 MJ/kmol] 340 °C, 100 s (3 species, 6 data) rate doubles in 10 °C. **L,** batch STR 20 °C, 20 000 s (1 species, 2 data) rate doubles in 50 °C.

Dehyrochlorination, **L**, no catalyst, series of CSTR, 110 °C, 15 000 s (chloroprene, 2 data).

Dehydrogenation, **G**, metal or metal oxide catalyst, adiabatic fixed bed or multitube [51 MJ/kmol] 250 °C, 5 s (5 species, 8 data) trajectory doubles in 65 °C for the range 225–400 °C; [130 MJ/kmol] 650 °C, 10 s (3 species, 17 data) rate doubles in 25 °C for the range 550–800 °C.

L, catalyst, CSTR 115 °C, 2000 s (2 species 6 data) trajectory doubles in 25 °C for the range 100–130 C.

Disproportionation, isomerization, **G**, catalytic, adiabatic fixed bed, moving bed [–10 MJ/kmol] 310–500 °C, 0.1–150 s (2 species, 15 data) no apparent trends. **L**, catalytic, 200 °C, 1300 s (xylene, 13 data) trajectory doubles in 80 °C for the range 30–350 °C.

Epoxidation, **L**, catalytic, series of CSTR, 75 °C, 10 000 s (2 species, 5 data) trajectory doubles in 40 °C for the range 50–110 °C.

Esterification, **L**, sulfuric acid or IX resin catalyst, CSTR, reactive distillation, [–30 MJ/kmol] 100 °C, 6000 s (7 species, 20 data) rate doubles in 15 °C for the range 70–160 °C.

Ethynylation, **GL**, homogeneous catalyst, PFTR tube, [–230 MJ/kmol] 30 °C, 200 s (methyl butynol, 2 data).

Fermentation, **L**, anaerobic: 20–30 °C, 20 000–280 000 s (for tropophase and idiophase but excluding time in the seed tank).

aerobic, **GL**, sparged STR, airlift, 20–65 °C, 1200–1 600 000 s. Figure 6.4 illustrates the residence times for different types of products.

Hydration, **G**, catalyst, adiabatic PFTR [–45 MJ/kmol] 300 °C, 2500–126 000 s (ethanol, 2 data). **L**, no catalyst, [–75 MJ/kmol] 175 °C, 3000 s (ethylene glycol, 2 data); acid catalyzed, 55 °C, 1800 s (1 species, 1 datum).

Hydrodealkylation, **G**, no catalyst, fire tube [–50 MJ/kmol] 675 °C, 30 s (2 species, 4 data) rate doubles in 30 °C for the range 625–725 °C. **G**, catalyst, 675 °C, 0.025 s (3 species, 5 data) rate double in 25 °C for the range 400–700 °C.

Hydrogenation, **G**, no catalyst, tank [–44 MJ/kmol] 700 °C, 7.5 s (benzene, 1 datum); catalyst, fluidized bed, fixed bed [–500 MJ/kmol] 300 °C, 1 s (aniline, 2 data) rate doubles in 30 °C for the range 250–380 °C. catalyst, fixed bed, multitube [–200 MJ/kmol] 200 °C, 0.5 s (cyclohexane, 4 data) rate doubles in 35 °C for the range 150–250 °C.

GL, Ni, Cu, Cr catalyst, sparge STR, slurry, trickle bed, fixed bed [–156 and varies MJ/kmol] 20–250 °C, 200–40 000 s (8 species, 10 data) relatively temperature independent, no apparent trends.

Hydrolysis, **L**, acid catalyst, [–15 to –55 MJ/kmol] 100 °C, 3000 s (7 species, 10 data), trajectory doubles in 20 °C for the range 10–160 °C.

Neutralization, **L**, no catalyst, STR or slurry pipe 60 °C, 220 s (sodium benzoate, 1 datum).

Nitration, L, catalyst, CSTR [–100 to 145 MJ/kmol] 100 °C, 5000 s (4 species, 9 data) trajectory doubles in 30 °C for the range 30–160 °C.

Oxidation, **G**, catalyzed, multitube, shallow adiabatic [–150 MJ/kmol] 400 °C, 0.08 s (3 species, 5 data) trajectory doubles in 30 °C for the range 130–350 °C. catalyzed, multitube, shallow adiabatic, [–250 MJ/kmol] 400 °C, 0.7 s (8 species, 18 data) trajectory doubles in 30 °C for the range 180–750 °C. Catalyzed, fixed bed, fluidized bed [–900 MJ/kmol] 400 °C, 10 s (3 species, 5 data) trajectory doubles in 30 °C for the range 300–900 °C.

GL and **L**, homogeneous catalyst, bubble column, sparged STR, CSTR [–100 to –250 MJ/kmol] 150 °C, 1800 s (14 species, 21 data) trajectory doubles in 20 °C for the range 10–200 °C.

GLS, catalyst and **GLL**, columns with air agitation, data above are reasonable (3 species, 6 data).

Polymerization (thanks to A.E. Hamielec and R. Hutchinson for their data) **L**, catalyzed, STR [– 55 to –95 MJ/kmol monomer] 70 °C, 18 000 s (7 species, 15 data) trajectory doubles in 25 °C for the range 50–270 °C. Batch RIM, 70 °C, 45 s (polyurethane, 1 data); high pressure, continuous tubular, 200 °C, 45 s (LDPE, 3 data). Acrylates $\{E = 15\text{–}18$ kJ/mol$\}$, methyl acrylate k_p at 30 °C = 14 000 L/mol s; dodecyl acrylate k_p at 30 °C = 21 000 L/mol s; Methacrylates $\{E = 21\text{–}23$ kJ/mol$\}$, methyl methacrylate k_p at 30 °C = 380 L/mol s; dodecyl methacrylate k_p at 30 °C = 600 L/mol s; Styrene$\{E = 32\text{–}33$ kJ/mol$\}$, k_p at 30 °C = 110 L/mol s; vinyl acetate $\{E = 20\text{–}21$ kJ/mol$\}$ k_p at 30 °C = 4000 L/mol s.

Reforming, cat, **G**, catalyst, fired tube, 550 °C, 0.2 s (refinery, 2 data).

Sulfonation, **G**, catalyst, furnace, fixed bed, 600 °C, 4 s,(2 species, 3 data) trajectory doubles in 25 °C for the range 370–700 °C. **L**, catalyst, CSTR, 100 °C, 7000 s, (2 species, 2 data) trajectory doubles in 25 °C for the range 30–150 °C.

Example, the target is to produce ethylene from ethane by pyrolysis at 800 °C; the heat of reaction is 144 MJ/kmol and no catalyst is used. Estimate the residence time. *Option 1*, at 800 °C the residence time might be between 0.5 and 5 s. *Option 2*, Consult cracking, thermal (pyrolysis) gas. The data are for no catalyst, a heat of reaction in the correct range and suggest 700 °C, 0.7 s with the trajectory doubling in 50 °C. Hence, since the temperature of 800 is 100 °C higher and since the rate doubles every 50 °C the residence time would be reduced by 100/50 = 2 or $2^2 = 4$ times faster or 0.7/4 s = 0.17 s or 0.2 s. *Comment:* published data report a residence time of 1.5 s or about 10 times more residence time required than predicted with Option 2. This illustrates the method and the error involved in this order-of-magnitude method.

The rest of the rules of thumb are organized based on reactor type.

6.4
Burner

- *Area of Application*

Suitable for **g**as reactions that are homogeneous and fast and are either highly exothermic or endothermic. Usually have a high reaction temperature. Short residence time.

- *Guidelines*

Burner designed to introduce reactants into the “combustion” zone. Be careful to ensure that the system is not operating within the explosive limits. Examples include the fluorination of UF_4 to UF_6 at 350–600 °C with solids feed at rate of 1 Mg/d; uranyl nitrate dehydrated and denitrified to uranium dioxide at rate of 1 Mg/d. Air oxidation of phosphorous to P_2O_5 at 2500 °C at 1.5 Mg/h. This reactor is 1.8 m diameter, 10 m high with gas flow of 1 m/s and molten flow of 0.4 kg/s. Most reactors have to be custom designed.

6.5
PFTR: Pipe/Tube, Empty Pipe for Fluid Systems

The empty tube can be coiled, straight, or hairpins; horizontal or vertical; in a cooling bath, in the atmosphere or can be placed in a furnace for temperatures > 500 °C. Can operate under pressure or vacuum. Synonyms include **“fire tube”** (for high temperature applications); **“tube loop”** (for gas liquid applications) where liquid is pumped into the bottom of a vertical coil, exits and recycles to the pump; gas is injected into the bottom of the loop. Another GL option is the **“tubular reactor with injector”** to create very fine bubbles and large surface area. For GL, the velocity and method of introduction of the second phase varies. Use external surface area if temperature control is important. Characteristics of these are given in Section 1.6.1.

The characteristics of this configuration are $Bd = \infty$. $Pe > 100$.

- *Area of Application*

Usually controlled by reaction kinetics or heat transfer or both. Provides a well-defined residence time and is capable of good temperature control.

Phases: Gas, liquid, gas–liquid, liquid–liquid. Use if the order of the reaction is positive and $> 95\,\%$ conversion is the target, and for consecutive reactions with an intermediate as the target product. For homogeneous reactions.

Gas (or gas with homogeneous catalyst): heat of reaction: endothermic; reaction rate, fast; capacity: 0.001–200 L/s; good selectivity for: consecutive reactions and irreversible first order; volume of reactor 1–10 000 L; OK for high pressures or vacuum. For temperatures < 500 °C. For temperatures > 500 °C use fire tube. For example, used for such homogeneous reactions as acetic acid cracked to ketene.

Liquid (or liquid with homogeneous catalyst): heat of reaction: endothermic; reaction rate, fast or slow; capacity: 0.001–200 L/s; good selectivity for consecutive reactions; volume of reactor 1–10 000 L; OK for high pressures. For temperatures > 500 °C use fire tube. For example, used for visbreaking and delayed coking.

Gas–liquid and **GL + microorganisms (bio):** Residence time: short; heat of reaction: primarily for endothermic reactions. Beware of highly exothermic reactions because of inability to control temperature; good selectivity for consecutive reactions in which the product formed can react further. see bubble reactors, Section 6.13. Use with irreversible reactions and pure gas feed. Area per unit volume 50

to 2000 m^2/m^3; high pressure drop. For tube loop: modest OTR, ease in injection along the tube. For injector into tube: extremely large surface area at the expense of power input. Bubbles 1 to 30 μm diameter.
Liquid–liquid: see also bubble reactors, Section 6.13.

• *Guidelines*
Gas: Residence time 0.5–1.3 s; gas velocity 3–10 m/s; $Re > 10^4$, $L/D > 100$. To eliminate backmixing $Pe > 100$. For temperatures > 500 °C place in a furnace.
Fire tube: or tubes in furnace.

Radiant heat flux in furnaces 30–80 kW/m^2.

Reformers:

- gas oil: heat flux: 40–50 kW/m^2; fluid velocity inside tubes 1.5–2.5 m/s
- light oil: heat flux: 25–40 kW/m^2; fluid velocity inside tubes 1.4–2.3 m/s
- heavy oil: heat flux: 25–35 kW/m^2; fluid velocity inside tubes 1.7–2.1 m/s

Cracking: ethylene ex

- ethane: heat flux: 23–28 kW/m^2 at exit conditions with double values at inlet
- propane: heat flux: 14–17 kW/m^2 at exit conditions with double values at inlet
- butane or naphtha: heat flux: 11–15 kW/m^2 at exit conditions; at inlet the values are twice as large.

See thermal energy: furnaces, Section 3.2.
Liquid: Residence time: 0.4–2000 s with the usual values 1–6 s; liquid velocity 1–2 m/s; $Re > 10^4$, $L/D > 100$. PFTR is smaller and less expensive than CSTR. PFTR is more efficient/volume than CSTR if the reaction order is positive with simple kinetics.

For fast reactions: use small diameter empty tube in turbulent flow.

For slow reactions: use large diameter empty tubes in laminar flow. If reaction is complex and a spread in RTD is harmful, consider adding static mixer, Section 6.6.

Examples: hydrolysis of corn starch to dextrose; polymerization of styrene; hydrolysis of chlorobenzene to phenol; esterification of lactic acid.
Gas–liquid including bio: The gas is introduced into the liquid via a tube or by an ejector. Surface area varies dramatically depending on the power input and configuration. In general, superficial gas velocity, 0.01 to 0.4 m/s; holdup 0.05 to 0.95; energy 0.1 to 100 kW/m^3. < 10 cm diameter tubes, $k_L\ a = 0.01$ to 0.7 1/s.
For tubes: 50–400 m^2/m^3; power 1–80 kW/m^3 total volume; for vertical **tube loop:** 50–2000 m^2/m^3; power 0.1–100 kW/m^3 total volume, OTR: 2.7 g/s m^3; mixing time: 80 s; gas content: 30 %; maximum volume 3000 m^3; for **horizontal coil** 50–700 m^2/m^3; for **ejector into a tube:** 40 000–500 000 m^2/m^3; power 100–

10 000 kW/m^3 total volume. Non-coalescing bubbles $k_{La}{}^{+} = 5 \times 10^{-5}$–$2 \times 10^{-4}$ and increasing with Power/Volume. OTR data, Section 1.6.1. See also two-phase flow Section 2.4.
Liquid–liquid: see size reduction, Sections 8.3 and 1.6.2.

6.6
PFTR: Static Mixer in Tube

- *Area of Application*

Phases: gas with mixer as catalyst, gas–liquid, liquid, liquid–liquid.

Fast competing parallel or consecutive reactions that are highly exothermic. For gas–liquid: fast reactions in the liquid phase. Flexible, interstage addition possible. Large heat transfer area; intensive radial mixing with negligible backmixing; narrow RTD; suitable for processes where viscosity increases. Not for foaming systems.

- *Guidelines*

See Heat transfer Section 3.5 and Mixing Sections 7.1 and 7.3.

For **gas** reactions: *Example: oxidation of ammonia to nitric acid, production of maleic anhydride, xylene, styrene, vinyl chloride monomer, ethylene dichloride. L/D* for mass transfer mixers 6:1–20:1. Gas velocity for turbulent flow.

For **gas–liquid** reactions: cocurrent mass transfer in bubble flow: gas superficial velocity 0.6–2 m/s; liquid superficial velocity 0.3–3 m/s; volumetric flowrate ratio of gas to liquid = 1 at the nozzle. Holdup 0.5, energy 10 to 700 kW/m^3; $k_L\, a = 0.1$ to 3 1/s. *spray flow*: gas superficial velocity 3–25 m/s; area to volume 1000–7000 m^2/m^3. See Section 1.6.1.

For **liquid–liquid** reactions: dispersed phase drops diameter 100–2000 μm with diameter decreasing as the velocity increases, the surface tension decreases and the hydraulic radius of the mixing element decreases; surface area 100–20 000 m^2/m^3 depending on the drop diameter and the concentration of dispersed phase. Turbulent flow. *Example reactions as a PFTR: polymerizations of polystyrene, nylon, urethane; sulfonation reactions and caustic washing*. See Size reduction Sections 8.3 and 1.6.2.

- *Good Practice*

Prefer because small volume provides a means of intensification (H).

6.7
PFTR: Empty Pipe/Tube for Fluids and Solids

Synonyms include "**transported** or **slurry reactors**" and "**transfer line**". The velocity and method of introduction of the second phase vary. Related options include open multitube, Section 6.8. fluidized reactor, Section 6.30.

- *Area of Application*

Phases: **Gas–solid**, **gas–solid reactant**, **liquid–solid**, **gas–liquid–solid**. Good for very fast reactions and for consecutive reactions. Large transfer area; temperature can be controlled by injection; little backmixing that gives a well-defined residence time.

Gas plus catalytic solid: Reaction rates very fast and very rapid deactivation of catalyst. Solid particle diameter 0.007–1.5 mm.

Gas plus solid reactant: solid particle diameter 0.007–1.5 mm.

Liquid plus solid catalyst: slurry reactors.

Gas–liquid plus solid catalyst: For fast hydrogenation reactions. Compared with trickle bed Section 6.17 or PFTR fixed bed with up flow, Section 6.9.

1. Catalyst particles are small so less chance of diffusional resistance to mass transfer.
2. Better control of temperature (because of better heat transfer efficiency and high heat capacity of slurries) attractive for exothermic reactions.
3. Don't have to shut down for catalyst replacement of reactivation.
4. Partial wetting and need to maintain a coating film of liquid (as needed in the trickle bed) are not issues.
5. Usually the space time yield is better in slurry reactors (under comparable conditions).

Gas–liquid plus microorganisms (bio) see Section 6.5.

- *Guidelines*

Gas plus catalytic solid: Gas residence time in milliseconds; see pneumatic conveying, Section 2.6 and transported bed drying, Section 5.6.

Gas plus solid reactant: Solid residence time, 0.8–300 s; gas residence time, < 1 s; see pneumatic conveying, Section 2.6.

Liquid plus solid catalyst: see Section 2.5.

Liquid plus solid reactant: see Section 2.5.

Gas liquid plus solid catalyst: Usually operate in the churn-slug and piston slug flow regimes with gas velocities > 0.05 m/s for water-like liquids. Flow regimes are given in Fig. 2.2, Section 2.4. Gas holdup is proportional to the (superficial gas velocity)^n where $n = 0.7$–1.2 in the bubbling regime and $n = 0.4$–0.7 in the churn turbulent regime. Gas holdup is independent of diameter but very sensitive to trace contaminants and foaming. Used for some hydrogenations.

- *Good Practice*

Ensure the flow regime is maintained.

6.8
PFTR: Empty Multitube, Nonadiabatic

Related to empty single tube, Section 6.5 or transfer line, Section 6.7.

- *Area of Application*

Suitable for fast, gas or liquid homogeneous, exothermic reactions. This provides narrow residence time distributions, and a large heat transfer area. Multistaging is possible. Static mixers can be used if viscosity is high.

- *Guidelines*

Size on residence time and heat transfer area, Section 3.3. Shell and tube exchanger with reactants inside the tube, 250–400 m^2/m^3. Tube diameter < 50 mm. The smaller the diameter of the tubes, the larger the surface area from the tubes.
Gas. Use high mass gas velocity to improve heat transfer kg/s $m^2 > 1.35$. To ensure good gas distribution and negligible backmixing, $Pe > 2$. Gas velocity 3–10 m/s; residence time 0.6–2 s. Heat transfer coefficient: Gas at 0.1 kPa g vs. liquid: $U = 0.05$ kW/m^2 K; Gas at 20 MPa vs. liquid: $U = 0.5$ kW/m^2 K.

Individual coefficient on shell side: *coolants*: boiling water, h = 1–3 kW/m^2 K; boiling organic, h = 0.2–1.5 kW/m^2 K; molten salts, h = 0.5–1.5 kW/m^2 K. *Heating agents:* steam, h = 2–5 kW/m^2 K; combustion gas, h = 0.01–0.03 kW/m^2 K.

6.9
PFTR: Fixed Bed Catalyst in Tube or Vessel: Adiabatic

- *Area of Application*

Phases: Gas, liquid, gas–liquid interacting with solid catalyst or inert solid. Use if the order of the reaction is positive and > 95 % conversion is the target, and for consecutive reactions with an intermediate as the target product. Caution use for highly exothermic reactions. Not suitable for Arr (ΔT_{ad}^{+}) > 10; or $\Delta T_{ad} > 100\,°C$; usually keep $\Delta T_{ad} < 50\,°C$. Provides large gas throughput. Related topics for **GL**, trickle reactor, Section 6.17, or bubble reactor, Section 6.13.
Gas with fixed bed of solid catalyst: heat of reaction: endothermic or slightly exothermic; reaction rate, fast; good selectivity and activity for: consecutive reactions and for irreversible first order reactions; volume of reactor 1–10 000 L; OK for high pressures. High conversion efficiency, simple, flexible, gives high ratio of catalyst to reactants.
Liquids plus fixed bed of solid catalyst: capacity: 0.001–200 L/s. Same general expectations as for gas.
Gas–liquid–solid: similar to trickle bed, Section 6.17.

- *Guidelines*

Catalyst diameter 1–5 mm.

Gas with fixed catalyst bed: Residence time < 1 s; favored if the life of the catalyst is > 3 months. If the catalyst deactivates rapidly select fluidized, Section 6.30 or slurry reactors, Section 6.7. Catalyst must have an axial crush strength > 50–$80\ \mathrm{kg/cm^2}$. To ensure good gas distribution and negligible backmixing, $\mathrm{Pe} > 2$; Height/catalyst particle diameter $H/D_\mathrm{p} > 100$ and $D_\mathrm{p}/D < 0.10$. Usually bed volume porosity 0.42 which decreases to 0.38 as the bed ages. PFTR gives less volume than slurry or fluidized bed reactors. If the main reactant undergoes 90 % conversion within a reactor length of bed height/catalyst particle diameter = 100, then the reaction is not mass transfer controlled. Select a bed height such that the length of the tube/mass flow velocity ($\mathrm{kg/s\ m^2}$) $> 0.5\ \mathrm{m^3\ s/kg}$ fluid. Δp is < 1 to 10 % of total pressure; if Δp too high then use larger catalyst or change catalyst.

For adiabatic operation with exothermic reactions, limit the height of the bed to keep temperature increase $< 50\,^\circ\mathrm{C}$. Tube diameter < 50 mm to minimize extremes in radial temperature gradient. For fast reactions, catalyst pore diffusion mass transfer may control if the catalyst diameter > 1.5 mm.

Temperature gradients within the catalyst and in the external bulk phase:

1. Within a catalyst pellet the internal temperature gradient is rarely > 1–$2\,^\circ\mathrm{C}$ between the surface and the center. Assume temperature at the center of the catalyst = surface temperature.
2. The external temperature gradient is usually high with the catalyst surface temperature 10–30 °C hotter than the temperature in the gas phase.

Concentration gradients within the catalyst and in the bulk phase:

3. Within the catalyst pellet the internal concentration gradient is often very high (with 0 concentration at the center).
4. External concentration gradient is usually small except for very fast reactions.

Shallow beds, including catalytic gauze, are used for high reaction rates and unstable products. These provide very short residence times. OK for autothermal operation.

Related topic gas adsorption, Section 4.11.

Liquids with fixed catalyst bed: To minimize backmixing, $\mathrm{Pe} > 1$; use $H/D_\mathrm{p} > 200$ and $D_\mathrm{p}/D < 0.10$. Temperature gradient within the catalyst and in the external bulk phase:

1. Within the catalyst, the internal temperature gradient is low. Assume the temperature at the center of the catalyst = surface temperature.
2. The external temperature gradient from the catalyst surface temperature to the bulk is low.

Concentration gradient within the catalyst and in the external bulk liquid phase:

3. Internal concentration gradient depends on the reaction.
4. External concentration gradient may be high because of slow mass transfer or fast reaction.

For IX resin, height/diameter = 0.5. If the main reactant undergoes 90 % conversion with the bed height/catalyst particle diameter = 10 000, then the reaction is not mass transfer controlled. Since this height/diameter ratio is usually not used, check if mass transfer controls.

Related topic liquid adsorption, Section 4.12 and IX, Section 4.13.
Gas–liquid downflow over fixed catalyst, see Trickle reactors, Section 6.17.

- *Good Practice*

The target inlet gas temperature should be such that the initial rate of reaction is in the following target ranges:

If the reaction is exothermic then set the inlet temperature such that the target rate of reaction is 0.2×10^{-5}–0.5×10^{-5} mol/s.g catalyst. For a catalyst with bulk density 1.4 Mg/m^3 this is about 1 1/s.

If the reaction is endothermic then set the inlet temperature such that the target rate of reaction is 0.4×10^{-4}–8×10^{-4} .

Increase the reaction temperature gradually to offset catalyst decay.

- *Trouble Shooting*[1]

Gas-catalytic reactions. Temperature and pressure drop across bed are usually key variables. When a hot spot develops, it usually develops at the front end of the bed and gradually moves through the bed. It may take three to four weeks to travel through the full bed. If the hot spot is 100–200 °C above normal, then usually carbon is deposited and the catalyst is irrevocably damaged. Temperature control is critical for exothermic reactions. *"Δp rapidly increases":* emergency shutdown?. *"Pressure surge":* possible shutdown?/[runaway reactor]*.
"Rapid decline in conversion": unfavorable shift in equilibrium at operating temperature, for exothermic reactions/[sintering]*/[agglomeration]*/poison in new feed. *"Gradual decline in conversion":* sample error/analysis error/temperature sensor error/[catalyst activity lost]*/[maldistribution]*/[unacceptable temperature profiles]*/wrong locations of feed, discharge or recycle lines/faulty design of feed and discharge ports/wrong internal baffles and internals/faulty bed voidage profiles. *"Gradual decline in conversion and axial temperature constant with depth of region increasing with time":* [poisoned catalyst]*. *"Gradual decline in conversion and axial temperatures < usual":* [poisoned catalyst]*. "*Gas exit concentration of reactants high*": sample error/analysis error/catalyst selectivity low/[catalyst activity lost]*. *"Exit concentration of product higher than design"*: reactor leaking. *"Change in prod-*

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[1] Based on R.B. Anderson, personal communication; H.F. Rase "Fixed bed reactor design and diagnostics", 1990, Wiley and Dutta, S. and R. Gauly, *Hydrocarbon Process.*, 1999, Sept., 43–50.

uct distribution": [maldistribution]*/[poisoned catalyst]*/feed contaminants/change in feed/change in temperature settings.

"Temperature runaways": [temperature hot spots]*/[reactor instability]*. *"Pressure and bed temperature and reactor unsteady":* water in feed/[maldistribution]*. *"Local high temperature/hot spot with $T > 100\,^\circ C$ above normal"*: [maldistribution of gas flow]*/instrument error/extraneous feed component that reacts exothermically. *"Local low temperature within the bed"*: [maldistribution of gas flow]*/instrument error/extraneous feed component that reacts endothermically. *"Exit gas temperature too high"*: instrument error/control system malfunction. *"Temperature varies axially across bed":* [maldistribution]*.

"Δp higher than design": catalyst degradation/instrument error/high gas flow/sudden coking/crud left in from construction or revamp. *"Δp increasing gradually yet flowrate constant":* [coke formation]*/[dust or corrosive products from upstream processes]*.

"Startup after catalyst regeneration, conversions < standard": [regeneration faulty]*. *"Startup after catalyst replacement, poor selectivity":* bad batch of catalyst/preconditioning of catalyst faulty/temperature and pressures incorrectly set/instrument error for pressure or temperature.

"Startup after catalyst replacement, Δp < expected and conversion < standard": [maldistribution]* and axial variation in temperature/larger size catalyst. *"Startup after catalyst replacement, conversion < standard and Δp increasing":* [maldistribution and axial temperatures different]*/feed precursors present for polymerization or coking. *"Startup after catalyst replacement, Δp for this batch of catalyst > previous batch":* catalyst fines produced during loading/poor loading. *"Startup after catalyst replacement, conversion < specifications per unit mass of catalyst and more side reactions":* [maldistribution]*/faulty inlet distributor/faulty exit distributor.

[Active species volatized]:* [regeneration faulty]*/faulty catalyst design for typical reaction temperature/[temperature hot spots]*.

[Agglomeration of packing or catalyst particles]:* [temperature hot spots]*.

*[Attrition of the catalyst]**: flowrates > expected/catalyst too fragile.

[Carbon buildup]:* [inadequate regeneration]*/[excessive carbon formed]*.

[Catalyst selectivity changes]:* [poisoned catalyst]*/feed contaminants/change in feed/change in temperature settings.

[Catalyst activity lost]:* [carbon buildup]*/[regeneration faulty]*/[sintered catalyst]*/excessive regeneration temperature/[poisoned catalyst]*/[loss of surface area]*/[agglomeration]*/[active species volatized]*.

[Excessive carbon formed]:* operating intensity above usual/feed changes/[temperature hot spots]*.

[Dust or corrosive products from upstream processes]:* in-line filters not working or not installed/dust in the atmosphere brought in with air/air filters not working or not installed.

[Loss of surface area]:* [sintered catalyst]*/[carbon buildup]*/[agglomeration]*.

[Maldistribution]:* faulty flow distributor design/plugging of flow distributors with fine solids, sticky byproducts or trace polymers/[sintered catalyst particles]*/

[agglomeration of packing or catalyst particles]*/fluid feed velocity too high/faulty loading of catalyst bed/incorrect flow collector at outlet.
[Poisoned catalyst]:* poisons in feed/flowrate of "counterpoison" insufficient/poison formed from unwanted reactions.
[Poisons in feed]:* depends on reaction/contamination in feed/upstream process or equipment upsets/changes in feed. Poisons for **platforming** include high sulfur in feed and high feed end point with upstream equipment failure being compressor failure/water upset/chloride upset.
[Reactor instability]:* control fault/poor controller tuning/wrong type of control/feed temperature exceeds threshold.
*[Regeneration doesn't remove all carbon from the catalyst]**: regeneration temperature not hot enough/regeneration time not long enough/[maldistribution]*.
[Regeneration faulty]:* temperatures too high/oxygen concentration < standard/oxygen concentration > standard causing too rapid a burn/incorrect temperature and time so that coke left on catalyst. [regeneration doesn't remove all carbon from the catalyst]*/excessive temperature during regeneration.
[Runaway reactor]:* feed temperature too high/[temperature hot spot]*.
[Sintered catalyst]:* temperature sensor error/[temperature hot spots]*/[maldistribution]*/temperature in reactor too high/regeneration temperature too high.
[Temperature hot spots]:* bed too deep/[maldistribution]*/flowrate < design/instrument error/extraneous feed component that reacts exothermically.

6.10
PFTR: Multi-bed Adiabatic with Inter-bed Quench or Heating

- *Area of Application*

Phases: Gas plus solid catalyst. For fast reactions, that are strongly exothermic or endothermic. Use if the order of the reaction is positive and > 95 % conversion is the target, and for consecutive reactions with an intermediate as the target product. Used primarily for equilibrium reactions.

- *Guidelines*

Limit the height of the bed to keep temperature increase < 50 °C to minimize effects of radial temperature gradients (see Section 6.9). The bed can be shallow and wide. Quench can include injection of cold reactants, internal or external heat exchangers.

- *Good Practice*

Gas flow down through the bed. Provide good gas distribution. Increase reaction temperature gradually to offset catalyst decay.

6.11
PFTR: Fixed Bed with Radial Flow

For fast reactions, strongly exothermic or endothermic reactions.

Phases: Gas with solid catalyst. Use to minimize pressure drop limitations. Multi-staging is possible. Care is needed in sizing the gas distribution and collection. Otherwise size, cost and trouble shoot similar to Sections 6.9 and 6.10.

6.12
PFTR: Multitube Fixed Bed Catalyst or Bed of Solid Inerts: Nonadiabatic

- *Area of Application*

Phase: Gas–liquid plus solid catalyst

Use if the order of the reaction is positive and $> 95\,\%$ conversion is the target, and for consecutive reactions with an intermediate as the target product. Exchange heat generated if the product of the Arrhenius number and the dimensionless adiabatic temperature rise > 10.

Homogeneous gas reactions requiring good temperature control via inert solids or heterogeneous gas reactions. Can provide continuous temperature control. Can be used for exothermic reactions.

- *Guidelines*

Shell and tube exchanger with reactants and catalyst inside the tube, 250–400 m^2/m^3. Tube diameter < 50 mm. The smaller the diameter of the tubes, the larger the surface area from the tubes.

Gas with fixed bed of catalyst: Use high mass gas velocity to improve heat transfer kg/s $m^2 > 1.35$. To ensure good gas distribution and negligible backmixing, Pe > 2; Height/catalyst particle diameter $H/D_p > 100$ and $D_p/D < 0.10$. Gas velocity 3–10 m/s; residence time 0.6–2 s. For fast reactions, catalyst pore diffusion mass transfer may control if catalyst diameter > 1.5 mm. Heat transfer coefficient: Gas at 0.1 kPa g vs. liquid: $U = 0.05$ kW/m^2 K; gas at 20 MPa vs. liquid: $U = 0.5$ kW/m^2 K.

Individual coefficient on shell side: *coolants*: boiling water, $h = 1$–3 kW/m^2 K; boiling organic, $h = 0.2$–1.5 kW/m^2 K; molten salts, $h = 0.5$–1.5 kW/m^2 K. *Heating agents:* steam, $h = 2$–5 kW/m^2 K; combustion gas, $h = 0.01$–0.03 kW/m^2 K.

Liquids with fixed bed of catalyst: To minimize backmixing, Pe > 1; use $H/D_p > 200$ and $D_p/D < 0.10$. Liquid velocity 1–2 m/s; residence time 2–6 s.

Heat transfer coefficient $U = 0.5$ kW/m^2 K. Cooling liquid vs. liquids: $U = 0.2$–1.2 kW/m^2 K. Heating liquids via steam, $U = 0.35$–1.2 kW/m^2 K.

- *Good Practice*

Gas: The target inlet gas temperature should be such that the initial rate of reaction is in the following target ranges:

If the reaction is exothermic then set the inlet temperature such that the target rate of reaction is 1×10^{-5}–2×10^{-5} mol/s g catalyst, and if endothermic then to 2×10^{-4}–4×10^{-4} mol/s g catalyst.

Increase reaction temperature gradually to offset catalyst decay.

- *Trouble Shooting*

See Section 6.9 plus the additional considerations because of the tubes.*"Δp increases dramatically, top of tubes hot, less conversion than expected":* possible shutdown?/contamination in feed/[poisoned catalyst]*.

"Gradual decline in conversion": sample error/analysis error/temperature sensor error/[catalyst activity lost]*/[maldistribution]*/[unacceptable temperature profiles]*/[inadequate heat transfer]*/wrong locations of feed, discharge or recycle lines/faulty design of feed and discharge ports/wrong internal baffles and internals/faulty bed voidage profiles. *"Exit gas temperature too high"*: instrument error/control system malfunction/fouled reactor coolant tubes. *"Soon after startup, temperature of tubewall near top > usual and increasing and perhaps Δp increase and less conversion than expected or operating temperatures > usual to obtain expected conversion":* inadequate catalyst regeneration/contamination in feed; for steam reforming sulfur concentration > specifications/wrong feed composition; for **steam reforming**: steam/CH_4 < 7 to 10. *"Soon after startup, temperatures over full length of some tubes > usual and perhaps Δp > or < usual and may increase with time":* faulty loading of the catalyst/[maldistribution]*. *"Hot bands or stripes; perhaps Δp increase":* low ratio of steam to methane/[carbon formation; whisker type]*/wrong feed composition: for steam reforming steam/methane < 7 to 10:1. *"Hot bands or stripes near top and perhaps over all tube and rapidly increasing Δp and conversion < specifications":* [deactivated catalyst by pyrolytic coke formation]*/feed concentration wrong: for **steam reforming** high concentration of heavier hydrocarbons/steam to hydrocarbon ratio low/[catalyst poisoned]* by sulfur. *"Temperature at inlet high and high Δp":* [for steam reforming: steam contaminated with inorganic solids]*. *"Hot bands in top 1/3 of tubes and methane > usual in exit gas and perhaps Δp increase":* contamination in feed/[poisoned catalyst]*.

"Startup after catalyst replacement, poor selectivity": bad batch of catalyst/preconditioning of catalyst faulty/[tube walls not passified]*/temperature and pressures incorrectly set/instrument error for pressure or temperature. *"Startup after catalyst replacement, increased side reactions and conversion < specification":* catalyst loading not the same in all tubes.

[Reactor instability]:* control fault/poor controller tuning/wrong type of control/insufficient heat transfer area/feed temperature exceeds threshold/coolant temperature exceeds threshold/coolant flowrate < threshold/tube diameter too large.

[Runaway reactor]:* feed temperature too high/[temperature hot spot]*/cooling water too hot/feed temperature too high.

[Tube walls not passified]:* walls activated unwanted side reactions and faulty passivation treatment/wrong passivation treatment/no passivation treatment.

6.13
PFTR: Bubble Reactor

Many different configurations fall under this general title. A **bubble column** is typically a tall, narrow column of liquid into which gas is sparged at the bottom. The bubbles rise through the liquid and react. The bubble column may be operated with liquid and gas flowing cocurrently or countercurrently. Packing can fill the column to create a **packed bubble column.** An **air lift loop** is a bubble column with a central draft tube. Compressed gas is injected at the bottom of the central draft tube. (Similar to a Pachuca tube reactor.) A **jet loop column** is a bubble column with a central draft tube with compressed gas and liquid injected at the bottom of the draft tube. The liquid is withdrawn from the annulus and pumped into the ejector below the draft tube. The power required (about 5 kW/m^3) is greater than that required for either an air lift or bubble column (about 3 kW/m^3). Other variations involve how the liquid recycles to the bottom. A **central baffle bubble column** provides a vertical axial baffle instead of a central draft tube with compressed gas being injected at one side of the baffle; liquid circulates back around the other side. An **external loop bubble column** is a vertical column, compressed air is injected at the bottom; an external pipe connects the liquid from the top to the bottom and this allows natural circulation. A **deep shaft; tower loop** with downflow air lift is a vertical column with a central draft tube. Compressed air is injected into the annulus; liquid is sparged downwards in the central annulus.

A bubble reactor is also used for aerobic reactors for the treatment of waste water. The configuration may be a basin, pond or lagoon. See Sections 6.31 and 6.32 for activated sludge reactors.

A specialized unit is an ozone generator and contact reactor.

Many other options are available for GL contacting and OTR, Sections 1.6.1 and 1.6.3 provide data to guide in selecting the options.

- *Area of Application*

Phases: GL, GLcS and LL. Relatively slow reactions. Use if the order of the reaction is positive and $>$ 95 % conversion is the target, and for consecutive reactions with an intermediate as the target product. The bubble columns tend to operate isothermally and, unless heat is removed in the external loop, this configuration is not used for highly exothermic reactions.

Gas–liquid: For large liquid holdup, slow reactions that are kinetically controlled reactions that require long residence times and low viscosity liquids. Preferred if large gas volumes needed or if the liquid vol $>$ 40 m^3; OK for high pressure. Cocurrent: surface area 50–400 m^2/m^3; Downflow: surface area 20–1000 m^2/m^3. Ha $<<$ 0.3 and $\delta^+ = 4000$–10 000. Can handle solids. Incurs a high pressure drop. **Gas–liquid–catalytic solid:** Surface area 50–350 m^2/m^3.

Liquid–liquid: Surface area 7–75 m^2/m^3. Rotating disk contactor, RDC, can handle dirty fluids and large throughputs. Need flow ratios 1:1; difficulty in handling systems with low interfacial tensions that tend to emulsify. Related topics solvent extraction, Section 4.10 and Size reduction, Section 8.3.

- *Guidelines*

Creation of bubbles. Bubbles can be created by injecting gas through holes in a pipe or sparger, injecting gas through a porous plate or diffuser, by introducing gas below an agitator by means of a sparger or a single injection tube or by inducing gas into a liquid via a jet or ejector. Diffuser Aeration: 0.3–0.5 $dm^3/s\ m^3$. 15–30 $dm^3/s\ m^2$ diffuser area; or 1.5–6 dm^3/s m of linear length of diffuser. Need 75–110 m^3 air/kg BOD removed. 0.018–0.04 g oxygen absorbed/dm^3 air sparged into the liquid. $k_L\ a = 0.0008$ 1/s. $k_L a = 0.02$–0.08 1/s for power input 0.15–1 kW/m^3. Efficiency of oxygen transfer is, in general, 5–15 % with 8 % for porous tube diffusers and 6 % for coarse-bubble diffusers.

Typical diameters of bubbles formed by these different methods are given in Fig. 1.2. The usual range is 200 μm to 3 mm. In CSTR reactors the bubble diameter is usually 2 to 2.5 mm; for froth flotation of minerals, 1 mm; for foam fractionation the diameter is in the range 0.8–1 mm; for DAF, the bubbles nucleate on particulates, their diameter is usually 70–90 μm.

Gas–liquid: Can operate countercurrently or cocurrently. Holdup: volumetric liquid holdup per total reactor volume: > 0.7 and usually 0.95, Gas holdup $= 0.05$–0.4 increasing with increase in gas velocity. Superficial gas velocity 1–30 cm/s although it has been as high as 50 cm/s. Mass transfer coefficients: typical liquid mass transfer coefficient = $k_L a = 0.005$–0.01 1/s; $k_L = 0.6$–0.7×10^{-4} m/s. For gas phase $k_G\ a = 1$–3 1/s.

Surface area gas–liquid per volume of reactor: 20–1000 m^2/m^3 volume reactor depending on flow conditions.

Surface area gas–liquid per volume of liquid phase: 120–700 m^2/m^3 liquid phase volumetric ratio liquid to mass transfer liquid film, $\delta^+ > 100$. Power: cocurrent: 0.03–2 kW/m^3; countercurrent: 0.04–1 kW/m^3. See Sections 1.6.1 or 1.6.3.

Bubble columns including bio: superficial gas velocity, 0.03 to 0.04 m/s; holdup < 0.2, $k_L\ a = 0.005$ to 0.01 1/s. $k_L\ a$ is independent of the diameter if column diameter > 0.15 m; $k_L\ a$ is not affected by the type of gas sparger if the gas velocity exiting the orifice > 0.03 m/s. If < 0.03 m/s, then use a sintered plate. Height: $3 <$ height < 12 m; allow 0.75 of diameter or 1 m at the top for foam disengagement. Energy 0.01 to 3.5 kW/m^3. OTR: 3.3 g/s m^3; mixing time: 200 s; gas content: 30 %; maximum volume 5000 m^3. We should note that the $k_L a$ values in practice differ from those reported for ideal systems such as air–water; air–nutrient; air–actual microbial system. These columns have been used for the production of steroids, acetic acid, SCP, single cell protein, beer, vinegar, yeasts, bacteria, mold fungi, baker's yeast and for waste water treatment.

Air lift loop including bio: These are used often. They provide good mixing, efficient OTR (but not as high as for STR described in Section 6.27), low shear, excellent heat transfer, 100 000 to 500 000 L. $k_L a = 0.01$–0.1 1/s for power input 0.5–1 kW/m^3, $k_L a = 0.01$–0.025 1/s for power input 0.2–0. 5 kW/m^3. Working volume 2/3 total volume. H/D = 5 to 10. Power: 0.2–3.5 kW/m^3; OTR: 2.7 g/s m^3; mixing time: 80 s; gas content: 30 %; maximum volume 3000 m^3. They have been used for culture broths of low viscosity, and for SCP: 30–40 kW/m^3; remove heat with $\Delta T < 10\,°C$ and keep reaction temperature about 37 °C.

Jet loop, with H/D = 5 to 20; jet velocity 20 m/s; internal draught tube. Power: 5 kW/m^3; OTR: 2.8 g/s m^3; mixing time: 60 s; gas content: 30 %; maximum volume 500 m^3. This has been used for the mass cultivation of yeast on paraffin and the cultivation of bacteria.

External downcomer loop has been used by ICI pressure process for SCP.

Deep shaft, tower loop, has been used for SCP from n-paraffins and for waste water treatment;

Gas–liquid–catalytic solid: including bioreactors. Catalyst diameter, < 0.1 mm. Operate semibatch. Holdup: volume fraction liquid 0.8–0.9; volume fraction catalyst 0.01; volume fraction gas 0.1–0.2. Gas holdup slightly less than for GL systems. Backmixing: solids backmixing Pe = 2–5 for superficial gas velocities of 2–7 cm/s; liquid phase backmixing about the same as GL systems; gas phase backmixing, about the same as GL systems. Surface area: surface area solid 500 m^2/m^3; surface area gas–liquid 100–400 m^2/m^3; power 0.1–2 kW/m^3 sufficient to keep catalyst in suspension. Heat transfer solid wall to mixture > 1 kW/m^2 K; presence of solids increases the heat transfer coefficient. Catalyst activity: variable but often able to avoid diffusion limitations because of small diameter catalyst. Catalyst selectivity: OK. Catalyst stability: change catalyst between batches. Heat exchange OK. Consider complications because of catalyst deposition and erosion.

Liquid–liquid: creation of drops, see Sections 5.3 and 8.3. Superficial dispersed drop velocity 0.001–0.02 m/s with usual values 5.5 L/s m^2. This bubble column gives the smallest reactor volume compared with STR. *For example, for esterification: reactor volume divided by the daily production, m^3 day/kg. PFTR 0.7 m^3 day/kg. 3 CSTR in series, Section 6.26, 0.85 m^3 day/kg. Batch STR, Section 6.27, 1.04 m^3 day/kg. CSTR, Section 6.29, 1.22 m^3 day/kg.*

RDC: sum of the superficial velocities for both phases is 1–2.5 cm/s; diameter < 9 m for SX but usually < 2.5 m for reactions. Related topic SX, Section 4.10.

Aeration basin: circular or rectangular basin of c/s or concrete with submerged air diffusers.

Liquid–solid with air used for mixing: example Pachuca leacher/reactor. L:D = 2.5:1.

- *Good Practice*

Electrolytes in the liquid alter the bubble diameter, the holdup, the interfacial area per unit volume in mechanically agitated devices and affects the k_La for bubble columns.

For gas–liquid, ensure operation is in the correct bubbling flow regime. See illustrative guide in Fig. 2.2, Section 2.4. Prevent foaming.

- *Trouble Shooting*

"Carryover": [foaming]*.

*[Foaming]**: surfactants present/dirt and corrosion solids/natural occurring surfactants/pH far from the zpc/naturally-occurring polymers/insufficient disengaging space above the liquid/antifoam ineffective (wrong type or incorrect rate of addition)/bubble rate too high/mechanical foam breaker not rotating/baffle foam breaker incorrectly designed or damaged/asphaltenes present/liquid downflow velocity through the foam is too low. See Section 1.12 for generic causes of [foaming]*.

See Trouble Shooting: STR, Section 6.27, for more on trouble shooting aerobic bioreactors.

6.14
PFTR: Spray Reactor and Jet Nozzle Reactor

Many options are available besides the traditional liquid **gravity spray** into a vessel filled with gas. These include options where the liquid is pumped through a jet or spray nozzle. **Venturi jet** the liquid and gas are mixed in the venturi. **Plunging jet** (buss loop reactor): vertical column filled about 2/3 with liquid, no internals. Liquid is withdrawn at the bottom and liquid is pumped into a top-mounted jet that induces air and resulting mix impinges vertically under the top surface of the liquid. (This is in contrast with the jet loop, Section 6.13, where the ejector is at the bottom of the liquid column.)

The **external circulating nozzle** does the **GL** mixing outside the column and injects the mixture into the top of the vessel. This is a vertical column with no internals. Liquid is withdrawn at the bottom and pumped through a venturi that induces air. The air–liquid mixture enters at the top of the column.

The **internal circulating nozzle**, or immersed column, is similar to the external circulating nozzle except that all the action takes place within the column. This is a vertical column with a small diameter central axial injection tube. Liquid is pumped from a submerged pump to the top of the tube; compressed air is introduced at the top of the tube and the two phase mixture is injected down the tube and into the bottom of the vessel.

- *Area of Application*

Phases: GL, LL, GLS (bio)

Gas liquid and GLS (bio): Residence time, very short. Reaction rates, very fast; need rapid absorption. Reaction is controlled by mass transfer. Very high gas capacity. Used for neutralization reactions with one of the reactants in the gas phase. $\mathrm{Ha} > 3$ and $\delta^+ = 2$–10. For surface area see Sections 1.6.1 and 1.6.3.

Gravity spray: surface area 30–70 m^2/m^3; target species Henry's law constant 10^3 to 10^4 kPa/mol fraction; feed gas concentration 0.3 to 4 vol%. Can handle foaming and solids-laden gases, low pressure drop. Reactions: good for reaction with highly soluble gases.

Venturi jet nozzle: Surface area: 200–2500 m^2/m^3; very soluble gas only with target species Henry's law constant $< 10^3$ kPa/mol fraction; feed gas concentration > 1 vol%.
Liquid–liquid: Surface area 7–75 m^2/m^3. Related topics: solvent extraction, Section 4.10 and size reduction, Section 8.3.

- *Guidelines*

Creation of the gas–liquid contact surface via sprays or venturi is discussed in Section 8.2 with surface area and power input information given in Sections 1.6.1 and 1.6.3. In general, for sprays created by a venturi the drop size is 1–30 μm.
Gravity Spray towers: superficial velocity about 5.5 L/s m^2; mass transfer coefficients liquid phase: $1.5 \times 10^{-4} < k_L < 3 \times 10^{-4}$ m/s; for the gas phase $0.4 < k_G < 1$ mol/m^2 atmos s or in other units $0.01 < k_G RT < 0.25$ m/s; $k_L a$ = 0.0007 to 0.015 1/s. critical energy consuming phase is the liquid atomization; gas energy 8 kJ/m^3; with liquid to gas ratio high; design on gas phase controlling. Superficial gas velocity 0.75–2 m/s and usually 1 m/s, holdup < 0.8. Power usage 0.03 to 0.5 kW s/m^3. Δp gas = 0.6 to 1.2 kPa. Related topic gas–solid separation, Section 5.2 and the use of spray nozzles to create a dispersion, Section 8.2.
Gas–liquid: Venturi: Δp gas = 1–6 kPa and usually 5 kPa, velocity in the throat 30–100 m/s and usually 100 m/s; mass transfer coefficient for liquid phase $k_L = 7 \times 10^{-4}$ m/s; for gas phase $k_G = 10^{-2}$–3×10^{-2} m/s; gas–liquid surface area 150–300 m^2/m^3. For fluids with surface tension 40–70 mN/m and viscosity of liquid = 1 mPa s; critical energy consuming phase is the gas at about 20 kJ/m^3 with liquid to gas ratio about 1.3 to 1.6 L/m^3; design on gas phase controlling. Power usage 0.04–8 kW s/m^3. Related topic Gas–Solid Separation, Section 5.2 and Size Reduction, Section 8.2.
For gas–liquid–solid:
Plunging jet: 8 to 12 m/s. Power requirement high but is reduced by increasing the volume of reactor: Power: 3–8 kW/m^3; OTR: 3.3 g/s m^3 ($k_L a$ up to 0.3 s^{-1}) ; gas content: 20%; maximum volume 200 m^3.
External circulating nozzle: Power: 6 kW/m^3; OTR: 0.8 g/s m^3; mixing time: 50 s; gas content: 30%; maximum volume 200 m^3.
Internal immersed column: Power: 0.08 kW/m^3; OTR: 0.003 g/s m^3; gas content: 2%; maximum volume 4000 m^3.
Liquid–liquid: Superficial velocity = 50% flooding. See also Section 1.6.2.

6.15
PFTR: Trays

The general characteristics of gas–liquid contacting are described in Section 1.6.1. Other operations that use this type of contactor include gas absorption, Section 4.8, gas desorption/stripping, Section 4.9; gas–liquid separations, Section 5.1; turbulent bed contactor (TCA, TVA) contactor, Section 5.2, distillation, Section 4.2, reactive distillation, Section 6.35 and direct contact heat exchange Sections 3.8 and 3.9.

- *Area of Application*

Phases: gas–liquid, liquid–liquid, gas–liquid and solid (bio). Intermediate reaction rates. High capacity, high conversion in both gas and liquid phases. Intensive dispersion of gas in liquid. Large number of plates gives plug flow. Some flexibility in varying liquid holdup; and exchange heat via coils on plates. $\delta^+ = 40–100$; $0.6 < \mathrm{Ha} < 3$.

Gas–liquid: Residence time, short. Use for very fast reactions, all reaction is in the liquid film and is mass transfer controlled. Gas–liquid surface area max. observed area 800 m^2/m^3 with the usual range 200–500 m^2/m^3 or slightly higher than a bubble column. Target species Henry's law constant $< 10^7$ kPa/mol fraction; feed gas concentration < 1 vol %. Not for foaming. Limited in handling corrosive or particulates. Some flexibility in varying the gas/liquid volumetric flowrates. Related topic about surface area Section 1.6.1.

Liquid–liquid: can operate as gravity flow or with fluid pulsed operation. For pulsed operation: surface area 75–3000 m^2/m^3. Related topics: solvent extraction, Section 4.10, direct contact heat exchange, Section 3.6 and size reduction, Section 8.3.

- *Guidelines*

General characteristics, Section 1.6.1.

Gas–liquid: liquid holdup = 0.15 with some flexibility in that the liquid holdup can be adjusted by the weir height; typical liquid mass transfer coefficient = $k_La = 0.01–0.05$ 1/s; $k_L = 1.5 \times 10^{-4}–4.5 \times 10^{-4}$ m/s; for gas phase $k_G = 0.02–0.2$ m/s sieve tray; power 0.01–2 kW/m^3 and usually 0.01 to 0.2 kW/m^3. superficial gas velocity, 0.75 to 1.5 m/s for atmospheric pressure; 0.2 m/s for pressure operation and 2.5 m/s for high vacuum; holdup < 0.8.

Gas–liquid–solid (bio): Power: 3 kW/m^3; OTR: 2.8 g/s m^3; mixing time: 300 s; gas content: 50 %; maximum volume 1000 m^3.

Liquid–liquid: Sieve tray holes 3–8 mm with a smaller diameter as the surface tension increases; spacing between the holes 3 to 4 times the diameter of the holes to prevent coalescence soon after the drops are formed. For pulsed operation: superficial velocities $2 \times 10^{-3}–0.02$ m/s.

- *Good Practice*

See Section 4.2.

6.16
PFTR: Packing

The general characteristics of gas–liquid contacting are described in Section 1.6.1. Other operations that use this type of contactor include gas absorption, Section 4.8, gas desorption/stripping, Section 4.9; gas–liquid separations, Section 5.1; turbulent bed contactor (TCA, TVA) contactor, Section 5.2, distillation, Section 4.2, reactive distillation, Section 6.35 and direct contact heat exchange Sections 3.8 and 3.9. Porosity 0.6–0.95 depending on the packing. (Contrast with trickle bed with solid catalyst “packing”, Section 6.17.) The liquid Peclet number is 0.1 to 0.5; the gaseous Peclet number is 1 to 5.

- *Area of Application*

Phases: gas–liquid, liquid–liquid, gas–liquid biosolids. Very fast reactions, essentially plug flow for both G and L. High capacity, high conversion in both gas and liquid phases. Difficult to control temperature, adiabatic. Conversion is often limited by equilibrium. Design like an absorber, Section 4.8. Dimensionless Hatta number, $0.3 < \mathrm{Ha} < 0.6$ and $\delta^+ = 10–100$.

Gas–liquid: Use for very fast reactions, all reaction is in the liquid film and is mass transfer controlled. Gas resistance important with very soluble gases.

Surface area gas–liquid per volume of reactor: 50–250 m^2/m^3 volume reactor; surface area gas–liquid per volume of liquid phase: 1000–1600 m^2/m^3 liquid phase. Cocurrent over packed: surface area 400–3000 m^2/m^3. Target species Henry’s law constant $< 10^7$ kPa/mol fraction; feed gas concentration < 1 vol%; vulnerable to plugging. Low pressure drop, cannot handle solids, can handle foaming by operating in the cocurrent upflow bubble region. Little flexibility in varying the gas/liquid volumetric flowrates because of flooding. OK for corrosive.

Liquid–liquid: Surface area 7–75 m^2/m^3. Sensitive to contamination. Related topics solvent extraction, Section 4.10 , direct contact heat exchange, Section 3.6 and size reduction, Section 8.3.

Gas–liquid biosolids: Gravity and rotating:

Gravity: Trickling filter reactor (carbon removal): the gas–liquid surface area 45–115 m^2/m^3; the solid surface area = 0.55–10.6 m^2/m^3; the biofilm area = 200 m^2/m^3. Holdup volume fraction solids = 0.55–0.7. Mass transfer: for gas–liquid $k_L a$ = 0.01–0.8 1/s; for liquid–solid, $k_L a$ = 0.06 1/s. Standard rate loading: 1.3–4.2 kg BOD_5/s m^3. High rate loading: 4.2–21 kg BOD_5/s m^3.

(carbon oxidation/nitrification combo): plastic media: loading < 4 kg BOD_5/s m^3.

Biofilter: (carbon removal) organic loading: 20–50 kg BOD_5/s m^3.

Rotating: rotating biological contactor:, RBC: (carbon oxidation): loading 0.250 g BOD_5/L; capacity 20–5000 L/s; (nitrification): loading 10–20 mg NH_3–N/L.

- *Guidelines*

General characteristics, Section 1.6.1.

Gas–liquid: Liquid holdup per total reactor volume: volume fraction liquid 0.05–0.15; Superficial velocities: select for loading on packing that are 0.5–0.7 times flooding conditions; Backmix: for short column heights = 0.2–0.3 m, significant backmixing can occur with Peclet for the liquid = 0.4–2; Peclet for the gas = 4–20. For short columns, double design height to account for backmixing. Bulk/film volume ratio, $\delta^+ = 10–100$. Superficial gas velocity, 0.75 to 1.5 m/s for atmospheric pressure; 0.2 m/s for pressure operation and 2.5 m/s for high vacuum; holdup < 0.95; energy 0.01 to 0.2 kW/m^3; $k_L a$ = 0.005 to 0.02 1/s; packing > 6 mm; catalyst > 3 mm. Column diameter/packing diameter > 8 and prefer > 30 to prevent liquid channeling. Redistributors every 3 to 4.5 m. Higher mass transfer coefficient, $k_L a$ = 0.15 1/s. for cocurrent upflow in the bubble regime.

Packing: (see Section 1.6.1) plastic packings have effective surface area = $\frac{1}{2}$ corresponding value for ceramic if fluids are polar. OK for nonpolar; metal stainless steel are less wetted than ceramic but better than plastic. Preferred packings include unglazed ceramic, intalox 2–3.8 cm but > 5 cm the interfacial area is too small and < 2 cm the capacity is reduced because of flooding. Other recommended packings include Pall rings, mini-rings, sulzer, multinit and Tellerettes. **Liquid–liquid:** Superficial velocity of continuous phase = 30 to 50 % of flooding. Backmixing less than in spray column or tray columns. The walls and packing must be preferentially wetted by the continuous phase. Packing size = 0.5–1 cm. Superficial velocities 0.001–0.02 m/s. Prefer diameter < 0.6 m; superficial velocity about 5.5 L/s m^2; 2.5 cm Pall rings. Redistribute the dispersed phase every 1.5–2 m.

Gas–liquid biosolid: Gravity:

Packed column: Power: 0.5 kW/m^3; OTR: 0.14 g/s m^3; gas content: 85 %; maximum volume 100 m^3.

Trickling filter reactor: Gas holdup 0.46–0.94; (carbon oxidation):

standard rate: liquid superficial velocity 0.01–0.04 L/s m^2, depth 1.8–3 m; recycle ratio 0;

high rate: liquid superficial velocity 0.1–0.4 L/s m^2, depth 0.9–2.4 m; recycle ratio 1/1–4/1.

(carbon oxidation/nitrification combo): liquid superficial velocity = 0.095–0.18 L/s m^2. 6 m depth, recirculation ratio 1:1.

(nitrification): liquid superficial velocity = 0.3–1.3 L/s m^2.

Biofilter reactor: media depth 1.5–6.5 m, usually 4 m; liquid recycle ratio 0.4; liquid loading: 2.3 L/s m^2.

Rotating: RBC: (carbon oxidation) Liquid residence time < 1 h; 3–3.6 m diameter; 40 % submerged; 1–2 rpm; bio layer 2–4 mm thick. Liquid loading 0.0005–0.004 L/s m^2; temperature > 13 °C; module 10 000 m^2; power typically = 3.5 kW. (nitrification): liquid loading 0.0004–0.0025 L/s m^2; temperature > 13 °C.

- *Good Practice*

For fast reactions, change in the flow regime has dramatic effects on performance. Prevent foaming. Liquid distributor design is very important. Carefully plan the liquid redistribution along the walls for columns < 2–3 m diameter. For these small columns place redistributors at distances = 8–10 times the column diameter. The critical surface tension of the solid packing should be greater than the surface tension of the liquid to ensure that the liquid film remains intact in a packed contactor.

- *Trouble Shooting*

Trickling filter: *"Plugged: interstitial voids become filled with biological growth"*: packing too small/packing of variable diameter/organic to liquid loading > design. *"Ice formation on top filter surface":* liquid maldistribution/feed liquid temperature too low/air temperature too cold. *"Odors":* loss of aerobic conditions/accumulation of sludge and biological growth/lack of chlorine in influent/high organic loadings in feed especially from milk processing and canneries. *[Foaming]**: see generic causes Section 1.12.

Gas–liquid–solid packed column bio reactor: *Carryover":* [foaming]*.

*[Foaming]**: liquid downflow velocity through the foam is too low and generic causes of [foaming]*, Section 1.12.

See trouble shooting: STR, Section 6.27 for more on trouble shooting aerobic bioreactors.

6.17
PFTR: Trickle Bed

Gas liquid flow cocurrently down through a packed bed of catalyst. Porosity 0.38–0.42. (Contrast with packing described in Section 6.16.)

- *Area of Application*

Phases: GLcS

Gas liquid catalytic solid: Use for very fast reactions, all reaction is in the liquid film and is mass transfer controlled. Ha > 3 and $\delta^{+} = 2$–10.

- *Guidelines*

Gas-liquid with solid catalyst: Catalyst particle diameter 1–5 mm. Operate close to the boundary between two phase (trickle) and pulse flow. Figure 6.8 illustrates, the flow regimes for nonfoaming systems.

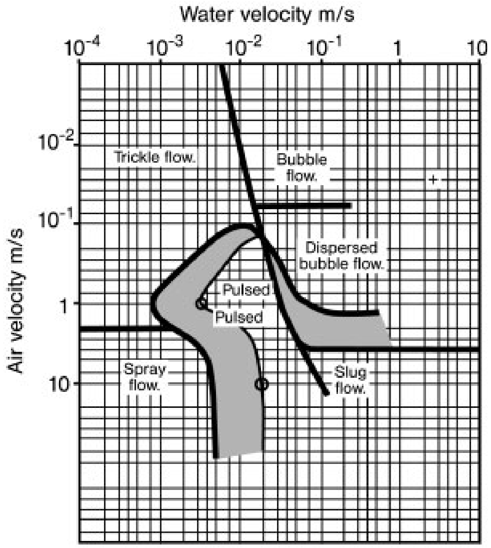

Figure 6.8 Flow regimes in trickle flow.

Superficial liquid velocity $0.005 < v_{Lo} < 9$ mm/s (although some operate in the range 0.8–25 L/s m ^{2} or mm/s). The velocity should be reduced if liquid tends to foam.

Superficial gas velocity > 0.010 m/s.

Holdup volume fraction liquid 0.05–0.25. Static liquid holdup is constant for low Eotvos number, $Eo < 4$ (Eo = density liquid × gravitational constant × particle diameter squared/liquid–gas surface tension). Liquid holdup increases with Eo for $Eo > 4$. Dynamic liquid holdup increases with liquid flowrate but is independent of gas flowrate.

The liquid axial backmixing is negligible if the height/particle diameter > 150.

Holdup volume fraction catalyst 0.6–0.7.

Holdup volume fraction gas 0.2–0.35.

Surface area solid 1000–2000 m^2/m^3.

Surface area gas–liquid 100–3500 m^2/m^3.

Power input 1–100 kW/m^3.

Catalyst activity: variable but often reduced because of mass transfer limitation. Plug flow is favorable.

Catalyst selectivity: often reduced because of mass transfer limitation; plug flow is favorable.

Catalyst stability: should have stability because of difficulty in replacing.

Heat exchange is challenging so we usually work adiabatically.

- *Good Practice*

Ensure operation in the correct flow regime. The effectiveness of the solid catalyst and of the gas–liquid mass transfer decrease if solid catalyst is not wet. For good wetting of the solid keep the surface tension of the solid > surface tension of the liquid. Prevent foaming. The efficiency depends on the skill in initially distributing the gas and the liquid. Use liquid distribution plate similar to design used for packed towers. The liquid distribution plate should have at least 50 holes/ m^2 of catalyst bed.

- *Trouble Shooting*[1)]

For trickle bed reactors with specific applications to hydrotreating.
"Low conversion": feed composition change/wrong catalyst for feed/sample error/flowrate error/feedrate higher but reactor temperature not increased/temperature profile wrong/thermocouple fault/controller fault/feed bypassing reactor through leak in heat exchanger/[channeling]*/[catalyst]*/[foaming]*/For **hydrotreating:** [hydrogen starvation]*/catalyst not presulfided/[incomplete presulfiding of catalyst]*. *"Sudden loss of activity of catalyst":* heat exchanger leak/change in feed composition/For hydrotreating: [hydrogen starvation]*

[1)] Based on Koros, R.M., *Engineering Aspects of Trickle Bed Reactors*, pp. 579 to 630 in "Chemical Reactor Design and Technology" H. de Lasa, ed, Martinus Nijhoff Publishers, 1986 and M.D. Edgar, D.A. Johnson, J.T. Pistorius, T. Varadi , Trouble Shooting Made Easy, *Hydrocarbon Process.*, May 1984, p. 65.

“Δp across the catalyst bed $>$ design”; [channeling]*/cracked hydrocarbon feed stored without effective nitrogen blanket/solids in feed/corrosion products from upstream operations/bypass on feed filter open/feed distributor fault/top catalyst support tray has holes that are too small/bottom catalyst bed support tray holes are too large/pugged or partially plugged outlet/crush strength of catalyst exceeded and fines plug bed/excessive recycle compressor surge causing breakdown of top layer of catalyst.

For hydrotreating: *“Rapid breakthrough of H_2S during catalyst sulfiding”:* [channeling]*

“Nonuniform bed temperatures across the diameter during sulfiding”: [channeling]*

“Color $>$ specifications”: composition change in feed/catalyst aged.

[Catalyst]:* regeneration failed to remove carbon from catalyst/excessive regeneration temperature $>$ 540 °C causing sintering, $>$ 760 °C molybdenum sublimation, $>$ 820 °C reduction in crush strength and change in alumina/poisons in feed/aged catalyst.

[Channeling]:* nonuniform catalyst bed density/low superficial flowrate < 1.4 kg/s m^2/off set, tilted or faulty feed distributor/thermal shock to upstream pipes or equipment causes scale to dislodge and buildup on bed/internal vessel obstructions such as thermowells or supports.

*[Foaming]**: residence time insufficient/designed for a vertical vessel but a horizontal vessel installed/liquid downflow velocity through the foam is too low/operating in the wrong flow regime and generic cause, Section 1.12.

[Hydrogen starvation]:* change in feed composition without corresponding change in hydrogen/leaks/dissolution of hydrogen in liquid product/lower concentration of hydrogen in treat gas/flowrate of treat gas < expected because of recycle compressor fault.

[Incomplete presulfiding of catalyst]:* contact with hydrogen at high temperature for too long a time/maximum temperature of 150–175 °C exceeded/use of cracked feed/excessive addition of presulfiding agents.

[Rapid coking of catalyst]:* [hydrogen starvation]*/temperatures too high.

[Hydrogen starvation]:* change in feed composition without corresponding change in hydrogen/leaks/dissolution of hydrogen in liquid product/lower concentration of hydrogen in treat gas/flowrate of treat gas < expected because of recycle compressor fault.

[Incomplete presulfiding of catalyst]:* contact with hydrogen at high temperature for too long a time/maximum temperature of 150–175 °C exceeded/use of cracked feed/excessive addition of presulfiding agents.

[Rapid coking of catalyst]:* [hydrogen starvation]*/temperatures too high.

6.18
PFTR: Monolithic

Related topics: static mixer in tube, Section 6.6, and trickle bed, Section 6.17.

- *Area of Application*

Phases: Gas with solid catalyst; liquid with solid catalyst; gas–liquid with solid catalyst. Use when mass transfer affects selectivity or reactivity. Perhaps not for highly exothermic reactions because of the limitation in radial heat transfer unless cross flow is used.

- *Guidelines*

Prefer because of intensification with 1.4–4 times the surface/volume. Possible to install in pipelines. See Section 3.3 Cubic/monolithic.

6.19
PFTR: Thin Film

Related topics evaporation: Section 4.1 for gravity and agitated falling films.

- *Area of Application*

Phases: Gas–liquid, liquid–liquid, GL solid bio. Absorption with fast and very exothermic reaction in viscous liquid or very endothermic reaction that produces volatiles whose desorption is desired.

Gas–liquid: Residence time 3–600 s; reaction rate: mass transfer controlled, fast absorption and highly exothermic reactions, very exothermic reactions in viscous liquids or highly endothermic reactions producing a volatile compound whose desorption is desirable to shift the equilibrium or prevent side reactions; volume 1–80 L; capacity 0.02–5 kg/s. Gravity falling film or agitated falling film for viscous fluids. *For gravity film:* Liquid residence time: 5–100 s; surface area gas–liquid per volume of reactor: 3–100 m^2/m^3 volume reactor; surface area gas–liquid per volume of liquid phase: 300–600 m^2/m^3 liquid phase; film surface area per unit 0.1–100 m^2/unit; viscosity < 1500 mPa s. *For agitated film*: Liquid residence time: 5–600 s; film surface area gas–liquid per total reactor 0.1–25 m^2/unit reactor; viscosity: $< 2\,000\,000$ mPa s. Hatta > 3; $\delta^+ = 10–200$.

Liquid–liquid: Surface area 5–120 m^2/m^3. Related topics: solvent extraction, Section 4.10, heat exchange, Sections 3.3 and 3.6 and size reduction, Section 8.3.

- *Guidelines*

Gas–liquid: gravity falling film: Holdup: liquid holdup per total reactor volume: volume fraction liquid 0.01–0.15; liquid holdup per total reactor volume: 0.0002–0.5 m^3; liquid loading: 0.06–1.1 L/s m of length. Energy for a falling film = energy as packed tower.

Gas–liquid: agitated thin film: Holdup: liquid holdup per total reactor volume: 0.0002–0.2 m^3; Liquid loading: 0.06–1.25 L/s m of length. Backmixing: liquid plug flow or as a series of at least 5 backmix stages; energy needed 1 kW/m^2 film surface. Mass transfer controlled reactions.

Liquid–liquid: gravity wetted wall; superficial velocities 2×10^{-5}–8×10^{-4} m/s.

Gas–liquid–biosolids: trickling continuous film, vertical vessel with liquid pumped from the bottom to top to be distributed onto wetted walls; compressed gas is introduced at the bottom and some may be recycled from top back to bottom inlet. Power: 1.5 kW/m^3; OTR: 0.8 g/s. m^3; gas content: 90 %; maximum volume 500 m^3.
Floating roller, horizontal wetted roller brings liquid in contact with air. Power: 0.1 kW/m^3; OTR: 0.05 g/s m^3; gas content: 0.1 %; maximum volume 1 m^3.

- *Good Practice*

See Section 4.1.

6.20
PFTR: Scraped Surface Reactor

A scraped surface device can process a thin viscous film. Here the focus is on its use as a reactor. Elsewhere are described its use to condition foodstuffs, Section 3.3, as a vertical device for evaporation, Section 4.1 and as a crystallizer, Section 4.6.

- *Area of Application*

Especially for viscous feed. OK for foaming, for fouling, crystal formation and suspended solids. Viscosities $>$ 2000 mPa s.

- *Guidelines*

Relative to agitated film, retention time of 1:1 and volume 1:1. Overall heat transfer coefficient for sulfonation, $U = 0.8–2.2$ kW/m^2 °C; for polymerization, $U = 1–2.8$ kW/m^2 °C. decreasing with increasing viscosity.

6.21
PFTR: Multiple Hearth

- *Area of Application*

Phases: Gas plus reactant solid. Regeneration of adsorbents, catalysts, incineration of sludges, reduction of ores and roasting of some solids. Capacity about 0.01–10 kg/s; solid particle diameter 0.2–20 mm. Temperatures for incineration in the range 790–980 °C.

- *Guidelines*

Solid residence time, 5000–30 000 s; usually 15 000–18 000. Hot combustion gas flows over the solids. Solids loading 1.25 to 2 g/s m^2 of single hearth or 2 to 20 g/s m^2 of total hearth.

  - activated carbon regeneration: 2 g/s m^2 of single effective hearth; 2.7–5.4 g/s m^2 of total effective hearth.
  - bauxite adsorbent, regeneration: 8–16 g/s m^2 of total effective hearth.
  - bone char, adsorbent, regeneration: 20–35 g/s m^2 of total effective hearth.

- calcination of kaolin for pigment: 4–6.5 g/s m^2 of total effective hearth.
- charcoal from wood: 2.5–5.2 g/s m^2 of total effective hearth.
- foundry sand reclamation: 20–35 g/s m^2 of total effective hearth.
- lime sludge recalcination: 2–3.5 g/s m^2 of total effective hearth.
- pyrites roasting: 1.25–2.5 g/s m^2 of single effective hearth.
- iron ore reduction to direct reduced iron (DRI): 15 g DRI/s m^2 of total effective hearth.
- sludge incineration: 1.8 g/s m^2 of single effective hearth; 9–18 g/s m^2 of total effective hearth.

The effective hearth area is 42–62 % of nominal area calculated from the overall OD with the higher % referring to larger diameter hearths. For fast reactions, bulk phase film diffusion may control and pore diffusion may control if the solid diameter $>$ 1.5 mm.

The heat load is 150–250 kW/m^3 with the usual design capacity about 7 MW.

Incineration: heat release from combustion 150–250 kW/m^3.

Reactors: solids residence time 4–5 h. For direct reduced iron, bed height of pellets, 2.0–2.5 cm; flame temperature 1300–1350 °C with flame composition CO/CO_2 = $>$ 2/1. A new variation for DRI is the *paired straight hearth furnaces* patented by Lu and Huang. For DRI, bed height of pellets, 12 cm; flame temperature 1600 °C and fully oxidized. The loading is 35 g DRI/s m^2 of total effective hearth.

6.22
PFTR: Traveling Grate

- *Area of Application*

Phases: Gas plus reactant solid. Feed solid particle diameter 8–30 mm. For sintering: product diameter 80–150 mm; product crush strength $> 10^4$ kPa. Capacity 1 to 300 kg/s.

- *Guidelines*

Solid residence time, 2500–20 000 s; gas residence time, $<$ 1 s. Processing gas flows through the bed.

Sintering: Capacity 0.015–0.04 kg/s m^2. For fast reactions, bulk phase film diffusion may control and pore diffusion may control if the solid diameter $>$ 1.5 mm. Windbox 1.1–1.2 $Nm^3/s\ m^2$ grate; discharge air 0.65 $Nm^3/s\ m^2$ grate at 50 m^2 to 0.35 $Nm^3/s\ m^2$ grate at 200 m^2.

Induration: Temperature depends on basicity: basic 1180–1250 °C; acid then it is a little lower temperature. The pellet layer is about 25 cm high but the bottom 5 cm is material that has already been fired. This protects the grate and improves the uniformity of heating. The flame is above, the gas flows down through the pellets and then later it flows up through the hot pellets to preheat the air. Usually use natural gas. Feed: pellets bound together by a water bridge containing 1 % bentonite. Induration is basically drying a pellet.

Incineration: temperature 1000 °C; solid residence 1200–2700 s.

6.23
PFTR: Rotary Kiln

Related topics drying, Section 5.6.

- *Area of Application*

Temperature 520 to 1700 °C; atmospheric pressure; Particle diameter 7 μm–20 mm; solid residence time 2000 –35 000 s. Phases: Gas plus reactant solid. Relatively large solids capacity 3 to 300 kg/s with the usual being 15–300 kg/s; solid particle diameter 7 μm–20 mm. Sinter product: product diameter 80–150 mm; product crush strength $> 10^4$ kPa.

- *Guidelines*

Solid residence time, 2500–20 000 s; gas residence time, < 1 s; 820–1600°C; heat load 250–400 kW/m^3 with the usual design capacity about 18.5 MW.
Incineration: Volumetric loading 5 % solids; temperatures 820–1600 °C; heat release from combustion 260–415 kW/m^3; gas velocity 4.5–6 m/s; solids residence time 1–2 h; gas residence time 2–4 s. L/D 3.4–4/1.
Sintering: 0.012 kg/s m^3 volume. For fast reactions, bulk phase film diffusion may control and pore diffusion may control if the solid diameter > 1.5 mm.
Reaction: Volumetric solids loading 3–12 %; heat usage: 25–60 kW/m^3 of kiln volume; solids capacity, g/s m^3 kiln volume; dry cement, 4–12; wet cement, 3–8.5; limestone calcination, 5–9.5; dolomite calcination, 4.5–6.5; alumina, 5.5–8.3; barium sulfide, 4–9.5; inorganic pigments, 2–20; iron pyrites roasting, 3–4; ore roasting, 3–7. The heat transfer is a function of the thickness of the layer of solids. For **ore roasting:** currently only small sized units are used with temperatures < 1000 °C. In larger sized units, the fines tend to coat and build up on the inside of the kiln. For the reduction of iron ore (SL/RN) process, feed is lump iron ore or pellet and special coals. For ore reduction the energy efficiency is relatively low. Further complications include a layer of solids that build up inside the drum.

- *Good Practice*

As incinerators: operate at –2 to –8 kPa g to provide slight vacuum.

6.24
PFTR, Shaft Furnace

(Thanks to W-K. Lu and G. Irons for their input.)

- *Area of Application*

Phases: Gas plus reacting solid. Solid particle diameter 8–300 mm. Capacity 0.2–1 kg/s. Can operate as a **shaft furnace** where the product is a solid, the furnace has countercurrent gas–solid flow and the **blast furnace** where the product is hot metal liquid; the furnace has countercurrent gas liquid solid flow. Blast furnace: Gas (upward flow of reducing gas) liquid (downward flow of molten metal) solid (coke): 4.5–200 kg iron/s or 2–3.5 net tones hotmetal/day m^3 working volume.

- *Guidelines*

Fundamentals: productivity is limited by the gas flow. Ergun equation: for pressure drop through a packed bed of particles of equivalent volume diameter D_v and sphericity = ψ.

$$(\Delta p/L)\ (k'/\varrho < v>^2) = 150\ ((1-\varepsilon)/Re) + 1.75$$

where $k' = \varepsilon^3\ \psi\ D_v/(1-\varepsilon)$

For turbulent conditions with $Re > 1000$; this becomes the Burke–Plummer equation:

$$(\Delta p/L)\ (k'/\varrho < v>^2) = 1.75$$
$$\text{or } (\Delta p/L) = \varrho < v>^2\ (1.75/k')$$

Some suggest that for wind flow in the blast furnace the factor 1.75 should be double or triple this value. In the blast furnace literature, the term $k'/1.75$ is called the burden permeability with values of 0.15–0.35 cm.

Solid residence time, 20 000–360 000 s; gas residence time, about 5 s. For fast reactions, bulk phase film diffusion may control and pore diffusion may control if the solid diameter > 1.5 mm.

Shaft furnace: Continuous lime kiln 0.3 kg/s m^2 cross sectional area; 0.035 kg/s m^3 furnace volume. For the reduction of iron ore, DRI, temperature of reducing gas entering 780–1000 °C, depending on oxygen injection practice. Temperature of the burden in the shaft furnace 790–900 °C; solids residence time 6–8 h. Furnace diameter 5.5 m. Reducing gas flows countercurrently. Natural gas, 260 Nm^3/tonne; oxygen, 0 to 40 Nm^3/tonne; % natural gas in incoming reducing gas: 3–4.5 %.

Blast furnace: iron ore blast furnace 0.35–0.8 kg/s m^2 hearth area with the usual value 0.65–0.70, 0.2–0.3 kg coke/s m^2 hearth area. For iron ore production of 70 kg/s; coke rate 0.45 Mg/Mg of hot metal; fuel rate 0.09 Mg/Mg; total burden 1.4–1.7 Mg/Mg hot metal; slag volume 0.16–0.29 Mg/Mg; blast volume 95 m^3/s. Height 32 m. Δp_{bosch} = 90–100 kPa; $\Delta p_{overall}$ = 30 kPa.

- *Good Practice*

For the blast furnace: Increase in blast temperature will increase production and decrease coke usage rate but the temperature is limited by the *hanging* of iron in the furnace.

Increase % of sinter will increase production +5 %; increase blast temperature from 1250 to 1300 °C will increase production +5 %; increase top pressure from 0.12–0.2 MPa g increases production by 10–15 %.

Coke production is a challenge because of environmental concerns related to its production so the shift is to inject fuel to decrease the amount of coke needed from, say 500 kg to 330 kg. The fuel injected varies between oil; natural gas and fine coal.

– top 193 °C , flame temp. 1995 °C
– top 160 °C , flame temp. 2040 °C
– top 116 °C , flame temp. 2090 °C

Top temperature should be as low as possible but > dew point.

Tuyere wind velocity 195–250 m/s; for coal injection, 165–195 m/s.

Moisture 6.8–9 g moisture above ambient/m^3 wind.

Example conditions: Flame temp. = 2175 °C; hot metal = 1500 °C; top gas = 72 °C; H_2 = 2.8

CO/CO_2 = 1.13.

- *Trouble Shooting*

"Top temperature and CO > expected": burden distribution problems.
"Hot metal sulfur too high:" coke and or burden has S > design/top pressure too high/slag basicity too low/slag composition has insufficient CaO/slag volume too low.
"Hot metal silicon too high:" flame temperature too high/coke has > SiO_2/top temperature too low/wind rates too low/contact time too long/slag chemistry (in particular CaO and SiO_2) incorrect/cohesive zone height too high.
"Productivity too low": furnace permeability too low/wind rate or oxygen enrichment too low/carbon rate requirement too high/burden materials have too low a metal content.
"Hanging (burden moves very slowly or stops descending)": furnace filling irregular/furnace filling even but erratic/water leak.
"Slipping (void under the hanging burden is filled rapidly)": furnace filling irregular/furnace filling even but erratic/water leak.
"Stockline index > 32": carbon demand varying/burden basicity varies/furnace filling irregularities.
"Δp too high": wind volume too high/oxygen too low/hydrogen content of the gas too low/burden permeability too low/top pressure too low/excessive fines in the charge/burden distribution faulty/high liquid level/high viscosity slag/steam injection too small.
"Top temperature too low": moisture content in feed charge too high/furnace channeling/poor burden distribution/fuel rate too low/flame temperature too high.
"Top temperature > 116 °C": furnace channeling/furnace hanging/poor burden distribution/coke rate higher than necessary/energy input too high/bosch gas volume too high/flame temperature too low/insufficient direct reduction.
"CO increase but no change in hot metal temperature or silicon": fuel injection too high or too low/burden distribution faulty.
"ETAH2/ETACO ratio changes or differences vary by > 2 std. deviations": water leaking into furnace/blast moisture instrumentation malfunction.
"Furnace goes cold very quickly": water leak

"Increase in top gas hydrogen": water leak
"Flame yellow/orange": water leak
"Loss of burden": water leak
"Ammonia smell": water leak.
"Iron temperature 1399–1400 °C; hot metal silica, 0.4 vs. 0.7 %; hot metal sulfur, 0.075 vs. 0.05 %, tuyeres look dim, blast pressure > normal, slag is more viscous, burden descent irregular": water leak/burden maldistribution/faulty process control giving weighing errors.
"Iron temperature 1371–1399 °C; hot metal silica, 0.2–0.3 vs. 0.7 %; hot metal sulfur, 0.1 vs. 0.05 %, burden hangs and slips": water leak/burden maldistribution/faulty process control giving weighing errors.
"Iron temperature < 1371 °C; hot metal silica, 0.08 vs. 0.7 %; hot metal sulfur, > 0.1 vs. 0.05 %, connection lost between the tuyere and tap hole, uncontrollable hangs and slips": water leak/burden maldistribution/faulty process control giving weighing errors.

6.25
PFTR, Melting Cyclone Burner

Incineration: rotating hearth with single, fixed plough. Combustion air enters tangentially and exits the top.

- *Area of Application*

Phases: Gas plus reacting solid. Solid residence time, 0.004–2 s; gas residence time, < 1 s; solid particle diameter 0.002–0.4 mm. Capacity solids: 0.3–0.55 kg wet solids/s.

- *Guidelines*

For fast reactions, bulk phase film diffusion may control. Incineration: diam. 4–9 m.

Requires 30–80 % excess air. Hearth loading 40 g wet solids/s m^2. Drive power 100–350 kW increasing as the hearth diameter increases. Feed is 20 to 40 % solids with the higher feed concentration requiring small hearth area. Usual design capacity about 6 MW.

6.26
PFTR via Multistage CSTR

$Bd = 2n$ where n = number of CSTRs in series. About 100 CSTR in series to provide negligible backmixing. In practice, about 4 CSTRs in series gives approximately PFTR behavior.

- *Area of Application*

Phases: liquid, gas–liquid–biosolids.

Suitable for slow reactions, residence time similar to PFTR, flexible and can change conditions along the stages. Used for polymerization and polycondensates. Use cascade if (i) the production upstream and downstream is continuous, (ii) good mixing is needed, (iii) the reaction in a single STR does not give the target yield, (iv) if the gradual addition of one of the reactants is desired.

Liquid:

Use for residence time > 4 h; for systems where PFTR conditions are desired, Heat of reaction: highly exothermic reaction rate, slow. Capacity 0.2–100 kg/s.

Gas–liquid–biosolids: variety of reactor configurations to remove soluble BOD_5 from waste water: aerated lagoon.

Pure-oxygen backmix activated sludge, **CSTR in series:** 85–95 % removal, compact unit for use where space is limited.

- *Guidelines*

Gas–liquid–biosolids:

Aerated lagoon: 3 CSTR in series: Residence time: 1 day for each CSTR, removal 80–95 %; GL bubble reactor: retention time less than a facultative lagoon, biomass suspended plus subsequent settling = no recycle activated sludge reactor. Oxygen requirements control if residence time < 1 d; mixing controls if residence time > 1 d; Length/width < 1.5; depth 2.4–5.4 m; SS concentration = 1–5 g/L; Power 0.011–0.023 kW/m^3; 80–95 % removal; food/microorganism ratio = 22 mg BOD_5/s kg MLSS; depth 2.4–5.4 m; 0.01–0.25 kW/m^3; SS 1–5 g/L.

Pure-oxygen backmix activated sludge, **CSTR in series with recycle:** mean cell residence time = 8–20 d; food/microorganism ratio = 3–12 mg BOD_5/s kg MLVSS: volumetric loading = 1.6–4 kg BOD_5/m^3; MLSS = 6–8 g/L; residence time = 1–3 h; recycle ratio = 0.25–0.5.

STR with multichamber: vertical multicompartment with axial stirring and gas injected at the bottom. cascading vertical multistage. Power: 1.5 kW/m^3; gas content: 20 %; maximum volume 120 m^3.

6.27
STR: Batch (Backmix)

$Bd = 0$; $Pe < 1$. Related topics: mixing, Sections 7.1 to 7.3. There are a variety of configurations: **STR** for homogeneous liquid reactions, the usual configuration is a central mechanical mixer sized according to the principles from Section 7.1. For multiphase systems, GL, GLS, LL or LS, the configuration may vary. For GL, five optional configurations include: (i) A **sparged STR** which is an STR with an axial mechanical mixer (single or mltiple impellers) above a gas sparge. (ii) A **sparged STR with inner draft tube** which is an STR with single axial impeller + gas sparge ring at the bottom plus central vertical draft tube. (iii) A **gas tube STR** which is an STR with gassing tube or hollow tube turbine. Here the STR has a single axial impeller + gas introduced to the eye of the impeller via a vertical central gas tube from the top. (iv) A **high efficiency STR** which is an STR with a single axial impeller + gas sparge ring at the bottom plus a central vertical draft tube plus rotating splash plate in the vapor space that creates a spray of liquid drops in the vapor space. (v) A **paddle wheel STR** which is a horizontal contactor. Half submerged along the horizontal axis is a rotating paddle wheel that plunges gas into the liquid.

- *Area of Application*

An STR can be operated batch, semibatch (Section 6.28) and continuous stirred tank reactors (Section 6.29). For all STRs, residence time 600–15 000 s (10 min to 4 h); heat of reaction: primarily exothermic; reaction rate slow to lengthy. High pressure autoclaves < 100 L. Flexible. Do not use for gaseous reactions or for very fast reactions in the liquid phase.

Unique to batch STR: Phases: L, LL, LcS, GL bio S, L bioS, low capacity < 3 L/s but usually < 0.3 L/s. Use (i) if the concentrations of all reactants are high; (ii) if need good selectivity for consecutive reactions; (iii) for low and variable production rate, (iv) a variety of similar products or several products sequentially. Batch STR usually have low fixed capital cost but the product cost is high because of the cycles. Usually batch is better than continuous (Section 6.29) for very slow reactions. If $(Da/St) < 1$.

Details of other applications and guidelines are given in Sections 6.28, semibatch, and 6.29, CSTR.

Liquid and liquid-liquid: commonly used for polymerizations and dehydrations.

Gas-liquid: area per unit volume 20 to 200 m^2/m^3; can suspend solids, maximum pressure limited by the seal around the rotating mixing shaft. $Ha << 0.3$ and $\delta^+ = 150–800$.

Gas-liquid-catalytic solid: hydrogenations.

Gas-liquid plus biosolid: Aerobic sparged reactors: For bioreactors, the main characteristic is a tradeoff between shear (to produce the bubbles) and pumping to create a uniform OTR environment and to suspend the particulates. The selection of the mixing is usually difficult. Vessels are narrow and tall with multiple impellers that are good for pumping and provide good shear to breakup the air bubbles and create the surface area. However, the shear should not be such that it breaks up the microorganisms.

Liquid plus biosolid: limited to lower pressures (because of the inability to seal the rotating mixing shaft) and smaller volumes. **Anaerobic digesters:** (first stage): STR batch: batch microbiological treatment of municipal sludge: high rate.

- *Guidelines*

Batch operation: size on operating cycle: load, temperature and pressure adjustment, react, return to usual conditions, discharge and perhaps, clean. Loading and discharge times are proportional to the volume of the reactor (0.75–1 h each); reactant heating and product cooling depend on the reaction temperature (about 1–3 h each); cleaning (for polymer reactors 0.5–1 h).

Liquid see Section 7.1 for details of agitator design; Section 3.3, for heat transfer for jacketed and cooling finger.

Liquid–liquid see Section 7.2 for details of agitator design; Section 3.3, for heat transfer for jacketed and cooling finger. See also Section 1.6.2 for area and holdup.

Gas liquid: *Creation of bubbles:* generally discussed in Section 6.13; bubble reactors. For bubble formation in an agitated system, usually select radial type turbines that provide a combination of shear and radial flow. Tanks are usually tall and narrow with $H{:}D > 1$; use multiple impellers on the shaft; use fully baffled. Prefer a sparger below the bottom impeller to a single injection tube. Increasing the gas input increases the power requirement for equal gas dispersion. Increasing the pressure decreases the power required. In gas–liquid mixing, gas has a tendency to accumulate on the backside of each blade causing the impeller power drawn to dropp. K factor is defined as the impeller power drawn with gas "on" compared with that of gas "off". K factor depends on the impeller configuration. If K factor is too high ($> 1.2{\sim}2$), it means not enough power is drawn to break gas bubbles, then, other impeller configuration with smaller K factor should be selected. See Section 1.6.1 for area, holdup, Sherwood number, OTR data.

Gas–liquid plus solid catalyst: hydrogenation, 0.2–0.8 kW/m^3; agitated at 90 rpm. working capacity = 0.85 nominal volume; usually keep the hydrogen superficial velocity < 0.03 m/s to minimize entrainment of oil in the top dead end. Overall working volume = 6–7 m^3/Mg of hydrogenated oil. Usually use 304 s/s. Hydrogenation of vegetable oil requires about 0.2 kW/m^3; halogenation of an organic via Friedel Crafts may require 2 kW/m^3. For hydrogenation, consider the use of high efficiency STR to reuse the hydrogen in the top dead end.

Gas-liquid-biosolid: agitation power $\propto$(cell concentration)$^{1.4}$

OTR decreases as the cell concentration increases because of the inherent viscosity increase: decreases from 6.5 to 4 mol/MJ as the cell concentration increases to 40 g/L.

Use STR when relatively small amounts of gas are needed, or low OTR is required. This is because the mechanism of bubble breakup is dictated by the efficiency with which the impeller can break up the gas stream. If the gas stream is too fast, then poor breakup occurs. Therefore, the mixing limits the gas input velocity to < 0.1 m/s. The tradeoff between mixing intensity and OTR is critical in selecting a configuration. See Table 6.10. Mixing ranges from as low as 0.08 kW/m^3 for an immersed column fermenter (Section 6.14) to 10 kW/m^3 for a high efficiency mechanically agitated reactor. See Sections 1.6.1 and 1.6.3 for area, holdup, Sherwood number, OTR data.

1. Sparged STR: sparge ring, impeller: H/D 1 to 3; Prefer $H/D = 3$ for high oxygen transfer, efficient heat transfer (ex aerobic cultivation of prokaryotic cells and fungi).

Prefer H/D = 2 for homogeneous mixing, low shear, bubble-free surface gassing the headspace of oxygen and carbon dioxide (ex animal cell cultures) especially for sizes > 3 m^3. Prefer $H/D = 1$ for antibiotics. Use multiple impellers if height of liquid/tank diameter $>$ 2. Maximum unaerated working liquid volume is 2/3 of total vessel volume with less depending on the gas hold-up and the foam.

Four baffles 0.1 D; baffle wall distance at least 0.02 D; double jacket; helical coil. Stirrer depends on flow patterns desired, gas dispersion needed and liquid viscosity. Low viscosity: marine propeller and turbine impeller. Medium viscosity: multistage impulse countercurrent stirrer MIG. Highly viscous: helical; anchors or multiple rod. Impeller diameter 0.3 to 0.5 of tank diameter.

Superficial gas velocity, 0.03 to 1 m/s; holdup < 0.1, $k_L a = 0.02$ to 0.2 1/s. 95 % of bioreactors are **STR**; usually $<$ 30 m^3. STR with multiple impellers + gas sparge ring at the bottom: turbines 0.55–0.7 g O_2/s kW; propellers; 0.2–0.3 g O_2/s kW. OTR: 1–3.5 g/s m^3. Power: 0.1 to 8 kW/m^3 with usual = 3.5 kW/m^3. The impeller power number for the agitator in a gas–liquid system = 0.4 times the power number for liquid system of the same configuration.

Reactors with **animal cells** require low mixing and without baffles; use marine propellers.

Configurations: $H/D_{\text{tank}} = 2$ to 3; $D_{\text{impeller}}/D_{\text{tank}} = 0.3$ to 0.5. $H_l/D_i = 0.3$ to 0.5; $H_i/D_i = 1$ to 2; 4 baffles of $L_b/D_t = 0.08$ to 0.1.

For **antibiotics**, volumes up to 400 m^3, stirrer powers up to 5 kW/m^3 and viscosities up to 2 Pa s. Design pressures up to 400 kPa gauge. Stirrer is multistage disk or turbine. Height liquid/diameter = 1; radial length of baffle/$D = 0.1$; height of impeller from bottom of vessel/$D = 0.3$; height of rotating axis in liquid/$D = 0.3$ for turbine or paddles, = 0.5–0.66 for propellers or disk.

2. Sparged STR with draft tube. Sparge ring; impeller, $H/D = 2$; for coalescence promoting media, higher $k_L a$. Power: 8 kW/m^3; OTR: 1.1 g/s m^3; gas content: 12 %; maximum volume 80 m^3.

3. STR with gassing tube or hollow tube turbine. STR with single axial impeller + gas introduced to eye of impeller via a vertical central gas tube from the top.

STR with tubular impeller: 0.4 g O_2/s kW; STR with single gassing tube: draft tube, impeller: Power: 4 kW/m^3; OTR: 2.8 g/s m^3; mixing time: 30 s; gas content: 13 %; maximum volume 80 m^3. Hollow tube stirrer, non-coalescing bubbles $k_L a^+ = 2 \times 10^{-5}$–$7 \times 10^{-3}$ and increasing with power/volume. Flat blade impeller, coalescing bubbles $k_L a^+ = 2 \times 10^{-6}$–$7 \times 10^{-4}$ and increasing with power/volume. $k_L a^+$ = dimensionless mass transfer coefficient = $k_L a$ (viscosity/liquid density $\times$ gravity$^2)^{0.66}$.

4. High efficiency STR: draft tube: sparge ring, impeller; power: 30 kW/m^3; OTR: 8.3 g/s m^3; mixing time: 4 s; gas content: 15 %; maximum volume 10 m^3.

5. Paddle wheel; horizontal, half submerged along the horizontal axis rotating paddle wheel that plunges gas into the liquid. Slow rpm; power: 10 kW/m^3; OTR: 4.2 g/s m^3; mixing time: 8 s; gas content: 50 %; maximum volume 50 m^3.

Liquid plus biosolid: Three types of STR reactors are (i) the blanket or UASB, (ii) upflow anaerobic sludge blanket and (iii) fixed bed. **Anaerobic digesters:** (first stage): residence time 10–20 d; 2–10 × washout retention time; operating temperature 18–38 °C usually 35 °C; organic VS loadings = 18–25 mg/s m^3 digester volume; pH 7–7.1; volatile acid concentration 0.2–0.8 g/L; alkalinity concentration 2–3.5 g/L; Circular, diameter 6–35 m; depth 6–14 m; power 0.006–0.03 kW/m^3.

For food, starch and dairy industries WHSV = 10–15 kg COD/m^3 d.

For distillers, chemical industries, food preserves WHSV = 5–10 kg COD/m^3 d.

- *Trouble Shooting*

Batch STR used for polymerization and, to a lesser extent, nitration, sulfonation, hydrolysis, neutralization and, to a much lesser extent, dehydrogenation, oxidation and esterification can pose potentially unsafe operation. Key indicators of such potential hazards include *"Sudden increase in pressure"*, *"Unexplained increase in temperature"*, *"Failure of the mixer"*, *"Power failure"*, and *"Loss of cooling water"*. For any of these conditions our first question should be: emergency shut down? Our knowledge of the MSDS information for the species and their interaction with each other and with the environment is critical.

Gas liquid reactors:

"Foaming": mixer tip speed too high/linear gas velocity too high/surfactant contaminants/decrease in electrolyte concentration in the liquid/change in pH/use of turbine impeller/lack of a gas sparger. See Section 1.12

"Flooded impeller": too small a diameter impeller/speed too slow.

Aerobic bioreactors: *"Inoculation cannot be used for the reactor/fermenter"*: [contamination]*. *"Product formation is inhibited":* [contamination]*. *"Target product cannot be separated from contaminating species"*: [contamination]*. *"Fermentation broth cannot be filtered"*: [contamination]* .

"Steam out of air filter yields dark brown liquid": media blowback.

"Reduction in cell volume, no further product production, no oxygen uptake, no heat production": [contamination by bacteriophage]* .

"Foaming": air leaks through gaskets, coils, jacket, hatch/pH shifted away from zpc/particles present/and generic causes, Section 1.12.

"Carryover": [foaming]*

*[Contamination in the first 24 hours]**: contaminated inoculum/poor sterilization of tank accessories and content/unsterile air.

*[Contamination comes in after 24 hours]**: air supply/nutrient recharges/antifoam feed/loss of pressure during the run/lumps in the media/media blowbacks.

*[Contamination]**: [stock culture contaminated]*/[raw materials contaminated]*/[inoculation tank contaminated]*/[fermenter contaminated]*/[incorrect procedures]*/[faulty maintenance]*/[contamination by bacteriophage]*.

[Contamination by bacteriophage]:* source usually difficult to trace/substitute an immune strain/develop strain resistant to the phage.

*[Faulty maintenance]**: braided packing (on agitator shafts for sterile vessels) not receiving enough germicide/mechanical seals (on agitator shafts for sterile vessels) not lubricated with sterilizing liquid/instruments faulty/bolts on flanges not tightened after heat up to 120 °C/packed bed air filters not packed to correct density of 200–250 kg/m^3.

*[Faulty sterilization]**: particles too coarse and dry/particles not wetted/particles not suspended/raw material contaminated with spores plus inadequate germination-sterilization.

[Fermenter contaminated]:* [inoculum tank contaminated]*/inoculum line contaminated/procedure wrong/tank dirty/air leak/leak from the coil or jacket/faulty sensors/antifoam is not sterile/dirty gaskets, bottom valve, sample line and valve, vent line valve, vacuum breaker/nutrient feed tank or line not sterile/all lines wee not up to sterilization temperature/steam condensate left in lines/the humidity of the fermenter air upstream of the "sterile filter" is $> 90\%$/pH and DO probes were not cleaned between runs/probe holders were not brushed and cleaned with a hypochlorite or formaldehyde solution/for a previously contaminated vessel the valves and gaskets were not replaced, instrument sensors were not removed and cleaned; high boiling germicide, such as sodium carbonate or sodium phosphate was not used.

*[Foaming]**: bubble rate too high/liquid downflow velocity through the foam is too low/and generic causes of [foaming]*, Section 1.12.

[Inoculation tank contaminated]:* wrong procedures/tank dirty/air leak/temperature and pressure instrument fault/sample line, inoculation fitting dirty/dirty dead spots, debris, corrosion/media blow back into air filter/unsterilized air filter/faulty antifoam or pH additive lines.

[Raw materials contaminated]:* dry materials not finely ground/lumps not removed/insoluble solids not suspended in solution well because of lumping or inadequate mixing/lumps too big to be sterilized in the time–temperature available/mixing inadequate to keep particles suspended/particles enter air sparger during filling operation/starches or proteins not prehydrolyzed with enzymes.

*[Stock culture contaminated]**: foreign microorganisms in culture stock/contaminated inoculation flash/wrong sterilization procedure/temperature and pressure instruments wrong/air left in sterilization chamber/sterile area contaminated/cotton plugs contaminated/[faulty sterilization]*/raw material contaminated with spores combined with inadequate germination-sterilization.

Anaerobic digesters: *"Sludge temperature fluctuates"*: instrument fault/fluctuating feedrate. *"Poor heat transfer with the hot water coils, exit water temperature < design: "* sludge solids adhere to heat transfer surface. *"Temperature constant but production of methane gas < design":* increased accumulation of scum or grit/excessive acid production with lower pH and volatile acid > 500 mg/L/organic overload/toxic metals in feed/highly acidic feed/overdigested sludge. *"Foaming":* incomplete digestion/feedrate > design/inadequate mixing/temperature too low/withdrawal of too much product (digested sludge)/rate of reaction > design/large quantities of organics in feed/insufficient reaction volume for the high organic feedrate/pH shift away from zpc and generic causes of foaming, Section 1.12.

6.28
STR: Semibatch

Bd = 0; *Pe* < 1. Related topics: mixing, Section 7.1.

- *Area of Application:*

Batch, semibatch and continuous stirred tank reactors: Residence time 600–15 000 s (10 min to 4 h); heat of reaction: primarily exothermic; reaction rate slow to moderate. High pressure autoclaves < 100 L.

Unique to **semibatch:** Phases: liquid, gas–liquid, liquid–liquid, gas–liquid–catalytic solid. Use where a batch operation is appropriate, Section 6.27, but one reactant, e.g. gas, needs to be added continuously or if the initial reaction rate is very high. Selectivity is best for parallel reactions. If (Da/St) > 1.

Fast and very exothermic reactions; flexible; and if some of the reactants may decompose, or if want gradual addition of reactants.

For more details see CSTR, Section 6.29 and STR Section 6.27.

- *Guidelines*

Batch operation: size on operating cycle: load, temperature and pressure adjustment, react, return to usual conditions, discharge and perhaps, clean. Loading and discharge times are proportional to the volume of the reactor (0.75–1 h each); reactant heating and product cooling depend on the reaction temperature (about 1–3 h each); cleaning (for polymer reactors 0.5–1 h).

- *Good Practice*

Agitated bubble reactors: Consider increasing the impeller diameter or using a disk turbine to increase mass transfer.

- *Trouble Shooting*

Semibatch STR used for polymerization and, to a lesser extent, nitration, sulfonation, hydrolysis, neutralization and, to a much lesser extent, dehydrogenation, oxidation and esterification can pose potentially unsafe operation. Key indicators of such potential hazards include *"Sudden increase in pressure"*, *"Unexplained increase in temperature"*, *"Failure of the mixer"*, *"Power failure"*, and *"Loss of cooling water"*. For any of these conditions our first question should be: emergency shut down? Our knowledge of the MSDS information for the species and their interaction with each other and with the environment is critical.

Polymerizer:

"Temperature increases suddenly: " emergency shutdown?/mixer stopped/fouling of heat exchanger/"gel effect" in polymerization reaction/coagulation and product fouls the walls of the reactor. *"Particle product size < design":* too many nucleation sites/lower level of oxygen than design/too much emulsifier/too much initiator. *"Particle product size > design":* coagulation/too few initial nucleation sites/too much oxygen in the feed/too little emulsifier/too little initiator/emulsifier post feed is too late. *"Temperature increases > design":* emergency shutdown?/coagula-

tion/emulsifier post feed too late. *"Batch times < design":* too many nucleation sites/lower level of oxygen than design/too much emulsifier/too much initiator. *"Batch times > design":* too few initial nucleation sites/too much oxygen in the feed/too little emulsifier/too little initiator.

Agitated bubble reactors:

"Foaming": mixer tip speed too high/linear gas velocity too high/use of turbine impeller/lack of a gas sparger/and generic causes, Section 1.12.

"Flooded impeller": too small a diameter impeller/speed too slow.

Gas–liquid–solid bioreactor: *Carryover":* [foaming]*

*[Foaming]**: bubble rate too high/liquid downflow velocity through the foam is too low. See Section 1.12 for generic causes of [foaming]*.

See Trouble shooting: STR, Section 6.27 for more on trouble shooting bioreactors.

6.29
CSTR: Mechanical Mixer (Backmix)

$Bd = 0$; $Pe < 1$. Related topics mixing, Section 7.1, solvent extraction, Section 4.10.

- *Area of Application*

Batch, semibatch and continuous stirred tank reactors: Residence time 600–15 000 s (10 min to 4 h); heat of reaction: primarily exothermic; reaction rate slow to moderate; High pressure autoclaves < 100 L.

Unique for **CSTR:** Phases: liquid, gas–liquid, liquid–liquid, liquid–catalytic solid, gas–liquid–catalytic solid, gas–liquid –biosolid. Capacity 0.0001–100 L/s and usually > 0.4 L/s; volumes 1–1 000 000 L. Autothermal reactions. Usually if the concentration of reactants is low, and need low concentration of reactants for selectivity. CSTR is larger and more expensive than PFTR. For multiphase, STR are characterized by high liquid holdups; holdup of the reactive phase is important if the reaction is slow $Ha < 1$; phase ratio is easy to control. Adiabatic, CSTR usually gives higher productivity for exothermic reactions than for STR batch or PFTR. Use for large capacity, otherwise batch. Heat recovery is easier in CSTR than in a batch STR.

Liquid: < 300 000 mPa s; volume < 75 m^3. Use for kinetically controlled reactions that require long residence times.

Liquid–liquid: surface area 400–3500 m^2/m^3 with area increasing with decreasing surface tension and increasing velocity. Drop diameter 4–5000 μm; for viscosities < 10^4 mPa s. Phase ratio is easy to control.

Gas–liquid: Surface area 60–500 m^2/m^3; surface area gas–liquid per volume of reactor: 200–2000 m^2/m^3 volume reactor; surface area gas–liquid per volume of liquid phase: 220–2500 m^2/m^3; liquid phase can handle viscous liquids and suspensions. only appropriate for smaller size reactors < 10–20 m^3.

Liquid with catalytic solid: catalyst diameter, < 0.1 mm; surface area solid 500 m^2/m^3.

Gas–liquid with catalyst solid: catalyst diameter, < 0.1 mm; Surface area 50–1200 m^2/m^3; surface area solid 500 m^2/m^3; surface area gas–liquid 100–1500 m^2/m^3.
Gas–liquid–biosolid: $Ha < < 0.3$ and $\delta^+ = 150–800$.
Aerobic sludge digesters: reduce the volume of and render biologically stable the sludge from a variety of sources: conventional activated sludge and primary clarifier.

- *Guidelines*

Reactor size 8 to 32 m^3, 1.5 MPa, with jacketed heat transfer surface 1.5–2.5 m^2/m^3 volume. Heat transfer coefficient $U = 0.06–0.35$ kW/m^2 K for jacket to inside reactor contents; coil 0.7–0.8 kW/m^2 K.

0.2–2 kW/m^2 see mixing Section 7.1 and heat transfer, Section 3.3.

Liquid: Power input to promote heat and mass transfer: 1–6 kW/m^3 reactor volume.
Liquid–liquid: Holdup: volume fraction dispersed liquid 0.01–0.5. Typical drop diameter is 150 μm; Power input 0.2–3 kW/$m^{3.}$. Related topic: solvent extraction, Sections 4.10 and 1.6.2.
Gas–liquid: Holdup: liquid holdup > 0.7, gas holdup < 0.1; bubble diameter = 2.5 mm regardless of the agitation and has a mean upward velocity of about 0.27 m/s; superficial gas velocity, 0.05 to 1 m/s; Backmix; complete; typical liquid mass transfer coefficient = $k_L a = 0.02–0.2$ 1/s; bulk/film volume ratio, $\delta^+ > 100$; power input 0.1–4 kW/$m^{3.}$. Height of liquid = tank diameter or use multiple impellers if height of liquid/tank diameter > 2. Impeller diameter 0.3 to 0.5 of tank diameter. See also Section 1.6.1
Liquid with catalytic solid: Holdup: volume fraction catalyst 0.01; volume fraction liquid 0.99; power input to facilitate heat and mass transfer, suspend solids and promote mass transfer: 1–4 kW/m^3 reactor volume.
Gas–liquid with catalyst solid: Holdup: volume fraction catalyst 0.01; volume fraction liquid 0.8–0.9; volume fraction gas 0.1–0.2. Power input 0.05–2 kW/m^3. Catalyst activity: variable but often able to avoid diffusion limitations because of small diameter catalyst. Catalyst selectivity: OK. Catalyst stability: change between batches.

Heat exchange OK.

Gas–liquid –biosolids: see STR, Sections 6.27 and 1.6.3.
Aerobic sludge digesters: CSTR designed on the basis of VSS reduction. Mixing to keep the solids suspended plus oxygenation. Cell residence time for cells 12–22 d depending on the source of the sludge. Typical organic load 4–26 μg VSS/s m^3; dissolved oxygen concentration 1–2 mg/L; air requirement for activated sludge = 0.25–0.33 $dm^3/s\ m^3$; mixture of primary plus activated sludge = 0.4–0.5 $dm^3/s\ m^3$; 1.42 kg O_2/kg biosolids digested. Oxygen usage 1.4–11 mg O_2/s kg VSS depending on the source of the sludge. For diffused air 0.33–1 $dm^3/s\ m^3$ depending on the sludge; surface aeration = 0.025–0.033 kW/m^3. Power = 0.015–0.02 kW/m^3.

- *Good Practice*

Consider complications because of catalyst deposition and erosion.

- *Trouble Shooting*

CSTR used for polymerization and, to a lesser extent, nitration, sulfonation, hydrolysis, neutralization and, to a much lesser extent, dehydrogenation, oxidation and esterification can pose potentially unsafe operation. Key indicators of such potential hazards include *"Sudden increase in pressure"*, *"Unexplained increase in temperature", "Failure of the mixer", "Power failure"*, and *"Loss of cooling water"*. For any of these conditions our first question should be: emergency shut down? Our knowledge of the MSDS information for the species and their interaction with each other and with the environment is critical. See semibatch and STR Sections 6.27 and 6.28 for more.

Liquid–liquid: Typically the reactor is a CSTR followed by a decanter to separate the phases and recycle the "catalyst" phase to the reactor. See decanter, Section 5.3.1. For **alkylation:** *"Alkylate is purple":* [stable emulsion formation]*/[density difference decrease]*/[drops don't settle]*/[acid runaway]*. *"Δp across the alkylate cooler> design":* [stable emulsion formation]*/[density difference decrease]*/[drops don't settle]*/[acid runaway]*/acid recirculation rate too fast.

"Temperature of the recycled acid is > 1.7 °C hotter than feed entering the reactor": [acid runaway]*/alkyl sulfates polymerize in the decanter/acid recirulation rate too fast.

[Acid runaway]:* excessive contaminants in feed to reactor/feed rate too fast/poor contact or mixing between isobutane, olefin and acid/fresh acid makeup feedrate stopped/faulty control/faulty meter/ratio of acid : hydrocarbon outside range 45–60 % v/v/ratio of isobutane : olefin < 8: 1/initial reactor temperature too hot or > 18 °C/poor mechanical design for fresh acid addition.

[Density difference decrease]:* dilution of the dense phase/reactions that dilute the dense phase; for **sulfuric acid alkylation:** if acid strength < 85 % w/w the olefins polymerize with subsequent oxidation of the polymers by sulfuric acid as a self-perpetuating continuing decrease in acid strength. Alkylate–acid separation is extremely difficult when acid concentration is 40 % w/w.

[Drop doesn't settle]:* [density difference decrease]*/[viscosity of the continuous phase increases]*/[drop size decreases]*/[residence time for settling too short]*/[phase inversion or wrong liquid is the continuous phase]*/pressure too low causing flashing and bubble formation.

[Drop settles and coalesces but is re-entrained]:* faulty location of exit nozzles for liquid phases/distance between exit nozzle and interface is < 0.2 m/overflow baffle corroded and failure/interface level at the wrong location/faulty control of interface/liquid exit velocities too high/vortex breaker missing or faulty on underflow line/no syphon break on underflow line/liquid exit velocities too high.

[Drop settles but doesn't coalesce]:* [phase inversion]*/pH far from zpc/surfactants, particulates or polymers present/electrolyte concentration in the continuous phase < expected/[coalescer pads ineffective]*/[drop size decrease]*/[secondary

haze forms]*/[stable emulsion formation]*/[interfacial tension too low]*/[Marangoni effect]*.

[Drop size decrease]:* feed distributor plugged/feed velocity > expected/feed flows puncture interface/local turbulence/distributor orifice velocity > design; **for amine units**: for amine > 0.8 m/s; for hydrocarbon > 0.4 m/s/[Marangoni effects]*/upstream pump generates small drops/[secondary haze forms]*/poor design of feed distributor.

[Inaccurate sensing of the interface]:* instrument fault/plugged site glass.

[Interfacial tension too small]:* temperature too high/[surfactants present]* at interface.

[Marangoni effects]:* nonequilibrated phases/local mass transfer leads to local changes in surface tension and stability analysis yields stable interfacial movement.

[Phase inversion]:* faulty startup/walls and internals preferentially wetted by the dispersed phase.

[Rag buildup]:* collection of material at the interface: [surfactants present]*/particulates: example, products of [corrosion see Section 1.3]*, amphoteric precipitates of aluminum/naturally-occurring or synthetic polymers.

[Residence time for settling too short]:* interface height of the continuous phase decreases/[inaccurate sensing of interface]*/turbulence in the continuous phase/flowrate in continuous phase > expected; for example > 3 L/s m^2/sludge settles and reduces effective height of continuous phase/[phase inversion]*/inlet conditions faulty.

[Secondary haze forms]:* small secondary drops are left behind when larger drop coalesces, need coalescer promoter, see Section 9.2.

[Stable emulsion formation]:* [surfactants present]*/contamination by particulates: example, products of [corrosion products. see Section 1.2]*, amphoteric precipitates of aluminum or iron/pH far from the zpc/contamination by polymers/temperature change/decrease in electrolyte concentration/the dispersed phase does not preferentially wet the materials of construction/coalescence -promoter malfunctioning/improper cleaning during shutdown/[rag buildup]*.

[Surfactants present]:* formed by reactions/enter with feed, example oils, hydrocarbons > C10, asphaltenes/left over from shutdown, example soaps and detergents/enter with the water, example natural biological species, trace detergents.

*[Viscosity of the continuous phase increases]**: temperature too low, for **alkylate-acid** separation, temperature < 4.4 °C/[phase inversion]*/contamination in the continuous phase/unexpected reaction in the continuous phase causing viscosity increase.

6.30
STR: Fluidized Bed (Backmix)

Related topics: heat transfer, Section 3.4, dryers, Section 5.6 and size enlargement, Section 9.4.

- *Area of Application*

Phases: GcS, GrS, LcS, GLcS: Residence time: for gas = seconds; for solids = minutes to hours. Primarily for highly exothermic, very fast reactions where the need is for uniform, closely controlled temperature; need fast reaction that occurs at the bottom of the bed. Not good if we have consecutive reactions to produce the product (because of backmixing). Relatively inflexible. Preferred over PFTR for strongly exothermic or endo reactions. Easier than fixed bed for catalyst regeneration, excellent heat transfer for high exothermic reactions; lower pore diffusional resistance because of smaller diameter catalyst particles. Select if catalyst life is < 3 month. Catalyst must withstand attrition.

Gas with catalytic solid: Solid residence time, 300–15 000 s; gas residence time, < 1 s; solid particle diameter 0.005–7 mm.

Gas with inert solid: gasification or incineration: use for homogeneous exothermic reactions where we need to control the heat release or for the creation of biogas from biomaterial (such as bagasse) in a fluidized bed of sand or incineration of wet sludge, again in a fluidized bed of sand.

Gas with reacting solid: Solid residence time, 300–15 000 s; gas residence time, < 1 s; solid particle diameter 0.005–7 mm. For combustion, gasification, incineration and ore roasting or reduction. Advantages: ease in solids handling, uniform temperature, thermal stability even for highly exothermic and endothermic reactions. Cannot be used for solids with partial fusion or softening of particles.

Liquid with catalytic solid: catalyst diameter, 0.1–5 mm; surface area solid 500–1000 m^2/m^3.

Gas–liquid with catalytic solid: catalyst diameter, 0.1–5 mm; surface area solid 500–1000 m^2/m^3; surface area gas–liquid 100–1000 m^2/m^3.

Gas–liquid with microorganisms (bio): Mainly used for cells immobilized on inert solid. Provides low shear. For gas–liquid k_La = 0.05–0.3 1/s; for liquid solid k_La = 0.1–0.5 1/s; solids holdup = 0.1–0.5 m^3/m^3 and biofilm area = 2000 m^2/m^3.

- *Guidelines*

Fundamentals: Solid particle diameter 60 to 80 μm diameter solid particles with ratio of maximum to minimum diameter about 11 to 25. More generally, particles usually in the range 40–100 μm corresponding to velocities of 0.1–0.3 m/s; and 70–1000 μm corresponding to 0.1–2.5 m/s for minimum for fluidization. Larger diameter particles tend to slug; smaller, tend to bubble.

The fluidization is characterized as “bubbling”, **B** (aggregate fluidization). Bubbling consists of two phases:

1. Gas bubbles: assume move through in plug flow; superficial gas velocity (0.1 m/s) $>>$ minimum superficial gas velocity to cause fluidization (0.01 m/s); mass transfer coefficient between the bubble and the emulsion phase = 0.01 m/s; the fraction of the volume of the fluidized bed occupied by the bubbles is 0.04.
2. Homogeneous emulsion phase: reaction occurs in the emulsion phase. Area between the bubble phase and the

emulsion phase = 10 m^2/m^3. Diffusivity of the reactant in the emulsion phase = diffusivity in the bubble phase = 10^{-5}–10^{-4} m^2/s.

The options include:
– single bubbling bed (BFB), gas velocity about 3–5 × the sedimentation velocity of the particles; usually 1–2 m/s. Height of the fluidized bed: shallow beds 0.15–0.2 m deep; deep beds 0.3–15 m but usually 0.5–1.9 m deep, regardless of the diameter. Usually try to have the height: diameter about 1–1.5: 1. For BFB, Archimedes no. ranges from 1–10^6; particle Froude no. (3/4 Fr_p $(\varrho_G/(\varrho_s - \varrho_G))$ in the range 10^{-4}–0.4 and the particle Reynolds no. 0.1–400.
– BFB/BFB combo with catalyst as the oxygen carrier,
– Circulating fluidized bed **CFB**, CFB are superceding BFB for many applications although one of their major limitations is the erosion from the particles. Used for short gas contact times, plug flow gas; for rapidly decaying catalyst or solids that must transport a lot of heat. Gas velocity is 4–8 m/s; the solids flux of minerals or catalyst is typically 100–1000 kg solids/s m^2 . For example, typically 500 kg catalyst solids/s m^2 for an fluid cat cracker, FCC.

For CFB, Archimedes no. ranges from 1–10^2; particle Froude no. in the range 10^{-2}–0.4 and the particle Reynolds no. 0.1–8.
– CFB/BFB combo with catalyst as the oxygen carrier,
– Multistage BFB,
– Multistage BFB with split air flow and temperature programming.

Incineration: BFB, gas velocity 0.5–1.5 m/s and use 1 m/s on heated air and 0.6 m/s on the freeboard; 650–980 °C; heat load 200–350 kW/m^3 with the usual design capacity about 6 MW. Operate 3 to 5 × minimum fluidizing velocity and usually 0.5–1.5 m/s, solid flux waste sludge = 0.06–0.07 kg wet feed/s m^2, coal = 0.01 to 0.015 kg coal/s m^2; for biomass **gasifiers** = 0.22 kg biomass feed/s m^2; gas residence time = 3 –4 s. Height: diameter usually about 1 to 1.2:1. Volumetric loading 5 % solids; temperatures 650–980 °C; heat release from combustion 200–340 kW/m^3; superficial gas velocity 60–75 g/s m^2 of cross sectional area for wet solids; 15–20 g/s m^2 of cross sectional area for dry solids combustion. **CFB:** gas velocity 6–8 m/s; used for coal combustion.

Gas plus catalyst solid: Usually **BFB**. For fast reactions, gas film diffusion may control and catalyst pore diffusion mass transfer may control if catalyst diameter $>$ 1.5 mm. Heat transfer: heat transfer coefficient wall to fluidized bed is 20–40 × gas-wall at the same superficial velocity, h = 0.15–0.3 kW/m^2 K. Nu = 0.5–2. Heat transfer from the bed to the walls: U = 0.45 to 1.1 kW/m^2 °C.; from bed to immersed tubes: U = 0.2 to 0.4 kW/m^2 °C; from solids to gas in the bed U = 0.017 to 0.055 kW/m^2 °C. Fluidized bed usually expands 10–25 %. Backmix type reactor which increases the volume of the reactor and usually gives a loss in selectivity. Usually characterized as backmix operation or more realistically as a series of CSTR if the height/diameter $>$ 2; Usually 1 CSTR for each $H/D = 1$. If the reactor operates in the bubble region, then much of the gas short circuits the catalyst so the overall apparent rate constant is lower by a factor of 10.

Minimum gas fluidization velocity of 0.5 mm/s to 15 mm/s or about a factor of 0.01 to 0.1 % of the pneumatic conveying velocity. Ratio of height to diameter ≥1. Bed depth usually 0.3 to 15 m. When used for heat transfer: particles and gas tend to leave the bed at the same temperature. Here are some guidelines from the few data that are available in the open literature:

For gas reactions with solid catalyst, **BFB:** gas velocity 0.5–1.5 m/s. propylene to acrylonitrile, the liquid product loading = 0.14 kg/s m^2 of grid area; the $H{:}D$ = 1.7:1 and the gas phase residence time = 12 s. For allyl chloride, the gas residence time is 0.4 s. For the Unipol production of LDPE polyethylene from ethylene, the $H{:}D$ = 2.6:1 with residence time for the solid = 3–5 h until the particles are 500 μm; for HDPE via the Union Carbide process the residence time for the solid is 2–3 h with 10 % per pass with recycle. For cat cracking, the liquid feed loading is 1.0 kg/s m^2 of grid area; the $H{:}D$ = 2:1 and the gas phase residence time = 11–75 s; solids residence time 5–10 min. For phthalic anhydride, gas phase residence time = 10–20 s. **CFB:** gas velocity 4–8 m/s; solid mass flux 100–1000 kg solids/s m^2 (usually 500) with the slip velocity (ratio of interstitial gas velocity to the solids velocity) usually 2. Used for cat cracking and Fischer Tropsch synthesis to produce hydrocarbons from hydrogen and carbon monoxide over an iron catalyst.

For gas–solid reactions (as in ore roasting or reduction and calcination), **BFB** or series of **four BFB**. gas velocity 0.5–1.5 m/s. feed solids flux 1 kg/s m^2; gas residence time per stage about 0.25 s; solid residence time per stage 3–5 h. Solids flux = 1 kg pyrites feed/s m^2; For multistage ore reduction, solids flux = 0.025 feed ore/s m^2 grid. For calciner solids feed flux = $<$ 1 kg/s m^2. **CFB** gas velocity 4–8 m/s; solid mass flux 100–1000 kg solids/s m^2 (usually 500) with the slip velocity (ratio of interstitial gas velocity to the solids velocity) usually 2. Solids residence time 40 min. $H{:}D$ = 3–20:1.

Liquid with catalytic solid: Particulate fluidization: homogeneous with no bubbles. For highly exothermic reactions, consider external recirculation through a heat exchanger.

Gas–liquid with catalytic solid: Holdup volume fraction catalyst 0.1–0.5; volume fraction liquid 0.2–0.8; volume fraction gas 0.05–0.02. Catalyst activity: variable but often reduced because of mass transfer limitation; backmixing is unfavorable. Catalyst selectivity: often reduced because of mass transfer limitation; backmixing is unfavorable. Catalyst stability: must withstand attrition; can be removed for regeneration. Heat exchange; good heat transfer. Isothermal efficiency may be 1 but with larger diameter particles this can decrease. May have lower isothermal efficiency because of diffusion into the pellet and the larger size pellet.

Gas–liquid with microorganisms (bio): For gas–liquid $k_L a$ = 0.05–0.3 1/s; for liquid–solid $k_L a$ = 0.1–0.5 1/s; solids holdup = 0.1–0.5 m^3/m^3 and biofilm area = 2000 m^2/m^3.

- *Good Practice*

Design of gas distributor to ensure uniform dispersion of the gas across the bed: select conditions to achieve the highest values from among the following

1. Δp across the distributor = 0.1 × Δp across the bed (latter = apparent weight of the bed)
2. 0.35 kPa
3. 100 × Δp for fluid in an empty tube.

- *Trouble Shooting*

First we consider fluidized bed reactors in general, then fluidized combustors or regenerators and then provide specifics for a fluid catalyst cracking unit, **FCCU**, which consists of a riser or fluidized bed reactor, cyclone separator, steam stripper, spend catalyst transport, air-oxidizing regenerator, cyclone separator and a regenerated catalyst return.[1]

General fluidized bed reactor: *"Gradual change in yield":* [carbon buildup]*. *"Poor yield":* [Loss of catalyst activity]*/[maldistribution]*/[unacceptable temperature profiles]*/[inadequate heat transfer]*/wrong locations of feed, discharge or recycle lines/faulty design of feed and discharge ports/[inadequate mixing]*/[excessive backmixing]*/wrong internal baffles and internals/[poor bubbling hydrodynamics]*/[inadequate solids circulation rates in reactor]*. *"Change in product distribution":* [maldistribution]*/poisoned catalyst/feed contaminants/change in feed/change in temperature settings.*"Temperature hot spots":* [maldistribution]*/ local exothermic reactions. *"Temperature runaways":* temperature hot spots. *"Pressure and bed temperature and reactor unsteady":* water in feed/reactor grid hole erosion/[maldistribution]*/for **FCCU:** surging regenerator holdup/unsteady reactor-regenerator Differential Pressure controller operation/rough circulation/incorrect aeration of U-bend/incorrect aeration of standpipe/sticky stack slide valves/sensor control performance for stack slide valve unsatisfactory.*"Particulate carry over that affects operation of downstream equipment":* [poor separation in cyclone]*. *"Shifts in yield distribution":* [Feed contaminated with light hydrocarbons]*/[sintered catalyst]*/coarse particles. *"Δp increase across the grid":* [plugged grid holes]*/fluid flow > usual. *"Δp across grid < expected":* air flowrate < design/[eroded grid holes]*/for **FCCU:** [Failure of internal seals in regenerator]*. *"Erratic or cycling pressures":* [surging of the catalyst bed]*. *"Catalyst losses increase":* [poor separation in cyclone]*/insufficient head space above bed/fluidization velocity too high/increase in volume of product through unexpected side reactions/change in feed flowrate/flowrate instrument error/velocity through reactor too high/pressure surges/attrition of catalyst.

*[Attrition of the catalyst]**: steam flowrate > expected/air flowrate > expected/local velocities into the dense phase > 60 m/s/catalyst too fragile.

[Carbon buildup]:* [inadequate regeneration]*/[excessive carbon formed]*.

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[1] Based on Luckenbach, E.C. et al. *Encyclopedia of Processing and Design*, Marcel Dekker, 1981, p. 89; Dutta, S., Gualy R., Overhaul process reactors, Hydrocarbon Process., 1999 Sept. pp. 43–50; Lieberman, N. P., *Troubleshooting Process Operations*, 2nd edn., 1985, Pennwell Books.

[Coarse particles (diameter $>$ design)]:* [generation of fines]*/[loss of catalyst fines]*/[poor separation in cyclone]*/agglomeration of catalyst/[sintered catalyst]*/wrong specifications for catalyst.

[Eroded grid holes]:* hole velocity too high/materials of construction/contaminants in fluid. *[Excessive backmixing]*:* [maldistribution]*/[poor bubbling hydrodynamics]*.

[Excessive carbon formed in cracker]:* cracker operating intensity above usual; for **FCCU** excess aromatics in feed/changes in feed/poor catalyst stripping/heavier recycle/leakage of fractionator bottoms into the feed/[sintered catalyst]*/[feed contaminated with metals]*/[feed contaminated with heavy hydrocarbons, especially aromatics]*.

[Failure of internal seals in regenerator for FCCU]:* pressure bump during startup/regenerator pressure too high/velocity through the grid too low/low flow of air to the grid/stresses too high/erosion/abnormal conditions with the auxiliary burner on startup.

[Gas bubbles too big]:* particles heavier than design/particles larger than design/sintered particles/single fluidized bed too deep.

[Gas bypassing in fluidized bed]:* particles heavier than design/particles larger than design/agglomerated particles/single fluidized bed too deep instead of multiple beds in series.

[Gas velocity too high]:* [increase in production of light ends in reactor]*.

[Generation of fines]:* [attrition of the catalyst]*/fines in the new catalyst.

[Inadequate heat transfer]:* [maldistribution]*/insufficient heat exchanger area/design error/fouled exchanger. See Section 3.3.

[Inadequate mixing]:* [maldistribution]*/[poor bubbling hydrodynamics]*.

[Inadequate regeneration]:* [regenerator doesn't remove all carbon from the catalyst]*/excessive temperature during regeneration/coarse particles.

[Loss of catalyst activity]:* [carbon buildup]*/[inadequate regeneration]*/[sintered catalyst]*/excessive regeneration temperature/[poisoned catalyst]*/[loss of surface area]*.

[Loss of catalyst fines]:* insufficient disengaging space above the top of the bed/agglomeration of catalyst/[poor separation in cyclone]*/Δp indicator for catalyst level faulty/Δp indicator for catalyst level OK but bed density incorrect.

[Loss of surface area]:* [sintered catalyst]*/[carbon buildup]*.

[Maldistribution]:* faulty feed distributor design/plugging of fluid distributors with fine solids, sticky byproducts or trace polymers/[temperature hot spots]*/[sintered catalyst particles]*/[poor bubbling hydrodynamics]*/[poor circulation]*.

[Plugged dipleg]:* spalled refractory plug/level of catalyst in bed too high/Δp indicator for catalyst level faulty/Δp indicator for catalyst level OK but bed density incorrect, air out periods with a lot of water or steam in vessel.

*[Plugged grid holes]**/foreign debris entering with fresh catalyst/faulty grid design/lumps of coke or refractory in catalyst/failure of grid hole inserts/[sintered catalyst]*/bits of refractory.

[Poisoned catalyst]:* poisons in feed/flowrate of "counterpoison" insufficient/poison formed from unwanted reactions.

[Poisons in feed]:* depends on reaction: for **FCCU** poisons in the feed include nickel, vanadium and sodium; the counterpoison is a solution of antimony.

[Poor bubbling hydrodynamics]:* [Gas bypassing in fluidized bed]*/[gas bubbles too big]* particles heavier than design/[particles larger than design]*/[sintered catalyst]*/fluid feed velocity too high/too deep a bed of catalyst/[maldistribution]*.

[Poor circulation]:* coarse particles/[maldistribution]*.

[Poor separation in cyclone]:* [stuck or failed trickle valve]*/[plugged dipleg]*/dipleg unsealed/solids level does not cover end of dipleg/gas velocity into cyclone too low or too high/faulty design of cyclone/solids concentration in feed too high/cyclone volute plugged/hole in cyclone body/Δp indicator for catalyst level faulty/Δp indicator for catalyst level OK but bed density incorrect/pressure surges.

"$\Delta p > $ design": fines in packed beds/fines in distributors/fines in exit nozzles/crud left in from construction or revamp.

[Reactor instability]:* control fault/poor controller tuning/wrong type of control/insufficient heat transfer area.

*[Regenerator doesn't remove all carbon from the catalyst]**: damaged air grid/insufficient air/excessive regenerator velocity/poor spent catalyst initial distribution/coarse particles.

[Sintered catalyst]:* local high temperatures/[maldistribution]*/for **FCCU** [afterburn in regenerator]*/[Feed contaminated]*/high temperature in the regenerator/[temperature hot spots in the reactor]*.

[Solids conveying lines flow capacity $<$ design]:* sticky fines buildup in lines/wrong Δp across line.

[Stuck or failed trickle valve]:* binding of hinge rings/angle incorrect/wrong material/hinged flapper plate stuck open/flapper plate missing.

[Surging of the catalyst bed]:* water in the feed/[plugged grid holes]*/faulty grid design/[grid holes eroded]*/[for FCCU: failure of internal seals in regenerator]*/for **FCCU:** [seal failures]*/hole in the overflow well/[reactor instability]*/control fault in Δp between cracker and regenerator.

[Unacceptable temperature profiles]:* fluctuating temperature/unsteady bed temperatures.

Specific for a fluidized bed combustion/catalyst regenerator: *"Increase in catalyst losses":* [poor separation in cyclone]*/[failure in regenerator plenum]*/for **FCCU** [failure of internal seals in regenerator]*.

[Failure in regenerator plenum]:* faulty cyclone design/catalyst feed too high/regenerator velocity too high/faulty spray nozzles causing impingement of plenum sprays/temperatures too high causing failure in plenum.

Specific for Fluid Cat Cracker Unit - including regenerator system: *"Overloaded wet gas compressor":* for **FCCU** high hydrogen production/increase in production of light ends. *"Gas compressor flow reversal":* [poisoned catalyst]*. *"Gas compressor surge":* [poisoned catalyst (that causes production of lower MM species)]*. *"Gas compressor flow reversal":* [poisoned catalyst]*. *"Wet gas compressor surge":* [poisoned catalyst (that causes production of lower MM species)]*.

"Hydrogen concentration in wet gas increases": [poisoned catalyst, especially with nickel and vanadium]*/[feed contaminated with metals, especially nickel and

vanadium]*/[loss of catalyst activity]*/feed concentration high in hydrogen/loss of antimony solution addition. *"Increase in the production of light ends":* for **FCCU** [feed contaminated with metals]*/feed concentration high in light ends.
"Erratic or cycling instrument records on holdup, density and the overflow well": [surging of the catalyst bed]*. *"Opaque flue gas from the regenerator":* [poor separation in cyclone in regenerator]/fluidization velocity too high/increase in volume of product through unexpected side reactions/change in feed flowrate/flowrate instrument error. *"Vibration in the preheat system":* [feed contaminated with water]*. *"Δp increase between reactor and fractionator inlet":* [coking in overhead lines]*. *"Δp lower on the regenerator slide valve":* [poisoned catalyst]*. *"Δp between cracker and regenerator incorrect":* fault with the input air blower/fault with the flue gas slide valve on the regenerator/fault with the regenerated catalyst slide valve/fault with the spent catalyst slide valve/fault with the wet gas compressor/fault downstream of the wet gas compressor, such as plugged fractionator overhead condensers (with ammonium chloride salts)/changes in environment air conditions. Regenerator should be about 20 kPa higher than the cracker for Δp across the regenerated catalyst slide valve. *"Δp between cracker and regenerator fluctuating":* fluctuating temperature in cracker/fluctuating pressure in regenerator/fluctuating catalyst circulation rate/fluctuating level in the overflow well/shift in catalyst between cracker and regenerator/incorrect aeration of U-bend/incorrect aeration of standpipe/sticky stack slide valves/sensor control performance for stack slide valve unsatisfactory/moisture in aeration medium/unsteady control of air/U-bend vibration. *"Δp across cylcone > expected":* steam flowrate > expected/air flowrate > expected. *"Pressure fluctuating in regenerator":* incorrect aeration of U-bend/incorrect aeration of standpipe/sticky stack slide valves/sensor control performance for stack slide valve unsatisfactory. *"Plugged pump on the bottoms of the fractionator":* [poor separation in cyclone]*/velocity through reactor too high/faulty cyclone design. *"Overflow well level low":* [eroded grid holes]*. *"Overflow well level high":* [plugged grid holes]*. *"Overflow well level fluctuating":* incorrect aeration of U-bend/incorrect aeration of standpipe/sticky stack slide valves/sensor control performance for stack slide valve unsatisfactory/hole in the overflow well.
"Catalyst loss from the regenerator increased": [plugged grid holes]*/[eroded grid holes]*/foreign debris entering with fresh catalyst/faulty grid design/[poor separation in cyclone]*/steam flowrate > design/air flowrate > design. *"Catalyst circulation fluctuates":* [Δp between cracker and regenerator fluctuating]*/fluctuating temperature in cracker/fluctuating temperature in regenerator/fluctuating level in the overflow well/shift in catalyst between cracker and regenerator/incorrect aeration of U-bend/incorrect aeration of standpipe/sensor control performance for air system unsatisfactory/moisture in aeration medium/unsteady control of air/U-bend vibration/coarse particles/hole in the overflow well/sticky stack slide valves/sensor control performance for stack slide valve unsatisfactory/[surging of the catalyst bed]*. "*Catalyst becomes lighter in regenerator gradually":* [afterburn in regenerator]*. *"Catalyst in fractionator bottoms"*: [poor separation in cyclone]*/velocity through reactor too high/faulty cyclone design. *"Catalyst has salt and pepper appearance after regeneration":* air grid deficiency/[failure of internal seals

in regenerator]*. *"Reduced rates of spent catalyst withdrawal":* [poor separation in cyclone in regenerator]*.

"Temperature difference between bed and cyclone inlet in regenerator": [failure of internal seals in regenerator]*/[afterburn in regenerator]* and [inadequate regeneration]*. *"Temperatures of bed and cyclone are uneven in the regenerator":* hole in the overflow well/[plugged grid holes]*/foreign debris entering with the fresh catalyst/faulty grid design. *"Temperature on regenerator shell or U-bend high":* damaged refractory. *"Temperature increase in the dilute phase relative to the dense phase":* [afterburn in regenerator]*. *"Temperature of the regenerator cannot be lowered":* [low catalyst circulation rate]*. *"Temperatures of regenerator too hot $> 750°C$ ":* excessive heat release.

"Temperature in dilute phase decreases relative to temperature of the dense bed in the regenerator": [regenerator doesn't remove all carbon from the catalyst]*. *"Feed preheat requirements $>$ usual":* [low catalyst circulation rate]*. *"Unexplained increase in coke":* [poor catalyst stripping]*. *"High bottom sediment and water levels in the slurry oil product":* [poor separation in cyclone in the cracker]*. *"Higher H/C ratio":* [poor catalyst stripping]*. *"Excess oxygen in regenerator high"*: [afterburn in regenerator]*/[plugged grid holes]*/[eroded grid holes]*/faulty grid design. *"Ratio of carbon dioxide to carbon monoxide is higher than usual":* [afterburn in regenerator]*. *"Uneven oxygen distribution in the dilute phase":* [failure of internal seals in regenerator]*. *"Unsteady heat balance":* [surging of the catalyst bed]*. *"Stripping steam flowrate $>$ expected":* flowmeter error/steam traps faulty/partially opened valves/missing restrictive orifice. *"Air flowrate $>$ expected":* flowmeter error/partially opened valves/missing restrictive orifice. *"Flow reversal with feed going incorrectly to the regenerator":* [Δp across the regenerator slide valve is $<$ design]*.

[Afterburn in regenerator]:* for **FCCU** [failure of internal seals in regenerator]*/too much excess air/oxygen recorder reading incorrect/meter error for feed and recycle flowmeters/meter error for cyclone flowmeter/[insufficient carbon production on catalyst during cracking]*/air flowrate to regenerator too high/[plugged grid holes]*/[eroded grid holes]*/faulty grid design causing localized air distribution problem.

[Coking in overhead lines]:* insulation missing or damaged on transfer line/extremely cold/increase in heavies and condensibles in reactor products.

[Control air flowrate too low]:* controller for air faulty or poorly tuned.

[Failure in regenerator plenum]:* faulty cyclone design/catalyst feed too high/regenerator velocity too high/faulty spray nozzles causing impingement of plenum sprays/temperatures too high causing failure in plenum.

[Feed contaminated with metals]:* abnormal operation in the upstream atmospheric and vacuum units.

[Feed contaminated with heavy hydrocarbons]:* leak in heat exchangers/partly open valves. *[Feed contaminated with light hydrocarbons]*:* leak in heat exchangers/partly open valves.

[Feed contaminated with sodium]:* seawater leak in upstream equipment/treated boiler feedwater leaks into feed/upset in upstream caustic unit.

[Feed contaminated with water]:* water in feed tanks/leaks from steam-out connections/steam leaks in tank heaters/water not cleaned out of the lines at startup/moist air not removed from lines at startup.
[Higher reactor velocities]:* [feed contaminated with metals]*.
[Higher regenerator holdup]:* hole in the overflow well.
*[Increased air requirements in regenerator for the same conversion in the cracker]**: [feed contaminated with heavy hydrocarbons]*/[inadequate regeneration]*/[coke on catalyst > usual].
[Insufficient coke production on catalyst during cracking]:* cracking operation intensity is lower than usual/higher quality of feed to the cracker than usual for **FCCU** fewer aromatics in feed.
[Low catalyst circulation rate]:* partial blockage of the U-bends/excessive stripping steam/insufficient aeration/[control air flowrate too low]*/differential pressure between cracker and regenerator set incorrectly or fluctuating.
[Poor catalyst stripping]:* insufficient steam stripping flowrate/faulty flow controller on steam flow/faulty design of stripper/reactor temperature too low/faulty contacting between steam and catalyst/circulation rate too high/coarse particles.
*[Δp across the regenerator slide valve is < design]**/sudden drop in regenerator pressure/regenerator slide valve sticking partly open/compressor surge (see Section 3.1).
[Regenerator doesn't remove all carbon from the catalyst]:* [excessive coke formed in cracker]*/low excess oxygen/oxygen sensor error/flowmeter error for air/[poor air distribution]*/flowmeter error for feed and recycle/air flowrate too small.
[Sodium on catalyst]:* carryover of sodium from upstream units (caustic)/treated boiler feedwater used in regenerator sprays/[feed contaminated with sodium]*.
[Uneven oxygen distribution in the regenerator]:* hole in the overflow well/[plugged grid holes]*/foreign debris entering with fresh catalyst/faulty grid design.
[Unstable catalyst bed]:* airflow too low/grid holes eroded/faulty grid design.
For calciner
"Excessive temperature rise in the freeboard": faulty solids introduction into calciner.
"Increased scale": faulty solids introduction into calciner.

6.31
TR: Tank Reactor

Minimum to no internal mixing. Could have external circulation.

- *Area of Application*

Phases: Gas–liquid–biosolid; liquid–biosolid.
Gas: use tank with external circulation for homogeneous, exothermic reactions with slow reaction rates.

Liquid plus biosolid:

Anaerobic digesters: (conventional first stage): batch microbiological treatment of municipal sludge; no mixing: use for < 50 m^3/s. For high strength waste water with COD > 4000 mg COD/L.

Anaerobic ponds: not common.

Facultative lagoons and ponds: use when the price of land is inconsequential. Low flows with COD about 500 mg COD/L and TSS about 500 mg TSS/L.

Aerobic ponds: use when the price of land is inconsequential. Low flows with COD about 500 mg COD/L and TSS about 500 mg TSS/L.

- *Guidelines*

Liquid plus biosolid:

Anaerobic digesters: (conventional first stage):Residence time 30–60 d (35 °C); organic loading = 4–9 mg VS/s m^3; Circular, diameter 6–35 m; depth = 6–14 m.

Anaerobic pond: residence time: 5 d; surface loading 600–3500 μg BOD$_5$/s m^2 with 150 μg BOD$_5$/s m^2 for winter conditions; volumetric loading 3–100 kg BOD$_5$/s m^3. pH 6.7–7.1; depth 1–2.5 m.

Facultative lagoon with surface aeration: residence time = 7–20 d, usually 4–8 d, and longer in cold temperatures; loading 40–130 μg BOD$_5$/s m^2; depth 2.4–4.8 m; surface aeration power to oxygenate.

Facultative pond: residence time: 7–50 d; surface loading 43–100 μg BOD$_5$/s m^2; (50–120 kg BOD$_5$/half day), depth 1–2.5 m; length/width = 3/1. No surface aeration; photosynthesis is source of oxygen; recycle ratio = 0.2–8, usually 4–8.

Aerobic pond: residence time: 2–6 d; surface loading 43–100 μg BOD$_5$/s m^2; (50–120 kg BOD$_5$/half day), depth 0.15–0.45 m; recirculation ratio = 0.2–2. 12 kW/m^3 Related topic aerobic lagoon, see Section 6.26.

6.32
Mix of CSTR, PFTR with Recycle

- *Application*

Phases: Gas–liquid and biosolid. Biosolid removes the soluble organics, COD or BOD$_5$, from waste water. Variety of reactor configurations. Related topics: trickling filter, Section 6.16, CSTR, Section 6.29, CSTR in series, Section 6.26. Slow reactions.

Conventional PFTR activated sludge: average strength domestic waste water with 500 mg COD/L, susceptible to shock loads, 85–95 % removal.

Conventional Backmix activated sludge: usual strength domestic waste water, resistant to shock loads, 85–95 % removal.

Step aeration, modified aeration PFTR activated sludge: higher strength domestic waste water, 85–95 % removal.

Contact stabilization: PFTR: OK for domestic waste water; unsuitable for most industrial waste water, flexible, 80–90 % removal.

Extended aeration Backmix activated sludge (oxidation ditch): average to low organic loadings (300–500 mg COD/L), small capacity $<$ 40 L/s; flexible, 75–95 % removal.
High rate aeration Backmix activated sludge: high strength domestic waste water, 75–90 % removal.

- *Guidelines*

Conventional PFTR activated sludge: mean cell residence time = 5–15 d; food/microorganism ratio = 2.3–4.6 mg BOD_5/s kg MLVSS; volumetric loading = 0.3–0.6 kg BOD_5/m^3; MLSS = 1.5–3 g/L; residence time = 4–8 h or 4–12 h for nitrification; recycle ratio = 0.25–0.5. Air requirements = 100 m^3/kg of input BOD_5.
Conventional Backmix activated sludge: mean cell residence time = 5–15 d; food/microorganism ratio = 2.3–7 mg BOD_5/s kg MLVSS; volumetric loading = 0.8–2 kg BOD_5/m^3; MLSS = 3–6 g/L; residence time = 3–5 h or 4–12 h for nitrification; recycle ratio = 0.25–1. Air requirements = 100 m^3/kg of input BOD_5.
Step aeration, modified aeration PFTR activated sludge: mean cell residence time = 5–15 d; food/microorganism ratio = 2.3–4.6 mg BOD_5/s kg MLVSS; volumetric loading = 0.6–1 kg BOD_5/m^3; MLSS = 2–3.5 g/L; residence time = 3–5 h; recycle ratio = 0.25–0.75. Air requirements = 100 m^3/kg of input BOD_5.
Contact stabilization: PFTR with recycle: mean cell residence time = 5–15 d; food/microorganism ratio = 2.3–7 mg BOD_5/s kg MLVSS; volumetric loading = 1–1.2 kg BOD_5/m^3; MLSS = 4–10 g/L; residence time = 4–10 h; recycle ratio = 0.25–1. Air requirements = 100 m^3/kg of input BOD_5.
Extended aeration activated sludge Backmix with recycle: mean cell residence time = 25–30 days; food/microorganism ratio = 0.6–1.8 mg BOD_5/s kg MLVSS; volumetric loading = 0.16–0.4 kg BOD_5/m^3; MLSS = 3–6 g/L; residence time = 18–36 h; recycle ratio = 0.75–1.5. Air requirements = 125 m^3/kg of input BOD_5.
High rate aeration activated sludge, Backmix with recycle: mean cell residence time = 5–10 d; food/microorganism ratio = 4.5–17 mg BOD_5/s kg MLVSS; volumetric loading = 1.6–16 kg BOD_5/m^3; MLSS = 4–10 g/L; residence time = 0.5–2 h; recycle ratio = 1–5. Air requirements = 25–100 m^3/kg of input BOD_5.

- *Trouble Shooting*

Conventional activated sludge: *"Increase in sludge volume index, 'bulking'":* faulty design preventing plug flow/insufficient oxygen/lack of nutrients/high density inerts in feed. *"Decrease in sludge volume index":* high concentration of dissolved organics in feed. *"Sludge rises":* excessive nitration. *"Frothing":* decrease in aeration suspended solids/increase in surfactants in feed/lipids in influent/aeration $>$ design/increase in temperature. *"Too much solids in effluent":* sludge blanket accumulation/return rate too low/too high overflow rate/bulking. *"Too much BOD_5 in effluent":* insufficient oxygen supply/too much solids in effluent/bulking. *"No nitrification":* low solids retention time/not enough oxygen/wrong pH/toxic substance in influent. *"Too much phosphors in effluent":* bulking/insufficient chemical addition.

6.33
STR: PFTR with Large Recycle

Reactor with external circulation, see also “loop reactor”, Sections 6.5 and 6.7.

- *Area of Application*

Phases: any. Recycle ratio = 20/1 gives backmix. Only exceed this recycle ratio if this is required for heat transfer. Low reaction rates; provides good mixing, cooling inside or outside the reactor. Large circulation rate prevents the buildup on walls as in slurry polymerization. Good backmixing and heat removal; suitable for slow reactions.

6.34
Reaction Injection Molding and Reactive Extrusion

- *Area of Application*

Phases: Liquid, liquid–liquid. Viscosities < 1000 mPa s; time for reaction to gel under adiabatic conditions > 0.1 s; small capacity: 0.150–2 kg/s.

- *Guidelines*

Viscosity 10–100 mPa s to prevent bubbles; $Re > 300$; fill time > 1 s and less than the reaction time to gel under adiabatic conditions. Mold temperature $< 100\,°C$ (or $< 200\,°C$ for high temperature operation). Mold temperature plus the adiabatic reaction exotherm must not exceed the degradation temperature. Reaction should be 95 % complete in < 3 min.

- *Good Practice*

Easy mold release.

- *Trouble Shooting*

“Inadequate mixing of liquid reactant with polymer”: liquid flowrate too high/screw channel under injection not full of polymer/faulty screw design. *“Residuals in final polymer $>$ design”:* vent temperature too low/screw speed too low/polymer feed rate too high/screw design does not provide enough shear/vent pressure too high. *“Polymer has crosslinked or degraded”:* screw rpm too high/degree of fill too low/feedrate too low/heat zone temperatures set too high/screw design fault giving excessive shear/[screw tip pressure too high]*.
“Extruder torque excessive”: throughput too high/screw speed too low/heat zone temperatures set too low/faulty screw design. *“Unable to melt material”:* throughput too high/screw speed too low/faulty screw design/material too slippery. *“Residence time too short”:* throughput too high/[degree of fill too high]*/faulty screw design. *“Residence time too long”:* throughput too low/[degree of fill too low]*/faulty screw design. *“Gels or crosslinked materials”:* localized initiator concentration too high/[melt temperature too high]*.

*[Degradation of melt in extruder]**: [RTD too wide]*/barrel temperature too high/ screw speed too high (causing overheating and shear damage)/oxygen present/ [oxidation]*/nitrogen purge ineffective/wrong stabilizer/wrong screw/flows not streamlined/stagnation areas present/extruder stopped when temperatures $> 200\,°C$/copolymer not purged with homopolymer before shutdown/[residence time too long]*.
[Degree of fill too high]:* feed rate too high/screw speed too slow.
*[Melt temperature too high]**: screw speed too high/exit barrel zone temperatures too high/screw tip pressure too high/degree of fill too low/[shear intensity too high]*/heat zone temperatures set too high/[screw tip pressure too high]*.
[RTD too narrow]:* [degree of fill too high]*
*[Screw tip pressure too high]**: screens plugged/die or adapter or breaker plates too restrictive and give too much Δp/[polymer viscosity too high]*/temperatures in die assembly too low/barrel temperature too low/screw speed too high/[shear intensity too low]*/lubricant needed/flow restriction/throughput too high/die land too short/cold start/[degradation of melt in extruder]*.
*[Shear intensity too low]**: screw speed too low/faulty screw design.

For other symptoms see Section 9.11.

6.35
Reactive Distillation, Extraction, Crystallization

Reactive distillation

Gas–liquid reaction with catalytic solid. Include the catalyst with structured packing in a distillation column. Related topic: distillation, Section 4.2.

- *Area of Application*

Phases: Gas–liquid, gas–liquid–catalytic solid.

Gas–liquid plus catalytic solid: Use when (i) the reaction occurs in the liquid phase (in the presence or not of homogeneous catalyst) or at the catalyst interface; (ii) temperatures and pressures for reaction are consistent with distillation conditions; (iii) reactions are reversible equilibrium; not irreversible; (iv) not for supercritical, gas phase reactions, or solid reactants or products, high temperatures or pressures. Minimizes catalyst poisoning, lower pressure than fixed bed. Used for hydrogenation reactions and MTBE and acrylamide production. For example, 90% conversion via reactive distillation contrasted with 70% conversion in fixed bed option.

Liquid with homogeneous catalyst: etherification, esterification

Liquid–liquid: HIGEE for fast, very fast and highly exothermic liquid–liquid reactions such as nitrations, sulfonations and polymerizations.

Equilibrium conversion $< 90\%$. Use a separate pre-reactor when the reaction rate at 80% conversion > 0.5 initial rate.

- *Guidelines*

Use concentration profiles developed from either equilibrium or nonequilibrium reaction-separation to identify the reactive zone. The reflux ratio for reactive distillation is greater than for distillation. Use 1.2–1.4 × minimum. Damkohler_{11} = 1–20 and usually 1–10.

- *Good Practice*

Use such multifunctional equipment to intensify (H). If the product has a lower boiling temperature than the reactant; feed to the reboiler and need only the rectification section of column. If the reactant has a lower boiling temperature than the product, feed at the top and need only the stripping section but consider withdrawal of product part way down the column.

Example: ethyl acetate [ex ethanol, acetic acid]; methylal [ex formaldehyde and methanol] methyl acetate [ex methanol, acetic acid] with sulfuric acid as catalyst; methyl-tert-butyl ether, MTBE [ex methanol, isobutene] IX resin catalyst.

Extractive fermentation:

combine solvent extraction with anaerobic fermentation for ethanol from grains or acetone-butanol from whey.

6.36
Membrane Reactors

- *Area of Application*

Phases: Gas–liquid, gas-liquid–catalytic solid, gas–liquid–biosolid. For equilibrium reactions where selective removal via membrane will shift equilibrium or use of membrane as catalyst. Use for organic reactions in inorganic membranes Pd, alumina ceramic or liquid membranes. Use where we can selectively shift the equilibrium by selectively removing products (dehydrogenations, of cyclohexane to benzene, of ethyl benzene to styrene); or by controlling the addition of reactants (oxidations, hydrogenations, oxidative dehydrogenation, of ethane to ethylene) or whenever trickle bed reactors, Section 6.17, are considered.

- *Guidelines*

Try to match permeation rate and reaction rate.

Gas–liquid–biosolid: Bubble-free membrane gassing: gas diffuses into the media without bubbles. Used for shear-sensitive animal cell cultures (ex insect cells) and for systems containing serum that are prone to foaming. Use 10 to 25 m^2/m^3 for volume < 150 L. Enzyme membrane reactor: Power: 10 kW/m^3; maximum volume 0.5 m^3. Membrane allows diffusion of gas into the liquid without having to use bubbles.

6.37
Liquid Piston Reactor

- *Area of Application*

Phases: Gas–liquid fast reaction when the upstream equipment operates under a vacuum. The liquid piston draws the vacuum with the vapor reacting with the liquid sealing the pump.

- *Guidelines*

The example is the reaction between ketene and acetic acid to make acetic anhydride.

References

Bartholomew, C.H., Farrauto R. J., *Fundamentals of Industrial Catalytic Processes*, 2nd edn., Wiley-Interscience, Hoboken, NJ, 2006.

Chauvel, A., Lefebrve, G., *Petrochemical Processes*, Vol. 1 and 2, Gulf Publishing, Houston, 1989.

Doraiswamy, L.K., *Organic Synthesis Engineering*, Oxford, London, 2001.

Horak, J., Pasek, J., *Design of Industrial Chemical Reactors from Laboratory Data*, Heyden, London, 1978.

Moulijn, J.A., Makee, M., van Diepen, A., *Chemical Process Technology*, John Wiley and Sons, Chichester, 2001.

Rase, H.F., *Chemical Reactor Design for Process Plants*, Vol. 1 and 2, John Wiley and Sons, New York, 1977.

Rase, H.F., *Fixed Bed Gaseous Reactor Design and Diagnosis*, Butterworths, Boston, 1990.

Trambouze, P., et al., *Chemical Reactors: Design, Engineering, Operation*, Editions Techniq, Paris, 1988.

7
Mixing

The type of mixing system used depends primarily on the phases present. For liquid systems, the mixing phenomena are different than those for gas–solid mixtures or for solids blending. The fundamentals for the mixing of liquids are described in Section 7.1, the mixing of immiscible liquids in Section 7.2, the mixing of liquid and solids in Section 7.3 and dry solids in Section 7.4.

Mixing of gas–liquid systems is discussed in bubble reactors, Section 6.13, aerated STR, Section 6.27 and static reactors, Section 6.6. Solids can be mixed by fluidization, but this is discussed under drying, Section 5.6 and fluidized reactors, Section 6.30. Thick pastes and foodstuffs are mixed in extruders for food stuffs and polymers and pugmills for clays, thick pastes and fertilizers, Section 9.11.

7.1
Liquids

(Thanks to Jesse Shen for his input to this and to Sections 7.2 and 7.3).

For the mechanical agitation of liquids (and liquid–gas, liquid–liquid and liquid–solid systems), the fundamental principles are as follows. The impeller should be designed to provide the proper combination of pumping and shearing of the fluids required by the specific application.

– *Pumping*: the liquid volume pumped by the impeller = $k_{pu}\ D_i^3\ N$ where k_{pu} is a constant dependent upon the impeller; D_i is the diameter of the impeller and N = rpm. For a three-bladed marine propeller whose pitch = D_i, $k_{pu} = 0.5$; many other types of impellers have smaller values, and therefore the marine propeller is one of the good axial flow impellers. In general, impellers giving axial flow are used in about 70 % of the mixing applications.

– *Shear*. The shear provided by the impeller is characterized by the shear number = $k_s\ (ND_i/D)^2\ (n_b\ B/D)\ (n\ D_i/H)^{0.6}$ where D is the tank diameter, n_b the number of baffles; B the effective baffle width; H the height of liquid in the tank; n the number of impellers on the drive shaft. The value of k_s depends on the type of impeller; for three-bladed marine = 1; for 6-bladed turbine = 5.5; for three-bladed swept-back impeller = 7.5; for 45° blades = 10. For polymer reactors, typical shear numbers are in the range 8000 to 10 000.

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– *Turnover rate:* pumping capacity/liquid volume. Sufficient turnover rate is an important consideration in mixing design, especially in those applications requiring axial flow.

– *Mixing time*: t_M is the time it takes for a mixer to create a homogeneous liquid. For turbines and marine propellers, the product of the rpm $\times\ t_M \approx$ constant and is in the range 20–100. The mixing time should be < 60 s and $Nt_M D_i^3 = 2$ to 3. For an STR the mixing times should be less than $0.1 \times$ residence time.

– *Power* required $P = k_{po}\varrho D_i^5 N^3$ where k_{po} is a constant dependent upon the impeller, but the value of k_{po} is relatively independent of the impeller *Re* for $Re > 10^3$ provided the effect of the Froude number is negligible.

– *rpm*. The impeller running speed is selected based on the impeller type, impeller diameter as well as the pumping capacity and turnover rate. Usually the rpm is < 400 rpm if the viscosity is > 200 mPa s or the volume is $> 7\ \mathrm{m}^3$. Use < 1150 rpm if the viscosity is > 50 mPa s or the volume is $> 2\ \mathrm{m}^3$. Use at least two impellers on the shaft if the viscosity is > 100 mPa s or the depth of liquid is > 4 impeller diameters, i.e. $H > 4D_i$.

– *Baffles*. Baffles help the impellers to form the mixing flow pattern. Baffles should be installed vertically along the wall side of the cylindrical tank. Normally, the baffle width is $0.1D$ and reduces as the fluid viscosities increase, for example, there may be no baffles needed for fluids with viscosities > 5000 mPa s. The number of the baffles is normally the same as the number of the impeller blades. The effective baffle width for a heat exchanger coil is $0.5 \times$ the projected area of the coil.

– *Impeller configuration*. There are many types of impeller configuration, the typical types of impellers include:

- three-bladed marine propeller (with square pitch) which supplies axial pumping (usually for viscosities < 2500 mPa s). The propeller agitator may be portable (for < 4 kW), side entry (for < 40 kW and tanks $H > 5$ m) or top entry. However, the diameter of the marine propeller is limited due to its weight and manufacturing cost.
- hydrofoil impellers which are a recent development to maximize axial flow capacity and are widely used in low viscosity media (< 1000 mPa s); typical applications include general blending and solids suspension.
- axial 45° four-bladed turbine which supplies a combination of pumping and shear.
- curved bladed turbine or backward bladed turbine which supplies shear and some pumping (for viscous media, as in polymer reactors, or liquids with fibers).
- radial four-bladed turbine which supplies radial pumping and shear (usually for viscosities $< 50\,000$ mPa s).
- flat-blade-disc turbine (Rushton Turbine) which supplies shear and gas holding for gas involved mixing applications.

- saw-disc turbine which supplies very high shear, mostly to be used to disperse very fine particles, typical applications are in the paint and ink industries.
- anchor which runs at a very low rpm to promote (jacket type) heat transfer in high viscosity fluids.
- double spiral with 2 helical flights which supply a downwards pushing movement in one flight and an upwards pulling movement in another flight to force the high viscosity fluids in blending.

– *Number of impellers on a single shaft:* Use at least two impellers on the shaft if the viscosity is > 100 mPa s or the depth of liquid is > 4 impeller diameters, i.e. $H > 4D_i$. Indeed, as the volume of the vessel increases, and the height of the liquid increases, impellers should be placed about every $4D_i$ vertical distance. The power required doubles if there are two impellers, triples if there are three and quadruples if there are four. For example, for a 100 m^3 fermenter requiring about 2–5.5 kW/m^3, the depth of the vessel is such that four impellers are needed on the single shaft; the total power requirement is about 250 kW. The impeller configuration is such that a single impeller would require about 63 kW.

Now that the fundamental principles have been reviewed, consider the application of mixing miscible liquids. Related topics: Stirred Tank Reactors, Sections 6.27–6.29. For the blending of miscible liquids the main characteristic is to create flow or pumping. However, there is a tradeoff between pumping and power.

- *Area of Application*

A wide range of applications: blending miscible liquids; heat transfer (Section 3.3) and chemical reactions (Sections 6.27–6.29).

Fluids viscosity, fluids ratio and volume to be mixed are the most significant factors.

Propellers: viscosity < 3000 mPa s; volume < 750 m^3.
Turbines-paddles: viscosity $< 50\,000$ mPa s; volume < 75 m^3.
Liquid jets: viscosity < 1000 mPa s; volume > 750 m^3.
Air agitation: viscosity < 1000 mPa s; volume > 750 m^3.
Anchors: viscosity $< 100\,000$ mPa s; $Re < 10\,000$; volume < 30 m^3.
Kneaders: viscosity 4000 to 1.5×10^6 mPa s; volume 3 to 75 m^3.
Roll mills: viscosity 10^3 to 200 000 mPa s; volume 60 to 450 m^3.

For viscosity $> 10^6$ consider **extruders**, **Banbury mixers** and **kneaders**.

Static mixers: viscosity ratio $< 100\,000{:}1$; continuous and constant flowrates; residence times < 30 min and flowrate ratio of $< 100{:}1$. Other related sections: size reduction, Sections 8.1 and 8.3; reactors, Section 6.10; heat transfer Section 3.5.

- *Guidelines*

For blending and heat transfer, identify the viscosity when turbulent mixing occurs. This usually occurs at an impeller Re of 200.

For heat transfer, usually for coils or jackets: select $D_i = 0.3D$ for low viscosity fluids and increase diameter with an increase in viscosity. Power is 0.4 to 2 kW/m^3.
Turbines, propellers and **paddles:** For blending miscible liquids, usually the tank height, H, = tank diameter D. If $H > 1.5D$, then use dual impellers; if $H < < D$, then place impeller $1.25D_i$ or $1/3H$ off the bottom and $2–3D_i$ below the liquid surface. For low viscosity fluids select diameter of impeller, $D_i = 0.25$ to $0.22D$; for higher viscosity, select $0.4–0.5D$. Power = 0.2–1.5 kW/m^3 for mixing liquids with impeller discharge rate > 20 × liquid flowrate into tank. For fluids of low viscosity and similar densities, use 12 to 15 turnovers to give uniform mix; for fluids with different viscosities, increase the turnovers to 30 to 40 to achieve uniformity. Heat transfer, 0.4–2 kW/m^3; mass transfer 2–4 kW/m^3. There is a trade-off between power and blend time: if 0.2 kW/m^3 blends the fluids in 4 h; then 0.4 kW/m^3 could achieve the same degree of blend in 2 h.
Turbines, propellers and **paddles:** Power = 1–4 kW/m^3 for mass transfer.
Air agitation: diffused air: 0.3 to 0.5 Ndm^3/s m^3. 1.5 to 6 dm^3/s m of linear distance along the basin. Diffusers 15 to 30 dm^3 air/s m^2 diffuser area with a pressure loss across the diffuser of 1.3 kPa. For 45 min detention time, 0.6 to 1 dm^3/L. See related topic: flocculation, Section 9.3. Air agitation is also used in Pachuca leachers.
Anchor: Power = 4–9 kW/m^3.
Static mixers: for viscosity ratio < 100:1 and $Re > 10\,000$, use turbulent vortex element; for viscosity ratio > 100:1 and $Re < 10\,000$ use helical elements. For pipe diameter < 0.3 m, element is 1.5 × pipe diameter; for pipe diameter > 0.3 m; element = pipe diameter. For $Re < 10$ use 18 elements with the number of elements reducing to 2 as Reynolds no. increases to > 5000.
Annular sparger in pipe: annular sparger blends liquid of equal viscosity and density in 50 pipe diameters; central injection blends liquid of equal viscosity and density in 80 pipe diameters; in mixing tee, after 10 pipe diameters. For viscosity differences < 10:1 inject the viscous liquid into the thin liquid.

- *Good Practice*

Prefer static mixers to intensify (H). For systems where the viscosity increases with time (e.g. polymer reactors) prefer turbines to propellers because turbines are power self-limiting. Check shaft wobble to ensure that impeller will not hit vessel walls if turned on in an empty tank. Consider a foot bearing.

- *Trouble Shooting*

Propeller/impeller mixers:
"Shaft wobble/vibration": impeller speed too close to the first critical speed/shaft runout at the impeller and impeller eccentricity too large/insufficient support.
"Excessive gear-reducer maintenance": excessive load/high shock loads/excessive shaft bending/excessive temperature of gearbox lubricant/incorrect lube oil selection and oil changing.
"Excessive stuffing box packing wear": insufficient lubrication/excessive shaft wobble/shaft is out of round/improper packing installation and maintenance.

"Failure of the mechanical seal": dirty seal lubricant/not enough seal lubricant pressure/excessive shaft wobble.
"Nonuniformity of blend": insufficient turnover/not enough time/improper impeller selection/pumping capacity < design/volume > design/relative difference in viscosity increases or differs from design.
"Power trips": viscosity too high/impeller diameter too large/rotational speed too high.
"Entrained air": usually entrained air is only a problem when the viscosity is high (> 2000 to 3000 mPa s) because otherwise the bubbles will rise out of the liquid/[unwanted vortex]*.
"Insufficient heat transfer": improper impeller selection/fouled tubes/no baffling/tube bundles poorly located so as not to supply good baffling.
[Unwanted vortex]:* baffles not high enough (not above liquid level)/no baffles/poor design/radial turbine selected instead of axial flow impeller/not sufficient baffles/rpm too high/impeller diameter too small.

7.2
Liquid–liquid (Immiscible)

The main characteristics are that the agitators should provide shear (and some pumping) to create the dispersion. Related topics: solvent extraction, Section 4.10, size reduction Section 8.3 and reactors, Sections 6.13–6.20, 6.27–6.29, 6.5.

- *Area of Application*

Three general areas: (i) emulsions–dispersions (as in cosmetics and formulations) drop size < 10 μm (for related topic see Section 8.3); (ii) solvent extraction with drop sizes 1 to 3 mm (for related topic see Section 4.10) and (iii) liquid–liquid reactions, usually with intermediate drop sizes.
For emulsion–dispersions: with a mechanical agitator it is difficult to get an emulsion < 2 μm; need to use colloid mill or homogenizer (as described in Section 8.3). For emulsions it is possible for 10–30 μm with a mechanical agitator. In general, the phase ratio should differ by less than 1:5. Ratios of 1:10 and 1:50 with the small one as continuous phase are extremely difficult to work with.

Fluid viscosity, interfacial tension and volume to be mixed are the most significant factors.

Propellers: viscosity < 3000 mPa s; volume < 750 m^3.
Turbines-paddles viscosity < 300 000 mPa s; volume < 75 m^3.
Static mixers viscosity < 50 mPa s.
For surface area generated see Sections 1.6.2 and 8.3.

- *Guidelines*

For emulsion-dispersions: Impeller should be located just below the interface (or just above) provided it is in the continuous phase (locate about 1/5 to 1/10 of the impeller diameter from the interface). Use impeller that provides shear with some axial flow. For propellers and turbines: power: 1 to 4 kW/m^3 for emulsification and mass transfer.

For solvent extraction: want uniform and diameter that is a balance between surface area for mass transfer and settling velocity. Suitable drop size for dispersed phase is about 1 to 3 mm. The impeller should be selected for both pumping capacity and shear. If the impeller is primarily shear, then the drops close to the impeller will be very small and the drops far from the impeller will be very large. Also, sufficient pumping capacity is the key to maintaining phase ratio stability in a continuous operation. Propellers and turbines: power: 0.2 to 1.5 kW/m^3 for mixing immiscible liquids with values decreasing as the interfacial tension decreases and for heat transfer.

For reactors: propellers and turbines for STR reactors: in the kinetic regime: use tip speed 2.5–3.3 m/s and 0.1 kW/m^3; for reactions in the fast regime, tip speed 5–6 m/s and 2 kW/m^3

Static mixers: see Section 8.3.

- *Trouble Shooting*

Drop size too large": shear insufficient/rpm too low/faulty selection of impeller/power too low/baffles missing/surface wettability wrong for the dispersed phase/order of feeding phases into mixer wrong (discontinuous phase sent first)/phase ratio incorrect/impeller not in the continuous phase at startup/surface tension higher than expected.

"Mass transfer < design": mixing not uniform/impeller in the dispersed phase instead of the continuous phase/phase ratio not stable/residence time too short/[holdup too small]*/flowrate > design/wrong impeller/[drop too large]*.

[Drop too large]:* rpm too small/surface tension larger than expected.

[Holdup too small]:* phase flowrate uneven/mixing in the wrong phase/impeller not enough pumping capacity/wrong impeller (designed for shear and not for flow).

*[Impeller not in the continuous phase]**: phase ratio differs from design/faulty design/wrong direction of mass transfer.

7.3
Liquid–Solid

For liquid–solid systems, mixing can be used for six general applications: solids suspension, solids dispersion, solids dissolving, solids flocculating, solids forming (as in crystallization) and solids reacting. The latter two are discussed elsewhere in crystallizers, Section 4.6 and reactors, Sections 6.27–6.29. Liquids and solids are also mixed in liquid fluidized beds; details are given in the specific applications of liquid fluidized beds: reactors, Section 6.30; liquid adsorption, Section 4.12, ion exchange, Section 4.13 and backwash fixed bed operations such as deep bed filters, Section 5.14, liquid adsorbers, Section 4.12 and ion exchangers, Section 4.13.

Sections 7.3.1 to 7.3.4 consider solids suspension, solids dispersion, solids dissolving, and solids flocculating respectively. General issues related to mixing using a fluidized bed are given in Section 7.3.5.

7.3.1
Solids Suspension

- *Areas of Application*

Solids suspension: three separate suspension conditions are employed in practice: (i) to create a uniform suspension (as might be needed in mineral leaching); (ii) to have all solids off the bottom but the concentration of suspended solids is not uniform; all solids in motion in liquid; (iii) particles on the bottom but the particles are kept moving along the bottom.

(i) **Uniform concentration:** usually in the mineral processing industry, leaching; solids concentration by weight 30 to 60 %, solids and particle size < 70 μm; see immersion leach, Section 5.15. Also for slurry drawoff by overflow or > 80 % of the height, solids concentration for slurry can be up to 65 to 70 % by weight.

(ii) **All particles completely off bottom:** usually for dissolving solids; uniformity in 1/3 of the fluid batch height; suitable for slurry drawoff at low exit nozzles.

(iii) **Particles move along bottom;** minimal suspension required.

- *Guidelines*

The key design is the relationship between the vertical flow velocity and the settling velocity of the particles. In general, baffle 4 @ 90°; off-the-wall distance = 0.015 × tank diameter or about 50 to 100 mm. to allow fluid circulation between the baffle and the wall. For low viscosity < 500 mPa s the baffle width = 0.10–0.11 tank diameter; for more viscous fluids, baffle width = 0.08–0.09 tank diameter. The baffle should be from the bottom up to or slightly above, the liquid surface.

1. **Uniform concentration:** design with the vertical flow velocity 10 × the particle settling velocity. Vertical flow velocity of a circulating axial flow pattern can be evaluated by the impeller's pumping capacity plus its induced flow (adjacent to impeller) divided by its cross sectional area for flow in one direction; use the same amount of total flow divided by the rest of the cross sectional area inside the tank for flow in the other direction, then, take the smaller velocity to compare with the largest particle settling velocity.

For minerals processing, usually the application is on a relatively large scale with tank diameters being 5 to 10 m; height 10 to 15 m and volume several hundreds m^3. The impeller diameter is not chosen based on a % of the tank diameter; but rather is selected on its pumping capacity. Use multiple impellers per shaft with the lowest one being 0.5 impeller diameter off the bottom, next one up 1 to 2 impeller diameters and the top one at least 0.5 impeller diameter below the liquid surface. The multiple impellers are to maintain the flow pattern. Usually the fluid flow is downward in the center. For very large tanks, the rpm is of the order of 16 to 20 rpm.

The properties of solids that need to be known include the solids concentration, the particle size distribution, settling velocity (free settling or hindered settling), and the slurry rheology.

2. **All particles off the bottom:** design with vertical flow velocity 2 to 3 × the settling velocity.

In mixing process design for solid suspension, normally, once the proper type of impeller is selected, the major job is to tradeoff the impeller diameter with rpm to get desire vertical flow velocity.

3. **Particles move along the bottom:** design for vertical flow velocity = settling velocity. Add rake to move the solids to a central exit. Power =1 kW at a cross sectional area, 35 m^2 with $n = 0.44$, for range 2–400 m^2. Power = 1 $(area/35)^{0.44}$.

- *Good Practice*

Startup may be tricky; liquid should be fed first, once the lower impeller is immersed, turn the motor couplings by hand to check that the impeller can turn completely around once unimpeded. If there is no obstacle, turn on the motor to start the mixing and start to feed solids with liquid. Try not to have a bottom bearing, but could use a bottom limit ring.

Restart: if accidentally there is a power outage and then we want to restart, some of the issues are: if the particles settled, are they densely packed or loose packed? How long does it take to settle? For most slurries, the restart procedure outlined above can be used if the restart can be done within 1~2 h. However, if longer and if the particles pack densely, then water or liquid injection near the lower impeller is needed to loosen the solids. From the solids concentration one can estimate how many impellers are immersed in the bed of particles. Perhaps use a two-speed motor or variable speed driver so that we can start at a lower rpm if the particles are loosely packed or only lower impellers are sitting in the bed of particles.

- *Trouble Shooting*

"Particles not suspended": power too small/wrong impeller/solids differ from design/concentration > design/not enough startup power/vertical flow velocity < settling velocity/temperature too cold/impeller eroded or missing, rpm wrong direction/impeller pitch wrong with successive impellers having contradictory pitches.

"Vortex happens at baffle": no gap between the baffle and wall or incorrect gap/diameter of impeller too large.

"Solids floating on the surface": particles not wetted/particles density close to density of liquid/small particle diameter/no vortex present/impeller supplies radial flow instead of axial flow.

"Power overload": solids concentration > expected/solids denser than expected/rpm > design/improper mechanical lubrication and maintenance.

7.3.2
Solids Dispersion

- *Areas of Application*

Creation of dispersions, slurries, pastes and compounds. For concentrations of solids in liquid $< 50\,\%$ see Section 7.3.1 on solids suspension to achieve a uniform concentration. For more concentrated solids and more viscous liquids, see Solids, Section 7.4 where pastes, melts, plastics and extrusion compounding are discussed.

- *Guidelines*

For blending powders into liquids, the wettability of the powder is important. Consider using a propeller with a vortex if some powders are floating on the surface. Size based on principles outlined in Section 7.3.1. For example, provide an additional pitched-bladed turbine a distance of $0.5 D_i$ below the liquid surface and reduce the baffle height from the top portion of the fluid to create a vortex (provided the vortex does not reach the eye of an impeller and then disperse air into the fluid). If clumps formed, use a pitched-bladed turbine which provides a combination of pumping and shear to break clumps quickly and to supply good blending so as to keep dispersion uniformity.

- *Trouble Shooting*

"Solids floating on the surface": particles not wetted/particles density close to density of liquid/small particle diameter/no vortex present/not proper baffles/impeller supplies radial flow instead of axial flow.

7.3.3
Solids Dissolving

- *Area of Application*

For readily soluble solids, use the principles of solids suspension, in Section 7.3.1, where flow and shear are supplied by the impeller to provide the mass transfer. However, select for flow because the resistance to mass transfer is usually low.

A unique challenge is polymer powder to be dissolved in a solvent.

- *Guidelines*

For dissolving polymer in solvent, the major problem is the small clumps of polymer formed in the viscous fluid. These clumps are difficult to break up. We need sufficient shear combined with axial flow in order to break the polymer quickly and immediately spread the polymer into the liquid for subsequent dissolution. Leave a small gap between the baffle and the tank wall in order to avoid the dead corner of undissolved polymer. If multiple impellers are used, then to save on power consumption, the bottom impeller might supply axial flow plus shear (as an open turbine) with the impeller above supplying axial flow. The Power number for the open turbine might be, for example, 1.2, whereas for axial flow the Power number value might be about 0.3.

- *Trouble Shooting*

"After a batch, lots of polymer encrusted on the bottom and on the shaft": insufficient shear/poor operating sequence/incorrect impeller arrangement with axial above axial-shear/impeller too large.
"Analysis of the liquid shows undissolved polymer": polymer added to the tank before the solvent/insufficient solvent added before starting.

7.3.4
Solids Flocculating

- *Area of Application:*

Paddle reel/stator-rotor: gentle mechanical mixing for coagulation, viscosity < 20 mPa s, volumes large. Size increase for particles, with details in Section 9.3.

- *Guidelines*

Gentle mechanical mixing, such as paddle reel or stator-rotor for flocculation, 0.035 to 0.04 tapering to 0.001 to 0.009 kW/m^3.

7.3.5
Liquid Fluidized Bed

In general particle diameter 0.5–5 mm with density and diameter of the particle dependent on the application. The superficial liquid velocity to fluidize the bed depends on both the diameter and the density difference between the liquid and the particle. Usually the operation is particulate fluidization.

Particle diameter 0.2–1 mm reactors; superficial liquid velocity 2–200 mm/s.
Fluidized adsorption: bed expands 20–30 %; superficial liquid velocity for usual carbon adsorbent = 8–14 mm/s.
Fluidized ion exchange: bed expands 50–200 %; superficial liquid velocity for usual ion exchange resin = 40 mm/s.
Backwash operations: fixed bed adsorption: superficial liquid velocity = 8–14 mm/s; fixed bed ion exchange: superficial backwash velocity = 3 mm/s.

7.4
Dry Solids

Use the Johanson indices to characterize dry particles: (details in Section 1.6.4; see also related topics: bins, Section 2.6, storage bins, Section 10.3).

Free flowing particles: **AI** < 0.06 m; **RI** < 0.3 m.

Moderately free flowing: **AI** < 0.18 m and mixtures of particles whose angle of repose or **RAS** differ by $> 4°$.

Moderately cohesive: 0.15 m $<$ **AI** < 0.3 m; **RI** < 1 m; **FRI** > 0.225 kg/s and mixtures of particles whose angle of repose or **RAS** differ by $< 3°$.

- *Areas of Application*

For free flowing particles that do not segregate, use mixers where the outside shell moves (cone, double cone, zig-zag).

For pastes, plastics, foodstuffs, ceramic pastes and powders that tend to segregate, use mixers with the outside shell fixed (ribbon, edge mill, double arm, Banbury, extruder).

For extrusion compounding, if the components have different densities (e.g. polymer versus fillers) or different shapes (pellets versus regrind flakes) then prefer to use the extruder for mixing. That is, operate the extruder with starved feeding conditions with the components metered separately into the extruder, see Section 9.11. On the other hand, for the blending of polymer feedstock for extrusion, if the components have very similar properties, then use tumble, rotating drum or ribbon blenders or rotor-stator blenders of the feed upstream of the extruder and use flood feeding of the mixture to the extruder.

More specifically:

Air pulse: OK for free flowing and wide range in particle size; i.e. one size > 3 times the other. Use when have fines with **FRI** < 2.2 kg/s and other components that have about the same size or are in same **FRI** range. OK for moderately free flowing dry solids.

Double cone: (tumble, V-mix; moving shell) limited to moderately cohesive solids that do not have sifting or repose-angle demixing.

Screw mixer: (rotating screw aligned along the inside of a cone hopper. Lifts solids from the bottom to the top. Progresses around the periphery of the cone.) Most effective when solids move along the conical hopper walls. Use for: moderately cohesive fines; different types of particles that have **RAS** differences $< 3°$; and usually require moderate amounts of liquid addition. Not for moderately free flowing.

Ribbon: For moderately cohesive components with $1 <$ **RI** < 3 m; **FRI** > 0.75 kg/s; **CI** $< 60°$.

Plough or paddle: (horizontal rotating shaft with fixed arms attached (plough or paddles): single shaft, double shaft.) Have sufficient liquid addition to produce **AI** > 0.18 m and **RI** > 1 m. Do not use single point feeding of the particles. Not for moderately free flowing.

Gravity flow: The solids must be free flowing. Large volumes to mix > 5.6 m^3.

Kneader double arm (Vertical shaft impeller mixer): Use to mix solids with liquids; blend solids that are nondegrading, fine, free flowing particles with melting temperature > temperature induced through mixing. **AI** > 0.18 m, **FRI** > 0.75 kg/s, **AAI** $< 10°$. Cannot be used for heat sensitive solids. Not for moderately free flowing. Rpm needs to be high enough to create a vortex. Power input/volume is large.

- *Guidelines*

Working capacity is 50 to 60 % of total internal volume. Mixing residence times are 3 to 10 min. Mixing time increases with (particle diameter)$^{0.5}$. Rpm 20 to 100 rpm.

Speed of rotation (rpm) × mixing time (min) = 300.
Double cone: 0.1 to 10 m^3 working capacity; 10 kW/m^3 reducing to 2 kW/m^3 as the working capacity increases.
Ribbon: 0.02 to 15 m^3 working capacity; 50 kW/m^3 reducing to 4 kW/m^3 as the working capacity increases. Typically 12 rpm.
Edge mill: 0.02 to 3 m^3 working capacity; 40 to 50 kW/m^3 and relatively independent of working volume.
Kneader, double arm: 0.05 to 3 m^3 working capacity; 100 kW/m^3 and relatively independent of working capacity.
Banbury: 0.05 to 0.6 m^3 working capacity; 2500 kW/m^3 and relatively independent of working capacity. Processing time = 3 min, rpm = 20–120.
Extruder compounding, pastes and foodstuffs: see Section 9.11.

- *Good Practice*

We can invest much effort into mixing solids, but we must prevent demixing after the blends are mixed. The four mechanisms of demixing are (i) sifting, (ii) angle of repose, (iii) fluidization and (iv) air-current. Here are the details: (i) Demixing via sifting: occurs if the particles are free flowing with mix of particle size with one size $>$ 3 × the diameter of the other. (ii) Demixing via angle of repose: this occurs with moderately free-flowing particles (**AI** $<$ 0.18 m) with different angles of repose or two different **RAS**. For particles characterized in this way, the only blender that seems to prevent demixing is the air pulse blender. (iii) Demixing by fluidization: tends to occur if the blend contains $>$ 20 % fluidizing fines characterized by **AI** $<$ 0.18 m, **RI** $<$ 1.5 m, **FRI** $<$ 0.76 kg/s plus coarser material with **AI** $<$ 0.012 m, **RI** $<$ 0.6 m and **FRI** $>$ 7.6 kg/s. This type of demixing tends to occur if the action of the mixer induces air. (iv) Demixing by air-current: air carries superfine, easy-flow, nonagglomerating particles into voids. This is a problem if **AI**$<$ 0.18 m, **RI** $<$ 1.5 m, **FRI** $<$ 0.4 kg/s. Again try to avoid mixers whose action induces air.

- *Trouble Shooting*

For polymer blenders of feedstock for extruder:
"Material does not flow": bridging/see also hoppers, Section 2.6.
"Components do not feed": jammed valve or auger/solids blockage or bridging/power fault in feeder. *"Inconsistent flowrate":* bridge or block in blender/jammed discharge mechanism/inconsistent feedrates to blender.
"Wrong blend compositions": calibration error in feeder.

8
Size Reduction

In this Chapter we consider options for creating drops and bubbles. Bubble formation is discussed in the section on bubble reactors, Section 6.13. Here the focus is on stable foams, Section 8.1. Although spray contactors have been described in other sections, here the focus is on the creation of the spray itself, Section 8.2. For liquid–liquid systems, the generation of dispersions of drops was summarized in the section on separating liquid–liquid systems, Section 5.3. Here the focus is on creating smaller size drops – emulsions, Section 8.3. Cell disintegration is featured in Section 8.4. The size reduction of solids by crushing and grinding is discussed in Section 8.5. Although two other “size reduction” options are (i) modifying the shape via extruders, pug mills and molding machines and (ii) modifying a liquid into a solid via prilling and flaking, these topics are discussed in detail in Chapter 9.

8.1
Gas in Liquid (Foams)

Gases are dispersed in liquids for reactions, absorptions, and a variety of separations via gas–liquid contactors. These aspects have been presented in detail elsewhere. Methods of creating bubbles have been described in reactors, Sections 6.13 and 6.27. Such systems are characterized in Section 1.6.1; with the flow characteristics summarized in Section 2.4. However, gases are also dispersed in liquids to create foams. Foams are used as foodstuffs, for foamed plastics, fire extinguishers, foam separations, Section 4.14 and mineral flotation, Section 5.19. Bubbles are used in dissolved air flotations but for DAF, Section 5.16, the bubbles nucleate on the particles present in the liquid.

- *Area of Application*

Creating a foam.

- *Guidelines*

Gas–liquid foams are stabilized by having a high disjoining pressure, by flooding the lamella with micelles or charged nonparticles. A high disjoining pressure

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arises because the GL surfaces contain ionized surfactants (while the bulk liquid in the thin lamella has a low concentration of electrolyte) or contain bulky polymeric species. Alternatively, flooding the thin lamella film with micelles or with uniform 150 nm diameter highly-charged latex spheres produces structured layers in the lamella that produce a stable foam.

8.2
Liquid in Gas (Sprays)

Spray scrubbers, absorbers and reactors have been discussed elsewhere. Here the focus is on the actual generation of the spray.

- *Area of Application*

Pressure nozzle: spray diameter 70 to 1000 μm; capacity 0.03 to 0.3 L/s; low viscosity and clean fluids.
Spinning disc: spray diameter 50 to 250 μm; capacity 0.0015 to 0.4 L/s; for usual fluids and for viscous fluid or for fluid containing solids.
Twin fluid: spray diameter 2 to 80 μm; capacity 0.03 L/s; increasing the ratio of atomizing fluid to liquid from 1 to 10 decreases the spray diameter by a factor of 10.
Rayleigh breakup to produce uniform drops of diameter 1.8 × diameter of orifice. Related topic: prilling, Section 9.12.
Surface aerators: for activated sludge oxidation (instead of diffused air aeration, Section 6.13).
Brush aerators: for oxidation ditches.
Static mixers: spray flow.

- *Guidelines*

Pressure nozzle: pressure 0.45 to 14 MPa; increasing the pressure increases the capacity.
Spinning disc: increasing the capacity increases the drop size.
Twin fluid: high energy input.
Surface aeration: 0.01–0.025 kW/m^3 or 0.3–1.2 kg O_2/MJ.
Brush aeration: 0.015–0.018 kW/m^3 or 0.6–0.8 kg O_2/MJ.
Static mixers: spray flow: gas superficial velocity 3–25 m/s; liquid superficial velocity 0–0.6 m/s. Turbulent flow.

8.3
Liquid–Liquid

Liquid–liquid contacting for reactions, separations, mixing. See reactions, Section 6.27, separations, Section 4.10 and mixing, Section 7.2, for separate rules of thumb. General characteristics of these systems are given in Section 1.6.2.

- *Area of Application*

Sparger: see Sections 6.13 and 6.27.
Mechanical agitator in tank: drop diameter 4–5000 μm; capacity > 0.05 L/s; for viscosities $< 10^4$ mPa s.
Colloid mill: drop diameter 1–8 μm; capacity 0.01–3 L/s; for viscosities $< 10^4$ mPa s but usually > 1000 mPa s.
Homogenizer: drop diameter 0.1–2 μm; capacity 0.03–30 L/s; for viscosities $< 10^3$ mPa s but usually < 200 mPa s; decrease the drop diameter by increasing the exit pressure.
High shear disperser: for viscosities 10^3–5×10^6 mPa s.
Roller mills: for viscosities $> 10^3$ mPa s.
Static mixer: drop diameter 100–1000 μm (about 0.15 times drop diameter for fluid velocity in a pipe without the mixer); capacity 0.3–5 L/s. The densities and flowrates of the two phases should be about equal; viscosities < 50 mPa s. See also Section 6.6.
Ultrasonic: drop diameter 1 to 2 μm; capacity 1 L/s.
Pipeline mixers: narrow residence times and drop size distributions, low holdup.

- *Guidelines*:

Sparger: see Sections 6.13 and 6.27.
Mixer in tank: surface area 100–80 000 m^2/m^3 with area increasing with decreasing surface tension and increasing velocity. Power 3 kW/m^3.
Colloid mill: surface area 10 000–2 000 000 m^2/m^3 with areas increasing with decreasing drop diameter and increasing volume fraction of dispersed phase. Power 40 to 200 kW s/L.
Homogenizer: surface area 20 000–10 000 000 m^2/m^3 with areas increasing with decreasing drop diameter and increasing volume fraction of dispersed phase. Power 25 to 120 kW s/L; 5 kW/m^3 for low viscosity. Power increases as exit pressure increase from 3.5 to 55 MPa. At 55 MPa for 0.1 μm drops at 100 kW s/L; 35 MPa for 0.5 μm drops at 45 kW s/L.
Static mixer: surface area 100–20 000 m^2/m^3 depending on the drop diameter and the concentration of dispersed phase. Velocity 0.25–2.5 m/s. Turbulent flow. Δp is $100 \times \Delta p$ in pipe without mixer; L/D about 33; power 0.001 to 0.015 kW s/L.
Ultrasonics: 18–30 kHz for 1–2 μm diameter drops.
Pipeline mixers: 1.2 kW s/L. Upstream use at least 3 pipe diameters of straight pipe.

- *Trouble Shooting*

See Sections 6.29 and 7.2.

8.4
Cell Disintegration

- *Area of Application*

Chemical treatment via acids, bases, solvents or detergents.

Physical freeze–thaw or osmotic shock.

Digestion by lytic enzymes.

Mechanical homogenizer cell disintegration while in suspension in a liquid.

Wet milling.

Pressure extrusion.

Sonification.

- *Guidelines*

Homogenizer: first order process; $\ln (R_{\max}/(R_{\max} - R) \propto p^{2.9}$ where $R_{\max}$ = maximum amount of released protein/unit mass; R = amount of protein released/unit mass at time t; p = pressure.

Temperature increases 2.2–2.4 °C/10 MPa. The power required is 0.35 kW/10 MPa.

- *Good Practice*

Homogenizer: Temperature control is difficult. Usually operated at constant throughput.

8.5
Solids: Crushing and Grinding

Capacities are expressed for open-circuit operation. For closed circuit with the same size reduction ratio, power, reduce the capacity by a factor of 2. Rod mill product is usually larger diameter than from a ball mill. Selection depends on the size of feed, the reduction ratio, the target diameter, the capacity, and the hardness, toughness, fibrous, and sticky nature and whether wet grinding is OK. Ball and rod mills can be used for most hardnesses including fibrous, friability and stickiness. Use jaw crushers for hard materials but shift to cone crushers when hardness Mohs < 8 but not for sticky materials.

Size reduction is about 1 to 5 % efficient; most of the energy generates heat. Very ductile materials are difficult to break mechanically; use cold temperature to make brittle.

Impact mills give products with less area per unit mass than ball or rod mills.

- *Area of Application*

Jaw crusher: feed diameter 0.1 to 1.5 m; reduction ratio 5:1 to 10:1; capacity 1 to 300 kg/s; Mohs hardness < 9 [reduction by compression].

Gyratory crusher: feed diameter 0.75 to 1.5 m; reduction ratio 5:1 to 10:1, usually 8:1; capacity 140 to 1000 kg/s; Mohs hardness < 9. More suitable for slabby feeds than jaw crusher. [reduction by compression].

Roll crusher: feed diameter 1 cm; reduction ratio 5:1 to 10:1; capacity 0.3 to 20 kg/s; Mohs hardness < 7.5. Suitable for softer, friable and nonabrasive materials. Ok for wet and sticky materials.

Cone crusher and short head cone: feed diameter < 25 cm; reduction ratio 5:1 to 10:1 usually 7:1; capacity 5 to 300 kg/s; Mohs hardness < 8. Usually secondary or tertiary crusher.

Impact crusher: pulverizers, shredders or smooth roll: feed diameter 1 cm with a reduction ratio of 7:1 to 10:1; capacity 0.3 to 50 kg/s.

Mills, hammer, feed diameter 10 mm, reduction ratio 10:1 to 50:1, capacity 0.01 to 5 kg/s; Mohs hardness < 4.5. maximum fines; feed not hard nor abrasive.

Mills, ball and rod: feed diameter 0.5 mm with a reduction ratio of 10:1 to 50:1; Mohs hardness < 9.

Mills, autogenous, semi-autogenous; feed diameter 200 mm, reduction ratio 10:1 to 50:1; capacity 0.1 to 100 kg/s; Mohs hardness < 6.

Mills, fluid energy: feed diameter 50 μm; reduction ratio 10:1 to 50:1; capacity < 2 kg/s; Mohs hardness < 4.5.

Comminutor: to reduce the size of solid material in waste water.

- *Guidelines*

Two-stage grinding has lower capital cost but higher operating cost than single-stage primary grinding. Ball mills have lower capital costs but higher operating costs than pebble mills. Semi-autogenous usually have lower capital and operating costs than fully autogenous.

Breakage by compression the power needed increases with increase in the hardness of the solid being processed.

Breakage by tumbling, the power increases with increase in the reduction ratio and is relatively independent of the hardness.

Jaw crushers: power 0.5 to 5 MJ/Mg; rpm 300–100; Maximum capacity occurs under choke feed; minimum of fines. Breakup by compression, product diameter determined by the adjustment clearance between compressing plates.

Gyratory crusher: power 3 to 10 MJ/Mg; rpm 450–110; minimum of fines. Breakup by compression, product diameter determined by the adjustment clearance between compressing plates.

Cone crusher: selected as secondary and tertiary reducers; power 0.9 to 5 MJ/Mg; rpm 290–220. Breakup by compression, product diameter determined by the adjustment clearance between compressing plates.

Short head cone crusher: power 3 to 12 MJ/Mg. Breakup by compression, product diameter determined by the adjustment clearance between compressing plates. Often choke fed as tertiary crusher.

Roll crusher: power 3 to 15 MJ/Mg. Breakup by compression, product diameter determined by the space between the rolls. Speed determines the capacity.

Roller mill: 50 to 500 kPa. Breakup by compression, product diameter determined by the space between the rollers. Speed determines the capacity.
Shredders: power 25 to 250 MJ/Mg.
Hammer mill: power 2 to 80 MJ/Mg. Breakup by impact against a plate traveling at 20 to 60 m/s, product diameter determined by exit screen size.
Cage mill: Breakup by impact against a plate traveling at 20 to 30 m/s, product diameter determined by exit screen size. Handles amorphous materials.
Pin-disc mill: Breakup by impact against a plate traveling at 200 m/s, product diameter determined by feed flowrate and speed of the pins. Ideal for soft material.
Impact mill: Breakup by impact against a plate traveling at 50 to 110 m/s, product diameter determined by exit screen size.
Autogenous mill: length:diameter 0.2 to 0.5 with 0.33 usual. Breakup by impact among particles.
Rod mill: power 5 to 80 MJ/Mg; length:diameter 1.4:1 to 1.6:1 with length $<$ 6.8 m; 35 to 40 % v/v rod charge to give total charge of 45 % v/v. Breakup by variety of mechanisms with revolving media.
Ball mill: power 30 to 10 000 MJ/Mg; length:diameter 1:1 to 2:1; 50 % v/v charge of balls. **B**reakup by variety of mechanisms with revolving media, large balls give coarse particles, small balls give fine particles.
Fluid energy mill; about 6 to 9 kg air/kg of solid or 1 to 4 kg steam/kg solid. Breakup by impact with other particles traveling at 100 to 300 m/s, product size determined by the feedrate. Power 700 to 1000 MJ/Mg.
Comminutor: used for reducing the size of the particulates in waste water.

- *Good Practice*

For more brittle materials, consider an impact crusher provided very abrasive (such as silica) or sticky materials (such as clay) are not present.

For gyratory crushers, no feed control is needed.

Rod mills can have spout feeder with head $>$ 1.5 m above mill center line with the length of rods at least 15 cm shorter than the working length of the mill.

Ball mills usually have double scoop feeder especially with higher loadings, closed circuit operations with a rake or spiral classifier. Makeup balls can be fed directly in if a spout feeder is used but makeup balls fed into the scoop box cause jamming. Use a central makeup ball feed pipe.

Measure the experimental Work Index at or near the target product size.

9
Size Enlargement

This chapter considers equipment to coalesce drops in gas, Section 9.1; coalesce liquid drops in a liquid environment, Section 9.2, and create solid aggregates or flocs in a liquid environment, Section 9.3. Then we consider the creation of larger size particle clusters fluidization, Section 9.4; spherical agglomeration, Section 9.5; disc agglomeration, Section 9.6; drum granulation, Section 9.7; briquetting, Section 9.8; tabletting, Section 9.9, and pelleting, Section 9.10. The last three processes considered in this chapter focus on *change in shape* by extrusion, Section 9.11; flaking, Section 9.12; and coating, Section 9.13. Other options for increasing the size of particles (such as crystallization, Section 4.6, spray or flash drying, Section 5.6 and sintering/pelletizing, Section 6.22) are discussed elsewhere.

The fundamentals upon which most of these operations are based are surface phenomena. Surfaces are attracted to each other by van der Waals forces; surfaces are repelled by the electrochemical double layer or by steric hindrance. Surface energies, contact angles, and wetting are important.

9.1
Size Enlargement: Liquid–Gas: Demisters

- *Area of Application*

In general, liquid should not bind to the inserts or walls; they should flow as rivulets or drops along the surface of the insert.
Vane separators: droplet diameter > 20 μm; droplet concentration > 0.1 mg/m^3.
Mesh pads: droplet diameter droplet diameter 3–20 μm; droplet concentration 0.01–0.1 mg/m^3.
Fiber beds designed for impaction (usually cylindrical or “candles”): droplet diameter 0.2–3 μm; droplet concentration 0.001–0.01 mg/m^3.
Fiber beds designed for Brownian motion (usually cylindrical or “candles”): < 0.1 μm; droplet concentration $< 10^{-3}$ mg/m^3.

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- *Guidelines*

For all devices inlet gas flow rates 80 to 120 % of design.

Vane separators: collecting fiber > 300 μm; gas velocity 2.5 to 5 m/s; Δp 0.03–0.25 kPa.

Mesh pads: collecting fiber 100–300 μm; gas velocity 2 to 4 m/s with smaller values used as liquid loading increases; Δp 0.1–0.75 kPa. For the suction side of compressors, the density weighted velocity through the mist eliminator pad: $k = 0.106$ m/s for operating pressure 0.7 MPa and k decreases by 0.003 for each increase in pressure by 0.7 MPa. Wire mesh demister removes droplets down to 10 μm and Δp about 0.25 kPa.

Fiber beds/Impact: collecting fiber 10–40 μm; gas velocity 1.25 to 2.5 m/s; Δp 1–2.5 kPa.

Fiber beds/Brownian motion: collecting fiber 8–10 μm; gas velocity 0.05 to 0.25 m/s; Δp 1–4.5 kPa.

- *Good Practice*

Consider using mesh pads upstream of impact filter beds to reduce the load on the filter bed. Consider installing mesh pads vertically to facilitate drainage and minimize re-entrainment. For noncorrosive and nonfouling, consider installing vane separators downstream of mesh pads to collect larger drops sheared off from the mesh pad.

Cannot be used for up to 25 % turnup capacity; avoid the use of inertial devices for up to 25 % turndown capacity.

- *Trouble Shooting*

"Demisters ineffective": temperature too hot/fibers have the same charge as the droplets/wetting properties of fibers changed/fibers "weathered" and need to be replaced/flow rate too slow through fibers/wrong mix of fibers/prefiltering ineffective/[foaming]*/wrong design/re-entrainment.
[Foaming]:* see Section 1.12.

9.2
Size Enlargement: Liquid–Liquid: Coalescers

For typical drop sizes produced from different sources, see Section 5.3. Related topic: decanters, Section 5.3.1.

Fundamentals, assume that all surfaces have a surface charge cause by the preferential adsorption of the charge determining ions (usually called the potential determining ions, PDI). The PDI is usually hydrogen ions; change the pH and change the surface charge. This surface charge is small but for small drops and bubbles with large surface area/volume the charge is enough to control behavior.

The solid surface should be preferentially wet by the dispersed phase, and the drops and the surface should have opposite surface charges so that they will attract.

- *Area of Application*

Stacked trays or parallel plates: feed droplet diameter > 10 μm and usually in the range 40–1000 μm; concentration < 15 % v/v.
Packed bed: feed droplet diameter 1 to 10 mm.
Mesh, wire or wool: feed droplet diameter 50 to 500 μm. and interfacial tension > 20 mN/m.
Co-knits of wire plus polymer: feed droplet diameter 10–200 μm.
Glass mats or co-knits of wire plus fiberglas: feed drop diameter 1–25 μm.
Fibrous bed: droplet diameter < 20 μm; usually 1 to 9 μm; concentration < 1 % v/v.
Deep bed: droplet diameter < 1 μm. See Section 5.14.
Ultrafiltration: see Section 4.22.

- *Guidelines*

For direct interception, the diameter of the fiber is usually chosen to be approximately the diameter of the inlet drops. The exit drop is two to four times larger than the feed diameter. The thickness of the bed is about 5 cm. The cross section of the coalescer is selected to give an approach velocity of the total liquid stream of about 5 L/s m^2 although some authors recommend 10–50 L/s m^2
Stacked trays: 1 to 25 L/s per pack of trays on 2 cm spacing with 75 m^2 area per pack. Diameter of captured drop increases as the flow rate increases and the density difference and interfacial tension decrease.
Packed beds: at lower capacities the exit drop diameter proportional to void diameter in the packing.
Mesh: use mix of high and low energy materials in mesh about 100 to 500 μm; flood velocities for mixed high and low energy fiber mesh < 1.2 m/s; usual design velocity 10–50 L/s m^2 Pressure drop 6 to 140 kPa.
Mesh, wire or wool: usual design velocity 5.6–12.5 L/s m^2.
Co-knits of wire plus polymer: usual design velocity 5.6–12.5 L/s m^2.
Glass mats or co-knits of wire plus fiberglas: usual design velocity 5.6–12.5 L/s m^2.
Fibrous bed: select fiber diameter that is about the diameter of droplets, fibers about 10 to 40 μm; typical exit drop diameter 2 to 4 times the inlet diameter; flood velocities 1 cm/s; usually design for 0.5 cm/s or 5 L/s m^2 with velocity decreasing as surface tension decreases. Try for surface tension > 20 mN/m.

- *Good Practice*

Consider decreasing the temperature to decrease the solubility and increase the surface tension.

Adjust pH for water flowing through fibrous and mesh beds so that drop and fiber have opposite surface charge. Promote coalescence in solvent extraction systems by using surface tension positive configurations.

- *Trouble Shooting*

"Coalescer pads ineffective": temperature too hot/pH incorrect/fibers have the same charge as the droplets/surface tension negative system/wetting properties of fibers changed/fibers "weathered" and need to be replaced/flow rate too slow

through fibers/wrong mix of fibers/prefiltering ineffective/surface tension < 1 mN/m for fluoropolymer fibers or < 20 mN/m for usual fibers/wrong design/included in decanter but should be separate horizontal coalescer promoter unit/faulty design/[stable emulsion formed]*.
[Stable emulsion formed]:* see Section 1.12.

9.3
Size Enlargement: Solid in Liquid: Coagulation/Flocculation

Related topics: flocculants for thickening Section 5.10 and precipitation of proteins from solution, Section 4.7.

- *Area of Application*

Particle diameter < 1 μm; solids concentration < 0.1 %.

- *Guidelines*

Add coagulant: usually alum in the sweep floc concentration of 20 to 50 mg/L; adjust pH to 6 to 9.
Rapid mix: 45 s residence time with 1.5 kW/m^3 turbine agitation.
Basin: velocity gradient, G, at the inlet 150 to 200 s^{-1} reduced to 50 s^{-1} later in the basin. Usually 150, 110 and 70 1/s. Allow residence time for $Gt = 10^5$. For choice of mixer see Section 7.3.4.

- *Trouble Shooting*

Coagulation and flocculation in general:
"Supernatant not clear": [coagulation doesn't occur]*/flocculation doesn't occur]*/[floc doesn't settle out]*/[floc forms but breaks up]*/faulty design of overflow weirs/short circuiting.
[Coagulation doesn't occur]:* wrong dosage of coagulant-flocculant/wrong counter-ion/pH different from expectations/pH far from zpc/faulty mixing in the rapid mix/valence on the counterion too small/charge on the dispersed particles or drops reversed from expectations.
[Flocculation doesn't occur]:* faulty fluid dynamics into the basin/reel at wrong rpm/residence time too short/mixing not tapered/unexpected turbulence/too short a residence time between coagulant and subsequent flocculant dosage/wrong flocculant.
[Floc doesn't settle out]:* floc formed is too loose/see settler design Section 5.8.
[Floc forms but breaks up]:* local turbulence $>$ shear strength of floc.
For water treatment:
"Coagulation-flocculation ineffective, supernatant murky": pH > 10/wrong dosage of alum or coagulant/pH < 4/increase in concentration of particles in feed/rpm of reels in flocculation basin too slow/feed temperature < 12 °C/rpm of reels in flocculation basin too fast.

For latex:
"Exit crumb too small": brine concentration too high/temperature too low/power input too high/wrong pH.
"Excessive amount of fines in supernatant": brine concentration too high/wrong pH/temperature too low. *"Strength of the resulting crumb < specifications":* pH too high and brine concentration too high.

9.4
Size Enlargement: Solids: Fluidization

Related topic: dryers, Section 5.6 and reactors, Section 6.30.

- *Area of Application*

Product diameter: 0.6 to 2.5 mm; batch process.

For spouted bed with feed diameter > 1 mm gives product diameter of 3 to 3.5 mm.

- *Guidelines*

Fluidized bed: 30 to 50 min for batch of 200 to 700 kg. Shallow bed, 0.3–0.6 m deep; gas velocity 0.1–2.5 m/s or 3–10 × minimum fluidization velocity. Evaporation rates 0.005–1 kg/s. m^2 cross sectional area.

9.5
Size Enlargement: Solids: Spherical agglomeration

- *Area of Application*

Product diameter: 2–3 mm; batch. Tensile strength of agglomerate: 10 to 100 kPa.

- *Guidelines*

Power 10 to 40 kW/m^3. Mixing time 30–300 s.

9.6
Size Enlargement: Solids: Disc Agglomeration

- *Area of Application*

Product diameter: 10 mm, fertilizer: 1.5–3.5 mm; ore 10–25 mm. Capacity < 25 kg/s. Tensile strength of agglomerate: 10 to 200 kPa depending on the binder. Produces more nearly uniform granules than drum, Section 9.7.

- *Guidelines*

Rotational speed about 50 % critical speed or 30 rpm decreasing to 6 rpm as diameter increases. Disc area = 01. to 200 m^2. L: D = 0.1 to 0.22; angle of inclination with the horizontal 40–70°. Power = 7 to 9 kW s/kg or MJ/Mg.

- *Good Practice*

Control dust.

9.7
Size Enlargement: Solids: Drum Granulator

- *Area of Application*

Product diameter 2–5 mm; capacity 0.001 to 30 kg/s. Tensile strength of the agglomerate: 10 to 200 kPa, depending on the binder.

- *Guidelines*

Drum volume: 5 to 100 m^3. L: D = 2 to 4; angle of inclination with the horizontal 10°. For fertilizer: 5 to 7 kW s/kg or MJ/Mg. For iron ore: 2 kW s/kg. 10–20 rpm. Product diameter controlled by speed, residence time and binder.

- *Good Practice*

Need closed circuit operation to achieve uniformity in product size.

9.8
Size Enlargement: Solids: Briquetting

Use of pressure to create agglomerate.

- *Area of Application*

Product diameter 15 to 80 mm; capacity 1 to 30 kg/s. Crushing strength of agglomerate 1–10 MPa.

- *Guidelines*

Constant product volume; operating pressure < 50 MPa. Power 2 to 50 MJ/Mg.

9.9
Size Enlargement: Solids: Tabletting

Use of pressure to create agglomerate.

- *Area of Application*

Product diameter 15 to 100 mm; capacity 0.011 to 1.5 kg/s. Crushing strength of agglomerate: 1.5–10 MPa.

- *Guidelines*

Operate either as constant volume machine: mechanical tabletter with operating pressure < 50 MPa or as constant mechanical tensile strength (constant pressure) machine: hydraulic tabletter with operating pressure 150 to 250 MPa. Power: 50–60 MJ/Mg.

- *Trouble Shooting*

"Product tablet weight > design" : sample error/lab error/excessive fines.

9.10
Size Enlargement: Solids: Pelleting

Use of pressure to create agglomerate or extrude molten polymer and shear off pellets.

- *Area of Application*

Product diameter: 2 to 30 mm; capacity < 6 kg/s. Cylindrical shape product; used primarily for food stuffs. Feed is usually a viscous paste.

For polymer pellets: strand pelletizer is versatile but capacity is limited by the strand handling capacity. Usually < 200 strands per machine. Water ring pelletizer: not for water sensitive polymers or high melt flow polymers and tend to produce nonspherical pellets. Underwater pelletizer: good for PE and PP; produces spherical pellets; not for nylon, PET or melts that solidify rapidly.

- *Guidelines*

Power 18 to 70 MJ/Mg.

Water ring pelletizer: die-swell allowance is critical.

- *Trouble Shooting*

For **strand** pelletizer for polymer resin. *"Pellet diameter too small":* hole too small for the desired throughput/extruder output too low. *"Pellet diameter too large":* output too high/speed too low/feedroll speed too low/output too high for die-size. *"Pellet too short or too long":* mismatch ratio of feedroll speed versus rotor teeth speed. *"Strands dropping":* feedroll pressure too small/throughput too low/dieplate has too many holes. *"Pellet cuts are angled":* feed not perpendicular to strands/strands overlapping. *"Pellet oval shaped":* feedroll pressure too high/inadequate cooling before cutting. *"Pellets has tails":* incorrect clearance between rotor and cutters.

For **water ring** pelletizer for polymer resin: *"Pellet diameter too small":* hole too small for the desired throughput/throughput too large. *"Pellet diameter too large":* output too low. *"Pellet too short or too long":* mismatch throughput versus cutter speed. *"Blocked holes":* nonuniform pressure on the die face/throughput too low/die-plate has too many holes. *"Pellet oval shaped":* cutter speed too high/inadequate cooling. *"Pellet has tails":* incorrect clearance between die and cutters/worn cutter blades.

9.11
Solids: Modify Size and Shape: Extruders, Food Extruders, Pug Mills and Molding Machines

See related topics: dewatering press, Section 5.17, reactive extrusion, Section 6.34 and coating, Section 9.13.

- *Area of Application*

– For polymers

Batch:

Injection molding machine: Thermoplastics: commodity resins, polyolefins (LDPE, HDPE, PP), styrenics (PS, PMMA, polycarbonates, ABS, PET) and engineered resins for higher impact strength. It is useful to classify thermoplastic polymers according to viscosity, as was done in Section 1.2, item 12.

Continuous:

Extruder: thermoplastics. Extruders are polymer mixers or reactors that push molten polymer through a die. The die configuration is chosen to produce blown film, coatings, sheets, monofilaments, coatings for wire and cable, cast film or special shapes like siding, downspouts. Three general types: single screw, vented and twin screw.

Single screw preferred for materials not particularly heat sensitive, e.g. PVC. Relatively poor mixing; improve with static mixer inserts or mixing zone. **Twin** give better mixing at lower temperatures and pressures. **Two stage vented excels** in devolatization, controlling foam.

Pipe and tube: usually PE, PVC, ABS.

Blown film: LDPE, PP, HDPE: thickness 34 μm.

Coating: primarily LDPE.

Casting and sheets: Casting: PP: fine film: 10–50 μm; cast film: 100–400 μm; thermoformable sheet: 200–2500 μm. High impact PS. also HDPE, PVC, ABS. Sheet thickness $>$ 0.25 mm; film $<$ 0.25 mm. (although blown film $<$ 0.5 mm).

Coating wire and cable: Usually PE and PVC coating on wire.

Monofilaments: Used for either mono or coextrusion. PP and nylon and most thermoplastics.

Special shapes: for siding, facia, downspouts, eavestrough. ABS, HIPS, RPVC, LDPE, PP, nylon.
– For foodstuffs: extruders used for pasta and cereals; food cooker-extruder used for soup bases, puffed products, dry cereals, textured proteins and pet foods.
– For clay and ceramics: extruders or pug mills: clay. materials for bricks, tiles and ceramics.

- *Guidelines*

– For polymers
Batch: cycle: fill, cool, unload.
Injection molding machine: cycle: injection fill, 1/4 cycle or about 3 s; cooling time 3/4 cycles; cool such that a release in pressure does not cause distortion, 17–30 s; machine open close, 7 s. Feed temperature = heat distortion temperature + 55 °C; example temperature 200 °C; mold temperature for commodity resins = 25 °C. viscosity 0.1–100 kPa s; Injection pressure 100 MPa. clamping force 38 MN/m^2 of projected area surface part for polyolefins; 25–30 MN/m^2 for styrenics. Cooling time: for polyolefins, 1 s/0.1 mm wall thickness; for styrenics × 1.3–1.8 longer (F). Cooling time also dependent on type of machine, toggle takes longer than hydraulic takes longer than electric.

The processing temperature ranges are: nylon: 260 to 290 °C; acetal: 185 to 225 °C;

For low viscosity polymers; PA, PE, PP, PS: Acrylic 180 to 250 °C; polypropylene 200 to 300 °C; polystyrene: 180 to 260 °C; polyethylene (LD): 160 to 240 °C; (HD) 200 to 280 °C;

For mid viscosity polymers: ABS, CA, POM, SB: ABS 180 to 240 °C;

For high viscosity polymers: PC, PMMA, PPO, PVC: PC: 280 to 310 °C; PVC rigid: 160 to 180 °C;

Commodity resins, the cheaper resins, include PE, PP, ABS and PMMA. Engineering resins are more expensive and include PC, nylon, acetal and fiber-filled grades.
For the extruder: Barrel and screw design: compression ratio 2.5:1 with a length:diameter ratio of 20:1. Recommended screw speeds are 25 to 75 rpm and depend on the diameter. Avoid the use of high screw rpm because of possible overheating of the melt. N [rpm] = 1910 v/D [cm] where D = screw diameter. v = barrel velocity, m/s and use v = 1 m/s for LDPE, = 0.5 m/s for most polymers and = 0.2 m/s for FPVC.

Select a machine such that the shot size is between 30 to 80 % of machine capacity and for higher temperature resins 60 to 80 % of machine capacity. Try to keep the residence time as short as possible.

Residence time in the barrel = rated capacity of injection cylinder [cm^3] × density [g/cm^3] × cycle time [s]/shot mass [g]

Select pressure, depending on the thickness of the part, the length of flow and the viscosity of the melt.
Nozzle opening at least 4.75 mm and usually 7.9 mm and 0.8 mm smaller than the orifice dimension of the sprue bushing; land length < 4.75 mm and nozzle

bore > 12.7 mm. Avoid the use of an injection nozzle shut-off valve except for structural foams and gas-assist molding.

Avoid excessive back pressure. Usual back pressure is 350 to 700 kPa g line pressure.

Nonreturn or check valve should be sliding check ring type with flow through clearances at least 80 % of the flow area in the metering area of the screw: do not use ball-check type valve; replace the check ring if it has any chips, cracks or damage; use a check ring nonreturn valve that has deep, large radius flutes and has a flow area equal to the screws; prefer a free-flow valve.

Hot or cold *runner* systems can be used. For cold runners, the sprue should contain a cold-slug well to receive the cold melt emerging first from the nozzle of the extruder. The cold well is typically the largest diameter of the sprue with a depth of 1.5 times this diameter. Runner size 6.3 to 9.5 mm diameter .

Mold materials are usually P-20 with Rockwell hardness of 55 to 57 or aluminum.

Vents 0.05 to 0.07 mm diameter.

Gates should be > 1 mm. The gate land should be short as possible.

The flow path length varies from 40 to 800 mm; the wall thickness ranges from 0.5 to 3 mm with the possible flow path increasing as the wall thickness increases (for 0.5 mm thick walls the flow path ranges from 35 to 130 mm). The required specific cavity pressure varies from 18 MPa for low viscosity melts, thick walls to 200 MPa for high viscosity, thin walls.

Continuous:

Extruder: for processing polymers.

Scale up of extruders:

scaling laws for single screw extruders to give the same melt temperature:

D = diameter of extruder:

metering depth (h) $h_1/h_2 = (D_1/D_2)^{0.75}$

screw speed, N $N_1/N_2 = (D_1/D_2)^{-0.75}$

output, F $F_1/F_2 = (D_1/D_2)^2\ (L_2/L_1)^{0.5}$

power, P $P_1/P_2 = (D_1/D_2)^{2.5}\ (L_1/L_2)^{0.8}$

Torque, Md $Md_1/Md_2 = (D_1/D_2)^{2.75}$

Drive power capacity: kW s/g: rigid PVC, 1.3–2; plasticized PVC, PS, PMMA, 0.7–1.1; PET, HIPS, 0.5–0.8; ABS, PP, 0.8–1.2; LDPE, 0.7–1.1; HDPE, 0.9–1.4; nylon 6, LLDPE, 1.1–1.6; nylon 66, PC, 1–1.5.

Single screw: $L/D = 20$ to 35; the screw turns as if to unscrew itself backwards out of the barrel. Shear rate ≈100 1/s in the screw channels; between 100 and 1000 1/s in most die lips and > 1000 1/s in flight-to wall clearances. Volumetric pumps with feed rate determined by the bulk density of the feed. Recommended rpm given previously. Output [kg/h] = $1000\ (D/16)^{2.15}$.

Two stage vented extruders $L/D = 24$ to 28. Output = 0.8 × output single stage.

Twin screw extruder: $L/D = 12$ to 16; compounding capacity is proportional to screw speed; conveying capacity = ½ the volume contained in one turn of the screw per revolution.

The heat to melt the resin comes from feed preheating, barrel and die heaters; frictional heat. The frictional heat because of the rotation of the screw accounts for > 50 % of energy input. Barrel and die heaters: resistance heaters 5 to 6 W/cm^2 of inner barrel surface. Power to covey and heat: 0.4 to 1 kW s/g or 400–1800 kJ/kg depending on screw design and polymer processed.

Pipe and tube: PE: front barrel temperature, 160 °C, die temperature, 165 °C, pressure, 10 MPa; rigid PVC: front barrel temperature, 160 °C, die temperature, 170 °C, pressure, 17.5 MPa; ABS: front barrel temperature, 195 °C, die temperature, 200 °C, pressure, 17.5 MPa.

Blown film: draw velocity 0.35 m/s; draw ratio 4:1; extrude at 180 °C; mass flow 0.2 g/s. PE: front barrel temperature, 160 °C, die temperature, 165 °C, pressure, 10 MPa; rigid PVC: front barrel temperature, 160 °C, die temperature, 170 °C, pressure, 17.5 MPa; ABS: front barrel temperature, 195 °C, die temperature, 200 °C, pressure, 17.5 MPa.

Coating: air gap is more critical for LDPE than for copolymers. Extruder: compression ratio > 4:1 and long metering sections; use of static mixers as inserts in the downspout; keep temperature variation across the polymer fed to the die of < 5 °C. 180 m/s to 360 m/s. $L/D = 24$. with 0.4 to 0.7 g/s cm of die width. PE: front barrel temperature, 315 °C, die temperature, 325 °C, pressure, 7.5 MPa.

Cast film and sheet extrusion: sheet 0.6 m × 50 μm; extrude at 200 °C; drum diameter 0.45 m. Film velocity 1 m/s. Take-off of sheet 2 to 3 m/s increasing to 15 to 20 m/s as the thickness decreases. Higher extrusion temperature at the die gives a more permanent gloss. Surface finish is very dependent on roll temperature: rolls should be run as hot as possible and just below the sticking point. Cooling rate is very important especially for thicker sheets; surface cooled too fast causes wrinkles. Edge trim is cost control issue. **Film:** PE: front barrel temperature, 160 °C, die temperature, 165 °C, pressure, 10 MPa; rigid PVC: front barrel temperature, 160 °C, die temperature, 170 °C, pressure, 15 MPa; plasticized PVC: front barrel temperature, 170 °C, die temperature, 175 °C, pressure, 10 MPa. **Sheet:** PE: front barrel temperature, 205 °C, die temperature, 200 °C, pressure, 17.5 MPa; PS: front barrel temperature, 200 °C, die temperature, 210 °C, pressure, 7 MPa.

Coating wire and cable: ID of the tip for the wire must be closely matched to the diameter of the wire to prevent polymer back-flow, especially during start up. Usually keep the extruder speed constant and adjust the speed of the wire. Usually rate of cooling is the limitation. Air gap between the die and cooling trough = 0.1 to 0.45 m for PE so that it enters cooling water 60 to 80 C; increase to up to 1 m for polyolefins. Polysulphone, = 0.05 m. Rear of barrel is run hotter to reduce the load on the extruder drive. PE: front barrel temperature, 240 °C, die temperature, 240 °C, pressure, 20 MPa; plasticized PVC: front barrel temperature, 160 °C, die temperature, 170 °C, pressure, 10 MPa; nylon: front barrel temperature, 295 °C, die temperature, 300 °C, pressure, 6 MPa.

Monofilament: Extruder-melt pump-spinneret-quench-stretch-“heat-set”-wind. For Newtonian fluids the critical draw-down ratio is about 20 (take up velocity/die exit velocity). Extrusion speeds 1 to 8 m/s. Feed must be dry. 20 to 200 filaments per spinneret. Operating limit is linear speed filaments can be drawn.

Die holes 2 to 4 × target filament diameter depending on the polymer, PVC is 2. PP: front barrel temperature, 240 °C, die temperature, 250 °C; nylon: front barrel temperature, 290 °C, die temperature, 300 °C; PS: front barrel temperature, 205 °C, die temperature, 210 °C, pressure, 10 MPa.

Special shapes: Extruder-cooling-puller-cutoff; usually twin screw extruder (although single screw used in the past). For each resin the final die lip plate dimensions must be correct (length of die/wall thickness) and die land length dependent on type of polymer. PS: front barrel temperature, 200 °C, die temperature, 205 °C, pressure, 10 MPa, land length ratio 15–25; plasticized PVC: front barrel temperature, 165 °C, die temperature, 165 °C, pressure, 7.5 MPa, land length ratio 10–25; rigid PVC: front barrel temperature, 165 °C, die temperature, 170 °C, pressure, 17.5 MPa.

– For dewatering:

Extruders for dewatering: 1 to 4 kW s/g or 1000–4000 kJ/kg. Related to rotary press, Section 5.17.

– For foodstuffs:

Extruders for foodstuffs: rpm 30–40; shear 5–10 1/s; power 200 kJ/kg or 0.1 to 0.4 kW s/g with values increasing with shear. For pasta, cookies, pastries and dough: rpm 30; shear 5 1/s; power 200 kJ/kg or 0.2 kW s/g with values increasing with shear and maximum temperature 50 °C. For RTE cereals, rpm 40; shear 10 1/s; power 200 kJ/kg or 0.2 kW s/g and temperature < 80 °C.

Extruders and cookers: If the moisture content is < 20 %, high shear is used with the power usage typically 0.36 kW s/g. If the moisture content is > 28 %, low shear is used with the power < 0.075 kW s/g. For low shear cookers (for soup bases): rpm 60–200; shear 20–100 1/s; power 75–200 kJ/kg or 0.075–0.2 kW s/g and temperature < 150 °C; *L*:*D* typically 12:1. For intermediate shear cookers (puffed products, relatively dry materials 20 to 28 % moisture) rpm 300; shear 140 1/s; power 450 kJ/kg or 0.45 kW s/g and temperature < 200 °C; *L*:*D* typically 3:1. For high shear cookers (dry cereals, textured proteins, pet foods): rpm 350–500; shear 120–180 1/s; power 500 kJ/kg or 0.5 kW s/g and temperature < 180 °C; *L*:*D* typically 15 to 20:1.

– For clays and ceramics:

Pug mills for clays, thick pastes and fertilizers: 0.004 kW s/g or 3–12 kJ/kg.

For a combination pugmill plus extruder for clay: 0.012 kW s/g.

- *Good Practice*

Consider first injection molding machines, then extruders.

Injection molding machines: Resin should be dried < 0.02 %. Do not use resin that has been out of the dryer for > 20 min. Cold molds are difficult to fill and require higher injection pressures. Hot molds, generally, give better finish and less molded-in stress. Melt temperature is very sensitive to very small changes in rpm or back pressure despite sensor or controller set point. Measure with hand held pyrometer or laser sensor. Need slower fill rate for sprue-gated parts to prevent blush, splash or jetting. If the walls are > 5 mm, then slow fill helps reduce sinks and voids.

Back pressures of 0.35 to 0.7 MPa help ensure homogeneous melt and consistent shot size. As back pressure increases, melt temperature increases. Holding or pack pressures that are 0.4 to 0.8 of injection pressures are typical. To purge a machine, acrylic is recommended.

- *Trouble Shooting*

Injection molding: Basically the cause can be with the material, the machine, the operator, the operating conditions, the mold or the part design. To check on the material, try material from another supplier; to check the machine, use same material, conditions, mold on another machine; if the trouble is random, then it is probably the machine; try a different operator on the machine; trouble appears same location in the product, then flow conditions and look for problems from the front of the piston to the gate. The symptom–cause information is presented as issues related to appearance (color, surface finish and transparency), strength and shape defects and operation and symptoms.

- *Appearance*

Color, surface finish, transparency

– Color. *"Discoloration (typically appears before burn marks appear; location appears at the weld line or where air is trapped in the mold)"*: [contamination in heating cylinder]*/sensor error/control error/[degradation, mechanical]*/[degradation, thermal]*/[melt too hot]*/[melt not homogeneous]*/overall cycle too long/[contamination in hopper and feed zones]*/incorrect cooling of ram and feed zone/[venting in mold insufficient]*/[residence time too long]*/cooling time too short/dryer residence time too long/excessive clearance between screw and barrel/clamp pressure too high/injection forward time too long/gate too small/runner-sprue-nozzle too small. *"Black specks inside transparent product":* faulty cleanout of machine from previous molding operations/failure to purge when not running for extended times/nozzle too hot/barrel temperature in the feed area is too low combined with high screw speed or high back pressure/sensor error/sensor located too far from heater bands/hangup in nozzle tip/nozzle adapter and endcap. *"Brown streaks/burning"*: wet feed/[melt too hot]*/[shear heating in the nozzle]*/[degradation, mechanical]*/loose nozzle/wrong nozzle/dead spots in hot manifold/mold should be cold runner system/gate or runner too small/[contamination]*/injection speed too fast/booster time too long/injection pressure too high/mold design lacks vents at burn location/gate size too small or at wrong location/plunger has insufficient tolerance to allow air to escape back around the plunger/poor part design/[venting of mold insufficient]*/[residence time too long]*. *"Brown streaks at the weld lines or at the end of flow paths, black or charred marks"*: [air trapped in mold]*. *"Brown streaks at the same location"*: nozzle loose, wrong, too hot/[shear heating (at gate, runner, cavity restrictions)]*. *"Brown streaks dispersed throughout"*: material fault at the hopper: wet material. *"Weld burns":* [melt too hot]*/injection speed too fast/[mold too cold]*/injection hold time too long/injection pressure too high/faulty nozzle heating bands/[air trapped in mold]*.

– **Surface finish:** *"Sink marks" (difficult to remove by changing processing conditions):* [cooling insufficient before removal from mold]*/[short shot]*/[melt too hot, causing excessive shrinkage]*/[solidification at mold wall too slow]*/wrong location for gate/holding pressure too low/injection speed too fast/back pressure too high/gates too small/faulty runners/booster time too low/fault with nozzle, sprue or runners/[mold temperature nonuniform]*/moist feed/[thick sections continue to shrink after the melt path is frozen]*/hold time too short/holding pressure too low/[backflow from mold]*/lubricant insufficient/volatiles in feed/[solidification at mold wall delayed]*/[viscosity too high]*/cooling water temperature too cold/excessive cushion in front of ram/size of nozzle, sprue and runner too small/[air trapped]*. *"Fine ridges running perpendicular to the flow front":* [melt too cold]*/[short shot]*. *"Flow lines" see also "jetting":* feed moist/injection pressure too low/[melt too cold]*/screw not rotating during injection/injection speed too slow/back pressure too low/nozzle orifice too small/[mold too cold]*/gates too small/[venting of mold insufficient]*/feed rate too small,/injection rate too low/injection hold time too low/booster time too low/relocate gates/faults with nozzle, runner, sprue or gate/clamp pressure too high/unequal filling rates between cavities/core position incorrect/gates too small/mold design fault with nonuniform thickness of sections or excessive heavy bosses or ribs. *"Low gloss, dull or rough surface":* moist feed/injection pressure too low/[mold too cold]*/[melt too cold]*/injection rate too slow/relocate gates/mold cooling time too short/surface of sprue, runner, or cavity rough/[contamination]*/[venting of mold insufficient]*/screw rpm too low/injection made without screw rotation/injection speed too fast/back pressure too low/nozzle orifice too small/increase or decrease mold temperature/gate size too small/[melt too hot]*/diameter or depth of cold slug is too small/wrong location of gate/wrong location for water channels/particle size not uniform/too many fines in feed/wrong type of lubricant. *"Streaks on part":* stock temperature too hot or too cold/screw rpm too fast/nozzle or shutoff valve no tight/injection speed too fast/back pressure too low/cooling and mold-open time too short. *"Splay marks: coarse lines or lumps":* [degradation of melt thermally]*/injection rate too fast/increase or decrease the mold temperature/screw decompression too long/overall cycle too long/[contamination, fluid]*/[shot size too large]*/[drooling]*/screw decompression is missing from the molding cycle/gates too small/fault in the hot runner system/nozzle orifice too small/sprue and runner size too small/gate not perpendicular to runner. *"Splay marks: fine lines":* wet feed/residual non-aqueous volatiles in feed. *"Blush at the gate, dull spot in the part at the gate":* moist feed/[melt fracture at the gate]*/[mold too cold]*/injection pressure too low/[melt too hot]*/injection speed too fast/injection hold time too short/nozzle diameter too small/gate land area too large/diameter of sprue, runner and/or nozzle too small/depth or diameter of cold slug too small/wrong location of gate/[venting of mold insufficient]*. *"Silver streaks":* moist feed/[nozzle or cylinder too hot]*/plasticizing capacity, in kg/s, of machine is exceeded/variation in temperature of feed in hopper/plastic temperature is too high/injection pressure too high/air trapped between granules in the cold end of the machine/[mold too cold]*/injection speed too fast/lack of or excessive external lubrication/feed is mixture of coarse and fine particles as with reground/rear cylinder temperature too hot/[venting of mold insufficient]*/gates not balanced or at wrong location/insufficient addition of zinc stearate when using reground/[air trapped in melt]*/[degradation of melt, thermally]*/[air trapped in mold]*/[cold slugs at the nozzle or hot tip]*/[contamination]*/faulty mold design with too many sharp corners or edges. *"Drag marks":* rough surface of mold/injection pressure too high/injection hold time too long. *"Worn tracks on part":* [melt too cold]*/[nozzle too cold]*/screw rpm too low/injection speed too fast/back pressure too low/nozzle orifice too small/gates too small/cold slug well too small. *"Jetting" dull spots and disturbances that look like a jet:* moist feed/[melt too cold]*/[mold too cold]*/injection rate too fast/nozzle diameter too small/depth or diameter of cold slug too small/diameter of sprue, and runner too small/wrong location of gate, incorrectly at a thick section/[nozzle too cold]*/gate too small/gate land length too long. *"Wave marks":* feedrate too small/injection pressure too low/[melt too hot]*/[mold too hot]*/clamp pressure too low/injection hold time too short/cycle time too short/wrong location of water channels/stock temperature either too hot or too cold/injection speed too fast or too slow/nozzle diameter too small/moist feed. *"Flashing": the flow of material into unwanted areas; if at the end of the flow paths then its cause is usually [shot size too big]; flash in the runner system may indicate continued holding pressure after the gates freeze off:* [melt too hot]*/injection pressure too high/injection hold time too long/injection speed too fast/clamp pressure too low/[mold too hot]*/rework the mold design/vents too deep/damaged mold/misaligned platen/wet feed/[shot size too big]*/[feed rate into mold too high]*/erratic feed/[design of part faulty]*/erratic cycle time. *"Weld lines, knit lines":* injection rate too small/injection pressure too low/injection hold time too short/[mold too cold]*/[melt too cold]*/vent missing in location of weld/overflow well missing next to the weld area/wrong gate location/too much filler.

– **Transparency**: *"Cloudiness or haze for clear plastics":* [contamination]*/moist feed/[melt too cold]*/faulty adjustment of barrel temperature profile/injection pressure too low/back pressure too low/[mold too cold]*. *"Bubbles in clear plastics":* moist feed/[melt too hot]*/injection pressure too low/injection rate too fast/injection hold time too short/booster time too low/[mold too cold]*/mold cooling time too short/[cooled too fast]*.

- *Strength or Shape Defects*

"Voids": [short shot]*/[mold: external surfaces solidify and shrinkage occurs internally]*/[thick sections continue to shrink after the melt path is frozen]*/injection rate too fast/[melt too hot]*/booster time too short/molding cooling time too short/[cooled too fast]*/feed moist/insufficient blowing agent. *"Blisters":* feed moist/injection pressure too low/back pressure too low. *"Lamination, peeling":* moist feed/[mold too cold]*/[melt too cold]*/injection speed too fast/nozzle diameter too small/gate land area too large/depth or diameter of the cold slug is too small/diameter of sprue, runners and or nozzle too small/[contamination]*/back pressure too low/injection made without screw rotation/screw rpm

too low/[nozzle too cold]*/injection rate too low. *"Warpage, part distortion"(usually caused by nonuniform shrinkage as the molded part cools from ejection temperature to room temperature):* incorrect differential in mold temperatures to account for geometry or mold design/incorrect handling after ejection/injection hold time too short and stopped before gate freezes/cooling time too short/injection pressure too high or too low/[mold too cold]*/shrink fixtures and jigs to promote uniform cooling are missing/wrong gate locations and too few/gates too small/faulty part design/uneven cooling system on molds/injection pressure too high/[melt too cold]*/holding pressure and time too long/screw not rotating with injection done/injection speed too fast/back pressure too low/mold temperature either too hot or too cold/time for cooling and mold-open are too short. *"Weld weak":* [mold too cold]*/injection speed too slow/[melt too cold]*/injection pressure too low/nozzle opening too small/gate land area too large/sprue, runner or gate size too small. *"Brittle"*: feed moist/[mold too cold]*/injection rate too fast/[melt too cold]*/injection pressure too high/gate diameter too small/nozzle orifice too small/not enough gates or gates at wrong location/injection pressure too low/gate land area too large/sprue, runner or gate size too small/gates too small/cold slug well too small/holding pressure and time too long/screw rpm too low/screw should rotate during injection/injection speed too fast/back pressure too low/mold temperature either too hot or too cold/sensor error/[degradation material]*/[stress high in part]*/faulty mold design with notches causing local stress. *"Dimensional variation":* faulty feed rate/[melt too cold]*/injection pressure too low/[mold too cold]*/injection hold time too short/injection speed too fast/cycle time too short/nozzle diameter too small/faulty gate location/gate land area too large/diameter of sprue, runner and or nozzle too small/incorrect location of water channels/[control of machine faulty]*/[mold conditions wrong]*/poor part design/moist feed/irregular particle size/batch to batch variation in feed. *"Cracking":* [mold too cold]*/wrong mold design/ejection pins poorly located and give unbalanced push/[shot size too large]*. *"Low heat distortion temperature":* [variation in section thickness]*/[mold too cold]*/mismatch between cylinder and mold temperatures/feed rate too high/pressure too high/plunger dwell too long/excessive temperature variation between front and back of mold/freezing in the gate because gate orifice too large.

- *Operation*

"Sticking in cavity": [mold too hot]*/[melt too hot]*/injection pressure too high/injection hold time too long/injection hold time too short/gate land area too large/diameter of sprue, runner or gate too small/mold surface is rough/injection speed too fast/faulty mold design/incorrect radius of nozzle and sprue bushing/mold release not used/air was not provided for ejection/hold pressure too high/feed not adjusted to provide a constant cushion/cooling time too long or too short/cavity or core temperatures do not have the $< 7\,^{\circ}\mathrm{C}$ differential between mold halves/nozzle too hot/mold has undercuts and insufficient drafts. *"Sticking parts":* [mold too hot]*/injection pressure too high/rough surface on mold/holding pressure too high/wet feed/cooling time too short/faulty design of ejector/

highly polished or chrome plated mold surfaces. *"Sticking in sprue bushing":* injection pressure too high/injection hold time too long/booster time too long/cooling time too short/mold is too hot at the sprue bushing/nozzle pulled back from mold/[nozzle too cold]*/incorrect seat between the sprue and mold/nozzle orifice is not 7.5 mm smaller in diameter than OD of sprue/rough surface on sprue/sprue puller ineffective/sprue does not have sufficient draft angle for easy release/screw decompression too low or missing. *"Runner breaks":* holding pressure and time too long/[mold too hot]*/sprue, runners and gates are rough/incorrect radius in the nozzle and sprue bushing/time for cooling and open time too short. *"Discoloration of sprue":* [melt too hot]*/nozzle or shutoff valve not tightened/injection speed too fast/nozzle orifice diameter too small/[mold too cold]*/cold slug well too small/gate diameter too small. *"Drooling at nozzle"*: shutoff valve dirty or clogged/injection too soon/wrong nozzle pressure/poor radius of nozzle and sprue bushing/[nozzle too hot]*. *"Screw does not return"*: screw rpm too low/back pressure too high/wet feed/hopper out of feed/obstruction/temperature in the rear zone too high. *"Ejection of part poor":* rough mold walls/[shot size too large]*/knockout system inadequate/insufficient taper. *"Cycle erratic":* operator/[pressure erratic]*/[feed rate erratic]*/[cylinder temperature cycles]*. *"Cycle too long":* [cooling cycle too long]*/[heating cycle too long]*/[operator issues]*/material should be more heat-resistant.

- *Symptoms*

[Air trapped in melt]:* screw decompression/back pressure too low.
[Air trapped in mold]:* [venting of mold insufficient]*/gate diameter too small/[mold too hot]*.
[Backflow from the mold]:* suck-back/faulty non-return valve.
[Back pressure too high]:* injection rate too fast.
*[Barrel too hot]**: melt temperature $>$ 271 °C/sensor error/faulty barrel heater control system/worn or incorrectly fitted screw and barrel configuration.
[Contamination]:* dirty machine/dirty hopper/moist feed/too many volatiles in feed/[degradation]*/lubricant or oil on mold/incorrect mold lubricant/feed contaminated during material handling/faulty raw material from supplier/poor shutdown procedures.
[Contamination, fluid]:* water or oil leaking into mold cavity.
[Control of machine faulty]:* incorrect screw stop action/inconsistent screw speed/malfunction of nonreturn valve/worn nonreturn valve/uneven control of back pressure/faulty temperature sensor/heater band faulty/control system fault or poorly tuned/machine has inadequate plasticizing capacity/inconsistent control of cycle.
[Cooling cycle too long]:* [melt too hot]*/[mold too hot]*/inadequate cooling in local heavy sections.
*[Cooling insufficient before removal from mold]**: faulty mold design especially for rib design/injection speed too slow/injection hold time too short/injection pressure too low/melt too hot/mold too hot/[venting of mold insufficient]*/sprue and runners too small diameter/gate too small/gate land length too long/gate not close to thicker areas/core missing from heavy section.

*[Cooled too fast]**: [mold too cold]*/mold cooling time too short.

[Cylinder overheated]:* nozzle too hot/cylinder temperature too hot.

[Cylinder temperature cycles]:* controller fault/sensor error/incorrect line voltage/power factor problems/heater bands faulty/variation in feed temperature.

[Degradation, mechanical]:* barrel temperature in the feed area is too low combined with high screw speed or high back pressure/short transition section in screw/radius between the screw root and the flighter is too small/small tolerance between the plunger and the wall/fine material trapped between the plunder and the wall/excessive reground/rear cylinder temperature too low/plunger off-center.

[Degradation in the extruder of melt thermally]:* temperature sensor error/[melt too hot]*/temperature controller fault/improperly designed or defective nonreturn valve.

[Design of part faulty]:* incorrect mold dimensions/unequalized filling rate in cavity/mold not sealing because of flash between surfaces/[venting of mold insufficient]*/vents too large/gate land area too large/runner, sprue and gate dimensions incorrect.

[Drooling, introduces solid material into part giving defects]:* wet feed/[melt too hot]*/suckback pressure too low/injection pressure too high/injection forward time too long/injection boost time too long/shutoff valve dirty or clogged/injection too soon/poor radius of nozzle and sprue bushing/[nozzle too hot]*.

[Feed rate erratic]:* feeding mechanism/bridging in hopper/hopper design fault.

[Feed rate into mold too high]:* injection feed rate too fast/feed setting too high/sensor error.

*[Flow of polymer into the cavity uneven during high velocity flow into an open area]**: injection rate too fast/faulty gate location/gate too small.

[Granules not melted]:* plastic temperature too low/cycle too short for cylinder capacity/nozzle diameter too large.

[Heating cycle too long]:* insufficient heating capacity.

[Injection too slow]:* screw rpm too fast/back pressure too high/injection speed too slow/injection pressure too low/injection forward time too short/booster time too short/cycle too short.

[Insufficient plastic in mold]:* thick sections, bosses, ribs/not enough feed/injection pressure too low/plunger forward time too short/unbalanced gates/piece ejected too hot/variation in mold open time/no cushion in front of injection ram with volumetric feed.

[Melt not homogeneous]:* back pressure too low.

[Melt too cold]:* sensor error/control system error/lack temperature confirmation via hand-held pyrometer or laser sensor/cylinder too cold/screw rpm too slow/back pressure too low/insufficient plasticizing capacity of machine/[nozzle too cold]*/heating band fault/excessive flow length in mold.

*[Melt too cold at the nozzle or hot tip]**: nozzle too cold/temperature sensor error/too few heater bands/heater bands to far from nozzle tip/hot tip heat source too far from orifice or faulty/sharp corners near the gate.

[Melt too hot]:* sensor error/control system error/lack temperature confirmation via hand-held pyrometer or laser sensor/cylinder too hot/screw rpm too fast/

back pressure too high/[mold too hot]*/[nozzle too hot]*/injection rate too slow/gate too large/gate land too short/resin too hot/holding pressure and time too long/moist feed/cooling and mold-open time too long/[residence time too long]*.

[Melt too hot, localized overheating]:* [barrel too hot]*/faulty barrel heater control system/[nozzle too hot]*/sensor error/faulty or incorrectly designed check valve/worn or incorrectly fitted screw and barrel configuration.

[Melt fracture at the gate]:* [melt too cold]*/temperature sensor error/injection rate too fast/gate too small/sharp edge in gate area/cold slug well in the runner too small.

[Mold conditions wrong] :* [mold temperature non-uniform]*/injection pressure low/injection forward time too short/injection boost time too short/[barrel too hot]*/[nozzle too hot]*/inconsistent control of cycle.

*[Mold temperature non-uniform or erratic]**: poorly designed water or coolant lines/[venting of mold insufficient]*/coolant supply fault.

[Mold: external surfaces solidify and shrinkage occurs internally]:* [mold too cold]*/mold includes sections that are "too thick"/[melt too cold]*.

[Mold too cold]:* cooling lines in wrong location/coolant too cold/coolant flow rate too high/sensor error.

[Mold too hot]:* cooling lines in wrong location/coolant too hot/coolant flow rate too low/sensor error.

[Non-uniform shrinkage as the molded part cools from ejection temperature to room temperature]:* wrong packing times/wrong packing pressures/wrong gate location/cooling system fault/temperature sensor fault/need separate temperature adjustment for mold halves.

[Nozzle too hot]:* sensor error/control error/temperature setpoint at nozzle too hot/localized heater bands on the nozzle instead of being spread along the nozzle.

[Operator issues]:* slow setup of mold/need to trim "flashing"/poor monitoring of cycle times/excessive machine dead time.

*[Premature gate freeze-off]**: gate size too small.

[Pressure too low]:* injection pressure too low/loss of injection pressure during the cycle/feed control set too high causing lower injection pressure.

[Pressure too high]:* injection pressure too high/injection time too long/boost time too long.

[Pressure erratic]:* sensor error/control system tuning fault/leaks in the hydraulics.

[Residence time too long]:* machine provides shot size that is too large/dead spots in hot manifold/temperature too hot/poorly designed manifold system/[contamination]*.

[Resin feed rate too low]:* no material in the hopper/hopper throat partially blocked/feed control set too low/faulty control of feed system/bridging in the hopper/faulty hopper design.

[Shear heating of melt]:* injection rate too fast/injection pressure too high/gates too small/nozzle orifice too small < 0.8 of sprue bushing/nozzle dirty/sharp corners/injection rate too fast/shutoff nozzle used instead of a general purpose nozzle/improperly designed or defective non-return valve.

*[Short shot]**: [resin feedrate too low]*/injection pressure too low/[mold too cold]*/injection speed too low/[melt too cold]*/injection hold time too short/cycle time too short/diameter of gate, sprue, and runner too small/nozzle orifice too small/gate land length too long/incorrect gate location/[venting of mold insufficient]*/[nozzle too cold]*/nozzle dirty/shutoff valve dirty/inject with screw not rotating/machine undersized for the shot required/cycling from wet to dry resin/excessive flow length in mold/excessive feed build upin cylinder/[mold temperature nonuniform]*/[air trapped in mold]*/not enough external lubricant/poor balance of plastic flow into multiple cavity mold/holding pressure too low.
[Shot size too large]:* resin feed rate too high/injection pressure too high/machine shot size much larger than mold requirement.
[Shrinkage excessive]:* [melt too hot]*.
[Solidification at the mold wall delayed]:* [mold too hot]*.
[Stress high in part]:* [mold too cold]*/[melt too cold]*/injection pressure too high/faulty post-mold conditioning/faulty mold design.
*[Thick sections continue to shrink after the melt path is frozen]**: faulty mold design, with too much variation in part cross-section/[premature gate freeze-off]*.
*[Venting of mold insufficient]**: injection rate too fast/booster time too long/injection pressure too high/vents plugged/not enough vents/clamp pressure too high/wrong location of gates relative to vents/[melt too hot]*/[mold too hot]*.
[Viscosity of melt too high]:* [melt too cold]*/wrong resin.

Extruders for polymers:

- *Good Practice*

For start up, the barrel heaters are critical because screw is not rotating. Major concerns about cold start. Rear barrel temperature usually remains important because it affects the "bite" or rate of solids conveyed in the feed. Barrel temp. must be set appropriately for polymer. Head and die temperatures = desired melt temp. (except where want gloss, flow distribution or pressure control).

Screw speed is changed by reducing the motor speed 10 to 20 in two stages: either pair of gears or pulley but second stage is always gears with the screw set in the middle of the last big "bull" gear. For very slow-moving extruders (e.g. twins for rigid PVC) there are usually three stages of reduction to get to < 30 rpm. Most extruder drives are constant torque with max. power only available at top screw speed with the reduction ratio sometimes mismatched to the job.

For maximum solids conveying "Stick to the barrel and slip on the screw". Most plastics normally slip on the root of the screw as long as the feed temperature $<$ melt temperature, with those that are most likely to stick being highly plasticized PVC, amorphous PET and certain polyolefin copolymers. For amorphous PET convert the feed to less-sticky semicrystalline form by heating to high temperature for at least an hour in an agitated hopper.

Particles must stick to the barrel; trouble occurs with a "slippery feed" such as HDPE and fluoroplastics.

Material is the biggest cost (usually 60 %) so reuse as much trim and scrap as possible and keep close thickness tolerances so as not to have excessive thickness.

Shear rate is important because this affects viscosity. All common plastics are "shear thinning" e.g. PVC flow is 10 × faster if double the push but LLDPE flow increases 3 to 4 times for double the push.

Single screw: typically operated 100 % filled. Usually flood feed.

Twin screw: typically operate 20-100 % filled. Cannot be flood fed if running at high speeds.

Twin screw with vent: melt seal is about 1 L/D upstream of the vent; feed screw section under the vent operate < 0.5 full. During start up increase the vacuum gradually. Use low degree of fill.

Coating wire and cable: preheat the wire to about 120 (for HDPE) to 175 °C (cellular PE) to minimize shrinkage.

- *Trouble Shooting*

Extruders: the approach usually is to (i) adjust the temperature profile, (ii) check the hardware such as the thermocouples, controllers, speed, (iii) alter the processing conditions or (iv) change the resin or the screw and barrel design. The symptom–cause information is presented as issues related to production, off-spec thickness or shape, off-spec-strength, off-spec surface features, and usual symptoms.

- *Production*

"Throughput $<$ design": [low bulk density of feed]*/wrong screw design/worn screw or barrel elements/screw rpm too low/wrong temperature set points/caking on the feed screw/caking on the feed port. *"Slow and steady reduction in throughput":* build up of contaminants on screen pack. *"Torque $>$ design":* feed rate too high/[degree of fill too high]*/screw speed too low/heat zone set points too low/faulty screw design.*"Machine stalls above a certain speed or with certain materials":* constant-torque drive (magnetic clutch)/AC–DC drive system with constant-drive and constant torque combination. *"Feed from hopper not feeding smoothly":* material too light and fluffy for gravity feed/material damp/bridging/screw channels in the feed zone are not deep enough/too much external lubricant. *"Drive amps $>$ design"*: polymer viscosity too high/screw pumping too high/screw speed too high/barrel temperatures set too low. *"Amps high for melt pump drive or pump won't rotate" :* shear pin/degraded polymer caught in gears. *"Variation in drive amps":* [solids conveying instabilities]*/ % regrind too high/feed bulk density wrong. *"Cycling motor amps":* [surging]*. *"Extruder noisy"*: loss of feed/foreign or metal contaminant in feed/bent screw/bent barrel/half heater burned out. *"Local temperature fluctuations with cycles $<$ 5 min":* instrument circuitry fault/inconsistent melt/poor heater contact/thermocouples poorly seated/sensor error/poor sensor location/heating element fault/controller fault/[solid conveying instabilities]*. *"Barrel temperatures differ from the set temperatures"*: controller fault/burnt-out heater/blue screw syndrome where the rear end bites off more than the front end can pump. *"Real wall temperature $>$ the set point"*: the rear end bites off

more than the front end can pump. *"Variations in melt pressure"*: drift or cycle time variation > 1 min: [low feeding efficiency]*/low friction characteristics/[low bulk density of feed]*/[melting too soon]*/adequate early barrel pressure but [melting unstable]*/first barrel heating too high/screw tip pressure too low. *"Screw tip pressure too low":* no resin in feed hopper/bridging in feed hopper/temperature too high in extruder entrance zone/polymer wrapped around screw. Related topic *[Screw tip pressure too high]**. *"Unstable melt pressure"*: screw speed too high/degree of fill too low/screw design gives mixing of melt inadequate or low shear/cycling control on heat zones/feeder problems. *"Unstable pumping"*: for **vented** extruders: first stage [surge]*/poor screw balance between stages. *"Material flow out vent"*: for **vented** extruders: poor vent diverter design/first stage pumping rate too fast/screw tip pressure too high/flow rate > design/temperature set points for last barrels too low or heaters faulty/screw design gives localized pressure under the vent/vacuum too high/if adding liquids, then poor mixing.

- *Product Thickness or Shape Does not Meet Specifications*

"Small size variation": variation in drive speed/wrong screw design/variation in puller. *"Large size variation":* [surging]*. Here are more specific details: *"Variation in thickness in transverse direction and always in the same place":* see "Variation in local temperature". *"Variation in thickness in transverse direction and floating across or around the product":* [mixing of melt inadequate]*/die temperature setting wrong/dirty die/[screw tip pressure too low]*/back pressure on extruder < 20 MPa/wrong design or die or screw/[degradation of melt in extruder]*/for **blown film**: air ring not centered or level/thermocouple error/bubble subjected to hot or cold air/polymer feed has > 6 °C variation in melt temperature. *"Waviness or ridges around the circumference":* [surging]*/nonuniform water cascade/uneven take-off speed/vibration in the take-off equipment. *"Variation in thickness in the direction of extrusion":* [surging]*/puller slip or incorrect control of tension/drawdown too much or too fast/poor alignment/variation in take-up reels/erratic variation in feed materials/hot-lips controller cycling/untuned controller/faulty controller/temperature variation in die/variation in motor load/variation in melt pressure/damaged orifices in die or feedblock/holes in die too large/incorrect barrel temperature profile/faulty adjustment of die/faulty screw design/plugged screen pack/temperature sensor fault in barrel/hopper bridging/throughput too high/gels/for **blown film:** inconsistent nip roll speed control/frost line too low/polymer melt temperatures too low/bubble cooling control fault/variation in air flow from blower/cooling air nonuniform/gap opening too large/cooling air flow rate too low. *"Periodic variation in thickness in direction of extrusion":* spinneret temperature too low/orifice wrong diameter/wrong draw-down ratio. *"Cyclical variation in thickness in the direction of extrusion":* [draw resistance instability]*.

*"**Filament** breaks":* [surging]*/some die holes blocked/temperature variation in head or die/melt temperature too low or too hot/drawdown too great/holes in die too large/moisture/[contamination]*/[melt too hot]*/gap between bath and die too large. *"Wrong filament shape: correct cross section but too large":* too little pull/draw distance from die to take-off is too short/take-off speed too slow/die

land length too short/melt temperature too low. *"Wrong filament shape: distorted cross section"*: unequal die temperatures/die incorrect shape. *"Wrong filament shape: size OK but warped":* cooling too intense/linear take-off speed too fast. *"Filament oval cross-section":* filaments too hot while passing over rolls/rolls too hot/die holes oval/temperature gradients in die/tension too high in take-up rolls. *"Holes in* ***blown film*** *or* ***coating****":* moisture in resin/die lip gap too large/air gap too small/vacuum too high; for coating: moisture/substrate too rough/coating thickness too thin/contamination/decomposition/compound temperature too hot/see also *"Gels"*.

- *Product Does not Meet Strength Specifications*

"Product strength $<$ specs for all samples": faults with the feed/[degradation of melt in extruder]*. *"Product strength $<$ specs for some samples":* [contamination]*/faults with the feed/[degradation of melt in extruder]*.*"* ***Pipe*** *strength $<$ specs":* melt temperature too low/throughput too fast/land length too short/air gap too short/excessive drawdown at cold temperatures/too much scrap in feed/moisture in resin/dirty metal surfaces/material sticking on extruder parts/short die land length/high internal angular discontinuities into the die-land section/linear extrusion speeds excessive/uneven water coolant cascade/misaligned sleeve/[mixing of melt inadequate]*. *"Stiffness $<$ design":* for **cast or sheet:** chill roll temperature too cold/low resin density. **For coatings:** *"Poor adhesion":* a variety of apparently contrary causes related to polymer viscosity [polymer viscosity too high]*, degradation especially [oxidation]*, tackiness, temperature: melt temperature too low or high/air gap too small/chill roll temperature too cold or hot/line speed too fast/poor match between coating and substrate/substrate problems. *"Low tenacity":* ratio of roll speeds too small/[degradation of melt in extruder]*/wrong resin/nicks in die. *"For* ***wire and cable****: covering separates from wire/adhesion":* wire not preheated hot enough/melt temperature too low/dirty or moist wire/[degradation of melt in extruder]*/cooled too fast/air-cooling gap too short/air trapped between wire and coating [trapped air]*. *"Low modulus of elasticity":* melt temperature too low/air gap distance too short. *"Interfacial instability for* ***coextruded film****":* excessive shear stress at the die gap $>$ 0.06 MPa/throughput too high/die gap too narrow, melt temperature too low/polymer viscosity too high/the relative velocities where polymer flows combine differ by $>$ 4: 1.

- *Appearance*

Gloss, fisheyes, shark skin, pits, holes, clarity. Some are surface effects, such as shark skin, regular, ridged, surface deformity with ridges perpendicular to extrusion direction. Others are defects of the whole body of extrudate, caused by [melt fracture]*. These include spiral, bamboo, regular ripple. *"Rough surface or dullness":* [contamination]*/moisture/linear speed too fast or screw speed too fast/die holes too small/die temperature too cold/die land too short/[mixing of melt inadequate]*/[melt fracture]*/no vents used/hopper vacuum inadequate/[screw tip pressure too low]*/discontinuity in the melt flowlines/low melt temperature/dirty metal surfaces/material sticking on extruder parts/uneven water coolant cascade/misaligned sleeve/faulty screw design/screw too hot/extrudate too hot in the coolant bath causing boiling. *"Pits on surface"*: [contamination]*/moisture/water sprays onto extrudate just after exiting the die/water bath too hot. *"Fisheyes in film"*: moisture/damp polymer/too many volatiles in polymer. *"Gels":* [contamination]*/[degradation of melt in extruder]*/[shear intensity too low]*/[screw tip pressure too low]*/number and density of the screen pack too low/moisture too high/screw speed too low/incompatible blend/[residence time too long]*/ lack of streamlines in extruder/incorrect start up procedures/[melting inadequate]*/[melt too hot]*/for reactive: localized initiator concentration too high. *"Shark skin"*: [melt fracture]*/die temperature too low at the land end/linear extrusion speed too high/throughput too high/viscosity of polymer too high/ MWD of polymer too narrow/lubricant additive missing/[shear intensity too high]*/die gap too small.

"Polymer build upon die": melt temperature too low/throughput too high/die gap too small/wrong screw design/low level of antioxidants.

"Porous or bubbles in product": poor melt quality at vent/plugged vent opening/insufficient vent vacuum/excessive volatiles in feed/screw speed too high/vacuum vent needed. *"Spotted, warped or pocked surface"*: [mixing of melt inadequate]*/ moisture/roll too cold/contamination/screen size too large/dirty die/[trapped air]*/dirt on rolls/drafty air/wrong tension/boiling on extrudate in cooling bath. *"Lines on the product"*: surface scratches on tip or die/local buildup/[die swell too high]*/throughput too high/polymer adhesion on channels, tip or die/incorrect contact in the quench tank/melt temperature too cold/throughput too fast/ land length too short. *"Indented pock marks on* ***pipe*** *after water cooling"*: coolant water spray velocity too high. *"Raised pock marks on* ***pipe****"*: water drops on surface in the air drying zone.

"Discolored material": temperatures too hot/wrong formulation/discontinuities inside extruder.

- *Symptoms*

*[Contamination]**: contaminated feed/contaminated additives/dirty die/polymer on die lips.

*[Degradation of melt in extruder]**: [RTD too wide]*/barrel temperature too high/ screw speed too high (causing overheating and shear damage)/oxygen present/ [oxidation]*/nitrogen purge ineffective/wrong stabilizer/wrong screw/flows not streamlined/stagnation areas present/extruder stopped when temperatures $> 200\,^{\circ}\mathrm{C}$/copolymer not purged with homopolymer before shutdown/[residence time too long]*.

*[Degree of fill too high]**: feed rate too high/screw speed too slow.

*[Die swell too high]**: tip too short/abrupt change in flow near tip or die/melt temperatures too low in die assembly.

*[Draw resistance instability]**: for blown film, fiber spinning, blow molding: draw ratio too high.

*[Extrusion instabilities]**: screw speed too high/screw temperature too high/barrel temperature at delivery end too high/channel depth too high in the metering sec-

tion/the length of the compression section too short/read barrel end temperatures too low/diehead pressure is too low.

*[Feedrate too high]**: screw speed too fast/feed from hopper too fast.

[Gels]:* [contamination]*/[degradation of melt in extruder]*/[shear intensity too low]*/[screw tip pressure too low]*/number and density of the screen pack too low/moisture too high/screw speed too low/incompatible blend/[residence time too long]*/lack of streamlines in extruder/incorrect start upprocedures/[melting inadequate]*/[melt too hot]*/for **reactive:** localized initiator concentration too high.

*[Low bulk density of feed]**: % regrind too high/grind too coarse.

*[Low feeding efficiency]** : low friction characteristics.

*["Melt fracture" where the critical shear stress of polymer (about 0.1 to 0.4 MPa) exceeded in the die; excessive shear stress at the wall > 0.1 MPa]**: exit speed at the die is too fast/melt too cold/throughput excessive/die land too short/die opening too small/entrance to die not sufficiently streamlined/screw speed too high/molar mass and melt viscosity too high/cross section area in exit flow channel too small/external lubricant additive missing.

*[Melt too hot]**: screw speed too high/exit barrel zone temperatures too high/degree of fill too low/[shear intensity too high]*/heat zone temperatures set too high/[screw tip pressure too high]*.

*[Melting inadequate]**: barrel or die temperature too low/screw speed too fast/screw design gives insufficient mixing/[shear intensity too low]*/feed rate too high/material too "slippery"/[degree of fill too high]*/additional component has too low a melting point/[residence time too short]*.

*[Melting too soon]**: wrong bulk density of feed.

*[Melting unstable]**: especially for screws with high compression ratio and short compression length: insufficient melt capacity/too large a channel depth in the metering section/temperature in the metering end of the screw too high/wrong screw design.

*[Mixing of melt inadequate]**: [screw tip pressure too low]*/[feed rate too high]*/screw speed too high and [residence time too short]*/screw speed too low and [shear intensity too low]*/[degree of fill too high]*/faulty screw design for mixing/temperature set points incorrect/instrument error in temperature sensors/temperatures too high/loading excessive for one component/no static mixer included/for reactive extrusion: liquid flow rate too high/screw channel under injection not full of polymer.

*[Oxidation]**: temperature too hot/screw speed too low/[residence time too long]*/oxygen present/nitrogen purge ineffective/antioxident stabilizer ineffective/[trapped.air]*/hopper vacuum inadequate.

*[Polymer viscosity too high]**: temperature too low/wrong blend/[shear intensity too low]*.

*[Residence time too short]**: screw speed too high/too much feed/[degree of fill too high]*/poor screw design.

*[Residence time distribution, RTD, too wide]**: [degree of fill too low]*/feedrate too small/screws speed too fast.

*[Screw tip pressure too high]**: screens plugged/die or adapter or breaker plates too restrictive and give too much Δp/[polymer viscosity too high]*/temperatures in die assembly too low/barrel temperature too low/screw speed too high/[shear intensity too low]*/lubricant needed/flow restriction/throughput too high/die land too short/cold start/[degradation of melt in extruder]*.
*[Shear intensity too low]**: screw speed too low/faulty screw design.
*[Solids conveying instability]**: feed hopper fault/internal deformation of the solid bed in the screw channel/insufficient friction against the barrel surface.
*[Surging]**: *30–90 s* : feed particles are not sufficiently softened (usually at the beginning of the second compression zone)/too rapid compression screws/[low feeding efficiency]*/low friction characteristics/low bulk density of feed/[melting too soon]*/adequate early barrel pressure but [melting unstable]*/first barrel heating too high/screw speed too fast/faulty screw design/additional compound slippery/bridging in resin feed hopper/feed zone temperature too high/[screw tip pressure too low]*/compound temperature too high/screw too hot/nonuniform take-off speed/take-off speed too high/throughput too fast/controller fault/feed resin not mixed well/melt temperature too low.
*[Trapped air in extruder]**: unvented extruder/wrong screw design/pressure too low/rear-barrel temperature too high/screw speed too high/vacuum too low in feed hopper/powder feed instead of pellets.

9.12
Solids: Solidify Liquid to Solid: Flakers, Belts and Prill Towers

Related topic: dryers, Section 5.6 but use refrigeration (instead of steam) to solidify liquid.

- *Area of Application*

Flaker: liquid feed. Product: flakes about 1 cm × 1 cm × 1 mm thick; capacity < 10 kg/s. Viscosity of liquid $< 10^5$ mPa s. Caustics, resins, resin intermediates, fatty acids and alcohols, detergents, waxes, pharmaceuticals, pesticides, explosives.
Chilled belt: liquid feed. Product: pastilles, flakes, pellets; capacity usually < 10 kg/s per unit. Antioxidants, adhesives, resins, aluminum sulfate, sugar, agar-agar, maleic anhydride, animal fat, phthalic anhydride, chocolate, surfactants, asphalt, stearic acid, waxes, fatty acids and fatty alcohols.
Prilling towers: liquid feed. Product diameter: spheres 1–3 mm. Capacity < 5 kg/s per unit.

- *Guidelines*

Flaker: 20–300 g/s m^2; heat transfer coefficient $U = 0.35$ kW/m^2 °C; power: 1–50 MJ/Mg depending on the material; lower values for ammonium nitrate, benzoic acid, tetrachlorobenzene, sodium hydroxide; higher power usages for waxes

and resins. Grooved surface drums for liquids that will not wet the surface. Power: 0.9–1.1 kW/m^2.
Chilled steel belt: four options for feeder: (i) heated overflow weir, viscosities < 1000 mPa s, produces flakes 1–3 mm thick; (ii) overhead double roll, viscosities $< 10^8$ mPa s, produces flakes; (iii) rotoformer to produce pastilles 1–10 mm diameter; (iv) heated strip former (for brittle products). Capacity 20–300 g/s m^2. Heat transfer coefficient $U = 0.35$ kW/m^2 °C; with underbelt water spray 230 W/m^2 °C. About half the heat load from the product is removed in the first one third of the length of the cooling belt. Power 1–50 MJ/Mg. depending on the material. Belts are typically 0.5 to 1.5 m wide and 2.4 to 5 m long.
Prilling tower: gas velocities less than the terminal velocity of the prill, < 1–2 m/s; gas to solids ratio 10 kg air/kg solids. Assume solid surface temperature = solidification temperature, volumetric heat transfer coefficient $U_v = 0.005$ kW/m^3 °C. Height < 60 m.

9.13
Coating

Related topics: extruder-coating, Section 9.11.

- *Area of Application*

Dip, shear stress 10–100 1/s.
Spray, shear stress 1000–10 000 1/s; OK for thick films but not as effective as dip or spin.
Forward roll, (meniscus roll coating), single layer coating, 1–50 mPa s; wet thickness 10–2000 μm; accuracy ± 8 %; speed 0.05–1 m/s with maximum speed 2.5 m/s; shear stress 10–1000 1/s. Not as precise as reverse roll. Thickness dependent on roll rpm, viscosity and gap.
Reverse roll, single layer coating, 1–500 000 mPa s; thickness 5–400 μm; accuracy ± 5 %; speed 0.02–8 m/s; shear stress 1000–100 000 1/s. More precise than forward roll. Web is usually closed and OK for materials that are easily deformed. Example jersey knits, plastic films. Probably the most versatile.
Roll with knife: single layer coating, 1000–10 000 mPa.s; thickness 50–2500 μm wet coat; web speed 0.05–2 m/s. Simple, low cost. Propensity for streaking.
Roll with air knife: single layer coating; 5–500 mPa s; thickness 0.1–120 μm; accuracy ± 5 %; maximum speed 8.2 m/s. OK for pigmented surfaces. Usually not used, prefer slide, curtain or extrusion. Examples book, litho, clay-coated sheet.
Spin coating: thin films 20 nm; ± 10 %.
Reverse gravure, single layer, 1–1500 mPa s; thickness 1–50 μm; accuracy ± 2 %; maximum speed 12 m/s; shear stress 40 000–10^6 1/s; precision for thin coatings, low surface tension, long runs are possible, room temperature, coatings may contain solvents. Example, silicones, adhesives, magnetic tape.
Extruder-slot die, single layer, premetered where the amount applied to web is metered; 50–5 000 000 mPa s; thickness 15–750 μm; accuracy ± 5 %; maximum

speed 11.5 m/s; shear stress 3000–100 000 1/s. Examples jersey knits, plastic films, web is closed.

Slot or **blade** single layer, premetered where the amount applied to web is metered, 5–20 000 mPa s; thickness 15–250 μm; accuracy ± 2%; maximum web speed 6 m/s; shear stress 20–40 000 1/s.

Slide, or cascade, multi layer, premetered where the amount applied to web is metered, 5–500 mPa s; thickness 15–250 μm; accuracy ± 2%; 0.1–4 m/s with maximum speed 5 m/s; shear stress 3000–120 000 1/s; usual gap width 0.1–0.5 mm with smaller gaps to providing more stability.

Curtain, multilayer, premetered where the amount applied to web is metered, 5–500 mPa s; thickness 2–500 μm; accuracy ± 2%; maximum speed 5 m/s; shear stress $10\,000–10^6$ 1/s.

- *Guidelines*

Reverse roll: film thickness is a function of the metering gap, speed of rotation of the applicator and metering rolls and the capillary number. The speed ratio is very important. Example film thickness/metering gap = 0.55; speed ratio of metering to applicator roll = 0.2 for $Ca < 2$.

Knife and roll coating: self metered, thickness of coat depends primarily on the gap and the geometry of the gap.

Slot or **extrusion:** edges must be sharp with radius of curvature < 50 μm. Gap width = double the final wet thickness.

Slide: top edge must be sharp with radius of curvature < 10% of slot opening.

Curtain: use for wider gap, usually at higher speeds than slide. Minimum flow > 0.5 cm^3/s cm width with design flow usually double minimum (= 1 cm^3/s cm width); surface tension usually about 30 mN/m with the dynamic surface tension of the top layer slightly lower than that of the other layers; curtain velocity 100 cm/s The minimum flow rates and minimum speeds = max. speed of a slide coater. Need care in balancing rheologies of the layers. Coat thicker when speed or viscosity increase. Gap tends to have negligible effect. Bottom layer is the most important.

- *Good Practice*

Ensure the coating speed is such that the dynamic contact angle between the liquid coating and the substrate is < 180° to prevent air entrainment. Web tension must be correct for both unwind and rewind. Web tension/width is in the range 40–300 N/m. For **multilayer slide coating**, the critical web speed is determined by the local viscosity of the layer that wets the web with low viscosity preferred. To improve operation consider the use of a "carrier layer" with a shear-thinning liquid. For **curtain coating**, use edge guides. Wettable guides give stable curtains but produce a thicker coating near the edge.

- *Trouble Shooting*

“Chatter defects” cross web lines, bands, uniform in width and period: edge not sharp/mechanical vibrations/web speed variation/pulsations in the coating bead/web speed too high/gap too large/bead vacuum insufficient.
“Streaks” downweb lines: gap too small/dirt accumulated/bubbles/nicks in coating head/pulsations in flow rate.
“Tearing of web”: incorrect tension/gap too small.
“Ribbing” evenly spaced lines down the web: Capillary number too high/coating too thin/wet coverage too low/Reynolds number too low/speed too fast/surface tension too high/gap too small.
[Air entrainment] = [Dynamic contact line approaches 180°]*:* web speed too fast/too little vacuum/gap too large/viscosity too high/*Ca* too high > 0.1/rough surface/surface tension too low.
Rolls, slot or knife coaters, slide:
“Ribbing” evenly spaced lines down the web: web speed too fast/viscosity too high/web coat too thin/flow rate too low/too little vacuum/[air entrainment]*/*Ca* too high/channel divergence angle too small/*Re* too small. Forward roll coaters are very sensitive to ribbing.
“Chatter defects” or barring ; cross web lines, bands, uniform in width and period: misaligned coating gap/edge not sharp/mechanical vibrations/web speed variation/pulsations in the coating bead/web speed too high/gap too large/bead vacuum insufficient.
“Streaks” downweb lines: pulsations in flow rate/vibrations at gap/gap too small/dirt accumulated/bubbles/nicks in coating head.
“Swelling and weeping of upstream meniscus”: web speed too slow/too much vacuum.
[Air entrainment] = [Dynamic contact line approaches 180°]*:* web speed too fast/too little vacuum/gap too large/viscosity too high/*Ca* too high > 0.1/rough surface/surface tension too low.
Knife coaters:
“Ribbing”: knife angle of inclination is too divergent/viscoelasticity is too high/knife angle of inclination is convergent and too high.
“Flooding”: feed film thickness is too thick.
“Starvation”: feed flow to knife is too low.
“Streaks”: unable to pin the static contact line to the downstream corner of the knife/contamination trapped in gap.
Slide: *“Waves”:* surface elasticity effects.
“Ribbing” with wavelength about 2 mm: pressure difference over the bead is too high.
Roll with air knife: usually coating flows are unstable because of the action of the air knife.
“Streaks and chatter” downweb lines: air flow at knife causes oscillations in the upstream bead/distance between the bottom of the air knife and the coating pan edge is too large/inadequate contact angle between the liquid and the web.

Curtain:
"Heel formation": web speed too low/curtain *Re* too high/high flow rates.
"Air entrainment and heel formation": impinging curtain velocity too high/curtain *Re* too high/high flow rates/high web speeds.
"Disintegration of curtain": curtain *Re* too low.
"Pulled film": curtain Re too low/web speed too high relative to curtain velocity $>$ 4.3/low flow rates and low coating speed/high surface tension/low curtain height.
"Air entrainment": web speed too high relative to curtain velocity/curtain *Re* too high/high web speed and relatively low flow rates.
Extrusion coating *"Poor adhesion"*: a variety of apparently contrary causes related to polymer viscosity, degradation, oxidation, tackiness, temperature: melt temperature too low or high/air gap too small/chill roll temperature too cold or hot/line speed too fast/poor match between coating and substrate.
"Rough wavy surface (applesauce)": wrong resin/temperature too low or high.
"Edge tear": draw ratio too high/die end temperature too low/temperature too low or high.
"Oxidation": temperature too hot/screw speed too low/flows not streamlined/extruder stopped when temperatures $>$ 200 °C/copolymer not purged with homopolymer before shutdown. *"Pinholes in coating":* substrate too rough/coating thickness too thin.
"Surging": bridging in resin feed hopper/feed zone temperature too high/wrong screw design. *"Voids"*: moisture/leaks in resin handling system/inadequate drying and storage/[thermal degradation]*/[gels]*.
"Die lines": nicks in die/dirty lips/particles in die.
"Pin holes and breaks": coating too thin/contamination/decomposition/compound temperature too hot/moisture.
"Web tears": compound temperature too cold/too much drawdown/die lip opening too large.
"Poor adhesion": compound temperature too low/substrate problems.
"Excessive neck-in": die-to-roll gap too large/material temperature too high/die-lip opening too large/throughput too low/use resin with lower Melt Index/die land length too long.

See Section 9.11 for the following [Contamination]*; [Degradation of melt in extruder]*; [Screw tip pressure too low]*; and [Shear intensity too low]*.
[Gels]:* [contamination]*/[degradation of melt in extruder]*/[shear intensity too low]*/[screw tip pressure too low]*/number and density of the screen pack too low/moisture too high/screw speed too low/incompatible blend/[residence time too long]*/lack of streamlines in extruder/incorrect start upprocedures/[melting inadequate]*/[melt too hot]*/for reactive: localized initiator concentration too high.
*[Surging]**: screw speed too high/take off speed too high/back pressure too low/compound temperature too high.
*[Thermal degradation/crosslinking]**: polymer temperature too hot/screw speed too low.

Curtain coaters: *"Entrained air":* web speed too high/coat too thin and Reynolds number too low.
"Waves": surface elasticity effects.
Related to downstream drying:
"Dryer bands": width of bands = hot air nozzle diameter: nonuniform air flow/velocity too high/coating too thick/coating viscosity too low.
"Mottle": air motion too vigorous/coating viscosity too low.
"Fat edges" or "picture framing": Marangoni effects.
"Nonuniform distribution of binder": Marangoni effects.
"Hexagonal pattern on surface": Marangoni effects.
"Curling and cracking": coating too thick/lack of plasticizer additives/air humidity too low or air too dry/temperature too low/pigment volume too high/Deborah number too high.
"Holes": dirt/oil/grease/particulates in air/Marangoni effects.
"Delamination": faults in the surfactant system.
"Blushing" milky opalescence: temperature drops below dew point of air.

10
Process Vessels and Facilities

This chapter considers process vessels (such as reflux drums, KO pots, columns) in Section 10.1, and storage tanks in Section 10.2. Bins and hoppers for the storage and delivery of solids are considered in Section 10.3. Bagging machines are discussed in Section 10.4.

10.1
Process Vessels

- *Area of Application*

Used for a wide range of temperatures, pressures and applications. Can be decanters, reflux drums, intermediate storage, columns, KO pots, reactors.

- *Guidelines*

Operating pressure and temperature constrain practical size of vessel. Design codes for pressure vessels vary slightly with the country. In general, for operating pressures > 10 MPa, vessel volume usually $< 1\ \text{m}^3$. Pressure decreases as temperatures exceed 250 °C. For temperatures above 350 °C consider carbon/molybdenum and for temperatures > 500 °C consider austenitic steels. See Fig. 6.2.
Corrosion allowance: 1.5 mm for corrosion rates 0.08 mm/a; 3 mm for rates 0.09–0.3 mm/a; 4.5 mm for 0.31–0.4 mm/a; 6 mm for > 0.4 mm/a. If pressure < 400 kPa use L/D of 2–3:1; for pressures > 400 kPa use L/D of 4–5:1.
Relating vessel mass to dimensions: product of (vessel height, m) $(\text{diameter, m})^{1.5}$ = 100 corresponds to a vessel mass of 30 Mg for vessel designed for pressure of 0.8 MPa with $n = 1.0$ for the product range 1–500. Pressure corrections: 0.8 MPa × 1.0; 2.7 MPa × 1.9.

For **surge vessels**, allow 2 min liquid residence time; for drawoff, use 15 min; for reflux use 5 min provided this allows sufficient time for controllers to function. Total volume = 1.3 × holdup if the holdup volume is $> 3\ \text{m}^3$.

For **equalization basins**, allow a detention time of 14 h.

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10.2
Storage Vessels for Gases and Liquids

- *Guidelines*

For liquids, consider floating head vertical cylinders for pressures < 100 kPa; spheres, vertical cylinders with dome ends for pressures < 250 kPa; small spheres and horizontal cylindrical tanks for pressures < 800 kPa.

For gases, consider pressure cylinders and small horizontal cylindrical tanks for pressures > 800 kPa.

10.3
Bins and Hoppers for Bulk Solids

Johanson's definitions of terms used to characterize solid particles are given in Section 1.6.4. Related topics include mixing of solids, Section 7.4 and transportation of solids, Section 2.6. The important terms are **AI**, **RI**, **HI**, **FRI**, **FDI**, **BDI**, **CI**, **RAS** and **SBI**.

- *Guidelines*

Promote mass flow with cone angle to the vertical related to the wall friction angle of the solid.

Wall friction angle (°)	Cone angle with the vertical (°) less than	Wedge angle with the vertical (°) less than
30	10	20
20	25	38
10	35	48
0	45	60

Both bottom angle and surface smoothness are important. For a circular cone the outlet should be at least 6–8 times the diameter of the largest particle. For wedge hoppers the discharge opening should be at least 3–4 times the diameter of the largest particle. The length of the slot opening should be at least 3 × the width. The desired mass flow requires the entire discharge opening to be active by the use of: a tapered interface belt conveyor, a tapered shaft screw conveyor, a screw conveyor with an increasing pitch (providing the length: screw diameter < 3:1) or a combination of screw conveyor with a tapered shaft plus increased pitch provided the length: screw diameter < 6:1.

Design hopper: prevent ratholing with hopper angle (with the vertical) < **HI** + 3°.

Diamondback hopper: tends to prevent bridging and ratholing.

- *Good Practice*

Bins and hoppers: In general, the cohesive strength of powders increases with consolidation pressure.

- *Trouble Shooting*

If the flow of solids is not as anticipated, a bin vibrator can be installed on the slope of the hopper.
"No flow": [arching]*/[ratholing]*.
"Erratic flow": obstructions alternating between arching and ratholing/cohesive material plus [sequential arching then ratholing]*/noncohesive plus bin walls not steep enough to produce flow at the wall/noncohesive plus star feeder draws only from one wall/noncohesive plus constant pitch screw conveyor with diameter < exit hole from hopper.
"Flooding or flushing" when a rathole collapses it entrains air, becomes fluidized and the material floods through the outlet uncontrollably:" fine powders such as pigments, additives and precipitates that tend to rathole/insufficient residence time in hopper for deaeration.
"Flow rate limitation": fine particles where movement of the interstitial air causes an adverse Δp.
"Limited live capacity": [ratholing]*.
"Product degradation": [ratholing]*.
"Incomplete or nonuniform processing": [ratholing]*.
*[Arching]**: particle diameter large compared to outlet/cohesive particles probably caused by moisture or compaction/**AI** too high/**AI** > conical hopper outlet diameter.
*[Ratholing]**: cohesive particles probably caused by increased moisture or by compaction (fine powders < 100 μm such as pigments, additives and precipitates)/ outlet diameter from hopper < **RI**/**HI**< steepest hopper angle (as measured from the vertical).
*[Semi-stable ratholing]**: outlet diameter of hopper slightly larger than **RI** and **HI** < steepest hopper angle and **AI** < conical hopper outlet diameter.
[Sequential arching then ratholing]:* cohesive material and bin walls not steep enough/cohesive material and bin walls wrong shape/cohesive material and screw conveyor diameter < exit hole from hopper.

feeders

"Solids initially flow from the hopper but if solids rest, then no flow": instantaneous **AI**< outlet diameter but after resting **AI** > outlet diameter. *"Flow initially OK but stops after several minutes:"* [ratholing]*.
"No flow at the front of the feeder": instantaneous **AI** < conical outlet diameter but instantaneous **RI** is large/solid is pressure sensitive.
"Sometimes the feeder is full; other times feeder is starved (all particles < 150 μm)": [semi-stable ratholing]*.
"Feeder overflows when solids level in hopper is low": **FRI** is small/small diameter particles do not allow entrapped air to escape.
"Feeder overflows when solids level in hopper is high": **FRI** is small and **HI** is small /source of air at or near hopper outlet causes fluidization.

"Feeder overflows only when solids are being conveying into the hopper": **FRI** is small/ air entrained with particles entering the hopper.

"Feeder overflows independent of level in hopper or solids entering hopper": **FRI** is small and **HI** is small/excess air entering hopper via leaks or with feed/gate partially closed/flexible sock partially closed/obstruction in the hopper exit.

"Solids flowrate from feeder does not increase with increasing speed of feeder": **FRI** < required flowrate/solids diameter small enough to form a limited rate into the feeder caused by the upflow of air a hopper exit/air injection location too low.

"Solids flowrate does not increase when rpm of rotary valve is increased": moderately low **FRI**/air introduced by the rotary valve at hopper outlet/venting the returning high-pressure cavity is insufficient.

10.4
Bagging Machines

- *Application*

Three options are usual: volume fill, simultaneous fill and weigh, SFW, and pre-weigh, PW.

Usually fill the 40–50 kg bag based on volume of powder, not weight – provided that the particles have consistent bulk density, are not easily aerated and the particles flow easily.

Volume fill: particles must have consistent bulk density.

Use SFW if bulk density varies; SFW with accuracy of ± 0.125 to 0.25 %; use PW for more accuracy.

Use valve bag filler for bag size 10–55 kg. Select the feed system based on density and size of the particles:

– for powders, flakes, granules 0.4–1.7 Mg/m^3; size 44–12 000 μm (examples cocoa, flour, black peppers, cement, plaster, pigments, organic resins), use auger.

– for free flowing, flaked or powdery, granules 0.13–1.9 Mg/m^3; (examples fertilizer, seeds, plastic pellets, concrete, stucco, grout, sand & refractory; bentonite, TiO2, iron oxide, carbon black), use air.

– for fine particles with mid to high density, 1–1.6 Mg/m^3; size < 3000 μm; (example portland cement, mortar mix, stucco, grout, lime gypsum, barite), select vertical impeller.

– for fine particles with low to mid density, 0.16–1 Mg/m^3; size < 3000 μm; (example lightweight concrete mixes, vermiculite, polystyrene, kaolin, silica, graphite, carbon black, organic pigments, oat and rice hull ash), select horizontal impeller.

– for extremely fine and light powders, 0.016–0.4 Mg/m^3; size < 150 μm; select vacuum.

– for free flowing granular, (example fertilizer, corn, soybeans, salt, sugar; sand, refractories, plastic pellets), select gravity.

– for pharmaceuticals, food products use polymer bags or kraft bag with polyethylene liner and thermally seal.

Auxiliary equipment includes vibrating packers: machines to vibrate a bag or solid container so that the maximum dry bulk solid is in the minimum container space.

- *Guidelines*

For 40–50 kg bags, one person can handle up to 5 bags/min. To achieve up to 8 bags/min add another set of scales.

For foodstuffs and pharmaceuticals, 25 bags/min with $<$ 20 kg bags. With 2 mil thick liner, the capacity is twice as fast as with 6 mil polymer liner.

Vibrating packer: about 0.7 kW drive motor.

- *Good Practice*

Air packer: if feed is not free flowing, set dribble time of 3 s. Do not place a partially filled bag into filler; this will produce subsequently many off spec bags.

- *Trouble Shooting*

"Erratic weights": bag too small/pressure chamber not filled/feed density $<$ design/obstruction between lower chamber and bag/bulk/dribble valve sticks/flow through valves different from design/vibration/sleeve of valve is not clear of the opening/vent in spout plugged/bag clamp fault/mechanical bind.
"Fill time excessive": bag incorrectly put on filling spout/excessive fluidization/density different from design.
"Chamber pressure does not drop to zero during refill": sticky valve/exhaust time incorrect.

Appendix A:
Units and Conversion of Units

The units are organized by dimension starting with length L and progressing through mass, force, energy, electrical and magnetic units. Under each cluster of units may also be included the reciprocal. Thus the set of units of dimensions M/L^2T also has the units of dimensions L^2T/M. Order-of-magnitude values are often included. At the end of this appendix are the physical constants and conversion of temperatures.

SI Prefixes:

10^{24}	yotta Y	10^{-1}	deci d
10^{21}	zetta Z	10^{-2}	centi c
10^{18}	exa E	10^{-3}	milli m
10^{15}	peta P	10^{-6}	micro μ
10^{12}	tera T	10^{-9}	nano n
10^{9}	giga G	10^{-12}	pico p
10^{6}	mega M	10^{-15}	femto f
10^{3}	kilo k	10^{-18}	atto a
10^{2}	hecto h	10^{-21}	zepto z
10	deca da	10^{-24}	yocto y

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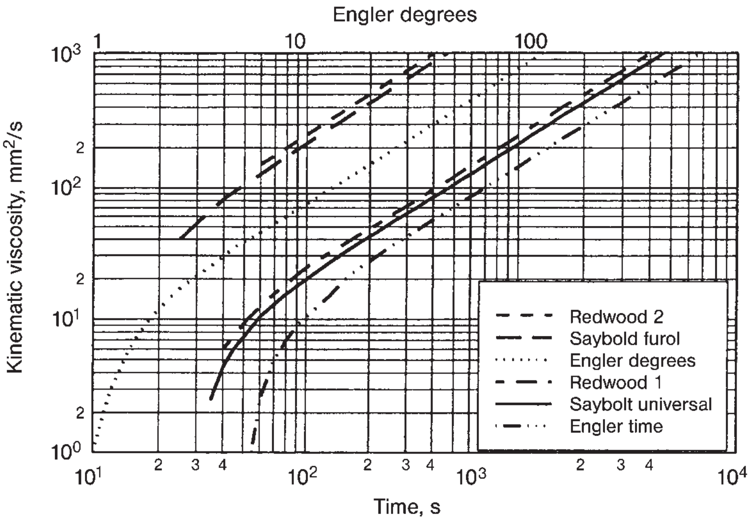

Figure A-1 Conversions among systems of units for kinematic viscosity for liquids.

Conversions for distance, length, dimensions: L

meter, m	inch	× 0.0254	= m
	foot	× 0.3048	= m
height of adult: 1.6 to 1.8 m	yard	× 0.914	= m
	mile	× 1.609	= km
height of giraffe: 10 m	μinch	× 0.0254	= μm
	mil	× 0.00254	= cm
	cm	× 0.01	= m
	angstrom	× 10^{-10}	= m
	angstrom	× 0.1	= nm
	micron	× 10^{-6}	= m
	nautical mile	× 1.853218	= km

Conversions for area, permeability, dimensions: L^2

square meter, m^2	inch^2	× 6.45E-4	= m^2
	ft^2	× 0.0929	= m^2
card table: 0.6 m^2	yard^2	× 0.836	= m^2
	mile^2	× 2.5899	= km^2
square micrometer, $\mu\mathrm{m}^2$	acre	× 4047	= m^2
	dm^2	× 10^{-2}	= m^2
28 μm filter: 10 $\mu\mathrm{m}^2$	cm^2	× 10^{-4}	= m^2
clay: 0.01 $\mu\mathrm{m}^2$	mm^2	× 10^{-6}	= m^2
	$\mathrm{angstrom}^2$	× 10^{-2}	= nm^2
	micron^2	× 10^{-12}	= m^2
	km^2	× 10^6	= m^2
	hectare (ha)	× 10^4	= m^2
	D'Arcy	× 0.9869	= $\mu\mathrm{m}^2$
	$\mathrm{ft}^3\mathrm{lb}_\mathrm{m}/\mathrm{h}^2\mathrm{lb}_\mathrm{f}$	× 222.62	= $\mu\mathrm{m}^2$
	$\mathrm{ft}^3\mathrm{lb}_\mathrm{m}/\mathrm{s}^2\mathrm{lb}_\mathrm{f}$	× 2.885E9	= $\mu\mathrm{m}^2$

Conversions for volume, dimensions: L^3

Volume. reciprocal: amount of substance/volume

cubic meter, m^3

box car: 100 m^3
refrigerator: 1 m^3
large pail: 10 L
brick: 1 L
golf ball: 40 cm^3
1 m^3 ~ 1 tonne water

standard conditions:
STP gas = 0 °C, 101.325 kPa dry; metric uses the prefix "N" to designate this condition.
Other "standard" conditions used include:
STD gas = 15.6 °C, 101.325 kPa dry
NTP(API) = 15 °C, 101.325 kPa

reciprocal

kilomol per cubic meter, kmol/m^3

pure gaseous CO$_2$ at STP: 0.0446 kmol/m^3

1 kmol = 22.4 m^3 at STP

DO NOT USE: molarity or "M" for molar solution.
Another obsolete term is molality: dimensions 1/M. This would have units of measurement of mol/kg

inch^3	× 16.39E-6	= m^3
ft^3	× 28.2E-3	= m^3
yard^3	× 0.7646	= m^3
Imp. gallon	× 4.55	= L
US gallon	× 3.785	= L
Imp. quart	× 1.1365	= L
kL	× 1	= m^3
barrel (oil)	× 0.15899	= m^3
fluid oz	× 28.413E-3	= L
pint	× 0.568	= L
std ft^3 (STP)	× 28.2E-3	= Nm^3 (STP)
std ft^3 (STD)	× 26.7E-3	= Nm^3 (STP)
std ft^3 (STP)	× 29.7E-3	= m^3 (STD)
dm^3 = L	× 10^{-3}	= m^3
hectoliter	× 0.10	= m^3
cm^3	× 10^{-6}	= m^3
cm^3	× 1	= mL
mm^3	× 10^{-9}	= m^3
nm^3	× 10^{-27}	= m^3
micron^3 = μm^3	× 10^{-18}	= m^3
(km)^3	× 10^9	= m^3
(hectom)^3	× 10^6	= m^3
(decam)^3	× 10^3	= m^3
bushel	× 3.524 × 10^{-2}	= m^3
mol/L	× 1	= kmol/m^3
lb mol/ft^3	× 16.02	= kmol/m^3

Conversions for volume ratio, dimensions: dimensionless

scfm/100 USgpm	× 7.45	= dm^3/100 L
USgal/1000 acf	× 0.134	= L/m^3
USgal/bbl.	× 0.0238	= m^3/m^3
scf/bbl	× 0.1773696	= m^3/m^3
UK gal/1000 ft^3	× 0.161348	= L/m^3

Conversions for surface/volume ratio, dimensions: 1/L

	cm^2/cm^3	× 100	= m^2/m^3
	ft^2/ft^3	× 3.28084	= m^2/m^3
	ft^2/UK gal	× 20.418	= m^2/m^3

Conversions for volumetric flow, dimensions: L^3/T

cubic meters per second, m^3/s	ft^3/s	× 28.317	= dm^3/s
cubic decimeter per second, dm^3/s or L/s	ft^3/min	× 0.4719	= dm^3/s
	scfm	× 1.6699	= m^3/h (STP)
fast running tap into a sink: 0.1 L/s	scfm	× 1.5	= Nm^3/h
liquid pumped through a 5 cm diam. pipe: 2.5 L/s	scfm	× 0.4719	= dm^3/s(STP)
	scfh	× 0.028	= m^3/h (STP)
	scfh	× 7.756	= cm^3/s
gas flowing through 10 cm diam. pipe: 150 dm^3/s	10^6 scfd	× 1.17E3	= m^3/h (STP)
	US gpm	× 0.0631	= L/s
	Imp. gpm	× 0.07577	= L/s
	Imp gph	× 1.26E-6	= m^3/s
	10^6 Imp. gpd	× 0.0526	= m^3/s
	10^6 US gpd	× 0.0438	= m^3/s
	10^3 bbl/d	× 1.84	= L/s
	10^3 bbl/d	× 6.62	= m^3/h
	bbl/d	× 0.159	= m^3/d
	mm^3/s	× 10^{-9}	= m^3/s
	cm^3/s	× 10^{-6}	= m^3/s
	dm^3/s = L/s	× 10^{-3}	= m^3/s
	L/s	× 3.6	= m^3/h
	L/min	× 1.667E-5	= m^3/s
	m^3/h	× 2.778E-4	= m^3/s
	Million scfd	× 0.325	= m^3/s
	USgph	× 0.0010514	= L/s
	in^3/s	× 16.39	= cm^3

Conversions for acceleration, dimensions: L/T^2

m/s^2	cm/s^2	× 10^{-2}	= m/s^2
	ft/s^2	× 0.3048	= m/s^2
acceleration of gravity ~ 9.8 m/s^2			
std. 9.80665 m/s^2			

Conversions for angular acceleration, dimensions: 1/T^2

radians per second, r/s^2

Conversions for velocity, dimensions: L/T

Volumetric flowrate per unit area, volume flux, mass transfer coefficient for a concentration driving force, mass flux per unit concentration driving force

meter per second, m/s

liquid pumped	*1 m/s*
highway driving	*25 m/s*

Mass transfer coefficient

for gases	*85 μm/s*
for liquids	*0.85 μm/s*

ft/s	× 0.3048	= m/s
ft/min	× 0.00508	= m/s
ft/min	× 5.08	= L/m^2 s
cfm/ft^2	× 0.00508	= m/s
ft^3/ft^2 min	× 5.08	= dm^3/m^2 s
US gal/ft^2 day	× 0.04074	= m^3/m^2 day
US gal/ft^2 day	× 4.715E-4	= L/m^2 s
US gal/ft^2 h	× 0.04074	= m^3/m^2 h
US gal/ft^2 h	× 0.011316	= L/m^2 s
US gal/ft^2 min	× 2.45	= m^3/m^2 h
US gal/ft^2 min	× 0.6789	= L/m^2 s
miles/h	× 1.6093	= km/h
miles/h	× 0.447	= m/s
ft^3/acre s	× 0.06998	= m^3/(ha.s)
ft^3/acre s	× 6.998E-6	= m/s
mpy (mil per year)	× 0.025	= mm/a
cm/s	× 10^{-2}	= m/s
cm/min	× 0.166	= L/m^2 s
cm^3/cm^2 h	× 0.0028	= L/m^2 s
dm/s	× 10^{-1}	= m/s
m/min	× 1.6667E-2	= m/s
m/h	× 2.7778E-4	= m/s
mm/s	× 1	= L/m^2 s
L/m^2 s	× 3.6	= m^3/m^2 h
scfm/1000 ft^3	× 0.01666	= dm^3/m^2.s.
10^6 US gal/acre-d	× 0.0108247	= L/m^2.s.
knot (nautical mile/h)	× 1.853184	= km/h

Conversions for volumetric flow per unit length, dimensions: L^2/T

Kinematic viscosity, thermal or molecular diffusivity; overflow weir rate

Square meter per second, m^2/s		US gal/(day ft)	× 0.01242	= m^3/day.m
		m^3/(day.m)	× 1.157E-5	= m^2/s
Diffusivities:		centistokes		= mm^2/s
for gases	*0.1 to 1 cm^2/s*	(1 stoke = cm^2/s)	× 10^{-4}	= m^2/s
		ft^2/s	× 0.0929	= m^2/s
for liquids	*1000 $\mu m^2/s$*	m^2/h	× 2.7778E-4	= m^2/s
		ft^2/h	× 2.5806E-5	= m^2/s
for solids	*0.1 to 10^4 nm^2/s*	in^2/s	× 6.451E-4	= m^2/s
		dm^2/s	× 10^{-2}	= m^2/s
Kinematic viscosity:		mm^2/s	× 10^{-6}	= m^2/s
		cm^2/s	× 10^{-4}	= m^2/s
for water	*10^6 $\mu m^2/s$*	cm^2/s	× 10^8	= $\mu m^2/s$
		$\mu m^2/s$	× 10^{-12}	= m^2/s
		nm^2/s	× 10^{-18}	= m^2/s
		SSU	× 2.165E-3	= cm^2/s
		USgpm/in	× 2.484252	= L/s.m
		USgpm/ft	× 0.207021	= L/s.m

Conversions for mass, dimensions: M

kilogram, kg	lb_m	× 0.4536	= kg
	grain	× 6.48E-2	= g
metric ton = Mg	ton (2000 lb_m)	× 0.9072	= Mg
	long ton (2240 lb_m)	× 1.016	= Mg
your mass 50 to 90 kg	metric tonne	× 1.000	= Mg
	g	× 10^{-3}	= kg
	mg	× 10^{-6}	= kg
	oz	× 28.349	= g
	cwt (long)	× 50.8023	= kg
	cwt (short)	× 45.3592	= kg

Conversions for molar mass, dimensions: M

kg/kmol
depends on the substance
g/mol

for water: molar mass is 18 kg/kmol

for air: molar mass is 29 kg/kmol

Conversions for amount of substance, dimensions: dimensionless

kmol: mass of a substance divided by the molar mass

1 mol of He = 1 gram-atom of He
1 mol of Na_2CO_3 = 1 gram-molecule of Na_2CO_3
1 mol of CLO^{-}_{4} = 1 gram-ion of CLO^{-}_{4}
1 mol of Cl_2 = mass of 70.914 g
1 mol of Cl^{-} = mass of 35.457 g
1 mol of $\frac{1}{2}$ Ca^{2+} = mass of 20.04 g
1 mol of e^{-} = mass of 548.6 μg

lb-mole	× 0.4536	= kmol
mol	× 10^{-3}	= kmol

DO NOT USE:
g-mole or kg-mole;
instead use:
mol or kmol, respectively.

Conversions for mass ratio, dimensions: dimensionless

grains/lb_m dry air	× 0.1429	= g/kg
lb_m/short ton	× 0.5	= kg/Mg

Conversions for mass per unit volume, dimensions: M/L^3

Density and mass concentration; reciprocal: volume/mass ratio

kilogram per cubic meter, kg/m^3

density of liquid water = 1 Mg/m^3
of air (STP) = 1.2 kg/m^3
of steel = 7.8 Mg/m^3
of mercury = 13.6 Mg/m^3

ppm ≈ mg/L

slug/ft^3	× 515.38	= kg/m^3
lb_m/ft^3	× 16.02	= kg/m^3
lb_m/1000 ft^3	× 0.01602	= kg/m^3
lb_m/UK gal	× 99.779	= kg/m^3
lb_m/US gal	× 119.8	= kg/m^3
lb_m/bbl	× 2.853	= kg/m^3
grains per US gal	× 17.12	= g/m^3
grains/ft^3	× 2.288	= g/m^3
g/cm^3	× 10^3	= kg/m^3
g/L	× 1	= kg/m^3
mg/L	× 10^{-3}	= kg/m^3
US gal/lb	× 8.34435	= L/kg

Conversions for mass/unit area or vice versa, dimensions: M/L^2

mass/area; reciprocal, surface area/mass			
kilogram per square meter, kg/m^2	lb$_m$/ft^2	× 4.882	= kg/m^2
	lb$_m$/in^2	× 703.069	= kg/m^2
	short tons/acre	× 0.224	= kg/m^2
	short tons/sq mile	× 350.265	= mg/m^2
reciprocal: **square meter per kilogram: m^2/kg**	cm^2/g	× 10^{-3}	= m^2/kg
	m^2/g	× 10^3	= m^2/kg
	ft^2/lb$_m$	× 0.2048	= m^2/kg

Conversions for length/mass ratio, dimensions: L/M

Filter cake resistance,			
filter cake:	ft/lb$_m$	× 0.67285	= m/kg

Conversions for mass rate/mass, dimensions: 1/T

Oxygen usage, utilization of a substrate			
Oxygen usage 1.4–11 mg O_2 /s.kg VSS			
k, = 60–80 mg COD/s.kg VSS.	mg/h..g	× 0.277	= mg/s. kg
food/microorganism ratio = 3–12 mg BOD$_5$/s.kg MLVSS	kg/day.kg	× 11.574	= mg/s.kg

Conversions for mass flowrate dimensions: M/T

kilogram/second: kg/s	lb$_m$/s	× 0.4536	= kg/s
	lb$_m$/min	× 7.56	= g/s
	lb$_m$/h	× 126	= mg/s
	lb$_m$/h	× 0.4536	= kg/h
	MM lb$_m$/a	× 0.4536	= Gg/a
	short ton/h	× 0.28224	= kg/s
	short ton/day	× 0.30	= Mg/a(330 day)
		× 0.33	= Mg/a(365 day)
		× 10.5	= g/s
	kg/h	× 2.7778E-4	= kg/s

Conversions for mass flowrate per unit length, dimensions: M/LT

Viscosity			
Pascal. second: kg/(s·m) = Pa·s = N·s/m^2	lb$_m$/(s.ft)	× 1.4882	= Pa·s
	lb$_m$/(h.ft)	× 0.41338	= mPa·s
viscosity of liquid water: 1 mPa·s	lb$_f$·s/ft^2	× 47.88	= Pa·s
	poundal·s/ft^2	× 1.488	= Pa·s
Poiseuille = Pa·s	g/(cm·s)	× 0.1	= Pa·s
	Poise	× 0.1	= Pa·s
	Centipoise	× 1	= mPa·s
	PI	× 10^3	= mPa·s
	kg/(m·h)	× 0.2777	= mPa·s

Conversions for mass flowrate per unit area, dimensions: M/L^{2}T

Mass flux and mass transfer coefficient per unit dimensionless driving force; surface loading: *reciprocal:* gas permeation unit

kilogram per second per square meter: kg/(s m^2)	lb$_m$/(s.ft^2)	× 4.882	= kg/(s.m^2)
	lb$_m$/(min.ft^2)	× 0.0814	= kg/(s.m^2)
	lb$_m$/(h.ft^2)	× 1.356	= g/(s.m^2)
	lb$_m$/(day.ft^2)	× 0.0565	= g/(s.m^2)
surface loading	ton/(h.ft^2)	× 2.712	= kg/(s.m^2)
anaerobic pond, summer	ton/(day.ft^2)	× 0.113	= kg/(s.m^2)
600–3500 μg BOD$_5$/s.m^2	g/(s.cm^2)	× 10	= kg/(s.m^2)
	kg/(h.m^2)	× 0.278	= g/(s.m^2)
	lb/(acre.day)	× 1.2973	= μg/(s.m^2)
	lb/(acre.day)	× 0.112	= g/(day.m^2)
	kg/(ha.day)	× 1.15745	= μg/(s.m^2)
reciprocal:			
GPU gas permeation unit	10^{-6} cm^3/(cm^2.s. cm Hg)	× 7.51879	= cm^3/(m^2.s.MPa)
GPU = Barrer/membrane thickness	m^3/m^2. h.bar	× 2.7777	= L/(m^2.s.MPa)

Conversions for mass flowrate per unit volume, dimensions: M/L^{3}T

Reaction rate: *reciprocal*: permeance, intrinsic permeability of membranes

kilogram per second per cubic meter:	lb$_m$/(s.ft^3)	× 16.085	= kg/(s.m^3)
kg/(s m^3)	lb$_m$/(h.ft^3)	× 4.46809	= g/(s.m^3)
	lb$_m$/(day. 1000 ft^3)	× 0.1861	= kg/(s.m^3)
liquid phase reaction rate: 10 to 200 g/s.m^3	g/(s.cm^3)	× 1	= Mg/(s.m^3)
	g/(h.L)	× 0.27778	= g/(s.m^3)
	kg/(h.m^3)	× 0.27778	= g/(s.m^3)
reciprocal	cm^2/s.atmos	× 0.098687	= (cm)^4/(s.N)
D'Arcy/viscosity, cp = cm^2/s.atmos	m^4/s.N	× 1000	= m^2/(s.kPa)
Barrer = 10^{-10} Ncm^3.cm/cm^2.s.cm Hg	cm^2/s.atmos	× 0.0098687	= cm^2/(s.kPa)
	10^{-10} Ncm^3.cm/ cm^2.s.cmHg	× 7.51879	= cm^3.μm/(m^2.s. MPa)

Conversions for mass flux per unit pressure driving force, dimensions: T/L

Mass transfer coefficient per unit pressure driving force.

kilogram per second per square meter per	lb$_m$/(h.ft^2·atmos.)	× 13.384	= mg/(s.m^2·kPa)
kilopascal driving force: kg/(s·m^2 kPa)	g/(s.cm^2·atmos.)	× 0.09869	= kg/(s.m^2·kPa)
	g/(s.cm^2·atmos.)	× 98.69	= kg/(s.m^2·MPa)
gas film controlled: 10 mg/s·m^2·kPa	kg/(h.m^2·atmos.)	× 2.741	= mg/(s.m^2·kPa)

Conversions for force, dimensions: ML/T^2

force, impact strength

Newton, N = kg.m/s^2	lb$_f$	× 4.448	= N
force acting on an apple in the earth's	poundal	× 0.138	= N
gravitational field is about 1 N	(2000 lb$_f$) ton$_f$	× 9.96	= kN
	kip	× 4.448	= kN
g = acceleration due to "standard"	kg$_f$	× 9.8067	= N
gravity = 9.8067 m/s^2	dyne	× 10^{-7}	= N
	ft lb$_f$/in	× 53.37795	= N

In a gravitational field of "g", the force on a mass M is Mg Newtons.

Conversions for momentum, dimensions: ML/T

kilogram meter per second: kg.m/s	lb_m.ft/s	× 0.138225	= kg.m/s
	lb_m.ft/h	× 3.8396E-5	= kg.m/s
	g.cm/s	× 10^{-5}	= kg.m/s

Conversions for angular momentum, dimensions: ML^2/T

kilogram square meter per second: kg.m^2/s	lb_m.ft^2/s	× 0.042145	= kg.m^2/s
	lb_m.ft^2/h	× 1.1706E-5	= kg.m^2/s
	g.cm^2/s	× 10^{-7}	= kg.m^2/s

Conversions for moment of inertia, dimensions: ML^2

kilogram square meter: kg.m^2	lb_m.ft^2	× 0.042145	= kg.m^2
	lb_m.in^2	× 2.926E-4	= kg.m^2
	slug.ft^2	× 1.355	= kg.m^2
	kg.cm^2	× 10^{-4}	= kg.m^2

Conversions for surface tension, dimensions: M/T^2

Newton per meter: N/m	dyne/cm	× 1	= mN/m
surface tension for water: 72 mN/m	lb_f/ft	× 14.59	= N/m
for oils: about 30 mN/m			

Conversions for force per unit area, dimension: M/LT^2

Pressure, stress, momentum flowrate per unit area; packing loading factor: *reciprocal:* volume flux per unit pressure driving force

kilopascal, kPa
Pressure is always absolute
(not gauge pressure)
≡ 1000 N/m^2
≡ 1/100 bar
≃ 1/100 atmos.
≃ blow into a manometer and display 10 cm water vertically.
Pa = kg.s^{-2}.m^{-1}
Atmospheric pressure: 101.325 kPa, 760 mm mercury, 29.921 inches mercury
Stress:

strength of concrete	*20 MPa*
design stress of concrete	*9 MPa*
yield strength of steel	*350 MPa*
design stress of steel	*165 MPa*

packing loading factor: sometimes expressed as (m/s)^2 (kg/m^3) and sometimes as (m/s) (kg/m^3)$^{0.5}$

_______________ reciprocal:

cubic meters per second per square meter per kiloPascal driving force: m^3/(s.m^2.kPa)

atmos	× 101.33	= kPa
bar	× 100	= kPa
psi	× 6.895	= kPa
inches water (at 3.9 °C)	× 0.249	= kPa
feet water	× 2.989	= kPa
cm water	× 0.098	= kPa
mm water	× 0.0098	= kPa
inches mercury (at 0 °C)	× 3.386	= kPa
mm mercury	× 0.133	= kPa
torr	× 0.133	= kPa
micron	× 0.133	= Pa
N/m^2	× 10^{-3}	= kPa
N/mm^2	× 1	= MPa
kg$_f$/cm^2	× 98.066	= kPa
lb$_f$/ft^2	× 47.88	= kPa
dyne/cm^2	× 0.1	= Pa
g/cm.s^2	× 0.1	= Pa
ksi	× 6.895	= MPa
tons$_f$/in^2	× 15.4	= MPa
(ft/s)^2 (lb$_m$/ft^3)	× 1.4883	= kg/s^2.m
US gal/ft^2.day.psi)	× 0.0706	= mL/m^2.s.MPa

Conversions for pressure/unit length, dimensions: M/L^{2}T^2

kPa/meter:

pressure drop for gas flowing through packed bed:
20 kPa/m

in water/ft	× 0.81693	= kPa/m
psi/ft	× 22.62	= kPa/m

Conversions for energy, dimension: ML^2/T^2

Torque, moment of force.

Joule, J ≡ N.m ≡ W.s

Joule is the amount of energy to raise the temperature of a cube of water 6 mm × 6 mm × 6 mm by 1 °C.

bbl crude oil equiv.	*× 5.9*	*= GJ*
Mg crude oil equiv.	*× 44*	*= GJ*
m^3 crude oil equiv.	*× 37*	*= GJ*
Mg coal equiv.	*× 29*	*= GJ*
m^3 natural gas equiv.	*× 37*	*= MJ*
ft^3 natural gas equiv.	*× 1.05*	*= MJ*
Mg deuterium (fusion equiv.)	*× 0.25*	*= EJ*
Mg uranium 235 (fission eq.)	*× 83*	*= PJ*
ton (nuclear equiv. of TNT)	*× 4.2*	*= GJ*
ton-day of refrigeration	*× 0.5275*	*= MJ*

cal	× 4.187	= J
BTU	× 1.055	= kJ
hp.hr	× 2.684	= MJ
kW.h	× 3.6	= MJ
MM BTU	× 1.055	= GJ
10^6 kcal	× 4.187	= GJ
kg_f.m	× 9.8066	= J
ft.lb_f	× 1.3558	= J
in.lb_f	× 0.133	= J
in.oz_f	× 7.062	= mJ
dyne.cm	× 10^{-7}	= J
erg	× 10^{-7}	= J
erg	× 0.1	= µJ
electron volt	× 0.1602	= aJ
therm	× 105.5	= MJ
CHU or PCU	× 1.899	= kJ
Quad	× 1.055	= EJ
litre-atmos.	× 0.1011	= kJ
ft^3-atmos.	× 2.869	= kJ
poncelet-h	× 3.353	= MJ

Conversions for energy/unit amount of substance, dimensions: ML^2/T^2

kilojoule per kilomole: kJ/kmol:

latent heat of evaporation for water:	*45 MJ/kmol*
latent heat of fusion for water:	*6 MJ/kmol*
typical heat of reaction:	*200 MJ/kmol*

cal/mol	× 4.1868	= kJ/kmol
BTU/lb-mole	× 2.326	= kJ/kmol

Conversions for force/unit length or energy per unit area, dimensions: M/T^2

Surface tension, surface energy per unit area.

Newton per meter: N/m or
joule per square meter: J/m^2

surface tension for water: 72 mN/m
for oils: about 20 mN/m

dyne/cm	× 1	= mN/m
lb_f/ft	× 14.59	= N/m
erg/cm^2	× 10^{-3}	= J/m^2
erg/cm^2	× 1	= mJ/m^2
mN/m	× 1	= mJ/m^2

Conversions for energy/unit volume, dimensions: M/T^2L

Hildebrand solubility parameters

Joule per cubic meter: kJ/m^3		cal/cm^3	× 4.1868	= MJ/m^3
heating values for:		kcal/m^3	× 4.1868	= kJ/m^3
low quality synthetic gas:	*15 MJ/m^3*	BTU/ft^3	× 37.26	= kJ/m^3
natural gas:	*35 MJ/m^3*	therm/ft^3	× 3.726	= GJ/m^3
No. 2 fuel oil:	*42 MJ/L*	1000 BTU/bbl.	× 6.636	= MJ/m^3
diesel oil:	*42 MJ/L*	kWh/bbl.	× 22.643	= MJ/m^3
bunker C fuel oil:	*42 MJ/L*	hp/1000 cfm	× 1.58	= kW.s/m^3
Hildebrand solubility parameters:		1000 BTU/UK gal	× 0.2318	= MJ/L
dispersion contribution:	*10 (J/cm^3)$^{1/2}$*	(cal/cm^3)$^{1/2}$	× 2.046	= (J/cm^3)$^{1/2}$

Conversions for energy/unit mass, dimension: L^2/T^2

Latent heat, specific enthalpy; reciprocal: mass of gas absorbed per energy input, oxygen transfer

kilojoule per kilogram, kJ/kg		cal/g	× 4.1868	= kJ/kg
		BTU/lb$_m$	× 2.326	= kJ/kg
Latent heat of water:	*2000 kJ/kg*	kW.h/lb$_m$	× 7775.7	= MJ/Mg
of organics:	*400 kJ/kg*	CHU or PCU/lb$_m$	× 4.1868	= kJ/kg
heat of fusion of water:	*300 kJ/kg*	reciprocal:		
of organics:	*125 kJ/kg*	lb$_m$/(hp.h)	× 0.169	= mg/J or mg/s.W
reciprocal:				
oxygen transfer: 0.3–1.5 g O_2/s.kW		lb$_m$/(hp.h)	× 0.6084	= kg/(kW.h)

Conversions for energy/degree/unit amount of substance, dimensions: $ML^2/T^2\theta$

Molar entropy, molar heat capacity

kilojoule per kilomole per degree Kelvin:		cal/mol.°C	× 4.1868	= kJ/(kmol.K)
kJ/(kmol.K):		BTU/lb-mole.°F	× 4.1868	= kJ/(kmol.K)
molar heat capacity:				
liquid water:	*75 kJ/(kmol.K)*			
air:	*30 kJ/(kmol.K)*			

Conversions for energy/unit degree/unit mass, dimensions: $L^2/T^2\theta$

Specific heat capacity

kilojoule per kilogram per degree Kelvin:	cal/g.°C	× 4.1868	= kJ/(kg.K)
kJ/(kg.K)	BTU/lb_m.°F	× 4.1868	= kJ/(kg.K)

heat capacity for liquid water: *4.2 kJ/(kg.K)*
for gas water: *2 kJ/(kg.K)*
for air: *1 kJ/(kg.K)*

Conversions for energy/unit time, dimensions: ML^2/T^3

Power, energy flowrate, energy "duty"

kilowatt: kW ≡ kJ/s ≡ kg.m^2/s^3	cal/s	× 4.187	= W
	kcal/h	× 1.163	= W
Boiler horsepower: 34.5 lb_m of water evaporated per hour of dry, saturated steam at 100°C	tonne-cal/h	× 1.163	= kW
	BTU/s	× 1.055	= kW
	k BTU/h	× 0.2931	= kW
	hp	× 0.7457	= kW
	kg_f.m/s	× 9.8066	= W
	ft.lb_f/s	× 1.3558	= W
	erg/s	× 10^{-7}	= W
	MJ/h	× 0.277	= kW
	cheval	× 0.736	= kW
	ton refrigeration	× 3.5169	= kW
	k CHU/h	× 0.52758	= kW

Conversions for energy/unit time/unit amount of substance dimensions: ML^2/T^3

Energy flowrate/amount of substance

kilowatt per kilomole: kW/kmol	BTU/lb-mole.h	× 0.646	= W/kmol

Conversions for energy/unit time/unit mass, dimensions: L^2/T^3

Energy flowrate/unit mass

kilowatt per kilogram: kW/kg	cal/(s.g)	× 4.1868	= kW/kg
	kcal/(h.kg)	× 1.163	= W/kg
	kBTU/(h.lb_m)	× 0.646	= kW/kg

Conversions for energy flowrate/unit area, dimensions: M/T^3

Heat flux density, energy flux

kilowatt per square meter: kW/m^2:		cal/(s.cm^2)	× 41.868	= kW/m^2
		kcal/(h.m^2)	× 1.163	= W/m^2
radiant heat transfer:	*40 to 60 kW/m^2*	kBTU/(h.ft^2)	× 3.1546	= kW/m^2
critical boiling heat flux:		MJ/(h.m^2)	× 0.277	= kW/m^2
for water	*1000 kW/m^2*	kJ/(h.m^2)	× 0.277	= W/m^2
for organics	*90 kW/m^2*	hp/ft^2	× 8.0269	= kW/m^2

Conversions for energy flowrate/unit volume, dimension: M/LT^3

Volumetric heat release rate, power per unit volume

watt per cubic meter: W/m^3	cal/(s.cm^3)	× 4.1868	= MW/m^3
	kcal/(h.m^3)	× 1.163	= W/m^3
Turbine mixing in a tank of liquid	kBTU/(h.ft^3)	× 10.35	= kW/m^3
1 kW/m^3	kcal/(h.ft^3)	× 41.07	= W/m^3
	hp/1000 US gal	× 0.197	= kW/m^3
	hp/1000 ft^3	× 0.0264	= kW/m^3
	ft.lb$_f$/(s.ft^3)	× 0.048	= kW/m^3

Conversions for energy flux per degree driving force, dimensions: $M/T^3\theta$

Heat transfer coefficient; reciprocal: fouling coefficient

watts per square meter per degree Kelvin:		cal/(s.cm^2.K)	× 41.868	= kW/m^2.K
W/(m^2.K):		kcal/(h.m^2.K)	× 1.163	= W/m^2.K
		kBTU/(h.ft^2.°F)	× 5.6784	= kW/m^2.K
condensing steam:	*5000 W/m^2.K*	CHU/(h.ft^2.K)	× 5.6784	= W/m^2.K
gas–gas transfer:	*25 W/(m^2.K)*	PCU/(h.ft^2.K)	× 5.6784	= W/m^2.K
		lb-cal/(h.ft^2.°C)	× 5.6784	= W/m^2.K
		cal/(h.cm^2.°C)	× 0.01163	= kW/m^2.K
reciprocal:		h.ft^2.F/BTU	× 0.1761	= m^2.K/W

Conversions for energy flux per degree per unit length, dimensions: ML/T$^3\theta$

Thermal conductivity

watts per square meter per degree Kelvin per meter: W/(m^2.K/m) ≡ W/(m.K)

thermal conductivity of

liquid water:	*0.6 W/(m.K)*
gas:	*20 mW/(m.K)*

cal/(s.cm.°C)	× 418.68	= W/(m.K)
kcal/(h.m.°C)	× 1.163	= W/(m.K)
BTU/(h.ft °F)	× 1.7308	= W/(m.K)
BTU/(h.ft^2.°F/in)	× 0.1442	= W/(m.K)

Conversions for energy flowrate/unit volume per degree driving force, dimensions: M/LT$^3\theta$

Volumetric heat transfer coefficient

watts per cubic meter per degree Kelvin: W/(m^3.K)

CHU/(h.ft^3.°C)	× 18.63	= W/(m^3.K)
BTU/(h.ft^3.°F)	× 18.63	= W/(m^3.K)

Conversions for charge, dimensions: IT

Coulomb, C

large value	*1 C*
medium value	*100 μC*
small value	*50 pC*
electrostatic charge on a person:	*100 nC*
charge on an electron:	*0.16 aC*
charge transfer in/out digital CMOS transistor:	*10 pC*
charge on 1000 μF capacitor at 10 V	*10 mC*

statcoulomb	× 0.3336	= nC
abcoulomb	× 10	= C
faraday		
(based on C^{12})	× 96.487	= kC
(chemical)	× 96.4957	= kC
(physical)	× 96.5219	= kC
ampère-hr	× 3600	= C

Conversions for charge per unit area, dimensions: IT/L^2

Surface charge density, electric derived field or displacement, dielectric polarization

Coulomb per square meter, C/m^2

clay particles in water	*40 mC/m^2*
small charge	*μC/m^2*
dielectric capacitors:	*mC/m^2*
on control electrode in CMOS device:	*mC/m^2*

statcoulomb/cm^2	× 3.336	= μC/m^2
abcoulomb/cm^2	× 0.1	= MC/m^2
statvolt/cm	× 0.2653	= μC/m^2
abvolt/cm	× 7.96	= kC/m^2

Conversions for charge per unit volume, dimensions: IT/L^3

Volumetric charge density.

Coulomb per cubic meter, C/m^3		statcoulomb/cm^3	× 0.3336	= mC/m^3
		abcoulomb/cm^3	× 10	= MC/m^3
conduction electric charge.				
in metal conductors:	*16 GC/m^3*			
in n-type semiconductors:	*1.6 kC/m^3*			

Conversions for charge flowrate, dimensions: I

Current

Ampère: A		statamp	× 0.33356	= nA
		abamp	× 10	= A
start a 0.25 kW motor	*13 A*	esu current	× 0.3336	= nA
electric kettle	*13 A*	emu current	× 10	= A
refine alumina	*10 kA*	amp-turn	× 10	= A
usual current in low power junction type semiconductor	*10 μA to 10 mA*	gilbert	× 0.7958	= A
usual control electrode or OFF current in CMOS devices:	*pA to nA*			
usual current in SCR power devices:	*1 A to 1 kA*			
dangerous lethal current inside human bodies:	*100 μA to 1 mA*			

Conversions for charge flowrate per unit length, dimensions: I/L

Magnetism, magnetic derived strength, magnetic intensity

Ampère per meter, A/m		esu	× 2.653	= nA/m
		gauss	× 79.577	= A/m
for iron	*1 kA/m*	oersted	× 79.577	= A/m
		abampère-turn/cm	× 1	= kA/m
		amp-turn/cm	× 100	= A/m
		amp-turn/in	× 39.37	= A/m
		praoerstead	× 4 π	= A/m

Conversions for charge flowrate per unit area, dimensions: I/L^2

Current density, current per unit area, charge flux

ampère per square meter, A/m^2		statamp/cm^2	× 3.336	= $\mu A/m^2$
		abamp/cm^2	× 100	= kA/m^2
electroplating or electrorefining:	*10 to 2000 A/m^2*	amp/ft^2	× 10.87	= A/m^2
semiconductor junction:	*10 MA/m^2*			
solar cell:	*400 A/m^2*			

Conversions for electric potential, dimensions: ML^2/IT^3

Electromotive force

Volt, V = J/A.s		statvolt	× 299.79	= V
Power transmission lines:	*250 kV, 500 kV*	esu electric pot.	× 299.79	= V
household circuits:		abvolt	× 10	= nV
North American	*110 V(rms)*	emu electric pot.	× 0.01	= μV
European & Asian	*240 V (rms)*			
clay particles suspended in water:	*80 mV*	International (1948) volt	× 1.000330	= V
magnetic phono cartridge signal output level:	*5 mV*			
muscle (EMG) cell potential:	*1 mV*			
electrostatic potential on human body:	*1 kV*			
accelerating voltage in TV picture tube:	*30 kV*			

Conversions for electric potential per unit length, dimensions: ML/IT^3

Potential gradient

Volt per meter, V/m = J/(m.A.s)		statvolt/cm	× 29.979	= kV/m
		abvolt/cm	× 1	= μV/m
breakdown occurs in air:	*2 MV/m*			
breakdown of semiconductors:	*20 MV/m*			
radiated field near a transformer:	*1 mV/m*			

Conversions for resistance, dimensions: ML^2/I^2T^3

Ohm, Ω = V/A		statohm	× 898.76	= GΩ
		esu resistance	× 898.76	= GΩ
leakage resistance of small telflon stand-off:	*10^{14} Ω*	abohm	× 1	= nΩ
coaxial cable:	*10^{11} Ω*	emu resistance	× 1	= nΩ
finger to finger resistance potential:	*50 kΩ*	Gaussian cgs	× 898.76	= GΩ
integrated circuit diffused resistors:	*<10 kΩ*	s/cm	× 898.76	= GΩ
		International (1948) ohm	× 1.000495	= Ω

Conversions for resistance per unit length, dimensions: ML/I^2T^3

Resistivity

Ohm-meter, Ωm		statohm.cm	× 8.9876	= GΩm
		esu resistance	× 8.9876	= GΩm
steel	*620 nΩ.m*	abohm.cm	× 10	= pΩm
copper	*17 nΩ.m*	emu resistance	× 10	= pΩm
nichrome	*1000 nΩ.m*	microohm-cm	× 10	= nΩm
semiconductors	*1 μΩ.m to 5 kΩ.m*	ohm-cm	× 0.01	= Ωm
insulators	*10 kΩ.m to 10^4 GΩ.m*	ohm-circular mil per ft	× 1.662	= nΩm

Conversions for conductance, dimensions: I^2T^3/ML^2

Electrical conductivity

Siemen, S = A/V		statmho	× 1.113	= pS
		abmho	× 1	= GS

Conversions for conductance per unit length, dimensions: I^2T^3/ML^3

Specific conductivity, length conductivity

Siemen per meter, S/m		statmho/cm	× 0.1113	= nS/m
liquid solutions	*1 mS/m*	abmho/cm	× 10	= TS/m

Conversions for conductance per unit volume, dimensions: I^2T^3/ML^5

Volume conductivity			
Siemens per cubic meter, S/m^3	statmho/cm^3	× 1.113	= µS/m^3
	abmho/cm^3	× 1000	= TS/m^3

Conversions for capacitance, dimensions: I^2T^4/ML^2

Farad, F = C/V	statfarad	× 1.113	= pF
large capacitances to correct power factor	esu capacitance	× 1.113	= pF
100 µF	abfarad	× 1	= GF
DC power supplies, rectification	emu capacitance	× 1	= GF
10 mF	Gaussian-cm	× 1.113	= pF
audio amplifier bypass	International		
50 µF	(1948) farad	× 0.999505	= F
radio frequency bypass			
1 nF			
oscilloscope probe-tip capacitance			
8 pF			
human body capacitance			
100 pF			
two, 3 cm conductors glued side by side			
1 pF			
integrated circuit device			
5 pF			

Conversions for magnetic volume susceptibility, dimensions: dimensionless

rationalized unit	emu/cm^3	× 4 π	= rationalized unit

Conversions for magnetic mass susceptibility, dimensions: L^3/M

cubic meters per kilogram, m^3/kg	emu/g	× 4 πE-3	= m^3/kg
	cm^3/g	× 4 πE-3	= m^3/kg

Conversions for magnetic flux, dimensions: ML^2/IT^2

Weber, Wb = V.s	esu line	× 0.2998	= kWb
	maxwell	× 0.01	= μWb
iron core magnet for HiFi speaker	Gauss-cm^2	× 0.01	= μWb
1 mWb	Maxwell	× 10	= nWb
	unit pole	× 0.12566	= μWb
	kiloline	× 10	= μWb

Conversions for magnetic flux density, dimensions: M/IT^2

Magnetic induction, magnetic force vector

Tesla, T = Wb/m^2		esu	× 0.2998	= MT
		gauss	× 0.10	= mT
iron core magnet	*1 T*	gamma	× 1	= nT
air core magnet	*1 mT*	kiloline/in^2	× 15.5	= mT
magnetic deflecting yoke of TV		A/m	× 4 πE-7	= T
picture tube provides field of	*2 mT*		× 0.4 π	= μT
earth's magnetic field	*0.1 mT*			
strong bar magnet	*0.2 T*			

Conversions for inductance, dimensions: ML^2/I^2T^2

Henry, H = Wb/A		stathenry	× 0.8988	= TH
5 cm length of 1 mm		esu inductance	× 0.8988	= TH
diameter wire	*10 nH*	Gaussian esu	× 0.8988	= TH
for very high radio		abhenry	× 1	= nH
frequencies	*μH*	emu inductance	× 1	= nH
usual radio		International		
frequencies	*μH to mH*	(1948) henry	× 1.000495	= H
audio frequencies	*H*			
iron core electromagnet at a				
scrap yard:	*10 H*			
small transformer with multiturns of				
very fine wire:	*5000 H*			

Conversions for luminous intensity, dimensions: dimensionless

Light intensity

candela, cd

LED (light emitting diode) = *10 mcd*

Conversions for luminance, dimensions: $1/L^2$

candela per square meter, $\mathrm{cd/m^2}$	$\mathrm{candle/ft^2}$	× 10.764	$= \mathrm{cd/m^2}$
	$\mathrm{candle/in^2}$	× 1.55	$= \mathrm{kcd/m^2}$
	ft-lambert	× 3.426	$= \mathrm{cd/m^2}$

Conversions for luminex flux, dimensions: dimensionless

lumen, ℓm = cd.sr

100 watt bulb emits *1.7 kℓm*

Conversions for luminex flux per unit area, dimensions: $1/L^2$

lux = lumens per square meter, $\ell\mathrm{m/m^2}$	ft candle	× 10.76391	$= \ell\mathrm{m/m^2}$

Conversions for time, dimensions: T

second, s	minute	× 60	= s
	h	× 3600	= s
	day	× 86400	= s
	a	× 31.55	= Ms

Conversions for frequency, dimensions: 1/T

hertz, Hz = 1 cycle per second

electrical circuit	*60 Hz*
audio frequency	*kHz*
radio frequency	*MHz*

Conversions for rotational frequency, dimensions: 1/T

rotational speed, angular velocity

radians per second, 1/s	r/min	× 2π/60	= rad/s
revolution per minute is commonly used and is accepted by the supplementary practice guide 1978.	rad/s	× 60/2π	= r/min
rpm for motors nominal 1800 r/min (1750 r/min actual)			

Conversions for plane angle, dimensions: dimensionless

radian, rad		degree	× 0.01745	= rad
circle	*= 2π rad*	minute (angle)	× 2.9088E-4	= rad
		second (angle)	× 4.848E-6	= rad

Some physical and engineering constants

air	23 % O_2; 76.8 % N_2 w/w 21 % O_2; 79 % N_2 v/v
molar volume	22.4 L at 0 °C and 101.325 kPa
std. atmosphere	101.325 kPa
std. gravity acceleration	9.80665 m/s^2
velocity of sound in dry air at 0 °C	331.5 m/s
mass density of water at 4 °C	0.999973 Mg/m^3
temperature at absolute zero	−273.15 °C −459.7 °F

π	3.1416
e	2.7183
Avogardo's number,	6.02217 E23 particles/mol
Ideal gas constant,	8.3143 J/mol.K 8.3143 Pa.m^3/mol.K
Boltzman constant, **k**	1.38 E-23 J/K
Faraday's constant	9.6487 E4 C/equivalent
charge on an electron	1.60219 E-19 C
velocity of light, **c**	2.997925 E8 m/s
mass of an electron	9.10956 E-31 kg
mass of a proton	1.67239 E-27 kg
mass of a neutron	1.6747 E-27 kg

Temperature conversion tables[a]

−459.4 to 0			0 to 100						100 to 1000						1000 to 2000						2000 to 3000					
C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F
−273	**−459.4**		−17.8	**0**	32	10.0	**50**	122.0	37.8	**100**	212	260	**500**	932	538	**1000**	1832	816	**1500**	2732	1093	**2000**	3632	1371	**2500**	4532
−268	**−450**		−17.2	**1**	33.8	10.6	**51**	123.8	43	**110**	230	266	**510**	950	543	**1010**	1850	821	**1510**	2750	1099	**2010**	3650	1377	**2510**	4550
−262	**−440**		−16.7	**2**	35.6	11.1	**52**	125.6	49	**120**	248	271	**520**	968	549	**1020**	1868	827	**1520**	2768	1104	**2020**	3668	1382	**2520**	4568
−257	**−430**		−16.1	**3**	37.4	11.7	**53**	127.4	54	**130**	266	277	**539**	986	554	**1030**	1886	832	**1530**	2786	1110	**2030**	3686	1388	**2530**	4586
−251	**−420**		−15.6	**4**	39.2	12.2	**54**	129.2	60	**140**	284	282	**540**	1004	560	**1040**	1904	838	**1540**	2804	1116	**2040**	3704	1393	**2540**	4604
−246	**−410**		−15.0	**5**	41.0	12.8	**55**	131.0	66	**150**	302	288	**550**	1022	566	**1050**	1922	843	**1550**	2822	1121	**2050**	3722	1399	**2550**	4622
−240	**−400**		−14.4	**6**	42.8	13.3	**56**	132.8	71	**160**	320	293	**560**	1040	571	**1060**	1940	849	**1560**	2840	1127	**2060**	3740	1404	**2560**	4640
−234	**−390**		−13.9	**7**	44.6	13.9	**57**	134.6	77	**170**	338	299	**570**	1058	577	**1070**	1958	854	**1570**	2858	1132	**2070**	3758	1410	**2570**	4658
−229	**−380**		−13.3	**8**	46.4	14.4	**58**	136.4	82	**180**	356	304	**580**	1076	582	**1080**	1976	860	**1580**	2876	1138	**2080**	3776	1416	**2580**	4676
−223	**−370**		−12.9	**9**	48.2	15.0	**59**	138.2	88	**190**	374	310	**590**	1094	588	**1090**	1994	866	**1590**	2894	1143	**2090**	3794	1421	**2590**	4694
−218	**−360**		−12.2	**10**	50.0	15.6	**60**	140.0	93	**200**	392	316	**600**	1112	593	**1100**	2012	871	**1600**	2912	1149	**2100**	3812	1427	**2600**	4712
−212	**−350**		−11.7	**11**	51.8	16.1	**61**	141.8	99	**210**	410	321	**610**	1130	599	**1110**	2030	877	**1610**	2930	1154	**2110**	3830	1432	**2610**	4730
−207	**−340**		−11.1	**12**	53.6	16.7	**62**	143.6	100	**212**	413	327	**620**	1148	604	**1120**	2048	882	**1620**	2948	1160	**2120**	3848	1438	**2620**	4748
−201	**−330**		−10.6	**13**	55.4	17.2	**63**	145.4	104	**220**	428	332	**630**	1166	610	**1130**	2066	888	**1630**	2966	1166	**2130**	3866	1443	**2630**	4766
−196	**−320**		−10.0	**14**	57.2	17.8	**64**	147.2	110	**230**	446	338	**640**	1184	616	**1140**	2084	893	**1640**	2984	1171	**2140**	3884	1449	**2640**	4784
−190	**−310**		− 9.44	**15**	59.0	18.3	**65**	149.0	116	**240**	464	343	**650**	1202	621	**1150**	2102	899	**1650**	3002	1177	**2150**	3902	1454	**2650**	4802
−184	**−300**		− 8.89	**16**	60.8	18.9	**66**	150.8	121	**250**	482	349	**660**	1220	627	**1160**	2120	904	**1660**	3020	1182	**2160**	3920	1460	**2660**	4820
−179	**−290**		− 8.33	**17**	62.6	19.4	**67**	152.6	127	**260**	500	354	**670**	1238	632	**1170**	2138	910	**1670**	3038	1188	**2170**	3938	1466	**2670**	4838
−173	**−280**		− 7.78	**18**	64.4	20.0	**68**	154.4	132	**270**	518	360	**680**	1256	638	**1180**	2156	916	**1680**	3056	1193	**2180**	3956	1471	**2680**	4856
−169	**−273**	−459.4	− 7.22	**19**	66.2	20.6	**69**	156.2	138	**280**	536	366	**690**	1274	643	**1190**	2174	921	**1690**	3074	1199	**2190**	3974	1477	**2690**	4874
−168	**−270**	−454	− 6.67	**20**	68.0	21.1	**70**	158.0	143	**290**	554	371	**700**	1292	649	**1200**	2192	927	**1700**	3092	1204	**2200**	3992	1482	**2700**	4892
−162	**−260**	−436	− 6.11	**21**	69.8	21.7	**71**	159.8	149	**300**	572	377	**710**	1310	654	**1210**	2210	932	**1710**	3110	1210	**2210**	4010	1488	**2710**	4910
−157	**−250**	−418	− 5.56	**22**	71.6	22.2	**72**	161.6	154	**310**	590	382	**720**	1328	660	**1220**	2228	938	**1720**	3128	1216	**2220**	4028	1493	**2720**	4928
−151	**−240**	−400	− 5.00	**23**	73.4	22.8	**73**	163.4	160	**320**	608	388	**730**	1346	666	**1230**	2246	943	**1730**	3146	1221	**2230**	4046	1499	**2730**	4946
−146	**−230**	−382	− 4.44	**24**	75.2	23.3	**74**	165.2	166	**330**	626	393	**740**	1364	671	**1240**	2264	949	**1740**	3164	1227	**2240**	4064	1504	**2740**	4964

Temperature conversion tables[a]

−459.4 to 0			0 to 100						100 to 1000						1000 to 2000						2000 to 3000					
C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F
–140	**–220**	–364	– 3.89	**25**	77.0	23.9	**75**	167.0	171	**340**	644	399	**750**	1382	677	**1250**	2282	954	**1750**	3182	1232	**2250**	4082	1510	**2750**	4982
–134	**–210**	–346	– 3.33	**26**	78.8	24.4	**76**	168.8	177	**350**	662	404	**760**	1400	682	**1260**	2300	960	**1760**	3200	1238	**2260**	4100	1516	**2760**	5000
–129	**–200**	–328	– 2.78	**27**	80.6	25.0	**77**	170.6	182	**360**	680	410	**770**	1418	688	**1270**	2318	966	**1770**	3218	1243	**2270**	4118	1521	**2770**	5018
–123	**–190**	–310	– 2.22	**28**	82.4	25.6	**78**	172.4	188	**370**	698	416	**780**	1436	693	**1280**	2336	971	**1780**	3236	1249	**2280**	4136	1527	**2780**	5036
–118	**–180**	–292	– 1.67	**29**	84.2	26.1	**79**	174.2	193	**380**	716	421	**790**	1454	699	**1290**	2354	977	**1790**	3254	1254	**2290**	4154	1532	**2790**	5054
–112	**–170**	–274	– 1.11	**30**	86.0	26.7	**80**	176.0	199	**390**	734	427	**800**	1472	704	**1300**	2372	982	**1800**	3272	1260	**2300**	4172	1538	**2800**	5072
–107	**–160**	–256	– 0.56	**31**	87.8	27.2	**81**	177.8	204	**400**	752	432	**810**	1490	710	**1310**	2390	988	**1810**	3290	1266	**2310**	5090	1543	**2810**	5090
–101	**–150**	–238	0	**32**	89.6	27.8	**82**	179.6	210	**410**	770	438	**820**	1508	716	**1320**	2408	993	**1820**	3308	1271	**2320**	4208	1549	**2820**	5108
– 95.6	**–140**	–220	0.56	**33**	91.4	28.3	**83**	181.4	216	**420**	788	443	**830**	1526	721	**1330**	2426	999	**1830**	3326	1277	**2330**	4226	1554	**2830**	5126
– 90.0	**–130**	–202	1.11	**34**	93.2	28.9	**84**	183.2	221	**430**	806	449	**840**	1544	727	**1340**	2444	1004	**1840**	3344	1282	**2340**	4244	1560	**2840**	5144
– 84.4	**–120**	–184	1.67	**35**	95.0	29.4	**85**	185.2	227	**440**	824	454	**850**	1562	732	**1350**	2462	1010	**1850**	3362	1288	**2350**	4262	1566	**2850**	5162
– 78.9	**–110**	–166	2.22	**36**	96.8	30.0	**86**	186.8	232	**450**	842	460	**860**	1580	738	**1360**	2480	1016	**1860**	3380	1293	**2360**	4280	1571	**2860**	5180
– 73.3	**–100**	–148	2.78	**37**	98.6	30.6	**87**	188.6	238	**460**	860	466	**870**	1598	743	**1370**	2498	1021	**1870**	3398	1299	**2370**	4298	1577	**2870**	5198
– 67.8	**– 90**	–130	3.33	**38**	100.4	31.1	**88**	190.4	243	**470**	878	471	**880**	1616	749	**1380**	2516	1027	**1880**	3416	1304	**2380**	4316	1582	**2880**	5216
– 62.2	**– 80**	–112	3.89	**39**	102.2	31.7	**89**	192.2	249	**480**	896	477	**890**	1634	754	**1390**	2534	1032	**1890**	3434	1310	**2390**	4334	1588	**2890**	5234
– 56.7	**– 70**	– 94	4.44	**40**	104.0	32.2	**90**	194.0	254	**490**	914	482	**900**	1652	760	**1400**	2552	1038	**1900**	3452	1316	**2400**	4352	1593	**2900**	5252
– 51.1	**– 60**	– 76	5.00	**41**	105.8	32.8	**91**	195.8				488	**910**	1670	766	**1410**	2570	1043	**1910**	3470	1321	**2410**	4370	1599	**2910**	5270
– 45.6	**– 50**	– 58	5.56	**42**	107.6	33.3	**92**	197.6				493	**920**	1688	771	**1420**	2588	1049	**1920**	3488	1327	**2420**	4388	1604	**2920**	5288
– 40.0	**– 40**	– 40	6.11	**43**	109.4	33.9	**93**	199.4				499	**930**	1706	777	**1430**	2606	1054	**1930**	3506	1332	**2430**	4406	1610	**2930**	5306
– 34.4	**– 30**	– 22	6.67	**44**	111.2	34.4	**94**	201.2				504	**940**	1724	782	**1440**	2624	1060	**1940**	3524	1338	**2440**	4424	1616	**2940**	5324
– 28.9	**– 20**	– 4	7.22	**45**	113.0	35.0	**95**	203.0				510	**950**	1742	788	**1450**	2642	1066	**1950**	3542	1343	**2450**	4442	1621	**2950**	5342
– 23.3	**– 10**	14	7.78	**46**	114.8	35.6	**96**	204.8				516	**960**	1760	793	**1460**	2660	1071	**1960**	3560	1349	**2460**	4460	1627	**2960**	5360
– 17.8	**0**	32	8.33	**47**	116.6	36.1	**97**	206.6				521	**970**	1778	799	**1470**	2678	1077	**1970**	3578	1354	**2470**	4478	1632	**2970**	5378
			8.89	**48**	118.4	36.7	**98**	208.4				527	**980**	1796	804	**1480**	2696	1082	**1980**	3596	1360	**2480**	4496	1638	**2980**	5596
			9.44	**49**	120.2	37.2	**99**	210.2				532	**990**	1814	810	**1490**	2714	1088	**1990**	3614	1366	**2490**	4514	1643	**2990**	5414
						37.8	**100**	212.0				538	**1000**	1832				1093	**2000**	3632				1649	**3000**	5432

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[a] The numbers in **Bold Face Type** refer to the temperature either in degrees Centigrade or Fahrenheit which it is desired to convert into the other scale. If converting Fahrenheit degrees to Centigrade degrees, the equivalent temperature will be found in the left column, while if converting from degrees Centigrade to degrees Fahrenheit, the answer will be found in the column on the right.
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Appendix B: Dimensionless Groups

Sometimes the dimensionless group is describing heat transfer and sometimes mass transfer. For example, the Biot number and the Peclet number have forms for both mass and heat transfer.

The symbol [=] means “has dimensions of”.

Some terms, such as reaction rate and gaseous mass transfer coefficient, can be expressed in different units. For a dimensionless number to be dimensionless, the units used for the terms must ensure that that happens.

Dimensionless number		**Word definition**	**Equation**	**Range**	**So what?**
Archimedes no., = *Ga* ($\Delta\varrho/\varrho$)	*Ar*	(inertial-gravity/viscous^2) × density ratio = *Re* (gravitational/viscous)	(Re^2/Fr) × dimensionless density ratio = (ϱ_G^2 D_p^3 $g)/\mu^2$) × ((ϱ_s–$\varrho_G)/\varrho_G$)	1 to 10^7	**Fluidization:** Ar: 1 to 10^6. For CFB, 1–100; for transported bed, 0.5–120; for fixed bed, 10^6–10^7; Particle settling/fluidization
Arrhenius no.	*Arr*	relative activation energy (molar activation energy)/(potential energy of fluid)	E/R T *E* = activation energy, kJ/mol	gas solid reactions: 5 to 40. liquid solid reactions: 5 to 40	**Reactions:** Use: to tell which is the controlling mechanism in a reaction: external mass transfer (*Arr* very small), transition, pore diffusion, transition, kinetic regime (*Arr* very large). Determines rates of chemical reactions

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Dimensionless number		Word definition	Equation	Range	So what?
Biot no. (for heat transfer)	Bi_H	external heat transfer to particle or solid/internal conduction; internal thermal resistance/surface resistance	hD/k	0.001–10 10–1000	**Unsteady state heat transfer**. high Bi = internal conduction controls
Biot no. (for mass transfer)	Bi_D	convective transport/molecular transport Mass transfer at interface/mass transfer in solid	k_G D/D where k_G [=] L/T k_G D/D D = diam. D = diffusivity	100–100 000	
Biot mass/ Biot heat	Bi_D/ Bi_H		Bi ratio = Bi_{mass}/ Bi_{heat} = $[\Delta c/\Delta T]$ internal/$[\Delta c/\Delta T]$ external ranges from 10–500 for gas–solid reactions meaning that heat transfer is the controlling resistance externally and mass transfer resistance controlled internally		**Reactions**: range 10–1000 for gas-solid reactions Bi ratio = 10 to 10^4 for gas solid = 10^{-4} to 10^{-1} for liquid solid. To identify the controlling mechanism in a gas–solid reaction: external mass transfer, transition, pore diffusion, transition, kinetic regime
Bird no.	Bir	mass of solids within a ± 0.1 density variation from the critical or cut density used to separate solids from solids	Need density distribution data for the feed	$<$ 15 then jigs, tables, sluices OK. $>$ 15 use DMS	**Solid-solid classification:** 0–7 easy separation 7–10 moderate 10–15 difficult 15–20 very difficult 20–25 exceedingly difficult $>$25 usually not possible

Dimensionless number		Word definition	Equation	Range	So what?
Bodenstein no. = *Pe* for mass transfer = *Re* Sc_{axial}	*Bd*	Flow velocity along a length/axial mixing along the length; Special case of *Pe* no. for mass transfer describing diffusion in a packed bed	$\langle v \rangle D/D$ or height of catalyst bed $\langle v \rangle / D_{axial}$		**Diffusion in a reactor. RTD.** If approaches ∞ there is negligible backmixing and plug flow occurs; $Bd = 0$; then complete mixing. $Bd/2$ = no. of ideally mixed cells in a catalyst bed of height H
Boltzmann no = Thring no.					
Bond no. (Eotvos no.)	*Bo*	gravitational forces/surface tension forces Often called the Eotvos no., Eo, when applied to particles or drops	$\varrho g D_p^2/\gamma$ where D = diameter of the tube or distance between plates or diameter of particle. $(\varrho_L - \varrho_G)\, g D_p^2/\gamma$ where D_p = drop diameter	0.05–1	**Coating**, surface shape of curved fluid surface: $Bo < 0.5$ for slot coating $Bo > 0.5$ for dip coating For coating, usually $Bo < 1$. Radii of curvature of meniscus, the shape is not affected by surface tension if *Bo* large; shape is not affected by hydrostatic pressure if *Bo* is small. *Bo* large when surface forces low. **Surface effects important in particulate systems:** $Bo < 1$. **Atomization**, **solvent extraction, trickle bed reactors**
Boussinesq no. see Froude no.	*Bq*	inertial forces/gravitational forces	$\langle v \rangle/(2\, g\, r_H)^{0.5}$ where r_H = hydraulic radius		Waves in an open channel

Dimensionless number		Word definition	Equation	Range	So what?
Bulk/film volume ratio	δ^{+}	relative volume of bulk liquid to the mass transfer film at the surface		1–10 000	**Reactions:** gas–liquid; characteristics of gas–liquid contactors. Thin film = 1; bubble column 4000 to 10 000
Capillary no.	Ca	viscous forces/surface tension forces	$\mu v/\gamma$ viscosity, velocity, surface tension	0.01–10	**Two phase flow:** in packed beds. **Free surface flows:** as in coating. **Coating:** For forward roll. **coating**, predicts stagnation line downstream of gap; For forward roll coating: predicts onset of ribbing at higher values (as a function of gap/diameter) For premetering: predicts dynamic contact angle θ proportional to $Ca^{0.22}$ but independent at $Ca < 5 \times 10^{-3}$. For slot coating: Minimum wet thickness as a function of Ca: for values of Ca of 0.1 to 0.8. There is a critical Ca above which the minimum wet thickness is constant; the critical Ca is linear function of gap; at 1000 μm gap, critical Ca = 0.7

Dimensionless number		**Word definition**	**Equation**	**Range**	**So what?**
Damkohler$_{\mathrm{I}}$ no.	Da_{I}	(chemical reaction rate [=] 1/T)/bulk mass flow rate or (time for fluid to flow a distance)/(time to complete the reaction)	equation depends on the kinetics: $r^* \mathrm{D}/<v>$ where r^* = reaction rate [=] 1/T D = length $r^* = k_A C^{n-1}$ for zero order $= k_A \mathrm{D}/(<v> [A])$ where [A] = bulk concentration of reactant for first order : $= k_A \mathrm{D}/<v>$ for second order: $= [A]\, k_A \mathrm{D}/<v>$	0.1–100	**Reactions:** If $Da <$ critical value, a flame is extinguished. For first order reactions and CSTRs in series, most reaction occurs in first reactors if $Da > 1$; for second order $Da > 20$
Damkohler$_{\mathrm{II}}$ no.	Da_{II}	(chemical reaction rate in flowing gaseous system, [=] 1/T)/(molecular diffusion rate)	(eq. depends on reaction kinetics) $r^* \mathrm{D}^2/D$ for first order: $k_A \mathrm{D}^2/D$		**Reactions:** large values for high temperature reactors; approaches 0 for low temp. bioreactors. For CSTR Da = 1 conversion < 10% = 10 conversion > 90% Da small = reaction controlled by mass transfer For reactive distillation, Da 10 to 20
Damkohler$_{\mathrm{III}}$ no.	Da_{III}	(heat liberated via chemical reaction)/(bulk transport of heat)	$\Delta H\, r^* \mathrm{D}/(c_p <v> T)$ where ΔH = heat liberated/unit mass T = temperature above the datum r^* = reaction rate [=] $1/T$		**Reactions** and heat transfer
Damkohler$_{\mathrm{IV}}$ no.	Da_{IV}	(heat liberated via chemical reaction)/(conductive or molecular heat transfer)	$\varrho\, \Delta H\, r^* \mathrm{D}^2/(kT)$		**Reactions** and heat transfer

Dimensionless number		Word definition	Equation	Range	So what?
Damkohler $_{\text{heat}}$	Da_{heat}	heat liberated/interphase heat transfer coefficient	$-\Delta H_{\text{react}}\,\mathbf{R}/a\,h\,T_{\text{inlet}}$ a = area/vol. of catalyst h = interphase heat transfer coefficient $\mathbf{R}$ = ideal gas constant		**Reactors**
Darcy coefficient: = 4 Fanning friction factor	$4f$	(head loss/velocity head) × (diameter/length)	$2\,g\,h_f\,D/(v^2\,L)$ where h_f = heat loss due to friction		**Fluid flow** in pipes/fittings/conduits
Deborah number	*De*	Relaxation time of system/flow characteristic time characteristic relaxation time of the coating liquid or dispersion/characteristic residence time in the process flow or time of observation	*De* increases with increase in speed of coater		**Coating:** High *De* makes processing in high speed blade coater problematic $De << 1$ equilibrium thermodynamics; any work done isothermally is immediately dispersed as heat. $De >> 1$ work done is stored in material Viscoelastic behavior
Deborah number for drying		rate of drying/rate of stress relaxation			**Drying of coating:** when *De* is high, coating cracks upon drying crack formation in coating
Elasticity, surface	E_S	viscous/change in capillary force because of surface tension lowering because of surfactant	$\mathbf{R}T\,\Gamma_\infty/\mu\ \langle v\rangle$ $(1/\mu\ \langle v\rangle)\ (d\gamma/d\ln\Gamma)$	0–110	**Coating**
Elasticity, Gibbs surface	*E*	surface tension variation/surface concentration	$(d\gamma/d\ln\Gamma)$		
Eotvos no. related to Bond no.					
fanning friction factor = Darcy/4		wall shear stress/velocity head	$2\,\tau_{\text{wall}}/(\varrho\,v^2)$	0.005 in turbulent flow	**Fluid flow** in pipes/conduits; relatively constant for $Re > 2000$. $16/Re$ in laminar flow

Dimensionless number		Word definition	Equation	Range	So what?
Fourier no.	*Fo*	time (thermal conduction/inertial heat)	$kt/\varrho\ c_p\ D^2$	0.1–20 Usually 0.1–1.5	**Heat transfer**: unsteady. Extent to which heating or cooling penetrates into a solid
Froude no. see also Boussinesq no., *Bq*	*Fr*	inertial forces/gravitational forces	v^2/gD where D = length N^2D/g where N = rpm D = impeller diameter		**Coating**; surface configuration in swirling flows. **Mixing:** vortex formation for a free surface in a mixing tank
Froude no. density weighted = $Fr\ (\varrho/\Delta\varrho)$	*Fr**	inertial forces/gravitational forces	$(v^2/gD)\ (\varrho/\Delta\varrho)$	10^{-7} to 10^{-4}	**Gas holdup** in bubble column
Galileo no. = *Re* x(gravitational/viscous)	*Ga*	intertial-gravity/viscous^2	(Re^2/Fr) = $(\varrho_G^2\ D_p^3\ g)/\mu^2)$	see *Ar*	**Fluidization**, circulation of fluids
Graetz = *Re Pr* (*D*/D)	*Gz*	thermal capacity of the fluid/conduction heat transfer	$F\ c_p/kD$ where F = mass flow D = length of heat transfer path	$10–10^4$	**Heat transfer**; coating manifold
Grashof no.$_H$ $Ga\ (\beta\ \Delta T)$ similar to *Ar*	Gr_H	free convection buoyancy force/viscous force = *Re* × (buoyancy forces/viscous force) = inertia-buoyance/viscous force^2	$D^3\ g\ \varrho^2\ \beta\ \Delta T/\mu^2$ where $\beta\ \Delta T$ = density difference caused by thermal difference. β =thermal expansion		**Heat transfer** under gravity flow; natural convection
Grashof no.$_D$	Gr_D		$D^3\ g\ \varrho\ \Delta\varrho/\mu^2$ where $\Delta\varrho$ =density difference caused by concentration difference		**Mass transfer** under gravity flow
Gr Pr					= 1000 heat transfer by conduction = 10^4 to 10^6 = heat transfer by natural convection

Dimensionless number		Word definition	Equation	Range	So what?
Hatta no.	*Ha*	reaction in the film/ reaction in the bulk	equation depends on the kinetics		**For gas–liquid reactions:** Ha $<$ 1: regime **1**: reaction occurs exclusively in bulk and is controlled by either chem. reaction, k (regime 1) overall temp effect positive or (regime **2**) diffusion across the liquid film controls, k_L slow reaction; overall temp effect negative regime $Ha << 1$ or kinetic regime; reaction is controlled by film diffusion. kinetics control
		for gas–liquid reactions	$(-\nu_1\ k_1\ D_{1L})^{0.5}/k_{1L}$ or $\{ (D_A\ k_{mn}\ (2/(m + 1)[A]^{*\ (-1)}\ [B]_b^{\ n})^{0.5} \}/ k_L$ or $\lambda/\tanh \lambda$ where $\lambda = D(k_n\ [B]^{n-1}/D_A)^{1/2}$ m order of the reaction of reactant A n order of the reaction of reactant B k_{mn} = volumetric rate constant for reaction of orders m and n between reagents A and B. D = diffusion path length = $(\mu^2/\varrho^2\ g)^{1/3}$ for packed column		
					regime **3** fast reaction: is so fast that occurs wherever A is reaction entirely in film: diffusion and reaction in film with negligible reaction in the bulk $Ha >> 1$ and $Ha << \{[B]_{bulk}/\varepsilon_B\ [A]_{bulk}\}\ (D_B/D_A)^{0.5}$; mass transfer through liquid film (increasing the temp. decreases the overall rate unless increasing the temp. increases the solubility)
					regime **4**: instantaneous reaction in both film and bulk $Ha >> \{[B]_{bulk}/\varepsilon_B\ [A]_{bulk}\}\ (D_B/D_A)^{0.5}$ effect of temperature increase is negligible

Dimensionless number		Word definition	Equation	Range	So what?
j-factor for heat transfer	j_H	$St\ Pr^{2/3} = Nu/(Re\ Pr^{0.3})$	$(h/\varrho\ c_p <\mathrm{v}>)[c_p\ \mu/k]^{2/3}$	0.001–0.02	**Heat transfer**: for turbulent 0.003 decreasing to 0.001
j-factor for mass transfer	j_D	$St_D\ Sc^{2/3}$	$(k_G/<\mathrm{v}>)[\mu/\varrho D]^{2/3}$ where k_G [=] L/T	0.002–0.007	**Mass transfer**: for gas or liquid $15 < Re < 1500$ $j_H = 1.2\ j_D$
Lewis no.	*Le*	*Sc*/*Pr*: mass transfer/heat transfer properties = thermal diffusivity/molecular diffusivity	$k/c_p\ \varrho\ D$	0.0001–0.11	**Mass and Heat transfer**: Material properties ratio of mass transfer relative to heat transfer
Luikov no.	*Lu*	mass diffusivity/thermal diffusivity	$k_G\ D\varrho\ c_p/k$ where D = length k_G [=] L/T		**Mass and Heat transfer**
Mach no.	*M*	velocity/sonic velocity	v/v_{sonic} for ideal gas $v/[(c_p/c_v)\ (\mathbf{RT/M})]^{0.5}$		**Compressible flow,** gas flow through a nozzle, aircraft speed
Marangoni no.	*Ma*	surface tension gradient forces/viscous stablizing forces	thermal $[d\gamma/dT]\ [dT/dy]\ \delta^2/[\mu\ \varrho\ c_v/k]$ δ = film thickness; k = thermal conductivity $[d\gamma/dT]\ \Delta T\ \delta/[\mu\ \varrho\ c_v/k]$		**Coating** surface defects- Benard cells; cells can occur for $Ma > 80$; roll cells for $\delta < 1$ mm, usually always occur because of Ma effects and not Rayleigh (density driven effects). For layers $\delta < 2$ mm, convection cells appear at Rayleigh and Marangoni values < the critical values listed above. **Mass transfer**: indicative of when mass transfer might be increased by rolls cells
Margoulis no. see Stanton no.					
Nusselt no. = *St Re Pr*	*Nu*	total heat transfer/conductive or molecular heat transfer	$h\ D/k$	10–1000	**Heat transfer**

Dimensionless number		Word definition	Equation	Range	So what?
Nusselt no.$_{AB}$, Nu_{AB}, see Sherwood No.					
Ohnesager no. = *We/Re*	Z	viscous/(inertial × surface tension)$^{0.5}$	$\mu/(\varrho \text{ D } \gamma)^{0.5}$	for G–L: 10^{-3} to 10	**Spray, drop breakup** water = 0.001 to 0.01; castor oil = 5
Peclet no. = *Re Pr* for heat transfer in pipes	Pe_H	bulk heat transport by convection/transport by conduction – diffusion	$\text{D}/F\ c_p/kA$; $<\text{v}> \text{D}\ \varrho\ c_p/k$		**Heat transfer**: forced convection
Peclet no. = *Re Sc* for mass transfer in pipe flow	Pe_D	total momentum transfer/(molecular mass transfer axial direction)	$<\text{v}> \text{D}/D_{ax}$ where D = diam. of tube		**Mass transfer, mixing**. For turbulent, homogeneous fluid $Re > 10^4$ $Pe_{axial} = 2$; $Pe_{radial} = 600$; $Pe = 0$ means complete mixing; $Pe = \infty$ means plug flow
Peclet no. = Re_p *Sc* for mass transfer in packed beds	Pe_D	(total momentum transport)/(molecular diffusion in axial direction)	$<\text{v}> \text{D}_p/D_{axial}$	0.01–10^5	**Mixing**. For *packed beds* $Re > 10$; $Pe_{\text{ axial}} = 2–3$; $Pe_{\text{ radial}} = 10$. Flow through a catalyst bed of particles of diameter, D_p, and depth H. Recommended range of H/D_p is 5 to 50. If 50 then plug flow. For *packed columns* $Pe_L = 0.4–2$; $Pe_G = 4–20$. If a column $H < 0.2–0.3$ m, then backmix causes problems
(Bodenstein no., for axial)		(total momentum transport)/(molecular diffusion in radial direction)	$<\text{v}> \text{D}_p/D_{radial}$ or for packed beds D = D_p diam. of particle		

Dimensionless number		Word definition	Equation	Range	So what?
Power no. = Newton no.	*Po*	drag on paddle/ inertial force	$P/(\varrho\ D_i^5\ N^3)$	10^4 to 10^{16}	**Agitation:** Power for mixing impellers; rotodynamic machinery. Power number = Newton no. if *Fr* no. not important; that is no vortex. For $Re > 10^4$, for turbines *Po* usually = 1–6; for marine propellers, *Po* usually = 0.2–1
Prandtl no.	*Pr*	molecular momentum transfer/molecular heat transfer	$c_p\ \mu/k$		**Heat transfer**: liquid metals: 0.005–0.2 gases: 0.6–1 liquids: 0.02–50 000
Prater no.	*Pra*	relative increase in temperature of the catalyst pellet = heat of reaction/thermal conduction of heat away	(concentration of reactant at surface) (heat of reaction) effective diffusivity in the pores)/ effective thermal conductivity of catalyst × surface temperature $[A]\ (-\Delta H)\ D/(kT)$		**Reactions**; heat transfer. $Pra < 0$ for endothermic reactions and usually in the range −0.8 to 0; the efficiency = (rate of reaction controlled by diffusion/rate of reaction without diffusion limitation) is always < 1. *Pra* > for exothermic and usually in the range 0 to 0.8. efficiency can be > 1, $= 1$ or < 1
Rayleigh no. = *Gr Pr*	*Ra*	(free convection buoyancy force)/ (thermal diffusivity)	$[\beta\ (dT/dy)\ g\ \delta^4\ \varrho^2\ c_v]/[k\ \mu]$ β = coefficient of thermal expansion; δ = film thickness $\beta \Delta T g\ D_p^3\ \varrho^2\ c_p/(k\ \mu)$		**Convection** **Coating:** critical value when roll cells might occur is between 320 and 1700 to support density driven roll cells

Dimensionless number		Word definition	Equation	Range	So what?
Reynolds no = Damkohler V, Da_V	Re	inertial forces/ viscous forces	pipe:		**Fluid flow in tubes:** laminar < 2300
			spinning flows $r^2 \Omega \varrho/\mu$ where Ω = rpm		**Coating flows and size reduction:** laminar film flow on spinning disk if Re < 10^5
			$\varrho \langle v \rangle b^2/L \mu$		**Coating flows:** Slot of height b and length L
			falling film as in curtain coating	1–100	**Coating**
			packed bed		
Schmidt no.	Sc	(molecular momentum transfer)/ (molecular mass transfer)	$\mu/\varrho D$	1–10^6	**Mass transfer:** material property ratio important for predicting mass transfer rates. ideal gas $Sc = 1$ usual gas = 0.8 inorganic gas = 0.6–1.1 water = 1200 organic liquids = 300–2000 **Combustion**
Sherwood no. = Taylor no	Sh	(total mass transfer)/(molecular mass transfer)	$k_G \mathrm{D}/D$ $k_L \mathrm{D}/D$ where k_G [=] L/T	2–100	**Mass transfer:** parameter for the mass transfer coefficient
Stanton no.	St	$Nu/(Re\ Pr)$: (total heat transfer)/ (turbulent momentum transfer)	h (or U)/ $(\varrho\ c_p \langle v \rangle)$		**Forced convection:** flowing system
Stanton no.$_{\mathrm{II}}$	St_{II}	cooling capacity of the system: heat transferred/volume of hot stuff	$(UAt)/(\varrho\ c_p\ V)$	0.01–2	**Reactor**: batch system
Stanton no. for mass transfer $Sh/(Re\ Sc)$	St_D	mass transfer coefficient/inertial	$k_G/\langle v \rangle$ where k_G [=] L/T		

Dimensionless number		Word definition	Equation	Range	So what?
Stokes		gravitational/viscous	$g\,D^2\varrho/\mu\,v$	0.7–800	**Particle dynamics; Coating**
Taylor no.	*Ta*		$r\,\omega\,(r_2-r_1)/(\mu\,[(r_2-r_1)/r_2]^{0.5})$	> 41.3	**Vortices** in annulus between rotating cylinders
Thring no. (Boltzman no)	*Th*	bulk heat transfer/radiation heat transfer	$\varrho\,c_p <\mathrm{v}>/\varepsilon\eta\,T^3$		**Heat transfer**
Weber	*We*	inertial force/surface tension force: = *Re Ca*	$\varrho_c\,D\,v^2/\gamma$ where D_p = drop diameter for drop breakup D_i = impeller diameter for breakup in stirred tank ϱ_c = density of the continuous phase		**Bubble and drop formation:** G–L or L–L: D_p drop breakup $We < 12$ vibrational mode $12 < We < 50$ bag mode $50 < We < 100$ bag-stamen $100 < We < 350$ sheet stripping mode $We > 350$ catastrophic **Coating:** Drop breakup

Appendix C:
Cox Charts – Vapor Pressures

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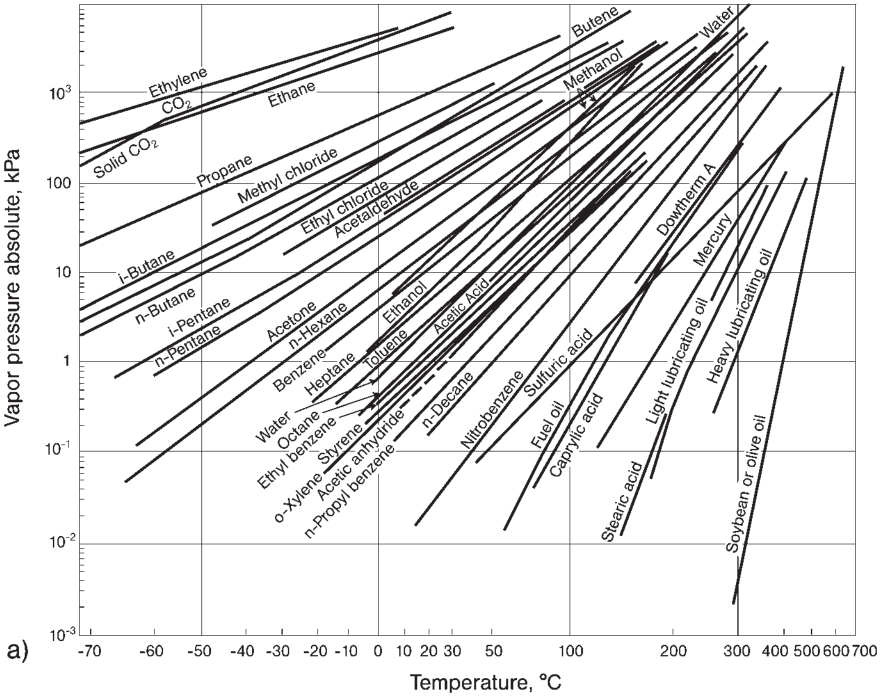
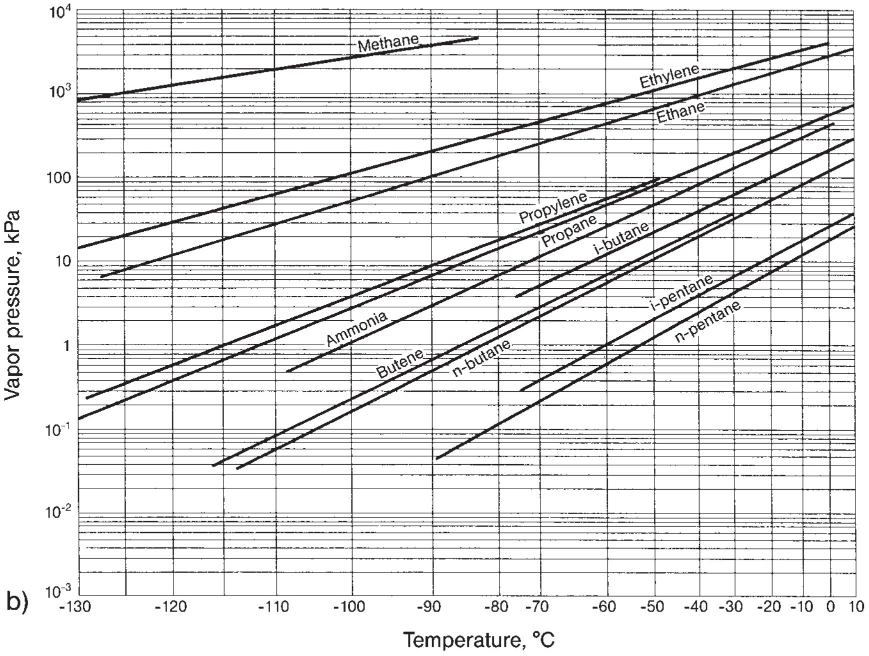

a)
Vapor pressure absolute, kPa
10^3
100
10
1
10^{-1}
10^{-2}
10^{-3}
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
50
100
200
300
400
500
600
700
Temperature, °C
Ethylene
CO_2
Ethane
Solid CO_2
Propane
Methyl chloride
Ethyl chloride
Acetaldehyde
i-Butane
n-Butane
i-Pentane
n-Pentane
Acetone
n-Hexane
Benzene
Heptane
Water
Octane
Ethyl benzene
o-Xylene
Styrene
Acetic anhydride
n-Propyl benzene
Toluene
Ethanol
Acetic Acid
n-Decane
Nitrobenzene
Butene
Methanol
Water
Sulfuric acid
Fuel oil
Caprylic acid
Dowtherm A
Mercury
Light lubricating oil
Stearic acid
Heavy lubricating oil
Soybean or olive oil


b)
Vapor pressure, kPa
10^4
10^3
100
10
1
10^{-1}
10^{-2}
10^{-3}
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
Temperature, °C
Methane
Ethylene
Ethane
Propylene
Propane
i-butane
Ammonia
Butene
n-butane
i-pentane
n-pentane

Appendix D:
Capital Cost Guidelines

Costs should be included with any rules of thumb because costs are such vital information to engineering practice. Therefore, in this book, cost correlations for the FOB cost and factors for estimation of the complete installation of that equipment into a working process are given for each type of equipment. The cost estimates are ball park ideas ± 30 %. Here we discuss the correlations, the L+M* factors to convert FOB costs into bare module costs, factors to obtain the fixed capital investment costs and finally the capital cost guidelines for the equipment described in the main text, with title captions that are the same as in the main text.

D.1
Equipment Cost Correlations

Costs are usually correlated in terms of a base cost multiplied by a ratio of sizes raised to the power "*n*". $\text{Cost}_2 = \text{Cost}_{\text{ref}}\,(\text{size}_2/\text{size}_{\text{ref}})^n$. The cost is usually the FOB cost although sometimes it is the field erected cost. The size should be a "cost dependent" parameter that is characteristic of the specific type of equipment. The size parameter that provides the least accurate estimate is the *flow* or *capacity*. In this book, sometimes several different parameters are given; use the size parameter *flow* or *capacity* as a last resort.

The guideline FOB cost is in US $ for a value of the *Chemical Engineering Index (1957–59 = 100),* CEPCI Index = 1000. The value of the *CEPCI* Index for the year 2003 was 395.6 so that the costs reported here are more than double the value in 2003.

D.2
Converting the FOB Cost into a Bare Module Cost

Although the FOB cost of equipment is of interest, usually we want to know the cost of a fully installed and functioning unit. The "bare module", BM, method is used in this book. In the BM method, the FOB cost is multiplied by factors that account for all the concrete, piping, electrical, insulation, painting, supports needed in a space about 1 m out from the sides of the equipment. This whole

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space is called a module. The module is sized so that by putting together a series of cost modules for the equipment in the process we will account for all the costs required to make the process work. For each module we define a factor, L+M*, that represents the labor and material costs for all the ancillary materials. Some of these may be shown as a range, for example, 2.3–3. This means that for the installation of a single piece of equipment (say, one pump), the higher value should be used; the lower value is used when there are many pumps installed in the particular process. The L+M* factor includes the free-on-board the supplier, FOB, cost for carbon steel and excludes taxes, freight, delivery, duties and instruments unless instruments are part of the package. The * is added to remind us that the instrumentation material and labor costs have been excluded, (whereas most L+M values published in the 60s, 70s and 80s included the instrumentation material and labor costs).

If the FOB cost is for non-carbon steel equipment, then the L+M* factor must be reduced (since the factor is to account for concrete, electrical, insulation, painting – items that are independent of the materials of construction of the equipment). Two ways to handle this are: (i)Reduce the L+M* factor, for s/s typically reduce by multiplying by 0.6 to 0.75. The corrections are given in Fig. D.1 (ii) Cost an imaginary carbon steel piece of equipment, multiply by the L+M* factor and then add the difference in FOB cost between the alloy equipment and the carbon steel equipment.

For some unit operations the equipment is built of concrete or is a lagoon. For such equipment the reported cost is the physical module, PM cost, that represents the FOB plus L+M* plus instruments plus taxes and duties. The cost excludes offsite, home office expense, field expense and contractor's fees and contingencies. Rules of thumb to account for the other cost items are given in Section 1.7. The pertinent sections of Section 1.7 are reproduced below.

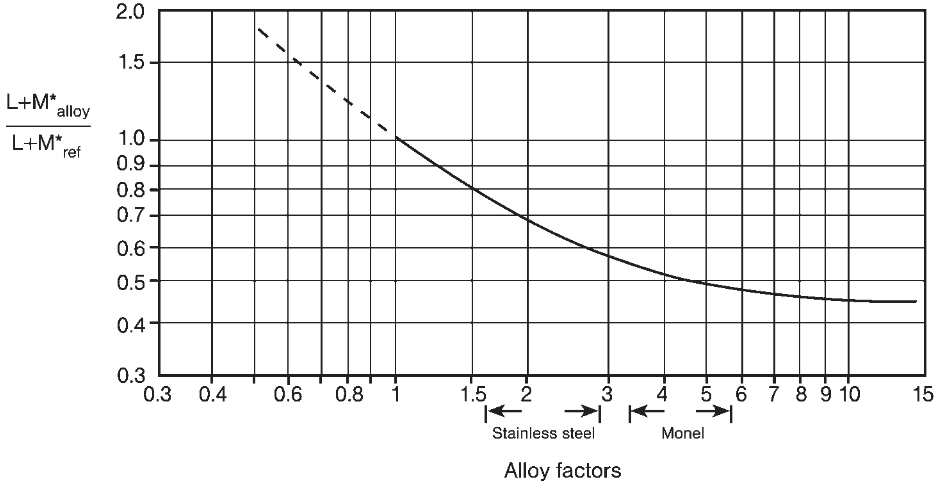

Figure D.1 Correction factors for L+M* as a function of alloy factor.

D.3
Converting FOB and L+M Costs into Total Fixed Capital Investment Costs

The rules of thumb refer to capital cost estimation.

1. Total fixed *capital cost estimation*, total fixed capital investment = 3 to 10 (4 to 5 usual) × FOB major pieces of equipment. The factor decreases as more alloys are used in the process.
2. For capital cost estimation: for carbon steel fabrication: L+M factors are in the range 1.5 to 3 with corresponding L/M ratios of 0.15 to 0.65 with 0.4 being usual. The factor decreases for alloys as shown in Fig. D.1.
3. For capital cost estimation: FOB equipment cost increases with size^n where n is usually 0.6 to 0.7. When $n = 1$ there is no capital cost advantage to building larger; increase size or capacity by duplicating equipment.
4. For capital cost estimates:

(FOB × L+M*) + installed instruments + buildings required within the battery limits = L+M cost.

L+M cost + taxes, freight and insurance at 15–25 % FOB cost = physical module cost, PM.

PM + offsites + indirects for home office and field expenses at 10–45 % of L+M with small values for large projects = bare module or BM cost.

BM cost + contractors fees (3–5 % BM) + contingency for unexpected delays (10–15 % BM) + design contingency for changes in scope during construction (10–30 % BM) = Fixed capital investment or total module, TM, cost.

To the fixed capital investment might be added, as needed:

1. royalties and licenses.
2. land (1–2 % TM).
3. spare parts (1–2 % TM).
4. legal fees (1 % TM).
5. working capital: for year-round commodities (15–20 % TM); for seasonal commodities (25–40 % TM). For specialties and pharmaceuticals (15–40 % of sales).
6. startup expenses (15–40 % TM).

D.4
Detailed Equipment Cost Data Based on Equipment Type

Here are the details of the cost correlations for the equipment discussed in the text. The subheading captions correspond directly with the titles in the text. All costs are FOB costs (unless stated otherwise). All costs are for the basis CEPCI = 1000.

Section 1.4
Rules of Thumb about the Context for a Chemical Process: Process Control Sensors

Pressure: FOB $4000. L+M* = 1.65. L/M = 0.09.
Temperature: FOB $6000. L+M* = 1.2. L/M = 0.09.
Flow: sensor, barrier and transmitter: coriolis: FOB $10 000; magnetic: 304 s/s with teflon lining. FOB cost = $11 000 for a pipe diameter = 15 cm with n = 0.26 for the range 1–15 and n = 1.67 for the range 15–25 cm. L+M* = 1.65. L/M = 0.09.
Level: electronic d/p cell: FOB $5000. L+M* = 1.1.
Level: visible flat-glass, s/s. FOB cost = $900 for a visible length = 75 cm with n = 0.9 for the range 20–200 cm. Alloy factor, s/s, × 1.00; c/s, × 0.8. L+M = 1.1.
Alarms:
Level alarm: FOB $1000. L+M* = 1.65. L/M = 0.09.
SIS:
Hi-lo level shutoff: FOB $5500. L+M* = 1.65. L/M = 0.09
Control valves:
Control valve: Fail open or fail close, cast steel, pneumatic diaphragm actuated, quick opening, V-pup or throttle plg, 316 s/s trim excluding valve positioner. FOB cost = $4800 for a valve diameter = 7.5 cm with n = 0.65 for the range 2.5–7.5 and n = 1.53 for the range 7.5–23 cm. FOB cost = $28 000 for a valve diameter = 23 cm with n = 3.0 for the range 23–30 cm. L+M = 1.10. L/M = 0.03. Alloy factors: cast steel, × 1.0; cast iron, × 0.63.
Control valves including all materials: cost $240 000 for the number of main plant items, MPI, = 75 with n = 1.2 for the range 15–400. Alloy cost factor: c/s × 1.00; chrome/moly × 2.4; s/s × 4.2.
Butterfly valve: c/s, piston. FOB cost = $6500 for a valve diameter = 28 cm with n = 0.28 for the range 5–28 and n = 1.28 for the range 28–40 cm.
Relief valves:
Spring loaded, Crosby style JO, type A, c/s body and spring. Maximum temperature 230 °C. FOB cost = $3800 for an inlet valve diameter = 5.5 cm with n = 0.75 for the range 2.5–5.5 and n = 1.00 for the range 5.5–15 cm. FOB cost = $10 000 for an inlet valve diameter = 15 cm with n = 2.1 for the range 15–20 cm. L+M* = 1.13. L/M = 0.1.
"Control systems": In the past, the cost of the control system for different process equipment was often estimated as a percentage of the FOB cost of the equipment and thus was included in the so-called L+M factor. More recently, and in this book, we use the L+M* factors that exclude an allowance for the cost of the instrumentation and control system. The instruments and control system should be costed separately. The installed instrumentation costs, excluding control valves, are (US dollars, CEPCI = 1000): for gas phase reactors, $63 000; for liquid phase reactors $70 500; for condensers, $40 000; heat exchanger or reboilers, $27 000; for distillation columns, $150 000; evaporators, $25 000; for storage tanks, $7000; pressure tank, $8300; intermediate process tank, $17 400; pump or a stage of a centrifugal compressor, $7000.

- *Example use*: Estimate the cost, at CEPCI = 800 for the installation of a conventional AVS centrifugal pump whose FOB cost (at CEPCI = 1,000) is \$20 000. From Section 2.3 the pump L+M* = 2.3–3; select 3 since this is a one-off installation. Therefore the L+M* module cost for the pump is \$20 000 × 3 = \$60 000. The cost of the installed instrumentation, from above, is \$7000 for a total of \$67 000 = L+M cost. To the L+M cost is added the taxes, freight and insurance at 15–25 % of FOB cost to yield the physical module cost, PM cost = \$67 000 + 18 % × \$20 000 (\$3600) = \$70 600. Neglecting offsites and building costs, to obtain the bare module, BM, cost add indirects for home office and field expenses at 20–45 % L+M with small values for large projects (or for this case) 0.4 × \$67 000 = \$93 800 + \$3600 = \$97 400 = BM cost.

The fixed capital investment = BM cost plus contractor's fee (3–5 % BM, select 5) plus contingency (10–15 % BM, select 15) plus design contingency for changes in scope during the project (10–30 % BM, select 10) to give a total = \$126 620 at CEPCI = 1000.

At CEPCI = 800 an estimate of the fixed capital cost =\$126 620 × 800/1000 = \$100 000 ± 20 %.

Section 2.1
Gas Moving: Pressure Service

Fans, centrifugal, radial bladed, 2.5 kPa g, excluding motor, starter, gearing. FOB cost = \$15 850 at inlet gas flow rate = 10 $\mathrm{Nm^3/s}$ with n = 0.78 for the range 2–100. L+M* = 1.4–1.7. L/M = 0.25. Alloy factors: c/s, × 1.00; fiberglass, ×1.8; s/s, × 2.5. Factors: radial bladed, × 1.00; backward bladed, × 1.20.
Fans, centrifugal, radial bladed, 2.5 kPa-g, TEFC motor, starter and gearing. FOB cost = \$27,750 at inlet gas flow rate = 10 $\mathrm{Nm^3/s}$ with n = 0.93 for the range 2–50. L+M* = 1.4–1.7. L/M = 0.25.
Fans, vane-axial, 0.5 kPa g, open drip proof motor. FOB cost = \$5000 at inlet gas flow rate = 1 $\mathrm{Nm^3/s}$ with n = 0.36 for the range 0.5–10. L+M* = 1.4–1.7. L/M = 0.25.
Fans, propeller, including motor and housing. FOB cost = \$4000 at inlet gas flow rate = 7 $\mathrm{Nm^3/s}$ with n = 0.58 for the range 0.5–7 and n = 0.36 for the range 7–50. L+M* = 1.4–1.7. L/M = 0.25.
Fan unit, air conditioning package with two fans, chiller, integral piping, heat exchangers, filter excluding ductwork, refrigeration and cooling tower circuits, overheads and building. L+M cost = \$48 000 at inlet gas flow rate = 3 $\mathrm{Nm^3/s}$ with n = 0.67 for the range 0.8–8.
Fan unit, air conditioning package with two fans, chiller, integral piping, heat exchangers, filter excluding ductwork, refrigeration and cooling tower circuits, overheads and building. FOB cost = \$490 000 at inlet gas flow rate = 30 $\mathrm{Nm^3/s}$ with n

= 0.90 for the range 15–120. Factor: FOB materials, × 1.00; field erected package, × 1.54.

Blowers, centrifugal, cast iron, 28 kPa g, motor and drive. FOB cost = \$760 000 at inlet gas flow rate = 30 Nm^3/s with n = 0.61 for the range 12–70. L+M* = 2–2.5. L/M = 0.25–0.53. Factors: pressure 28 kPa, × 1.00; 7 kPa, × 0.30; 14 kPa, × 0.45; 50–70 kPa, × 1.75; 140–200 kPa, × 4.5. Factors: including motor and drive, × 1.00; excluding motor and drive, × 0.63. Alloy factors: cast iron, × 1.00; fiberglass, × 2.6; s/s, × 2.6.

Blowers, rotary lobe, cast iron, 70 kPa g, drip proof motor and drive; single stage. FOB cost = \$25 000 at drive power = 30 kW with n = 0.55 for the range 4–60. L+M* = 2–2.5. L/M = 0.25–0.53. Factors: one stage, × 1.00; two stage, × 2.7.

Blowers, rotary sliding vane, 275 kPa g, with lubricator, coupling and base but excluding motor and drive. FOB cost = \$30 000 at inlet gas flow rate = 0.1 Nm^3/s with n = 0.40 for the range 0.01–0.4. L+M* = 2.0–2.5. L/M = 0.25.

Compressors, centrifugal, < 7 MPa, cast steel with drip proof induction motor, starter, base plate, gearing and lube system. FOB cost = \$1 350 000 at drive power = 1000 kW with n = 0.90 for the range 2–4000. FOB cost = \$10 300 000 at drive power = 10 000 kW with n = 0.71 for the range 8000–25 000. L+M* = 1.3–2.15. L/M = 0.37–0.38. Alloy factors: cast steel, × 1.00; s/s, × 2.5; nickel, × 5.0. Factor, motor drive, × 1.00; turbine drive, ×1.0.

Compressors, centrifugal, 7 MPa, cast steel with base plate, excluding motor, starter, gearing and lube system. FOB cost = \$875 000 at drive power = 1000 kW with n = 0.53 for the range 500–4000. L+M* = 1.3–2.15. L/M = 0.37–0.38. Factors: exit pressure, 7 MPa, × 1.00; 1.7 MPa, × 0.8; 14 MPa, × 1.15; 34 MPa, × 1.43; 48 MPa, × 1.51.

Compressors, axial 15-stage with steam turbine drive, base plate and lubrication. FOB cost = \$20 000 at drive power = 10 000 kW with n = 1.33 for the range 4000–20 000. FOB cost = \$18 000 at inlet gas capacity = 100 Nm^3/s with n = 0.91 for the range 30–300. L+M* = 1.3–2.15. L/M = 0.37–0.38.

Compressors, helical screw with drip proof motor, starter, base plate, gearing and lube system. FOB cost = \$475 000 at drive power = 300 kW with n = 0.77 for the range 100–600 and at inlet gas capacity = 1 Nm^3/s with n = 0.85 for the range 30–300. L+M* = 1.3–2.15. L/M = 0.37–0.38.

Compressors, reciprocating, < 7 MPa with base plate, drip proof motor, starter, gearing, lube system and aftercooler. FOB cost = \$180 000 at drive power = 100 kW with n = 0.79 for the range 1–10 000. L+M* = 2.25–2.82. L/M = 0.34. Alloy factors: cast steel, × 1.00; s/s, ×2.5; nickel, × 5.0. Factors: exit pressure, < 7 MPa, × 1.00; 17 MPa, × 1.25; 34 MPa, × 1.5; 41 MPa, × 1.60; 48 MPa, × 1.68; 55 MPa, × 1.78; 62 MPa, × 186; 69 MPa, × 1.95. Drive factors: electric motor, × 1.00; steam turbine, × 1.4; gas engine, × 2.8.

Compressors, reciprocating, < 7 MPa with base plate, starter, gearing, lube system and aftercooler but excluding drip proof motor. FOB cost = \$65 000 at drive power = 100 kW with n = 1.04 for the range 10–1000. L+M* = 2. L/M = 0.35.

Compressors, reciprocating, 0.86 MPa single stage with base plate, drip proof motor, starter, gearing, and lube system. FOB cost = \$65 000 at inlet air flow rate = 0.1 Nm^3/s with $n = 0.77$ for the range 0.002–5. L+M* = 2. L/M = 0.35.

Compressors, reciprocating, 3.5 MPa double stage with base plate, drip proof motor, starter, gearing, intercooler and lube system. FOB cost = \$100 000 at inlet air flow rate = 0.1 Nm^3/s with $n = 0.53$ for the range 0.03–0.2. L+M* = 2. L/M = 0.35. Factors: two stage, × 1.00; three stage, × 1.7.

Compressor station, centrifugal or reciprocating, installed station, compressor, electric motor. TM cost = \$2 850 000 at drive power = 1000 kW with $n = 0.65$ for the range 150–2500 and \$18 000 000 at drive power = 10 000 kW with $n = 0.70$ for the range 3000–13 000.

Compressor station, reciprocating, installed station, compressor, gas engine. TM cost = \$4 000 000 at drive power = 1000 kW with $n = 0.75$ for the range 150–2500 and \$40 000 000 at drive power = 10 000 kW with $n = 0.70$ for the range 3000–13 000.

Compressor station, centrifugal or reciprocating installed station, compressor, steam or gas turbine. TM cost = \$2 850 000 at drive power = 1000 kW with $n = 0.65$ for the range 150–2500 and \$26 000 000 at drive power = 10 000 kW with $n = 0.70$ for the range 3000–13 000. 2.25–2.82. L/M = 0.34. Alloy FOB cost factors: c/s × 1.00; nickel × 5.0; s/s × 2.5.

Section 2.2
Gas Moving: Vacuum Service

Rotary vane vacuum pump, 10–15 kPa-abs, drip proof motor, base plate, gearing and reservoir. FOB cost = \$22 000 at free air displacement = 170 dm^3/s with $n = 0.38$ for the range 3–1670. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Rotary liquid piston vacuum pump, 10–15 kPa-abs, with base plate and reservoir but excluding motor. FOB cost = \$103 000 at actual free air displacement = 1700 dm^3/s with $n = 0.73$ for the range 83–5000. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Dry reciprocating vacuum pump, cast iron with TEFC motor, base plate V-belt drive. FOB cost = \$12 700 at ratio of gas capacity (kg/h)/absolute pressure (kPa-abs) = 1 with $n = 0.66$ for the range 0.1–80. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Dry reciprocating vacuum pump, cast iron with base plate, V-belt drive but excluding motor. FOB cost = \$27 000 at drive power = 10 kW with $n = 0.88$ for the range 4–80 and at inlet gas capacity = 100 dm^3/s with $n = 0.69$ for the range 3–1200. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Steam ejector system, single stage, 6–40 kPa-abs, steam pressure 0.7 MPa, ejector only. FOB cost = \$4750 at the ratio of the gas capacity (kg/h)/the absolute pressure (kPa) = 10 with $n = 0.45$ for the range 0.015–750. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Steam ejector system, two stage with barometric condenser, 1.3–13 kPa-abs, steam pressure 0.7 MPa, and 29 °C water including two ejectors, barometric condenser and interstage piping. FOB cost = \$23 000 at the ratio of the gas capacity (kg/h)/the absolute pressure (kPa) = 10 with $n = 0.39$ for the range 0.7–20. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Steam ejector system, multistage with barometric condensers, 0.07–27 kPa-abs, steam pressure 0.7 MPa, and 29 °C water including two ejectors, barometric condenser and interstage piping. FOB cost = \$28 500 at the ratio of the gas capacity (kg/h)/the absolute pressure (kPa) = 10 with $n = 0.24$ for the range 0.8–80. L+M* = 1.7–2.1. L/M = 0.1–0.15. Alloy factors: cast iron, × 1.00; c/s, ×1.30; s/s, × 2; Hastelloy, × 3.0. Factors, barometric condensers, × 1.0; surface or shell and tube indirect contact condensers, × 1.25.

Rotary piston oil-sealed vacuum pump, 0.015 kPa-abs, with base plate, drip proof motor, belt guard and drive. FOB cost = \$10 000 at free air displacement = 17 dm^3/s with $n = 0.55$ for the range 0.3–1700. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Generalized vacuum pump including TEFC motor, base plate and belt drive. FOB cost = \$50 000 at the ratio of the gas capacity (kg/h)/the absolute pressure (kPa) = 10 with $n = 0.64$ for the range 0.01–500. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Oil diffusion vacuum pump, complete unit. FOB cost = \$4200 at free air displacement = 1.4 m^3/s with $n = 0.22$ for the range 0.007–1.4 and $n = 0.89$ for the range 1.4–17. L+M* = 1.7–2.1. L/M = 0.1–0.15.

Section 2.3
Liquid

Pumps, centrifugal, AVS, 1800 rpm, 15 m head, radial flow, cast iron with housing, impeller, mechanical seal, base plate, coupling but excluding motor. Four correlations are available. FOB cost = \$7000 at drive power = 16 kW with $n = 0.26$ for the range 0.2–16 and $n = 0.43$ for the range 16–400; *or* FOB cost = \$9500 at rated capacity 8.3 L/s with $n = 0.34$ for the range 1–500; *or* FOB cost = \$10 000 at product of (capacity, m^3/s) and (head, m)$^{0.5}$ = 10 with $n = 0.34$ for the range 1–300, *or* FOB cost = \$15 000 at the product of (capacity, $m^3/s)^{0.6}$ and (head, m)$^{2.5}$ = 5000 with $n = 0.34$ for the range 1000 to 30 000. L+M* = 1.47. L/M = 0.28. Alloy factors: cast iron, × 1.00; c/s. 1.3; bronze, ×1.5; 316 s/s alloy, × 1.9; clad, × 1.4; 304 s/s alloy, × 1.9; nickel, × 3.0; monel, × 3.0; Alloy 20, × 1.9; Hastelloy C, × 2.8; titanium, × 9.5. Pressure factors: suction pressure, 1.1 MPa, × 1.00; 3.5 MPa, × 1.6; 7. MPa, × 2.0. Type factors: self priming, × 1.5; heavy duty, × 1.10; closed impeller, × 1.15. Stage factors: single stage, × 1.00; two stage, × 1.3; three stage, ×1.4; four stage, × 1.5; five stage, × 1.7; six stage, × 1.9.

Pumps, centrifugal, AVS, 1800 rpm, 15 m head, radial flow, cast iron with housing, impeller, mechanical seal, base plate, coupling, and TEFC motor. Three correlations are available. FOB cost = \$9500 at drive power = 23 kW with $n = 0.29$ for the range 1–23 and $n = 0.79$ for the range 23–250; *or* FOB cost = \$12 700 at rated capacity 16.7 L/s with $n = 0.59$ for the range 0.5–500 *or* FOB cost = \$10 000 at the product of (capacity, L/s) and (head, m) = 1000 with $n = 0.29$ for the range 100–1000 and $n = 0.75$ for the range 1000–100 000. L+M* = 1.47. L/M = 0.4. Alloy factors: cast iron, × 1.00; c/s. 1.3; bronze, × 1.28; 316 s/s alloy, × 1.93; clad, ×1.45; 304 s/s alloy, × 1.9; nickel, × 3.5; monel, × 3.2; Alloy 20, × 2.3; Hastelloy C,

× 2.95; titanium, × 9.0. Pressure factors: suction pressure, 1.1 MPa, × 1.00; 3.5 MPa, × 1.5; 7 MPa, × 1.9. AVS, × 1.00; APS, ×1.6.

Pumps, centrifugal, heavy duty, non-clog, 1800 rpm, cast iron with base plate, coupling and mechanical seal excluding motor. FOB cost = \$9000 at drive power = 19 kW with n = 0.11 for the range 0.8–19 and n = 1.10 for the range 19–150. L+M* = 2.3. L/M = 0.15.

Pumps, in-line, API-610: vertical, 1.1 MPa, cast iron with base plate, coupling, TEFC motor. FOB cost = \$8000 at drive power = 11 kW with n = 0.28 for the range 0.5–122 and n = 0.58 for the range 11–60 *or* FOB cost = \$20 000 at the product of (capacity, L/s) and (head, m) = 2,000 with n = 0.17 for the range 100–1000 and n = 0.75 for the range 1000–100 000. L+M* = 1.72. L/M = 0.15. Alloy FOB cost factors: cast iron × 1.00; cast steel × 1.3; s/s × 1.6; s/s clad × 1.3. Pressure factors: 1.1 MPa, × 1.00; 3.6 MPa, × 1.5; 7 MPa, × 1.92.

Pumps, axial flow: steel, with impeller, mechanical seal, base plate, coupling, and TEFC motor. Three correlations: FOB cost = \$150 000 at flow rate = 0.67 m^3/s with n = 0.03 for the range 0.06–0.67 and n = 0.65 for the range 0.67–17 *or* FOB cost = \$76 000 at the product of (capacity, L/s) and (head, m) = 1000 with n = 0.79 for the range 100–100 000 *or* FOB cost = \$76 000 at drive power = 10 kW with n = 0.79 for the range 1–1000. L+M* = 2.0. L/M = 0.2. Factors: axial flow, × 1.00; mixed flow, × 1.6.

Pumps, peripheral/turbine: steel with impeller, mechanical seal, base plate, coupling, TEFC motor. Two correlations: FOB cost = \$11 000 at drive power = 10 kW with n = 0.48 for the range 1–500 *or* at the product of (capacity, L/s) and (head, m) = 600 with n = 0.48 for the range 300–10 000. L+M* = 1.8. L/M = 0.4–0.41. Alloy factors: steel, × 1.00; cast iron, × 0.6; bronze fitted, × 0.65; all bronze, × 1.00; s/s, × 1.6.

Pumps, reciprocating: piston or plunger type, cast iron, 1.1 MPa suction pressure, 150–300 rpm with the exit pressure < 7 MPa with base plate, gears and TEFC motor. FOB cost \$25 000 at drive power = 5 kW with n = 0.16 for the range 0.5–5 and n = 0.59 for the range 5–200. L+M* = 2.4. L/M = 0.3. Alloy factors: cast iron × 1.00; cast steel × 1.8; s/s × 2.4; nickel alloy × 5.0.

Pumps, reciprocating: piston or plunger type, cast iron, 1.1 MPa suction pressure, 150–300 rpm with the exit pressure < 7 MPa with base plate, gears excluding TEFC motor. FOB cost = \$12 500 at drive power = 10 kW with n = 0.52 for the range 0.5–200. L+M* = 2.3. L/M = 0.25–0.4. Alloy factors: cast iron, × 1.0; c/s, × 1.55; s/s, × 2.1. Suction pressure factors: 1.1 MPa, 1.00; 3.5 MPa, × 1.2; 7 MPa, × 1.4; Exit pressure factors, < 7 MPa, × 1.00; 35–70 MPa, × 2.5.

Pumps, reciprocating metering pumps: 316 s/s with drive, base plate, gears and TEFC motor. FOB cost = \$14 200 at drive power = 1 kW with n = 0.85 for the range 0.2–3. L+M* = 1.5. L/M = 0.3. Alloy factors: 316 s/s, × 1.00; cast steel, × 0.64; cast iron, × 0.5. Discharge pressure factors: 1.1 MPa, × 1.00; 3.5 MPa, × 1.37; 7 MPa, × 1.79.

Pumps, diaphragm: cast iron with drive, base plate, gears and TEFC motor. FOB cost \$7000 at a drive power = 10 kW with n = 0.43 for the range 6–300 or at the product of (capacity, L/s) and (head, m) = 600 with $n = 0.43$ for the range 400–20 000. L+M* = 1.6 -2.3. L/M = 0.15.

Pumps, diaphragm: 316 s/s with PTFE diaphragm, drive, base plate, gears and TEFC motor. FOB cost = $18 000 at drive power = 1 kW with $n = 0.67$ for the range 0.2–3. L+M* = 1.5. L/M = 0.3. Alloy factors: 316 s/s, × 1.00; cast steel, × 0.64; cast iron, × 0.5. Discharge pressure factors: 1.1 MPa, × 1.00; 3.5 MPa, × 1.37; 7 MPa, × 1.79.

Pumps, rotary screw moyno: cast iron with pump, base plate, V-belt drive but excluding motor. FOB cost $10 000 at flow rate = 5.5 L/s with $n = 0.5$ for the range 1–5.5 and $n = 0.6$ for the range 5.5–25. L+M* = 1.6–2.2. L/M = 0.15. Factor: without motor, × 1.00; with TEFC motor, × 1.2.

Pumps, gear: cast iron with base plate, gear reducer and open drip proof motor. FOB cost = $6000 at flow rate = 10 L/s with $n = 0.43$. L+M* = 1.6–2.3. L/M = 0.15. Alloy factors: cast iron × 1.00; 316 s/s × 2.4; glass lined × 3.6; bronze × 1.4. Pump only, × 0.30.

Pumps, sliding vane: cast iron with pump, base plate, hear box or coupling but excluding motor. FOB cost $10 000 at a capacity = 10 L/s with $n = 0.75$ for the range 0.4–120. L+M* = 1.6–2.3. L/M = 0.15. Factor: without motor, × 1.00; with motor, × 1.7.

Pumps, Archimedes screw: c/s with 38° inclination with shaft and flights, upper and lower bearing mounts, V belt drive and TEFC motor excluding concrete channel and influent and effluent basins. FOB cost $160 000 at drive power = 10 kW with $n = 0.58$ for the range 0.6–100. L+M* = 1.7–2.1. L/M = 0.3–0.41.

Section 2.4
Gas-Liquid (Two-phase Flow)

Cost as a pipe, Section 2.7, plus the necessary auxiliaries, such as gas injection and fluid pumping as required for the application. Costs for some configurations are given in Section 6.5.

Section 2.5
Pumping Slurries: Liquid–Solid Systems

Cost as a pipe, Section 2.7, plus the necessary auxiliaries, such as fluid pumping as required for the application.

Section 2.6
Solids

Belt conveyors: belt speed 1 m/s handling solids of density 1.6 $\mathrm{Mg/m^3}$ with steel welded frame, head and tail pulley, troughing idlers, roller bearings, cold rolled steel shafters, four ply, 28 oz belt excluding motor, drive and supports. FOB cost = $21 000 for the product of (solids capacity, Mg/h) × $(\text{length, m})^{2.5} = 10^6$ with $n = 0.20$ for the range $5000–5 \times 10^7$. L+M* = 1.7–2.7. L/M = 0.3.

Bucket elevators: handling solids of density 1.6 Mg/m^3 with single vertical leg, casing, chain or belt, sprockets, malleable iron buckets, roller bearings, screw takeup, boot and head excluding motor and drive. FOB cost = $25 000 for the product of (solids capacity, Mg/h) × (vertical lift, m) = 500 with $n = 0.50$ for the range 10–3000. L+M* = 1.9–2.35. L/M = 0.44. Discharge factors: centrifugal discharge of chain-bucket, × 1.00; centrifugal discharge belt, × 1.25; continuous discharge, × 1.25.

Screw conveyors: c/s with trough, cover, screw flights, bearings, inlets and outlets excluding motor, drive and supports. FOB cost = $36 000 for the product (solids capacity, Mg/h) × (length, m) = 5000 with $n = 0.46$. L+M* = 1.6–2.4. L/M = 0.25. Alloy factors: c/s, × 1.00; s/s, × 3.5.

Oscillating conveyors: excluding motor and drive. FOB cost = $6500 for the product of $(\text{width, m})^{0.75}$ × (length, m) = 10 with $n = 0.93$ for the range 2–100. L+M* = 1.7. L/M = 0.25.

Roller conveyors: FOB cost = $600 for the product of (length, m) × (width, cm) with $n = 0.90$ for the range 10–500. L+M* = 1.65. L/M = 0.3.

Pneumatic conveyors, dilute phase: low pressure or vacuum, c/s duct excluding blower and motor. FOB cost $145 000 for the product of $(\text{diameter, m})^2$ × (length, m) = 2.2 with $n = 0.14$ for the range 0.18–2.2 and $n = 0.38$ for the range 2.2–15. L+M* = 2.0. L/M = 0.3. Alloy factors: carbon steel, × 1.00, s/s × 2.23.

Pneumatic conveyors, dense phase: batch, high pressure, with fluidizer only, excluding piping, fittings, switches, air supply and air compressor. FOB fluidizer cost = $40 000 for the product of $(\text{diameter, m})^2$ × (length, m) with $n = 0.47$ for the range 0.8–7. L+M* = 2.0. L/M = 0.3.

Hoists for medium lift, heavy duty with push trolley, multiple disc brakes including motor and drive. FOB cost = $16 000 for lifting capacity = 2.6 Mg with $n = 0.36$ for the range 4.5–26 and $n = 1.48$ for the range 26–45. For motor driven trolley × 1.6.

Hoists for long lift with motor driven trolley, cab or floor controlled, variable speed, mechanical or electric load braking, double reeving, single or twin load hooks, overload relays, AC current. FOB cost = $40 000 for lifting capacity = 3 Mg with $n = 0.82$ for the range 2–20. For DC current × 1.05. L+M* = 1.5. L/M = 0.22.

Cranes bridge type, with bridge, crane trolley, controls, motors, floor operated at 0.75 m/s, AC current. FOB = $185 000 at lifting capacity = 15 Mg with $n = 0.23$ for the range 3–15 and $n = 0.56$ for the range 15–20. L+M* = 1.6. L/M = 0.25. Factors: floor operated, × 1.00; cab operated at 1.5 m/s, × 1.07; AC current, × 1.00; DC current, × 1.07.

Feeder: star or rotary: hot rolled steel excluding motor. FOB cost = $6600 for a diameter = 20 cm with $n = 0.52$ for the range 15–30. L+M* = 2.0. L/M = 0.3. Alloy factors: hot rolled steel, × 1.00; s/s, × 1.07.

Feeder, apron, with motor and drive excluding hopper. FOB cost = $90 000 for the product of $(\text{width, m})^2$ × (length, m) = 2 m^3 with $n = 0.18$ for the range 0.75–25. L+M* = 2.0. L/M = 0.3.

Feeder, vibratory with motor and drive. FOB cost = \$27 000 for the product of (width, m) × (length, m) = 1.8 m^2 with $n = 0.62$ for the range 0.4–1.8 and $n = 1.1$ for the range 1.8–8. L+M* = 2.15–2.65. L/M = 0.28.

Section 2.7
Ducts and Pipes

Cost of pipes and fittings are usually included in the L+M* factors. For those special cases where estimates are needed just of the pipe:

Ducts:

Installed cost per meter \$700 for cross sectional area of 4 m^2, $n = 0.53$; for diameter of 2.3 m, $n = 1.08$. Alloy cost factor: galvanized × 1.00; aluminum × 2; s/s × 4.3.

Pipes:

FOB cost per meter \$80 for 15 cm diameter, $n = 1.33$ for the range 10–70. L+M* = 13 (including fittings, supports, insulation, labor cost to install 30 valves but excludes cost of valves). Alloy cost factors: c/s × 1.00; c/s galvanized × 0.92; aluminum × 1.82; PVC × 0.9–1.1; 316 s/s × 3.77; 304 s/s × 2.90; monel × 4; nickel × 4.53; c/s glass lined × 3.17; c/s PTFE lined × 3.17.

Section 3.1
Drives

Gas diesel engines FOB cost = \$250 000 at 300 kW with $n = 0.82$ for the range 20–50 000 kW. L+M* = 2.0. L/M = 0.3.

Electric motors, induction, squirrel cage: 3 phase, AC, TEFC, 1800 rpm excluding starter, gearing. FOB cost = \$19 000 at drive power = 75 kW with $n = 1.1$ for the range 0.3–1500. L+M* = 1.36. L/M = 0.58. Factors: 1800 rpm, × 1.00; 900 rpm, × 1.3; 1200 rpm, × 1.5; 3600 rpm, × 1.3. Enclosure factors: TEFC, × 1.00; open drip proof, × 0.7; guarded drip proof, × 0.9; explosion proof, × 1.15.

Electric motors, induction, wound rotor: 3 phase, AC, open drip proof, 1800 rpm, excluding starter. FOB cost = \$8000 at drive power = 50 kW with $n = 0.93$ for the range 8–150. L+M* = 1.6. L/M = 0.58.

Electric motors, synchronous: AC open drip proof, 1800 rpm excluding gears. FOB cost = \$380 000 at drive power = 2235 kW with $n = 0.96$ for the range 350–7000 kW. L+M* = 1.6. L/M = 0.26.

Electric motors, synchronous, open drip proof: AC, 1200 rpm excluding gears. FOB cost = \$260 000 at drive power = 2235 kW with $n = 0.81$ for the range 500–7000 kW. L+M* = 1.3. L/M = 0.26. Factors: 1200 rpm, × 1.00; 900 rpm, × 1.10; 514 rpm, × 125.

Electric motors, gear reduced TEFC: 1800 rpm plus gear reducer to give fixed output rpm. FOB cost = \$1800 at drive power = 1.8 kW with $n = 0.20$ for the range 0.35–1.8 and $n = 0.53$ for the range 1.8–15. L+M* = 1.67. L/M = 0.26.

Electric motors, variable speed TEFC: 1800 rpm plus V-belt unit for speed control 2/1 to 5/1 at 3480, 520 and 30 rpm. FOB cost = \$8000 at the ratio of (drive power at 1800 rpm, kW)/(rpm)$^{0.2}$ = 1.5 with n = 0.63 for the range 0.35–7.5. L+M* = 1.67. L/M = 0.26.

Drives, gear units: general, single, double, triple reduction on concentric, offset or vertical right angle drives, excluding lubrication system and motor. FOB cost = \$6000 at the product of (drive power at 1800 rpm, kW) × (reduction ratio)$^{0.5}$ = 50 with n = 0.45 for the range 3–50 and n = 0.75 for the range 50–1500. L+M* = 1.5. L/M = 0.2.

Drives, gear units: medium duty, single reduction 20/1 to 50/1 excluding lubrication system and motor. FOB cost = \$5300 at the product of (drive power at 1800 rpm, kW) × (reduction ratio)$^{0.5}$ = 180 with n = 0.54 for the range 3–180 and n = 1.90 for the range 180–1500. L+M* = 1.5. L/M = 0.2.

Steam turbines: noncondensing, steam 2 MPa, 100–150 °C superheat, backpressure $<$ 0.7 MPa, wheel diameter about 60 cm excluding gears and lubrication. For single valve, single stage, FOB cost = \$90 000 at power = 300 kW with n = 0.51 for the range 7–3000. For single valve, multistage, FOB cost = \$800 000 at power = 3000 kW with n = 0.46 for the range 700–15 000. For multivalve, multistage, FOB cost = \$1 250 000 at power = 3000 kW with n = 0.35 for the range 1500–15 000. L+M* = 1.4–1.5. L/M = 0.26. Factors: steam pressure 2 MPa, × 1.00; 4 MPa, × 1.22; 6 MPa, × 1.50; 14 MPa, × 1.60. Steam superheat: $<$ 50 °C, × 1.08; 50–100 °C, × 0.97; 150–200 °C, × 1.05; $>$ 200 °C, × 1.10. Noncondensing, × 1.00; condensing including condenser and integral piping, × 1.85.

Gas driven turbine: excluding equipment needed for gas supply. FOB cost = \$2 000 000 at output power = 5,000 kW with n = 0.8 for the range 1000–30 000. L+M* = 1.4–1.5. L/M = 0.26.

Gas combustion turbines: with inlet air system, compressor, combustion chamber, firing, turbine, starter and exhaust system. FOB cost \$4 000 000 at output drive power = 5000 kW with n = 0.55 for the range 650–15 000. L+M* = 1.4–1.5. L/M = 0.26.

Electric power generators: steam raising plus turbines: for steam at 1–1.7 MPa or for gas driven without regenerator. FOB cost \$4 800 000 for power output = 10 000 kW with n = 0.73 for the range 3000–50 000. L+M* = 1.6. L/M = 0.25. Factors for steam driven: steam pressure, 1–1.7 MPa, × 1.00; 6 MPa, × 1.3; 17 MPa, × 1.5. Factors for gas driven: without gas regenerator, × 1.00; with regenerator, × 1.25.

AC–DC converters: uni-converter, current single direction; voltage, either. Input 3 phase AC 230/460/575. Nema 1. FOB cost = \$40 000 at power = 30 kW with n = 0.61 for the range 10–80. Factors: uni, × 1.00; dual with current and voltage either direction, Nema 1, × 1.1; Nema 12 enclosures, × 1.64.

Section 3.2
Thermal Energy: Furnaces

Box type furnace, fired: horizontal radiant c/s tubes for process service, Field erected cost \$1 500 000 at 10 MW heat absorbed, n = 0.87, range 2–100 MW. L+M* = 1.3. L/M = 0.22. Alloy FOB cost factors: c/s × 1.00; Cr–Mo × 1.24;

304 s/s × 1.34; 316 s/s × 1.34; Incalloy × 2. Pyrolysis furnace configuration × 1.09; reformer configuration, × 1.34. Pressure factors 3.4 MPa, × 1.05; 7 MPa, 1.15; 15 MPa, × 1.3; 20 MPa, × 1.4.

Cylindrical type furnace, fired: high grade c/s in both radiant and convection sections, vertical, 3.6 MPa, Field erected, \$250 000 at 1 MW heat absorbed, $n = 0.74$, range 0.5–100. L+M* = 1.57–1.62. L/M = 0.22. Alloy FOB cost factors: c/s × 1.00; Cr–Mo × 1.45; s/s × 1.5. Pressure factors: 0.7 MPa, × 0.35; 7 MPa, × 1.15; 10 MPa, × 1.2; Dowtherm, × 1.33.

See also Section 3.12 for costs of steam boilers.

Section 3.3
Thermal Energy: Fluid Heat Exchangers, Condensers and Boilers

Shell and tube: floating head, 1.1 MPa, c/s in c/s shell, bare tube. FOB cost = \$70 000 for heat transfer area = 100 m^2 with $n = 0.71$ for the range 20–2000. L+M* = 2.2–2.8. L/M = 0.35–0.37. Alloy FOB factors for tubes in c/s shell: c/s × 1.00; aluminum × 1.2; copper × 1.35; brass × 1.3; Admiralty × 1.5; 70–30 Cu–Ni × 1.7; nickel × 2.8; 316 s/s × 2.4; 304 s/s × 2.0; Monel × 3.0; titanium × 9.0; Inconel × 2.4; Hastalloy C × 8.5. Alloy FOB factors for tubes and shell of 316 s/s × 3; 304 s/s × 2.8; Monel × 4.0; titanium × 13.0. Factors: floating head, × 1.00; fixed head, × 0.85; U-tube, × 0.87; as kettle reboiler, × 1.35.

Spiral plate (Rosenblad): c/s and 350 kPa. FOB cost = \$30 000 at heat transfer area = 10 m^2 with $n = 0.47$ for the range 1–100. L+M* = 2.2–2.8. L/M = 0.35–0.37. Alloy FOB factors: c/c in c/c × 1.00; 316 s/s × 2.8.

Spiral tube heat exchanger (Heliflow): c/s tube. FOB cost = \$1100 at heat transfer area = 0.7 m^2 with $n = 0.43$ for the range 0.25–0.7 and $n = 0.83$ for the range 0.7–6. L+M* = 1.53. L/M = 0.35–0.37. Alloy factors: c/s, × 1.0; s/s, × 4.0.

Plate coil, exchanger: c/s plate with double embossed serpentine or header coil on plate. FOB cost = \$600 for a surface area = 2.5 m^2 with $n = 0.38$ for the range 0.5–2.5 and $n = 1.07$ for the range 2.5–10. L+M* = 1.6. L/M = 0.22. Alloy factor: c/s, × 1.00; s/s, × 4.4. Double embossed, × 1.00; single embossed, × 2.8.

Plate and frame heat exchanger: 316 s/s, 0.7 MPa. FOB cost = \$120 000 at heat transfer area = 100 m^2 with $n = 0.65$ for the range 10–600. L+M* = 1.53. L/M = 0.35–0.37. Alloy FOB factors: c/s × 0.43; 316 s/s × 1.0; 304 s/s, × 0.95; nickel × 1.1; titanium × 2.6.

Cubic/monolithic heat exchanger: graphite in c/s shell. FOB cost = \$14 000 for heat transfer area = 6.5 m^2 with $n = 0.71$ for the range 1–20 m^2. L+M* = 2.2–2.8. L/M = 0.35–0.37.

Double pipe heat exchanger: c/s inside c/s with inner tube finned. Total area: bare tube area = 5–10:1. Increase in area by selection of fins and tube length. Duplication of units not allowed in this correlation. FOB cost \$30 000 at 3 m^2 total heat transfer area, $n = 0.14$, range 0.1–20. L+M* = 2.57. L/M = 0.35–0.37. Alloy FOB factors in c/s outside jacket: c/s × 1.00; s/s × 1.85–2.65; unfinned central s/s tube × 2.1. Alloy FOB factors for tubes and jacket: s/s × 5.5. Pressure factor: 6 MPa × 1.10; 7 MPa × 1.25.

For duplication of units, FOB cost \$30 000 at 3 m^2 total area with $n = 1.23$ for sizes > 3 m^2.

Air cooled heat exchanger: FOB cost for c/s 1 MPa including bundle, heater, fan, explosion-proof motor, case but excluding foundation, water trim cooler, fireproofing. \$70 000 at bare tube heat transfer area = 100 m^2, $n = 0.39$ for range 10–10 000. Finned area: bare area = 16:1. L+M* = 1.6–2.1. L/M = 0.21–0.24. Alloy factors: c/s × 1.00; aluminum × 1.5; Admiralty × 1.08; s/s × 2.85; Monel × 3.2. Pressure factors, 1 MPa × 1.; 1.7 MPa × 1.05; 3 MPa × 1.1; 7 MPa × 1.15. Add water trim cooler, × 1.15–1.2.

Coil heat exchanger in tank: c/s coil excluding tank. FOB cost = \$2300 for a heat transfer area = 2.8 m^2 with $n = 0.62$ for the range 0.1–30. L+M* = 2.2–2.8. L/M = 0.35–0.37. Alloy FOB factors: c/s coil × 1.00; s/s × 2.3; glass × 3.5; teflon × 3.0.

Ramen/lamella plate fin heat exchanger: brazed alumina, pressure < 7 MPa. FOB cost = \$48 000 for a heat transfer area = 1300 m^2 with $n = 0.34$ for the range 100–1300 and $n = 1.00$ for the range 1300 to 10 000. L+M* = 2.2–2.8. L/M = 0.35–0.37.

Thermal screw heat exchanger: single screw, c/s with screw and trough but excluding motor and drive. FOB cost = \$65 000 for a transfer area = 7.5 m^2 with $n = 0.13$ for the range 1–7.5 and $n = 0.78$ for the range 7.5–40. L+M* = 1.53. L/M = 0.35–0.37. Related to drying, Section 5.6.

Section 3.4
Thermal Energy: Fluidized Bed (Coils in Bed)

Bayonet heat exchanger: c/s. FOB cost = \$930 at heat transfer area = 1.3 m^2 with $n = 0.25$ for the range 0.1–1.3 and $n = 1.33$ for the range 1.3–12. L+M* = 1.53. L/M = 0.35–0.37.

Section 3.5
Thermal Energy: Static Mixers

See Section 6.6.

Section 3.6
Thermal Energy: Direct Contact L–L Immiscible Liquids

Costs see process vessels, Section 10.1.

Section 3.7
Thermal Energy: Direct Contact G–L Cooling Towers

Cooling tower: induced or forced draft, approach temperature 5.5 °C, wet bulb temperature 23.8 °C, cooling range 5.5 °C. Package with fans, motors, integral piping, erection and labor excluding foundations, basin, water pumps, external and distribution piping. Packed FOB = \$1 200 000 for water flow rate = 1000 L/s with $n = 1.00$ for the range 100–1000 and $n = 0.64$ for the range

1000–12 000. L+M = 1.22. L/M = 0.2. Factors: including foundations and basin, × 1.7–3.0; including distribution piping, × 1.3. Factors to adjust for different approach temperatures, wet bulb temperatures and cooling range vary from 0.4–2.0.

Section 3.8

Thermal Energy: Direct Contact G–L Quenchers

For spray tower and baffle tower, see Section 5.2. For tray and packing see Section 4.2.

Section 3.9

Thermal Energy: Direct Contact G–L Condensers

Direct contact: barometric condensers: c/s multijet spray type excluding hot well. FOB cost = \$22 000 for a water flow rate = 33 L/s with n = 0.6 for the range 3.3–600. FOB cost = \$36 000 for a body diameter = 1 m with n = 1.37 for the range 0.1–2.5 m. L+M* = 1.6. L/M = 0.17. Alloy FOB factors: c/s × 1.00; cast iron × 1.5; rubber lined × 2.0.

Section 3.10

Thermal Energy: G–G Thermal Wheels and Pebble Regenerators and Regenerators

Thermal wheel: (Ljungstom heater) Low temperature operation $< 400\,°C$ aluminum or asbestos coated including wheel, wheel housing, drive and motor designed for a face velocity = 3.5 m/s for each side of a balanced flow exchanger but excluding air chambers, fans and reheat coil. FOB cost = \$50 000 for a nominal gas flow rate = 5 Ndm^3/s with n = 0.50 for the range 1–15. L+M* = 1.6. L/M = 0.17. Alloy FOB factors: aluminum × 1.00; 316 s/s or enamel for temperatures $< 400\,°C$ × 1.75.

Thermal wheel: (Ljungstom heater) High temperature operation $< 800\,°C$, for conditions described above. FOB cost = \$175 000 for a nominal gas flow rate = 5 Ndm^3/s with n = 0.75 for the range 2–10. L+M* = 1.6. L/M = 0.17.

Section 3.11

Thermal Energy: Refrigeration

Refrigeration, package unit: mechanical vapor recompression, c/s, evaporator temperature 4.4 °C with centrifugal compressor, condensers, insulation, instrumentation, field erection excluding cooling tower. Package delivered and field erected cost = \$800 000 at a refrigeration capacity = 1000 kW with n = 0.77 for the range 20–5000 kW. L+M = 1.3. L/M = 0.82. Evaporator temperature factors: 4.4 °C, × 1.00; 9.9 °C, 0.94; –1.1 °C, × 1.08; –6.6 °C, × 1.4; –17.7 °C, × 1.8; –29 °C, × 3.0; –40 °C, × 4.0; –51 °C, × 7.0; –62 °C, × 15.0. Factor: including cooling tower, × 5.5.

Section 3.12
Thermal Energy: Steam Generation and Distribution

Boiler, fired, package: gas–oil fired, water tube with fire tube for smaller size, 1.5 MPa with boiler, burner, fan, deaearator, chemical injection, stack, integral piping, instruments. FOB cost \$500 000 for saturated steam generated = 2.7 kg/s with n = 0.92 for the range 1–10; cost = \$2 850 000 for saturated steam generated = 14 kg/s with n = 0.35. L+M = 1.35. L/M = 0.13.
Boiler, field erected: gas–oil fired, water tube, 1.5 MPa, excluding distribution facilities and housing. Delivered and field erected cost = \$8 000 000 at saturated steam generated = 22 kg/s with n = 0.59. L+M* = 1.2–1.8. L/M = 0.26. Factors: 3.5 MPa, × 1.02; 4.2 MPa, × 1.08; 5.6 MPa, × 1.15; 7.0 MPa, × 1.25; 10 MPa, × 1.3. Housed, × 1.20; including distribution facilities, × 2.5.

Section 3.13
High Temperature Heat Transfer Fluids

Dowtherm furnace: package unit including firing. FOB cost = \$110 000 for heat absorbed = 280 kJ/s with n = 0.61 for the range 40–2800.

Section 3.14
Tempered Heat Exchange Systems

Tempered glycol system for heating: package unit: c/s, with low pressure steam to heat the circulating 50 % glycol solution from 35 to 65 °C including heat exchangers, tank, TEFC motors, circulating pump, integral piping, valves, fittings, instrumentation excluding foundation and hookup. BM cost = \$93 000 for a circulation rate = 10 L/s with n = 0.23 for the range 1.5–20.
Tempered glycol system for cooling, package unit: c/s, with cooling water to cool the circulating 50 % glycol solution with heat exchangers, tank, TEFC motors, circulating pump, integral piping, valves, fittings, instrumentation excluding foundation and hookup. BM cost = \$170 000 for a heat load of 1 MW with n = 0.23 for the range 0.3–1 and n = 0.53 for the range 1–3.

Section 4.1
Evaporation

External short tube, vertical exchanger, natural circulation: including vapor piping, barometric condenser, vacuum equipment, integral piping, condensate receivers. FOB cost \$80 000 at 5 m^2 heat transfer area, n = 0.50 for the range 2–20. L+M* = 1.6–1.9. L/M = 0.34–0.7. Alloy cost factors: c/s × 1.00; copper × 1.3; s/s × 2.3; nickel alloy × 2.8; titanium × 6.6. Evaporator body only × 0.3.
External short tube, vertical exchanger, forced circulation: including vapor piping, barometric condenser, vacuum equipment, integral piping, condensate receivers, circulating pump and drive. FOB cost \$1 200 000 at 100 m^2 heat transfer area,

$n = 0.74$ for the range 20–500. L+M* = 1.6–1.9. L/M = 0.35. Alloy cost factors: c/s × 1.00; monel clad × 1.8; nickel clad × 1.5; copper × 1.3; s/s × 2.3; nickel alloy × 2.8; titanium × 6.6.

Internal calandria, horizontal short tube: including all auxiliaries vapor piping, barometric condenser, vacuum equipment, integral piping, condensate receivers. FOB cost \$205 000 at 45 m^2 heat transfer area, $n = 0.47$ for the range 10–900. L+M* = 1.6–1.9. L/M = 0.35. Alloy cost factors: c/s × 1.00; cast iron with copper tubes × 1.0; lead lined × 2.0; copper × 1.3; s/s × 2.3; nickel alloy × 2.8; titanium × 6.6.

Internal calandria, vertical short tube: including vapor piping, barometric condenser, vacuum equipment, integral piping, condensate receivers. FOB cost \$220 000 at 45 m^2 heat transfer area, $n = 0.55$ for the range 10–600. L+M* = 1.6–1.9. L/M = 0.35. Alloy cost factors: c/s × 1.00; cast iron with copper tubes × 1.0; lead lined × 2.0; copper × 1.3; s/s × 2.3; nickel alloy × 2.8; titanium × 6.6.

Long tube, rising or falling film: including vapor piping, barometric condenser, vacuum equipment, integral piping. FOB cost \$350 000 at 100 m^2 heat transfer area, $n = 0.68$ for the range 1–10 000. L+M* = 2.5. L/M = 0.35. Alloy cost factors: c/s × 1.00; cast iron body with copper tubes × 2.0; rubber lined with karbate tubes × 3; nickel × 10; copper × 3.5. Evaporator only × 0.85.

Agitated falling film: including thermal section, separator, drive but excluding auxiliaries and vacuum equipment. FOB cost \$80 000 at 0.5 m^2 heat transfer area, $n = 0.36$ (range 0.1–1 m^2); \$350 000 at 10 m^2 with $n = 0.62$ for the range 1–25. L+M* = 1.4–2.5. L/M = 0.35. Alloy cost factors: 304 s/s × 1.00; 316 s/s × 1.1. Including vacuum equipment × 1.5.

See Section 4.6 for mechanical recompression applied to crystallization.

Section 4.2
Distillation

Column, vertical: FOB, 1 MPa, cylindrical, dished ends, usual nozzles, access hole, support, excluding internals, c/s, \$100 000 for vessel mass of 8 Mg mass, $n = 0.58$ range 0.4–200 Mg; for the product of (height, m) (diameter, m)$^{1.5}$ = 20, $n = 0.81$ for range 0.5–1000. Pressure adjustment: 1 MPa × 1.0; 5 MPa × 1.6; 10 MPa, × 2.3; 20 MPa, × 4.35; 30 MPa × 6.1; 40 MPa × 7.8. Alloy factors: c/s × 1.0; 316 s/s × 3.6; 316 s/s/clad × 2.5; 304 s/s × 2.75; 304 s/s clad × 2.5; 310 s/s × 3.25; 410 s/s × 2.1; nickel × 8; monel × 6.5; monel clad × 4.0; Hastalloy × 15; titanium × 8; titanium clad × 4.2. L+M* = 3. L/M = 0.5.

Tray columns, c/s column with c/s sieve trays on 0.6 m spacing. FOB units with trays shop- installed complete with some nozzles but no access holes or tooling up fee. FOB cost \$545 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 100 with $n = 0.57$ for the range 4–150 $m^{2.5}$. L+M* = 2.95. L/M = 0.43–0.58.

Tray columns, c/s column with c/s sieve trays on 0.6 m spacing. FOB units with trays shop-installed with nozzles, access holes and tooling up charge. FOB cost \$545 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 100 with $n = 0.53$ for the range 4–150 $m^{2.5}$. L+M* = 2.95. L/M = 0.43–0.58.

Tray columns, 316 s/s column with 316 s/s sieve trays on 0.3 m spacing. FOB units with trays shop-installed complete with some nozzles but no access holes or tooling up fee. FOB cost \$234 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 14 with n = 0.78 for the range 5–14 m$^{2.5}$ and n = 0.93 for the range 14–100. L+M* = 1.78. L/M = 0.28–0.38. Factor, tray spacing, 0.3 m, × 1.00; 0.6 m, × 1.5.

Tray columns, 316 s/s column with 316 s/s sieve trays on 0.3 m spacing. FOB units with trays shop-installed complete with nozzles, no access holes and tooling up fee. FOB cost \$360 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 22 with n = 0.52 for the range 5–22 m$^{2.5}$ and n = 0.96 for the range 22–100. L+M* = 1.78. L/M = 0.28–0.33. Factor, tray spacing, 0.3 m, × 1.00; 0.6 m, × 1.5.

Trays stack: c/s trays, supports, fittings, shop fabrication and installation at 0.6 m tray spacing into a column but excluding the cost of the column and tooling up fee but accounting for the penalty charge based on the number of trays ordered. Installed cost = \$135 000 at the product of (stack height, m) (diameter, m)$^{1.5}$ = 100 with n = 0.78 for the range 1.5–250 m$^{2.5}$.

Trays stack: c/s trays, supports, fittings, shop fabrication and installation at 0.6 m tray spacing into a column and including tooling up fee and accounting for the penalty charge based on the number of trays ordered but excluding the cost of the column. Installed cost = \$167 000 at the product of (stack height, m) (diameter, m)$^{1.5}$ = 66 with n = 0.39 for the range 1.5–66 m$^{2.5}$ and n = 0.78 for the range 66–250.

Trays stack: 316 s/s as above but excluding tooling up fee. Installed cost = \$420 000 at the product of (stack height, m) (diameter, m)$^{1.5}$ = 87 with n = 0.76 for the range 2.5–200 m$^{2.5}$.

Trays stack: 316 s/s as above and including tooling up fee. Installed cost = \$420 000 at the product of (stack height, m) (diameter, m)$^{1.5}$ = 87 with n = 0.54 for the range 2.5–87 m$^{2.5}$ and n = 0.76 for the range 87–200.

Tray, individual sieve tray, c/s, single pass, installed in column excluding the cost of the column and for orders of > 40 trays. Installed cost per tray = \$2500 at tray diameter = 2.13 m with n = 0.80 for the range 0.9–2.13 and n = 2.01 for the range 2.13–4.6 m. Factors: c/s, × 1.00; copper, × 3.2; 304 s/s, × 2.5; 316 s/s, × 2.7; monel, × 9.9. Type of pass, single pass, × 1.00; double pass, × 1.2. Type of tray, sieve, × 1.00; turbogrid, × 1.0; valve, × 1.4; trough, × 1.4; bubble cap, × 2.4. Size of the order, > 40, × 1.0; 20–40, × 1.2; 10–20, × 1.5; 5–10, × 1.7; 1 tray, × 2.5. Trays installed in the shop, × 1.00; in the field, × 1.2. Tooling up fee, \$50 000 US.

Packed columns, c/s column with c/s Raschig rings including support trays, hold-down plates, distributor and redistributor trays including column with some nozzles but no access holes. FOB cost \$ 28 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 2.8 with n = 0.65 for the range 0.5–2.8 m$^{2.5}$ and n = 0.9 for the range 2.8–85. L+M* = 2.9. L/M = 0. 4.

Packed columns, 316 s/s column with 316 s/s Pall rings including support trays, hold-down plates, distributor and redistributor trays including column with some nozzles but no access holes. FOB cost \$ 1 425 000 at the product of (column height, m) (diameter, m)$^{1.5}$ = 65 with n = 0.90 for the range 0.5–75 m$^{2.5}$. L+M* = 1.8. L/M = 0.3.

Packing: The cost of the column can be determined from Section 10.1. The internals and packing can be estimated from the following prices for different types of packing. To this cost needs to be added the cost of support trays (one every 8 m for ceramic packings and one every 10 m for metal, hold down tray, redistribution tray and liquid distributor tray). These trays can be costed as sieve trays.

Pall rings: c/s, FOB cost/m^3 = \$2500 for a diameter = 2.5 cm with n = – 0.64 for the range 2.5–7.6. L+M* = 2.2. L/M = 0.43–0.58. Alloy cost factors: c/s × 1.00; 316 s/s × 3.3.

Pall rings: polypropylene, FOB cost/m^3 = \$1800 for a diameter = 2.5 cm with n = –0.95 for the range 2.5–7.6. L+M* = 2.2. L/M = 0.43–0.58.

Pall rings: aluminum, FOB cost/m^3 = \$3300 for a diameter = 2.7 cm with n = –0.26 for the range 2.5–7.6. L+M* = 2.2. L/M = 0.43–0.58.

Intalox: porcelain, FOB cost/m^3 = \$2400 for diameter = 2.5 cm with n = – 0.4. L+M* = 2.2. L/M = 0.43–0.58. Alloy cost factors: porcelain × 1.00; stoneware × 0.94.

Intalox: polypropylene, FOB cost/m^3 = \$1500 for diameter = 5 cm with n = –0.95 for the range 2.5–9. L+M* = 2.2. L/M = 0.43–0.58. Alloy cost factors: polypropylene, × 1.00; polyethylene, × 0.95.

Intalox: PVC, FOB cost/m^3 = \$2500 for diameter = 5 cm with n = – 0.71 for the range 2.5–7.5. L+M* = 2.2. L/M = 0.43–0.58.

Intalox: Kynar, FOB cost/m^3 = \$1500 for diameter = 5 cm with n = – 0.53 for the range 2.5–7.5. L+M* = 2.2. L/M = 0.43–0.58.

Superintalox = intalox × 1.10.

Raschig rings: porcelain, FOB cost/m^3 = \$2200 for diameter = 2.5 cm with n = –0.5 for the range 2.5–7.5. L+M* = 2.2. L/M = 0.43–0.58. Alloy cost factors: porcelain × 1.0; stoneware × 1.00; c/s × 1.58; 316 s/s × 6.1; carbon × 2.35.

Beryl saddles: porcelain, FOB cost/m^3 = \$3500 for a diameter = 2.5 cm with n = –1.00 for the range 1.2–5. L+M* = 2.2. L/M = 0.43–0.58. Alloy cost factors: porcelain × 1.00; stoneware × 1.24.

Hypac: c/s, FOB cost/m^3 = \$2500 at diameter = 5 cm with n = – 0.58 for the range 2.5–9. Alloy cost factors: c/s × 1.00; 316 s/s × 2.5.

Molecular distillation: constructed with s/s and glass including diffusion pump and nominal auxiliaries but excluding degassifier. FOB cost= \$275000 for a capacity = 0.03 kg/s with n = 0.81 for the range 0.006–0.3. L+M* = 1.6. L/M = 0.43–0.58. Factors: including degassifier, × 1.43.

Section 4.3
Freeze Concentration

Cost the individual components, wash column from Section 10.1; refrigeration unit, Section 3.12, pumps and compressors, Sections 2.1 and 2.3 and heat exchangers, Section 3.3.

For a complete process to concentrate fruit juices, or coffee, the TM cost = \$7 000 000 for a processing capacity = 1 kg/s with n = 0.48 for the range 0.03–7 kg/s.

Section 4.4
Melt Crystallization

Cost as a process vessel, Section 10.1.

Section 4.5
Zone Refining

Cost as a process vessel, Section 10.1.

Section 4.6
Solution Crystallization

Batch: evaporative cooling, c/s with vacuum equipment, mixer, central draft tube (if desired). FOB cost = \$250 000 for a working volume = 7.5 m^3 with n = 0.68 for the range 0.2–30 or for a crystal capacity of 0.55 kg/s with n = 0.68 for the range 0.2–25. L+M* = 1.6–2.6. L/M = 0.25–0.26. Alloy cost factors: c/s, × 1.00; rubber lined, × 1.27; clad 316 s/s, × 2.4.
Forced circulation growth type: c/s with pump, drive, heat exchanger, vacuum equipment and crystallizer. FOB cost \$675 000 for a crystal capacity = 1 kg/s with n = 0.53 for the range 0.1 –10. L+M* = 1.7–2.7. L/M = 0.38. Alloy cost factors: c/s, × 1.00; cast iron, × 1.0; rubber lined, × 0.75; s/s, × 3.0; copper alloy, × 1.3; nickel alloy, × 2.6; titanium, × 6.0.
Draft tube MSMPR: c/s, FOB cost \$700 000 for a crystal capacity = 1 kg/s with n = 0.63 for the range 0.5–20. L+M* = 1.75. L/M = 0.38. Alloy cost factors: c/s × 1.00; cast iron × 1.0; rubber lined × 0.75; s/s × 3.0; copper alloy × 1.3; nickel alloy × 2.6; titanium × 6.0.
CPR: Oslo, Krystall: c/s, vapor body, retention chamber, heating element, recirculation pump, TEFC motor and drive, condenser, ejectors and integral piping. FOB cost = \$1 000 000 for a crystal capacity = 1 kg/s with n = 0.62 for the range 0.1–100. FOB cost = \$720 000 for a heat transfer area = 93 m^2 with n = 0.57 for the range 10–100. L+M* = 1.75–2.75. L/M = 0.38. Alloy cost factors: c/s, × 1.00; rubber lined, × 1.2; s/s, × 2.1; copper alloy, × 1.3; nickel alloy, × 2.6; titanium, × 6.0. Factors: Oslo and Krystal type, × 1.00; flash growth type, Pachuca, × 0.7.
Scraped surface crystallizer: c/s excluding motor and drive. FOB cost \$50 000 for a cooling area = 10 m^2 with n = 0.79 for the range 7–60. L+M* = 1.6. L/M = 0.25.
Triple effect forced circulation: c/s. FOB cost \$2 230 000 for a crystal capacity = 2.5 kg/s with n = 0.63 for the range 0.75–10. L+M* = 1.75. L/M = 0.38. Alloy cost factors: c/s × 1.00; cast iron × 1.0; rubber lined × 0.75; s/s × 3.0; copper alloy × 1.3; nickel alloy × 2.6; titanium × 6.0.

Mechanical vapor recompression: c/s. FOB cost \$3 400 000 for a crystal capacity = 2.5 kg/s with n = 0.75 for the range 0.75–10. L+M* = 1.6. L/M = 0.38.

Section 4.7
Precipitation

Cost as a process vessel, Section 10.1.

Section 4.8
Gas Absorption

See Section 4.2 for cost guidelines for packed and tray columns. See Section 10.1 for pressure vessels.
For scrubbers, see Section 5.2.

Section 4.9
Gas Desorption/Stripping

See Section 4.8.
Vacuum type: c/s including vessel, pump, motor, drive and vacuum equipment. FOB cost \$70 000 for a liquid flow rate = 12.6 L/s with n = 0.43 for the range 2–60. L+M* = 1.7. L/M = 0.4.
Forced draft packed: c/s with fan , motor, tower, catch basin, level controllers, two s/s pumps and motors. FOB cost \$40 000 for a liquid flow rate = 6.3 L/s with n = 0.45 for the range 2–60. L+M* = 1.7. L/M = 0.4.
Gas stripping, forced draft, packed, ammonia: Installed cost = \$5 000 000 for a liquid flow rate = 200 L/s with n = 0.38 for the range 40–200 and n = 0.88 for range 200–4000 L/s.
Gas stripping packed or tray column; ammonia, column only with internals. FOB cost = \$550 000 at design flow rate of sour water = 12 L/s with n = 0.53 for the range 3–55 L/s. L+M* = 3.0. Factors: tower only, × 1.00; tower plus reboiler, condensers, accumulators, shutdown tankage, piping, × 4.2. Retrofit, × 1.6.
Edible oil deodorizing vessel: with preheater, deaerator, booster and steam ejectors with dry condensers, polishing filters and all MPI. FOB 304 s/s cost \$2 500 000 for a feed rate = 2 kg/s with n = 0.7 for the range 0.6–10. L+M* = 1.8. L/M = 0.30.

Section 4.10
Solvent Extraction, SX

Gravity spray tower: see Sections 10.1 and 5.2.
Tray and packed columns: see Section 4.2.
Stirred column extractor (Oldshue–Rushton, Scheibel) 304 s/s including motor and variable speed drive. FOB cost \$380 000 at the product of (height, m) (diameter, m)$^{1.5}$ = 10 with n = 0.66 for the range 0.5–55. L+M* = 2.0; L/M = 0.48.

Pulsed plate column, 316 s/s tower and plates at 100 mm separation including pulsing mechanism and necessary auxiliaries excluding pump, piping, foundations. FOB cost = \$425 000 at the product of (height, m) (diameter, m)$^{1.5}$ = 10 with $n = 0.81$ for the range 0.5–100. L+M* = 2.0. L/M = 0.48.

Reciprocating plate column 316 s/s tower and plates including reciprocating mechanism, explosion-proof motor and drive excluding pump, piping, foundations. FOB cost = \$425 000 at the product of (height, m) (diameter, m)$^{1.5}$ = 10 with $n = 0.75$ for the range 0.5–100. L+M* = 2.0. L/M = 0.48.

Mixer-settler, c/s with separate mixer and settler vessels including explosion-proof motor, drive for mixer excluding pipes, tankage, crud/rag removal system and pumps. Aqueous: oil ratio = 1:1. FOB cost for a single stage \$30 000 for volumetric flow rate of aqueous phase to be treated = 10 L/s with $n = 0.22$ for the range 1–10 and $n = 0.60$ for the range 10–100. FOB cost \$30 000 at total mixer-settler volume = 20 m^3 with $n = 0.27$ for the range 1–20 and $n = 0.61$ for the range 20–300. L+M* = 1.52. L/M = 0.25. Factors: c/s, × 1.00; PVC, × 1.75; rubber lined, × 2.1; PVC + fiber-glass reinforced polyester lined, × 2.0; 304 s/s, × 3.00; opanol lined, × 2.4. Factors, excluding, interstage piping and pumps and tankage and crud removal, × 1.00; including interstage piping and pumps excluding tankage and crud removal, × 1.54–1.75; including tankage and crud removal, × 2.00.

Mixer-settler, c/s with separate mixer and settler vessels including explosion-proof motor, drive for mixer excluding pipes, tankage, crud/rag removal system and pumps. Aqueous:oil ratio = 1:1. Including piping, concrete, steel, instruments, electrical, insulation, painting and necessary labor to install the module. L+M cost for a single stage \$29 000 for volumetric flow rate of aqueous phase to be treated = 1.5 L/s with $n = 0$ for the range 0.1–1.5 L/s with $n = 0.40$ for the range 1.5–10. L+M cost for a single stage \$63 000 for volumetric flow rate of aqueous phase to be treated = 10 L/s with $n = 0.70$ for the range 10–1000. Factors: c/s, × 1.00; concrete, × 0.70; rubber-lined, × 1.4; 316 s/s, × 2.00.

RDC: c/s vertical pressure vessel including internals, rotor, drive and explosive-proof motor, FOB cost \$110 000 at the product of (height, m) (diameter, m)$^{1.5}$ = 10 with $n = 0.61$ for the range 0.5–75. L+M* = 3.0; L/M = 0.96.

Centrifuge, continuous extraction, 316 s/s including flexible connections, explosion-proof motor, variable speed drive, ammeter, tachometer, excluding pumps, starter, flowmeters and control valves. FOB cost \$220,000 at aqueous feed rated capacity = 2.2 L/s with $n = 0.25$ for the range 0.03–2.2 and $n = 0.38$ for the range 2.2–36. L+M* = 1.70. L/M = 0.96.

Centrifuge, continuous extraction, Alloy 20 including flexible connections, explosion-proof motor, variable speed drive, ammeter, tachometer, excluding pumps, starter, flowmeters and control valves. FOB cost \$355 000 at aqueous feed rated capacity = 2.2 L/s with $n = 0.48$ for the range 1.9–20. L+M* = 1.45.

Section 4.11

Adsorption: Gas

Cost the column as a pressure vessel, Section 10.1 and include regeneration equipment as a heat exchanger, Section 3.3, or as a multiple hearth furnace, Section 6.21.
Fixed bed: activated carbon, c/s with instruments and controls. FOB cost = \$235 000 for a mass of carbon = 2200 kg with $n = 0.32$ for the range 500–2200 and $n = 0.51$ for the range 2200–13000. FOB cost = \$560 000 for a mass of carbon = 13 000 kg with $n = 0.75$ for the range 13000–45000. L+M = 1.3–2.74. L/M = 0.37.
Fixed bed including regeneration equipment: air or gas drying, heat regenerated, including regeneration equipment and filters. FOB c/s cost = \$23 500 for a gas flow rate = 70 dm^3/s with $n = 0.32$ for the range 7–70 and $n = 0.67$ for the range 70–700. L+M* = 1.3–2.74. L/M = 0.37.

Section 4.12

Adsorption: Liquid

Carbon adsorption for two downflow, **fixed bed** adsorbers operating at 0.95 MPa with two-stage operation with backwash, then carbon exchange, c/s excluding carbon, building, foundations, hookup, carbon storage, regeneration and spent carbon storage. FOB cost \$500 000 at active column cross-sectional area = 12 m^2 with $n = 0.52$ for the range 1.2–12 and $n = 1.00$ for the range 12–300. L+M* = 1.44–1.5. Factors, single stage × 1.00; two stage series, × 0.96; 3-stage series, × 1.05; 4-stage series, × 1.15. Backwash pressure 0.95 MPa, × 1.00; 0.6 MPa, × 0.90.
Carbon cost = 0.3 FOB cost of adsorber. Regeneration cost = 0.36–0.4 FOB cost of adsorber.
Carbon \$6–8/kg.

Section 4.13

Ion Exchange

Ion exchange: single fixed bed, 1.3 MPa pressure units for sodium form resin with rubber-lined c/s exchange columns for continuous operation excluding resin. FOB cost \$100 000 at resin volume = 30 m^3 with $n = 0.67$ for the range 0.3–30 and $n = 1.00$ for the range 30–2000. Factors: rubber-lined c/s, × 1.00; 304 s/s, × 2–3.5; 316 s/s, × 2.3–4.2. Forms of resin: sodium form, × 1.00; hydrogen form, × 1.33. Pressure: 1.3 MPa, × 1.00; $<$ 0.7 MPa g, × 0.8. L+M* = 1.6–1.7.
Ion exchange resin: strong acid cationic hydrogen form or MR/MP form. FOB cost \$17.60 for resin volume = 1 m^3 with $n = 0.95$ for the range 1–18 m^3. Factors: hydrogen form, × 1.00; sodium form, × 1.05; gel form, × 0.7–0.8.
Ion exchange resin: weak acid cationic hydrogen form or MR/MP form. FOB cost \$32.50 for resin volume = 1 m^3 with $n = 0.95$ for the range 1–18 m^3. Factors: hydrogen form, × 1.00; sodium form, × 0.75; gel form, × 1.05.

Ion exchange resin: strong and weak base anionic hydrogen or sodium form. FOB cost \$35.30 for resin volume = 1 m^3 with $n = 0.95$ for the range 1–18 m^3. Factors: gel form, SBA, × 0.4–0.85; gel form, WBA, × 0.75–1.0.

Section 4.14

Foam Fractionation

Cost as a vessel, Section 10.1 and add blowers, Section 2.1 and other auxiliaries. **Installed unit for waste water treatment:** Installed cost \$450 000 at waste water capacity = 44 L/s with $n = 0.8$.

Section 4.15

Membranes and Membrane Configurations

Costs not included in this section.

Section 4.16

Membranes: Gas

For VOC removal from air: Full process cost \$250 000 for a gas flow rate = 18 dm^3/s with $n = 0.46$ for 4.5–18 and $n = 0.72$ for 18–40.
For separation of permanent gases: Full process cost \$2 000 000 for a gas flow rate = 1 m^3/s with $n = 0.93$. Sensitive to concentration of target gas and compression. Flat and hollow fiber membrane only cost \$150/m^2.
Permeation: FOB membrane flat, or hollow fiber excluding auxiliary equipment. FOB cost = \$130 000 at membrane area = 560 m^2 with $n = 0.42$ for the range 100–560 and $n = 1.00$ for the range 560–10 000.

Section 4.17

Membranes: Dialysis

Dialysis: Hollow fiber throwaway units for medical application. FOB cost = \$100 for a surface area = 1 m^2.

Section 4.18

Membranes: Electrodialysis

Electrodialysis, reverse polarity for 4000 mg/L TDS alkalinity to 500 mg/L with minimum pretreatment including brine recirculation pumps, ED stack, electrical equipment, brine discharge facilities, product water treatment and storage, building, intake pipes and transfer pumps. TM cost = \$25 000 000 at feed rate = 100 L/s with $n = 0.82$ for the range 40–1500 L/s. Feed factors: 4000 ppm, × 1.00; 2000 ppm, × 0.7; 850 ppm, × 0.1.

Electrodialysis: ED stack, spacers, end plates, electrodes and stack hardware. FOB cost = \$2 800 000 for a membrane area = 3000 m^2 with $n = 0.7$ for the range 1500–7000 m^2. Factor: FOB, × 1.00; TM unit including stacks, rectifiers, auxiliary equipment, treatment building and pumping stations, × 2.7.

Section 4.19

Membranes: Pervaporation

See Section 4.22.

Section 4.20

Membranes: Reverse Osmosis, RO

Spiral wound membrane without pressure vessel and auxiliaries. FOB cost = \$2000 at liquid feed rate = 0.15 L/s with $n = 0.84$. L+M* = 2.3. L/M = 0.4.
Reverse osmosis unit, including membrane, pressure vessels, single pass system with either spiral wound or hollow fiber membranes. FOB cost \$220 000 at membrane area = 1600 m^2 with $n = 0.47$ for the range 12–1600 and $n = 0.85$ for the range 1600–3 000 000. L+M* = 1.2–3.2 with large values for smaller size.

Section 4.21

Membranes: Nanofiltration

See Section 4.22.

Section 4.22

Membranes: Ultrafiltration, UF

Spiral wound: FOB membrane cost \$240/m^2 with $n = 1.0$. FOB skid mounted unit: membrane cost is 5 to 15 % of total for small areas and 50 % of total cost for largest membrane area per module. L+M* = 2.3. L/M = 0.4.
Hollow fiber: spiral × 0.85.
Tubular: spiral × 2.0.
Ultrafiltration: unit including hollow fiber membrane cartridges, pressure vessel excluding piping, valves, pumps, instrumentation and control, cleaning equipment and housing. FOB cost \$70 000 at design flow rate = 0.8 L/s with $n = 0.80$ for the range 0.1–0.8 and $n = 0.41$ for 0.8–45 L/s. L+M = 1.4–1.7. Factors: including housing, × 1.3.

Section 4.23

Membranes: Microfiltration

FOB cost for membrane and housing \$5000–\$8000/m^2.
FOB for 316 s/s housing: \$150 000 for membrane area of 50 m^2, $n = 0.92$.

Section 4.24
Chromatography

Package unit including column, packing, storage tanks, pumps, controls, high pressure, stainless steel. PM cost = \$750 000 at 450 L column volume with $n = 0.14$ for volumes < 450 L and $n = 0.38$ for 450–4500 L column volume. For low pressure, plastic columns and peripherals = × 0.5.

Section 5.1
Gas–Liquid

See Section 4.2 for cost guidelines for packed and tray columns or as pressure vessel Section 10.1. See Section 5.2 for gravity spray, baffled tower, atmospheric scrubber, venturi and wet cyclone. Demister, see Section 9.1.

Section 5.2
Gas–Solid

Cyclones, dry, high efficiency, c/s, excluding fans, ductwork and instrumentation. FOB cost = \$35 000 at inlet gas flow rate = 10 Nm^3/s with $n = 0.56$ for the range 0.5–40. L+M* = 2.5. L/M = 0.34. Factors: high efficiency, × 1.00; low efficiency, × 0.4.
Multicyclones, dry, c/s excluding fan, ductwork and instrumentation. FOB cost = \$25 000 at inlet gas flow rate = 10 Nm^3/s with $n = 0.66$ for the range 0.5–80 Nm^3/s. L+M* = 2.5. L/M = 0.34. Factor, fully installed module for a pelletizing plant, × 28.5.
Dry louvered impingement collector, c/s, parallel louvers with minimum pressure drop, including hopper. FOB cost = \$25 000 at inlet gas feed rate = 5 Nm^3/s with $n = 0.39$ for the range 2.5–15. L+M* = 1.85–2.7. L/M = 0.34. Factors: parallel louvers, × 1.00; centrifugal louvers, × 1.7.
Bag filters, c/s, continuous, reverse jet type, low temperature excluding air compressor and jet mechanism. FOB cost = \$82 000 at inlet gas feed rate = 10 Nm^3/s with $n = 0.71$ for the range 2.5–30. L+M* = 1.85–2.7. L/M = 0.34. Factors: low temperature, × 1.00; high temperature, × 1.3.
Bag filters, c/s, intermittent, shaker type, light duty, insolation damper, dust hopper including motor and drive for shakers but excluding fans, duct work and instrumentation. FOB cost = \$50 000 at inlet gas feed rate = 10 Nm^3/s with $n = 0.79$ for the range 0.5–2.5. L+M* = 1.85–2.7. L/M = 0.34. Alloy factor: c/s, × 1.00; s/s, × 1.6. Factors: light duty, × 1.00; heavy duty, × 3.0; including fan, × 1.25.
Bag filter system, installed module for metallurgical open hearth, sinter windbox or sintering materials handling excluding waste heat boiler and fans. TM cost = \$320 000 at inlet gas flow rate = 5 Nm^3/s with $n = 1.09$ for the range 1–10. TM cost = \$6 800 000 at inlet gas flow rate = 50 Nm^3/s with $n = 0.76$ for the range 10–500. For tar-fired furnace, × 1.6.

Electrostatic precipitators: for noncorrosive gas, minimum cost construction including collector plates, transformer, mechanical rectifier excluding foundation and supports. FOB cost = \$900 000 at inlet gas flow rate = 100 Nm^3/s with n = 0.39 for the range 0.5–100 and n = 0.8 for the range 100–600. L+M* = 2.74–3.0. L/M = 0.32. Factors: minimum cost, × 1.00; fly ash service, × 2.0; blast furnace service, × 2.0; acid service, × 12. TM for installed facility for sintering plant or power plant, × 7.0; for scarfing plant, × 5.0; for new open hearth, × 10; for retrofit to existing open hearth, × 13; for blast furnace, × 18.

Wet scrubber: impingement baffle (Peabody), c/s, excluding fan, ductwork and instrumentation. FOB cost = \$58 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.68 for the range 0.5–35 Nm^3/s. L+M* = 2.5. L/M = 0.34. Factors: Alloy factors: c/s, × 1.00; s/s, × 1.65. FOB cost for wet Peabody scrubber for acid service, × 35; low complexity installed module including fans, pumps, piping for metallurgical applications, × 40; high complexity installed module including fans, pumps and piping for metallurgical applications, × 100.

Wet scrubber: wet cyclone or centrifugal scrubber, c/s, including housing and spray excluding fan, ductwork and instrumentation. FOB cost = \$50 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.68 for the range 0.5–35 Nm^3/s. L+M* = 2.5. L/M = 0.34. Alloy factors: c/s, × 1.00; s/s, × 1.4–1.6.

Wet scrubber, venturi: c/s, low energy, excluding fan, pumps, ductwork and instrumentation. FOB cost = \$53 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.5 for the range 0.5–50 Nm^3/s. L+M* = 2.5. L/M = 0.34. Alloy factors, c/s, × 1.00; s/s, 1.7–2.0; Factors: low energy, × 1.00; high energy, × 2.0; submerged jet, × 0.7.

Wet scrubber, venturi: s/s, heavy duty, high efficiency, single stage excluding fan, pumps, ductwork and instrumentation. FOB cost = \$200 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.88 for the range 0.2–60 Nm^3/s. L+M* = 2.0. L/M = 0.34. Factors: high efficiency, × 1.00; medium efficiency, × 0.80.

Wet scrubber, venturi: high efficiency, two-stage, installed unit for open hearth furnace applications. PM cost = \$2 200 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.84 for the range 10–115 Nm^3/s.

Wet scrubber, venturi: high efficiency, two-stage, installed unit for blast furnace applications. PM cost = \$12 000 000 at inlet gas flow rate = 30 Nm^3/s with n = 0.70 for the range 20–115 Nm^3/s.

Wet scrubber, venturi: for SO_2 application using the double alkali process. Venturi only made of Carpenter 20 in the throat, otherwise 6 mm neoprene on c/s, excluding sump. FOB cost = \$1 110 000 at inlet gas flow rate = 140 Nm^3/s with n = 0.62 for the range 8–280 Nm^3/s. L+M* = 2.0. L/M = 0.34. Factors: excluding sump, × 1.00; including sump, × 1.44.

Wet scrubber, gravity spray: c/s, light duty, housing and spray nozzles excluding fan, ductwork and instrumentation. FOB cost = \$37 000 at inlet gas flow rate = 10 Nm^3/s with n = 0.7 for the range 0.3–130 Nm^3/s. L+M* = 2.5. L/M = 0.34. Factors: light duty, × 1.00; heavy duty, × 3.0.

TCA Wet scrubber, turbulent bed contactor: 6 mm neoprene on c/s, 316 s/s grids, HDPE spheres, demisters and spray headers. FOB cost = \$2 000 000 at inlet gas flow rate = 140 Nm^3/s with $n = 0.84$ for the range 85–280 Nm^3/s. L+M* = 2.11. L/M = 0.32.

Wet scrubber, packed column, polyester fiberglas including packing excluding fans, ductwork, pumps and instrumentation. FOB cost = \$35 000 at inlet gas flow rate = 1.65 Nm^3/s with $n = 0.39$ for the range 0.5–1.65 and $n = 0.68$ for the range 1.65–15. L+M* = 3.0. L/M = 0.5.

Dynamic wet–dry separator including hopper but excluding motor, drive and settler. FOB cost = \$35 000 at inlet gas feed rate = 8 Nm^3/s with $n = 0.61$ for the range 0.5–8 and $n = 1.00$ for the range 8–30. L+M* = 2.5. L/M = 0.34.

Section 5.3
Liquid–Liquid

Section 5.3.1
Decanter

API Oil–water "skimmer" separator, PM cost including separator fully installed, \$190 000 at design flow rate = 12 L/s with $n = 0.84$ for the range 1.2–340 L/s.

Oil–water skimmer separator, fully enclosed c/s horizontal cylinder excluding oil or water pumps. FOB cost \$105 000 at horizontal area = 20 m^2 with $n = 1.00$. Rectangular separator, × 1.23. For estimating purposes, FOB cost \$90 000 at nominal feed rate = 12 L/s when the density difference = 0.08 Mg/m^3 with $n = 0.70$ for the range 4.5–30 L/s. Factors: density difference = 0.08, × 1.00; density difference = 0.15 Mg/m^3, × 0.6. L+M* = 2.3. L/M = 0.4. Alloy cost factors: c/s × 1.0; aluminum × 1.4; rubber lined × 1.5; lead lined × 1.5; redwood × 0.5; glass lined × 4.3; 304 s/s clad × 1.5, alloy × 3; 316 s/s clad × 2.5, alloy × 2.5; inconel clad × 3, alloy × 5.8; nickel clad × 3, alloy × 5.9; monel clad × 3, alloy × 5.1.
See also mixer settler, Section 4.10 and pressure vessel, Section 10.1.

Section 5.3.2
Hydrocyclone

Costs see Section 5.9.

Section 5.3.3
Sedimentation Centrifuge

Centrifuge, differential type, continuous, 316 s/s including flexible connections, explosion-proof motor, variable speed drive, ammeter, tachometer, excluding pumps, starter, flowmeters and control valves. FOB cost \$220 000 at aqueous feed rated capacity = 2.2 L/s with $n = 0.25$ for the range 0.03–2.2 and $n = 0.38$ for the range 2.2–36. L+M* = 1.70.
Centrifuge, differential type, continuous, Alloy 20 including flexible connections, explosion-proof motor, variable speed drive, ammeter, tachometer, excluding pumps, starter, flowmeters and control valves. FOB cost \$355 000 at aqueous feed rated capacity = 2.2 L/s with $n = 0.48$ for the range 1.9–20. L+M* = 1.45.

Section 5.4
Gas–Liquid–Liquid Separators

See Pressure vessel, horizontal, Section 5.3.1 or Section 10.1.

Section 5.5
Liquid–Solid: General Selection

No costs pertinent to this section.

Section 5.6
Dryers

Tray/shelf, (batch, conduction) vacuum, including vacuum-tight box, shelves excluding vacuum equipment and trays. FOB \$30 000 at shelf area = 30 m^2 with $n = 0.56$ for the range 1–100. L+M* = 2.2–2.75. L/M = 0.36. Alloy cost factors: c/s × 1.00; s/s, × 2.2. Factors: excluding vacuum equipment, × 1.00; including vacuum equipment, × 1.5–1.9.
Agitated pan dryer, (batch, conduction) vacuum, with jacketed bottom and sidewalls with top-entry agitator, c/s, excluding motor and drive. FOB = \$90 000 at working volume = 3 m^3 with $n = 0.32$ for the range 0.1–6. FOB = \$90 000 at drying surface area = 4.4 m^2 with $n = 0.40$ for the range 1–12. L+M* = 2.2–2.75. L/M = 0.36. Alloy factors: c/s, × 1.00; cast iron, × 1.0; 304 s/s clad, × 1.25; 304 s/s alloy, × 1.7; 316 s/s clad, × 1.6; 316 s/s alloy, × 2.3; nickel, × 2.4. Factors: vacuum, × 1.00; atmospheric, × 0.8; including motor and drive, × 1.3.
Rotary, horizontal, (batch, conduction) vacuum, c/s, including vacuum equipment, motor and drive with rotating agitator. FOB cost = \$238 000 at drying surface area = 10 m^2 with $n = 0.65$ for the range 1–60. L+M* = 1.74. L/M = 0.36. Alloy factors: c/s, × 1.00; s/s, × 1.7.
Cone dryer (batch, conduction) vacuum tumble dryer, jacketted, s/s inside, including butterfly valve, stand, drive, motor, guard, vacuum equipment. FOB cost = \$73 000 at working capacity = 0.28 m^3 with $n = 0.50$ for the range 0.03–8.5 m^3.

L+M* = 2.2–2.75. L/M = 0.36. Alloy factors, s/s, × 1.00; glass lined, × 2; clad s/s, × 0.8. Factors, dryer system, × 1.00; dryer only, × 0.5.

Drum dryer, double drum, (conduction) atmospheric pressure, cast iron, chrome plated with 304 s/s side and cross conveyors, dip pan, knife assembly, rotary steam/water joints, end scrapers, drive, motor and fume hood. FOB cost \$210 000 at total drum area = 9 m^2 with n = 0.52 for the range 0.9–40 m^2. L+M* = 2.6–2.75. L/M = 0.3–0.36. Alloy factors: cast iron chrome-plated, × 1.0; c/s, × 0.9. Factors: drum configuration: double drum, × 1.0; single drum, × 0.9; twin drum, × 1.0.

Drum dryer, (continuous, conduction) vacuum, c/s including details as above. FOB cost \$590 000 at total drum area = 9 m^2 with n = 0.70 for the range 0.9–40. L+M* = 2.2-2.75. L/M = 0.36. Factors as for atmospheric drum dryer.

Screw conveyor/ribbon dryer (continuous, conduction) c/s atmospheric, including motor, variable speed drive, feeder and discharge. FOB cost = \$150 000 at heated surface area = 10 m^2 with n = 0.62 for the range 1–30. L+M* = 2.4. L/M = 0.38. Alloy factor: c/s, × 1.00; 304 s/s, × 1.35. Atmospheric, × 1.00; vacuum, × 2.0.

Solid band (continuous, conduction), c/s including fans, motors, conveyor feeder for bands $>$ 6 m long. Band width 1.2, 1.5, 2 and 2.8 m. For low temperatures. FOB cost = \$132 000 at band area = 10 m^2 with n = 1.04 for the range 1.5–25. L+M* = 2.4. L/M = 0.38. Alloy factor: c/s, × 1.00; 304 s/s, × 1.45; 316 s/s, × 2.3.

Tray or truck dryers, (batch, convection) insulated aluminum panel, steel frame designed for side to side circulation, atmospheric pressure, steam heating including steam heating oils, fan, motor, drive, instrumentation excluding trays and trucks. FOB cost = \$31 000 at total tray surface area = 10 m^2 with n = 0.37 for the range 2–100. Alloy factors, aluminum, × 1.00; c/s, × 1.00; s/s, × 2.5. Factors: atmospheric, × 1.00; vacuum, × 1.45. L+M* = 1.72. L/M = 0.35. Tray and trucks: not supplied, × 1.00; with c/s galvanized tray rack with c/s enamel trays 33 mm deep, × 1.1; s/s tray rack and trays, × 1.4.

Tray or truck dryers, (batch, convection), brick enclosure with back to front circulation, atmospheric pressure, steam heating including steam heating oils, fan, motor, drive, instrumentation excluding trays and trucks. PM cost = \$53 000 at total tray surface area = 10 m^2 with n = 0.37 for the range 2–100. Factors: econo brick enclosure, × 1.00; acid-resisting glazed brick, × 1.14. Cost trucks and trays from incremental cost above.

Open sand bed for drying sludge, (batch, convection) including normal excavations, piping for sludge, distribution, sand and gravel drainage beds and underground collection piping. PM cost = \$395 000 at surface area = 4185 m^2 with n = 0.65 for the range 560–4185 and n = 1.00 for the range 4185–45 000 m^2.

Spray dryers, (continuous, indirect convection) c/s, inlet temperature 150 °C exit temperature 75 °C, including instrumentation, pressure nozzle atomization, residence time about 16 s, access platform, support steel, air preheater, feed system, fan, motor and drive and dust collectors. FOB cost = \$2 000 000 at evaporative capacity = 1 kg water evaporated/s with n = 0.42 for the range 0.1–10 kg/s. L+M* = 2.0. L/M = 0.35. Factors: c/s, × 1.00; 304 s/s, × 2.0, nickel alloy × 3.7. Factors to account for the mechanism of heating the inlet air: inlet temperature, 150 °C, × 1.00; 100 °C, × 1.25; 250 °C, × 0.62; 550 °C, × 0.35.

Flash/Transported bed dryer: (continuous, indirect convection) c/s inlet temperature 650 °C, including dust separators, motors, cage mill/pulverizer. FOB cost \$320 000 at 0.125 kg water evaporated/s; $n = 0.42$ for range 0.03–3. L+M* = 2.75. L/M = 0.35. Alloy cost factors: c/s × 1.00; s/s × 1.6–2.0; without cage mill × 0.85.

Fluidized bed dryer, (continuous, indirect or direct convection) direct gas fired, including auxiliaries but excluding support structure, c/s. FOB cost = \$350 000 at volume = 100 m^2 with $n = 0.53$ for the range 0.3–1000; FOB cost = \$350 000 for the product of (bed diameter, m) (fluidizing velocity, m/s)$^{0.35}$ = 2 $m^{1.35}/s^{\ 0.35}$ with $n = 0.73$ for the range 0.5–5. L+M* = 2.2. L/M = 0.35. Alloy factors: c/s, × 1.00; s/s, × 2.2; nickel alloy, × 3.7. Factors: direct gas fired, × 1.00; indirect, × 1.3.

Turbo dryer, (continuous, indirect convection) c/s packaged, or for sizes > 40 m^2 field erected outside including TEFC motors, drive, insulation, variable speed drive, excluding internal or external heaters. FOB cost = \$183 000 at net drying area = 42 m^3 with $n = 0.30$ for the range 5–42 and $n = 0.65$ for the range 42–512. FOB = \$873 000 at net dying area = 512 m^2 with $n = 1.02$ for the range 512–900. Alloy factors: c/s, × 1.00; aluminum, × 1.23; 304 s/s, × 1.77. Factors: add internal heaters, × 1.25; add external heaters, × 1.15. L+M* = 1.2–1.3 for sizes > 40 m^2.

Desolventizer: (continuous, convection) FOB for soybean leaching operation \$1 200 000 at soybean capacity = 11.5 kg/s with $n = 0.48$ for the range 6–18 kg/s. L+M* = 1.8; L/M = 0.3.

Toaster: (continuous, convection) FOB cost \$1 300 000 at overall plant capacity for soybeans = 11.4 kg/s with $n = 0.48$ for the range 6–18. L+M* = 1.6.

Tunnel dryer: (continuous, convection) insulated aluminum panels, s/s conveying apron including heating coils, fans, motors, drives and instrumentation. FOB cost \$500 000 at an exposed conveying surface area = 40 m^2 with $n = 0.94$ for the range 15–100 . L+M* = 2.75. L/M = 0.35.

Rotary dryer, (continuous, indirect convection) atmospheric, steam tube, c/s including shell and flights, motor, drive, intake hopper, discharge. FOB \$155 000 at heat transfer area = 100 m^2 with $n = 0.75$ for the range 40–700. L+M* = 2.2–3. L/M = 0.4. Alloy cost factors: c/s × 1.00; s/s shell and flights × 1.25.

Rotary kiln/dryer hot air indirect: (continuous, indirect convection) hot air, c/s including solids feeder, motor, drive, shell and flights and heating equipment instrumentation. FOB cost \$590 000 at peripheral surface area = 100 m^2 with $n = 1.00$ for the range 10–400. L+M* = 2.2–3. L/M = 0.4. Alloy cost factors: c/s, × 1.00; s/s, × 2.5.

Rotary roto louvre: (continuous, indirect or direct convection) atmospheric, c/s including heater or steam coil, dust collection, fans, motors, derives and controls. FOB cost = \$740 000 at peripheral area = 100 m^2 with $n = 0.62$ for the range 5–100. L+M* = 2.2–3. L/M = 0.4.

Solid band (convection), c/s including fans, motors, direct firing, conveyor feeder for bands > 6 m long. Band width 1.2, 1.5, 2 and 2.8 m. For intermediate temperatures, 260 °C. FOB cost = \$220 000 at band area = 10 m^2 with n = 1.04 for the range 1.5–25. L+M* = 2.4. L/M = 0.38. Factors temperature 260 °C, × 1.00; > 540 °C, × 1.9; low temperature, × 0.6. Alloy factor: c/s, × 1.00; 304 s/s, × 1.45; 316 s/s, × 2.3.
Belt/band with flow through circulation (convection) c/s including fan, motor, feeders. FOB cost = \$350 000 at drying area = 10 m^2 with n = 1.0 for the range 1–10; FOB cost = \$450 000 at drying area = 20 m^2 for the range 20–40. L+M* = 2.4. L/M = 0.38. Alloy factor: c/s, × 1.00; 304 s/s, × 1.45; 316 s/s, × 2.3.
Vibrating conveyor belt, (convection) c/s, including motor, feeders. FOB cost = \$200 000 at drying area = 10 m^2 with n = 0.83 for the range 1–30. L+M* = 2.4. L/M = 0.38. Alloy factor: c/s, × 1.00; 304 s/s, × 1.45; 316 s/s, × 2.3.
Rotary kiln/dryer direct fired: (continuous, direct convection) hot air, c/s including induced draft fan, stack, cyclone, oil burner, solids feeder, motor, drive, shell and flights and instrumentation. FOB cost \$330 000 at peripheral surface area = 100 m^2 with n = 0.88 for the range 10–400. L+M* = 2.2–3. L/M = 0.4. Alloy cost factors: c/s, × 1.00; s/s, × 2.5; nickel alloy, × 3.7; brick lined, × 3.2. Factors: hot air, × 1.00; flue gas, × 1.5–1.7.

Section 5.7
Screens for "Dewatering"

Grizzly bar screen: Screen with drive but excluding motor and starter. FOB cost = \$135 000 for (length, m) × $(\text{width, m})^2$ = 10 m^3 with n = 0.42 for the range 4.5–15. L+M* = 1.32. L/M = 0.2.
Fixed inclined wedge wire screen: with pneumatic wrapper and controls, 45° horizontal; height = 1.83 m. FOB cost = \$45 000 for a width = 0.4 m with n = 0.67 for the range 0.3–1 m. L+M* = 1.32. L/M = 0.2.

Section 5.8
Settlers

Preliminary treatment unit. bar screen, grit chamber, overflow and bypass chamber and Parshall flume, PM cost \$270 000 at design flow rate = 58 L/s with n = 0.64 for the range 1–10 000 L/s.
Grit removal unit including controlled velocity grit chamber with grit removal and washing equipment, PM cost \$220 000 at design flow rate = 115 L/s with n = 0.60 for the range 0.25–200. Factors: controlled velocity, × 1.00; aerated grit chamber, × 1.45.
Primary clarifier, cylindrical c/s for above ground installation excluding painting and mechanism. FOB \$130 000 at a surface area = 100 m^2 with n = 0.46 for the range 50–800. Factors: including painting, × 1.2; installed below grade × 1.3–1.5. L+M* = 3.2–4.3.

Primary clarifier rectangular basin, concrete excluding the earthwork and mechanism. Installed cost \$160 000 at surface area = 400 m^2 with n = 0.56 for the range 60–400 and n = 1.45 for the range 400–800.
Primary clarifier rectangular basin, concrete, chain and flight collector, collector drive mechanism, weirs, troughs, piping excluding the earthwork. Installed cost \$230 000 at surface area = 400 m^2 with n = 1.07 for the range 80–4000. L+M* = 4.5–5.0.

Section 5.9
Hydrocyclones

Hydrocyclone, c/s cyclone only excluding piping, instrumentation and pumps. FOB cost \$6000 at a nominal body diameter = 25 cm with n = 1.07 for the range 2–200 cm. FOB cost \$38 000 at a total liquid flow capacity = 50 L/s with n = 0.35 for the range 9–1300 L/s. L+M* = 1.8.
Hydrocyclone, c/s cyclone for aqueous:oil ratio of 1:1 excluding piping, instrumentation and pumps. FOB cost \$3600 at the ratio of $(\Sigma, \text{m}^2)/(\Delta p, \text{kPa})^{0.8} = 10$ with n = 2.19 for the range 3–20 $\text{m}^2/\text{kPa}^{0.8}$. L+M* = 1.8. Factors for aqueous:water (A:O) ratio in the feed: ratio 1:1, × 1.00; 1:2, × 1.3; 1:5, × 1.26; 1:9, × 6.5.

Section 5.10
Thickener

Thickener, conventional with central mechanism, c/s tank, motor, drive, weirs, baffles excluding sludge pump. FOB cost = \$460 000 for a surface area = 300 m^2 with n = 0.58 for the range 40–800. TM = 3.0.
Thickener, conventional with central mechanism, rubber-lined c/s tank, motor, drive, weirs, pumps and pump boxes for acid-leached mineral processing with some flocculant addition. FOB cost = \$950 000 for a surface area = 300 m^2 with n = 0.48 for the range 70–2800. TM = 3.0. Factor: conventional with some flocculant addition, × 1.00; high capacity via flocculant addition, × 1.25.
Thickener, single compartment, concrete with 3 m walls, overflow weir, launder excluding central rake, excavation, site preparation, piping feed launder, overflow pump. PM cost = \$400 000 for a surface area = 100 m^2 with n = 0.38 for the range 80–2000. L+M* = 3.1. L/M = 0.4. Alloy cost factors: c/s × 0.7, concrete × 1.0; rubber lined for acid-leach mineral processing × 1.22.
Thickener mechanism: unpainted c/s including drive, motor, access platform, central shaft and bridge but excluding inlet pipe and overflow launders. FOB cost \$98 000 at surface area = 100 m^2 with n = 0.62 for the range 60–7000. Factors: sandblast and paint, × 1.2. L+M* = 1.35.

Section 5.11
CCD: Counter Current Decantation

CCD circuit single thickener stage. FOB unit including c/s thickener tank, mechanism, motors and drive; single compartment unit, FOB cost \$515 000 at surface area = 300 m^2 with $n = 0.50$ for the range 8 to 2000. Factors, single compartment, × 1.00; three compartment, × 1.10. L+M * = 1.8–2.0.

Section 5.12
Sedimentation Centrifuges

Tubular bowl: s/s excluding motor and drive. FOB cost = \$53 000 for a tube/body diameter = 10 cm with $n = 1.54$ for the range 4.5–15. FOB cost = \$63 000 for a nominal drive power = 5 kW with $n = 0.67$ for the range 0.4–6 kW. L+M* = 2.15–3. L/M = 0.35–0.5. Alloy cost factors: s/s × 1.0; c/s × 0.7.
Solid bowl, disc, manual discharge, batch: 316 s/s excluding motor and drive. FOB cost = \$260 000 for a bowl diameter = 45 cm with $n = 1.13$ for the range 25–100 cm. L+M* = 2.15–3. L/M = 0.35–0.5. Alloy cost factors: c/s × 0.68; 316 s/s × 1.0; Monel × 1.35; nickel × 1.7; Hastelloy C × 2.6.
Solid bowl, disc, intermittent nozzle discharge: 316 s/s excluding motor and drive. FOB cost = \$300 000 for a total feed flow rate = 7.9 L/s with $n = 0.77$ for the range 1–30 L/s; FOB cost = \$260 000 for a bowl diameter = 45 cm with $n = 1.13$ for the range 25–100; FOB cost = \$215 000 drive power = 30 kW, $n = 0.67$ for the range 15–100; FOB cost = \$260 000 for a capacity factor $\Sigma = 40\,000$ m^2 with $n = 0.73$ for the range 6000–220 000. L+M* = 1.6. L/M = 0.35–0.5. Alloy cost factors: c/s × 0.68; 316 s/s × 1.0; Monel × 1.35; nickel × 1.7; Hastelloy C × 2.6.
Solid bowl, disc, intermittent nozzle discharge: c/s with motor drive, sludge pumps, sludge cake conveying and hoists for waste water sludge dewatering. Installed module cost, PM cost = \$1 600 000 for a dry solids capacity of 1 Mg/h with $n = 0.78$ for the range 0.2–8 Mg/h.
Solid bowl, horizontal with continuous scroll discharge. 316 s/s excluding motor, drive, polymer feed system and electrical control panel. FOB cost = \$320 000 for capacity factor $\Sigma = 2650$ m^2 with $n = 0.57$ for the range 150–10 000 m^2; for drive power = 60 kW with $n = 0.60$ for the range 6–120 kW; for liquid feed flow rate = 3 L/s with $n = 0.47$ for the range 1–20 L/s and for bowl diameter = 50 cm with $n = 0.90$ for the range 15–50 cm and with $n = 1.43$ for the range 50–150 cm. L+M* = 1.6. L/M = 0.4. Alloy factors: 316 s/s, × 1.00; c/s, × 0.77; monel, × 1.35; nickel, × 1.7; Hastelloy C, × 2.5. Complexity factors: not sealed, × 1.00; sealed from oxygen, × 1.1–1.2.

Section 5.13
Filtering Centrifuge

Vertical basket: under-driven with batch top discharge: c/s, excluding motor and drive. FOB cost = \$60 000 for a basket diameter = 60 cm with *n* = 1.04 for the range 30–125 cm. L+M* = 2.15–3. L/M = 0.23. Alloy cost factors: c/s × 1.00; 316 s/s × 1.5; rubber lined × 1.2. Complexity factors: excluding motor and drive, × 1.00; including motor and drive, × 1.35; including skim device and controls, × 1.57.
Vertical basket: top-driven, suspended basket: with batch top discharge: c/s, excluding motor and drive, fume hood and automatic feed controls. FOB cost = \$60 000 for a basket diameter = 60 cm with *n* = 1.0 for the range 30–125 cm. L+M* = 1.3–2. L/M = 0.23. Alloy cost factors: c/s × 1.00; 316 s/s × 1.7; 304 s/s × 1.5; rubber lined × 1.35. Complexity factors: excluding motor and drive, × 1.00; including motor and drive, × 1.35.
Horizontal, batch automatic: 316 s/s excluding motor and drive and unsealed against oxygen. FOB cost = \$210 000 for a basket diameter = 60 cm with *n* = 0.97 for the range 35–200. L+M* = 2.2–3. L/M = 0.27. Alloy cost factors: c/s × 0.83; 316 s/s × 1.0; rubber lined × 1.0; titanium trim × 1.00; titanium alloy × 2.1; monel × 1.35; nickel × 1.8; Hastelloy C × 2.5.
Pusher: horizontal, centrifugal filter with pusher or reciprocating conveyor: 316 s/s excluding motor and drive. FOB cost = \$300 000 for a basket diameter = 60 cm with *n* = 1.0 for the range 30–140 cm. L+M* = 2.2–3. L/M = 0.27. Alloy cost factors: c/s × 0.74; 316 s/s × 1.0; Monel × 1.35; nickel × 1.7; Hastelloy C × 2.6.

Section 5.14
Filter

Filter, plate and frame: cast iron, with frames, plates, stand excluding filter medium. FOB cost = \$16 000 for an effective filter area = 10 m^2 with *n* = 0.55 for the range 1–150. L+M* = 1.8. L/M = 0.42. Alloy factors: cast iron, × 1.00; bronze, × 3.0; lead, × 2.4; rubber lined, × 2.7; PVC, × 2.0.
Filter, plate and frame: yellow pine, with frames, plates, stand excluding filter medium. FOB cost = \$14 200 for an effective filter area = 10 m^2 with *n* = 0.50 for the range 1–150.
Filter, plate and frame: aluminum, with frames, plates, stand excluding filter medium. FOB cost = \$20 000 for an effective filter area = 10 m^2 with *n* = 0.65 for the range 1–150.
Filter, plate and frame: 316 s/s, with frames, plates, stand excluding filter medium. FOB cost = \$55 000 for an effective filter area = 10 m^2 with *n* = 0.65 for the range 1–150.
Filter, plate and frame, diaphragm: cast iron or polypropylene, recessed plate, 2.5 cm chambers, all equipment for automatic operation, chemical feed system, excluding sludge pump and conveyor. FOB cost = \$600 000 for an effective solids handling volume within the press: press volume = 3 m^3 with *n* = 0.60 for the

range 0.7–3 and n = 0.85 for the range 3–8. L+M* = 1.8. L/M = 0.42. Factors: automatic, × 1.00; semi-automatic, × 0.7; manual, × 0.4.

Leaf filter, pressure, vertical, c/s, wet discharge including c/s tank, 304 s/s leaves and internal filtrate manifold, quick opening closure. FOB cost = \$50 000 for an effective filter area = 10 m^2 with n = 0.57 for the range 2–150. L+M* = 1.8. L/M = 0.42. Alloy factors: c/s, × 1.00; 316 s/s, × 1.25; 304 s/s, × 1.15. Factors: wet discharge, × 1.00; dry discharge, × 1.2.

Leaf filter, pressure, horizontal, c/s, dry cake discharge including c/s tank, 304 s/s leaves and internal filtrate manifold, quick opening closure. FOB cost = \$70 000 for an effective filter area = 10 m^2 with n = 0.51 for the range 3–150. L+M* = 1.8. L/M = 0.42. Alloy factors: c/s, × 1.00; 316 s/s, × 1.5.

Leaf filter, pressure, horizontal, c/s, dry cake discharge including c/s tank, 304 s/s leaves and internal filtrate manifold, quick opening closure. Automatic. FOB cost = \$125 000 for an effective filter area = 10 m^2 with n = 0.63 for the range 1–100. L+M* = 1.8. L/M = 0.42. TM = 3.5. Alloy factors: c/s, × 1.00; 316 s/s, × 1.5.

Leaf filter, pressure, horizontal, c/s, dry cake discharge including c/s tank, 304 s/s leaves and internal filtrate manifold, quick opening closure. Precoat facilities including tank, mixer, pumps and distribution unit. FOB cost = \$120 000 for an effective filter area = 10 m^2 with n = 0.63 for the range 1–100. L+M* = 1.8. L/M = 0.42. TM = 4.0.

Leaf filter, pressure, as applied to sludge dewatering. FOB cost = \$3 100 000 for an effective solids handling volume within the press, press volume = 15 m^3 with n = 0.29 for the range 1–15 and n = 1.05 for the range 15–60. L+M* = 1.9. L/M = 0.42.

Leaf filter, vacuum, horizontal, c/s, including tank and leaves. FOB cost = \$230 000 for an effective filter area = 150 m^2 with n = 0.6 for the range 0.5–150. L+M* = 1.8. L/M = 0.42. TM = 3.0.

Rotary drum filter, vacuum, c/s with swing agitator, panel or wire-wound drum, wash apparatus, variable speed drum drive, trunions, stuffing boxes, scraper discharge, motor and drive excluding vacuum system and vacuum receiver. FOB cost = \$210 000 for a total drum, πDL, area = 22 m^2 with n = 0.25 for the range 2–22 and n = 0.7 for the range 22–200. FOB cost = \$210 000 for an effective filter area = 8.8 m^2 with n = 0.25 for the range 0.8–8.8 and n = 0.7 for the range 8.8–50. L+M* = 1.6 to 2. L/M = 0.4. Alloy factors: c/s. × 1.00; 316 s/s, × 1.15 to 1.7. Factors for discharge configuration: scraper, × 1.00; string, × 1.15; roll, × 1.15; precoat, × 1.2; belt, × 1.2. Factors for high hydraulic load, as in the pulp and paper applications: c/s, × 2.75; 304 s/s, × 3.75; 316 s/s, × 4.2; 317 s/s, × 4.85.

Rotary drum filter, vacuum, c/s with swing agitator, panel or wire-wound drum, wash apparatus, variable speed drum drive, trunions, stuffing boxes, scraper discharge, motor and drive including vacuum system and vacuum receiver. FOB cost = \$333 000 for a total drum, πDL, area = 22 m^2 with n = 0.34 for the range 2.4–22 and n = 0.6 for the range 22–60. FOB cost = \$333 000 for an effective filter area = 8.8 m^2 with n = 0.45 for the range 0.8–40. L+M* = 1.6 to 2. L/M = 0.4. Factors for discharge configuration: scraper, × 1.00; flexibelt or fabric belt takeup, × 1.10–1.18; s/s coil, × 1.3–1.4.

Rotary drum filter, vacuum, acid accepting with swing agitator, panel or wire-wound drum, wash apparatus, variable speed drum drive, trunions, stuffing boxes, scraper discharge, motor and drive including vacuum system and vacuum receiver excluding repulper, filtrate receiver, moisture traps and filtrate pumps. FOB cost = \$280 000 for a total drum, πDL, area = 22 m^2 with $n = 0.65$ for the range 2–100. L+M* = 2.5. L/M = 0.4; TM = 4. Factors: excluding repulper and auxiliaries, × 1.00; including repulper, filtrate receiver, moisture traps and filtrate pumps, × 3.3.

Rotary drum filter, vacuum, for waste water sludge dewatering, s/s coil, wash apparatus, variable speed drum drive, trunions, stuffing boxes, scraper discharge, motor and drive, vacuum system and vacuum receiver, conditioning tank, chemical feeder, wet-type lime feeder, electrical panel, excluding sludge pump, belt conveyor, building, heating and ventilation. FOB cost = \$400 000 for a total drum, πDL, area = 8.5 m^2 with $n = 0.17$ for the range 5.5–8.5 and with $n = 0.46$ for the range 8.5–75. L+M* = 1.6. L/M = 0.4.

Rotary disk filter, vacuum, c/s, heavy duty mineral processing with filter and agitator but excluding vacuum system and vacuum receiver, filtrate pump, moisture trap and scrubber condenser. FOB cost = \$265 000 for a total disk, number × 2πD, area = 100 m^2 with $n = 0.38$ for the range 8–100 and $n = 0.55$ for the range 100–250. TM = 4 if installed on floor; 4.5 if installed elevated.

Rotary disk filter, vacuum, 304 s/s, high hydraulic loading, filter and agitator, filter box, hood and repulper but excluding vacuum system and vacuum receiver. FOB cost = \$610 000 for a total disk, number × 2πD, area = 100 m^2 with $n =$ 0.38 for the range 20–100 and $n = 0.84$ for the range 100–500. L+M* = 1.5. Alloy factors: 304 s/s, × 1.00; 316 s/s, × 1.2.

Deep bed: Gravity filter, (slow sand, rapid sand, dual media, multimedia, deep bed and high rate) including filter structure, underdrains, wash-water troughs, pipes, valves, backwash facilities, filter media, surface wash system, instrumentation, control and housing. PM cost \$820 000 at surface area = 10 m^2 with $n = 0.69$ for the range 0.1–2400.

Deep bed filter: Including media as stand alone unit with c/s housing. FOB cost = \$180 000 for a horizontal cross sectional area = 5 m^2 with $n = 0.75$ for the range 1–7. L+M* = 1.4–3.2. L/M = 0.42. TM = 4. Alloy cost factor: c/s, × 1.0; concrete, × 1.0.

Cartridge filter, batch volume < 1 m^3: c/s, filter only. FOB cost = \$150 for a batch volume = 0.5 m^3 with $n = 0.62$ for the range 0.3–0.7. L+M* = 1.4–3.2. L/M = 0.42. Alloy cost factor: c/s, × 1.0; 316 s/s, × 5.

Cartridge filter, batch volume > 1.5 m^3: c/s, filter only. FOB cost = \$1500 for a batch volume = 5 m^3 with $n = 0.41$ for the range 1.5–6. L+M* = 1.4–3.2. L/M = 0.42. Alloy cost factor: c/s, × 1.0; 316 s/s, × 3.5.

Table/pan filter, vacuum, horizontal tilting: c/s, open type, automatic valves, wash apparatus, variable speed drive, horizontal scroll feed, including drive and motor but excluding vacuum equipment, platforms, tanks, pumps and piping for feed and wash. FOB cost = \$400 000 for a filter area = 36 m^2 with $n = 0.33$ for the range 1–36 and $n = 0.81$ for the range 36–140. For a waste water sludge flow rate = 1.6 L/s with $n = 0.2$ for the range 0.16–1.6 and $n = 0.87$ for the range

1.6–30. L+M* = 2.68. L/M = 0.48. Alloy cost factor: c/s, × 1.00; rubber-lined, × 2; s/s, × 2.1. Complexity factors: without vacuum, traps and filtrate receivers, × 1.00; with vacuum, traps and filtrate receivers, × 1.83.

Belt filter, horizontal vacuum: 316 s/s for parts contacting the liquid, including drive and motor but excluding vacuum equipment, platforms, tanks, pumps and piping for feed and wash. FOB cost = \$400 000 for an effective filter area = 9 m^2 with $n = 0.64$ for the range 10–60. L+M* = 2.2–3.2. L/M = 0.42. Alloy factors: 316 s/s, × 1.00; rubber-coated, × 1.0; c/s, × 0.60. Complexity factors: excluding vacuum auxiliaries, × 1.00; including vacuum auxiliaries, × 1.3.

Belt filter, horizontal vacuum: c/s for dewatering sludge from waste water treatment, including drive and motor including vacuum equipment, platforms, tanks, pumps and piping for feed and wash. FOB cost = \$400 000 for a sludge flow rate = 1.6 L/s with $n = 0.2$ for the range 0.16–1.6 and $n = 0.87$ for the range 1.6–300. L+M* = 2.2–3.2. L/M = 0.42. Alloy cost factors: c/s, × 1.0; rubber coated, × 1.67; 316 s/s, × 1.67.

Microstrainer for waste water applications, c/s including screen and mechanism but excluding chamber, influent and effluent construction. FOB cost = \$85 000 for a waste water feed flow rate = 155 L/s with $n = 0.36$ for the range 44–155 and $n = 0.8$ for the range 155–450. Complexity factor: FOB screen and mechanism only, × 1.00; fully installed working module, × 12.3.

Revolving drum filter (microscreen), rotary screen mechanism, motor and drive. FOB cost \$250 000 at screen area = 15 m^2 with $n = 0.83$ for the range 1–950. L+M* = 3–3.2.

Section 5.15
Leacher

Pachuca: vertical cylinder with central draft tube, steeply sloped conical bottom with air introduction at the bottom, including lining. FOB cost = \$700 000 at active volume = 600 m^3 with $n = 0.70$ for the range 100–3000. L+M* = 2.0; L/M = 0.35–0.5.

Belt with shallow moving bed: FOB cost = \$800 000 for soybean capacity = 11.5 kg/s with $n = 0.48$ for the range 5–17 kg/s. L+M* = 1.95. L/M = 0.35. Factors, leacher only, × 1.00; leacher plus desolventizers, toaster, dryer and cooler, × 3.00; leacher, desolventizer, toaster, dryer, cooler and miscella recovery, × 13.

Section 5.16
Liquid–Solid: Dissolved Air Flotation, DAF

DAF, includes all necessary tankage, pumps, motors, piping, electrical, control and instrumentation, as well as all necessary labor and materials for installation. For sizes $< 50\ \mathrm{m}^2$ c/s vessels are used. Concrete basins are used for sizes $> 50\ \mathrm{m}^2$. PM cost = \$1 225 000 for a surface area = 50 m^2 with $n = 0.48$ for the range 5–1000.

DAF packaged plant but excluding concrete pad. c/s FOB cost = \$500 000 at a surface area = 20 m^2 with $n = 0.48$ for the range 5–50. L+M* = 1.5.

Section 5.17
Liquid–Solid: Expeller and Hydraulic Press

Hydraulic press: horizontal, c/s, 0.78 MPa with hydraulic system and drive. FOB cost = \$525 000 at a total pressing area (plate area × number of plattens) = 27.5 m^2 with n = 0.23 for the range 0.5–27.5 and n = 1.00 for the range 27.5–80. L+M* = 1.75. L/M = 0.36. Factors: operating pressure: 0.78 MPa, × 1.00; 2.1 MPa, × 1.6; 3.5 MPa, × 2.1; 7 MPa, × 2.6.
Expeller: 316 s/s with drive and motor. FOB cost = \$200 000 for a drive power = 10 kW with n = 0.54 for the range 2–100. L+M* = 3. L/M = 0.4.

Section 5.18
Solid–Solid: General Selection

No cost information in this section.

Section 5.19
Froth Flotation

Mechanical cell, induced draft flotation: c/s excluding connection and discharge boxes, motors, blowers and launders. FOB cost = \$20 000 at liquid working cell volume = 2.8 m^3 with n = 0.37 for the range 1–2.8 and n = 0.74 for the range 2.8–25 m^3. L+M* = 1.45. L/M = 0.21. TM = 2.8. Factors: excluding boxes, motors, blowers, × 1.00; including all boxes, motors and blowers but excluding launders, × 1.10.
Pneumatic cell, less than mechanical cell.

Section 5.20
Electrostatic

Electrostatic separator: with motor, drive, switches but excluding rectifiers, transformers, air valve controls. FOB cost = \$35 000 at a (solids nominal capacity, kg/s) × (rotor diameter, cm)$^{0.65}$ = 2.3 kg cm$^{0.65}$/s with n = 0.58 for the range 2–70. L+M* = 2. L/M = 0.35. Factors: excluding rectifiers, etc., × 1.00; including rectifiers, transformers and air valve controls, × 1.25.

Section 5.21
Magnetic

Plate, permanent:. single gap, magnet only. FOB cost = \$2500 for a width = 76 cm with n = 1.02 for the range 15–125 cm. L+M* = 1.5. L/M = 0.45. Factors: double gap suspended at 5 cm from conveyor, × 1.7; suspended 7.6 cm, × 2.5; suspended 10 cm, × 3.0; suspended 13 cm, × 3.2.

Grate, permanent: c/s with four banks of magnetic tubes in drawer. FOB cost = \$16 000 for a tube length = 25 cm with n = 1.0 for the range 15–38. L+M* = 1.5. L/M = 0.45. Alloy factors: c/s, × 1.00; s/s, × 1.4.

Grate, permanent: c/s with two banks of magnetic tubes in drawer. FOB cost = \$4000 for a tube length = 25 cm with n = 1.13 for the range 15–63. L+M* = 1.5. L/M = 0.45. Alloy factors: c/s, × 1.00; s/s, × 1.4.

Suspended, permanent: rectangular of width 60 cm, including clearing bar. FOB cost = \$17 500 for a length = 60 cm with n = 1.53 for the length range 45–120. L+M* = 1.7. L/M = 0.45. Factors: width 60 cm, × 1.00; 40 cm, × 0.72; 75 cm, × 1.25; 135 cm, × 2.0.

Suspended, electromagnet: rectangular, lift with transformer oil, ring and sling, DC disconnect but excluding rectifier. FOB cost = \$30 000 at a power = 5 kW with n = 1.0 for the range 2–12. L+M* = 2.5. L/M = 0.45.

Continuous:

Pulley: tramp metal removal, 1000 G at 2.5 cm excluding surface lagging, drive and motor. FOB cost = \$12 500 for a (width, m) × (diameter, m)$^{1.65}$ = 0.16 m$^{2.65}$ with n = 0.86 for the range 0.03–0.5. L+M* = 1.5. L/M = 0.45. Factors: 1000 G, × 1.00; 1400 G, × 1.2.

Pulley: ore cobbing, 1500 G at 2.5 cm excluding surface lagging, drive and motor. FOB cost = \$16 500 for a (width, m) × (diameter, m)$^{1.5}$ = 0.2 m$^{2.65}$ with n = 0.82 for the range 0.05–1. L+M* = 1.5 . L/M = 0.45.

Belts/cross or in-line, permanent: with belt, magnet, drive and motor. FOB cost = \$46 000 for a belt width = 75 cm with n = 1.4 for the range 50–120. L+M* = 2.5. L/M = 0.45. Factors: in-line, × 1.00; cross-belted, × 1.42.

Dry drum/LGMS, permanent: 530 G with drive, TEFC motor and chute. FOB cost \$16 000 at (drum width, m) × (diameter, m)$^{1.25}$ = 0.13 with n = 0.26 for the range 0.036–0.13 and n = 0.66 for the range 0.13–0.6. L+M* = 2.5 . L/M = 0.45. Factors: 530 G, × 1.00; 400 G, × 0.92.

Dry drum/LGMS, permanent: 530 G with drive, and open drip-proof motor. FOB cost \$40 000 at drum width = 1.2 m with n = 0.75 for the range 0.75–1.65. L+M* = 2.5 . L/M = 0.45. Factors: 530 G, × 1.00; 400 G, × 0.92.

Dry drum magnet, High speed/MGMS, permanent: high intensity, alternating polarity, 75 cm diameter drum with motor, starter, housing and drive. FOB cost = \$70 000 for a drum width = 75 cm with n = 0.27 for the range 30–180. L+M* = 2.5 . L/M = 0.45. Factors: without belt, × 1.00; with in-line belt, head and tail pulley, frame, drive and motor, × 1.85; with cross-belt, × 1.87.

Dry drum magnet High speed/MGMS, electro: 75 cm diameter drum with motor, starter housing, drive, control panel but excluding rectifiers. FOB cost \$75 000 for a drum width = 75 cm with n = 0.46 for the range 30–180 cm. L+M* = 2.5. L/M = 0.45. Factors: drum only, × 0.60.

Dry drum magnet High speed/MGMS, electro: 75 cm diameter drum with motor, starter housing, drive, control panel but excluding rectifiers. FOB cost \$60 000 for a power = 1.5 kW with n = 0.58 for the range 1.2–1.7. FOB cost = \$100 000 for power = 5 kW with n = 0.79 for the range 4–7 kW. L+M* = 2.5. L/M = 0.45. Factors: drum only, × 0.60.

Dry rotor magnet HGMS (induction): 16 000 G; 6 cm diameter rotor with base, drive, starter, rectifier but excluding transformer, air valve, controls. FOB cost = \$65 000 for a nominal solids capacity = 0.4 kg/s with $n = 0.58$ for the range 0.2–3. L+M* = 2.5. L/M = 0.45. Factors: including air valve, transformer, × 1.08; with 18 000 G, × 1.16.

Dry rotor magnet HGMS (induction): 10–76 cm diameter rotor for 7 g/s linear cm with motor, drives, starters, housing and control panel. FOB cost = \$65 000 for power = 0.9 kW with $n = 0.70$ for the range 0.5–4 kW. L+M* = 2.5. L/M = 0.45. Factors: throughput 7 g/s linear cm, × 1.00; throughput 14 g/s linear cm, × 1.65.

Wet rotor HGMS (induction): with motor, drive, starter, rotating separation zones, waterproof magnetic coils, excluding rectifier and variable speed drive. FOB cost = \$150 000 at a nominal capacity = 1.25 kg/s with $n = 0.68$ for the range 0.4–3.2. L+M* = 2.5. L/M = 0.45.

Wet drum/LGMS, permanent: 500 G finisher, s/s wear shell and drive, excluding motor. FOB cost \$63 000 for a drum width = 2.1 m with $n = 1$ for the range 1–3. L+M* = 2.5. L/M = 0.45. Factors: 500 G finisher, × 1.00; 700 G finisher, × 1.23; 750–800 G rougher, × 1.55; 880 G cobber, × 1.7; ceramic wear shell, × 1.10.

Section 5.22
Hydrocyclones

For solid–solid separation.

Hydrocyclone as a wet classifier system of particulates where 65 % < 74 μm. FOB cost = \$20 000 at a dry solids capacity = 50 Mg/h with $n = 0.45$ for the range 7.5–50 and $n = 1$ for the range 50–380. L+M* = 1.6. L/M = 0.45. TM = 3.

Section 5.23
Air Classifiers

Gas cyclone: classifier system with blowers, lines and all auxiliaries. FOB cost \$70 000 for a solids capacity = 0.9 Mg/h with $n = 0.06$ for the range 0.1–0.9 and with $n = 0.42$ for the range 0.9–10 Mg/h. FOB cost for the system = \$170 000 at 10 Mg/h with $n = 0.82$ for the range 10–70. L+M* = 1.6 . L/M = 0.45.

Section 5.24
Rake Classifiers

Superceded by hydrocyclones (Sections 5.22 and 5.9).

Section 5.25
Spiral Classifiers

Spiral classifiers: including motor and drive. FOB cost = \$99 000 for a spiral diameter = 1.25 m with $n = 1.53$ for the range 0.63–1.9 m. L+M* = 2.6–3.1 L/M = 0.21.

Section 5.26
Jig Concentrators

Jig classifier: with drive, motor and ragging. FOB cost = \$20 000 for a solids capacity = 100 Mg/d with n = 0.17 for the range 40–350 Mg solids/d. FOB cost = \$70 000 for a solids capacity = 1000 Mg/d with n = 1.56 for the range 700–1400 Mg/d. L+M* = 1.5. L/M = 0.45. TM = 3.

Section 5.27
Table Concentrators

Table concentrators: rubber top with liners, motor and drive. FOB cost = \$20 000 for a deck or table area = 4.65 m^2 with n = 0.35 for the range 2.3–8. L+M* = 1.5. L/M = 0.45. TM = 3.0.

Section 5.28
Sluice Concentrators

Humphrey spiral classifier: c/s, 0.6 m diameter spiral with five turns with distribution and collection manifolds and supports. FOB cost = \$475 000 at solids capacity = 100 Mg/h with n = 1.0. L+M* = 1.6. L/M = 0.45. TM = 3.0. Alloy cost factors: c/s × 1.0; fiberglass × 0.85.

Section 5.29
Dense Media concentrators, DMS

Dense media separator, DMS: complete circuit with heavy media separators, screens, densifiers, magnetic separators, hoppers, sumps, launders, motors, drives and controls. FOB cost = \$870 000 for a solids capacity = 100 Mg/h with n = 0.18 for the range 25–200. L+M* = 1.7. L/M = 0.45.

Section 5.30
Screens

For solid–solid separation.
Screen, vibrating: single deck, open housing, fixed elevation, c/s; including frame, pulley, eccentric, screen deck cloth, motor but excluding bottom hopper. FOB cost = \$45 000 for a screen area = 1.5 m^2 of single screen with n = 0.3 for the range 0.25–1.5 and n = 0.62 for the range 1.5–7.5. L+M* = 1.4–2.8. L/M = 0.17–0.2. Alloy cost factors: c/s × 1.00; s/s × 1.25; nickel alloy × 1.8. Factors: single deck, × 1.00; double deck, cost for single deck area × 1.3; triple deck, × 1.4; adjustable slope and motor, × 1.3; bottom hopper, × 1.1; totally enclosed, × 1.25.

Sections
6.1 to 6.3 Consider Principles of Selecting Reactors

No costs are included.

Section 6.4
Burner

Pressure vessel costs are given in Section 10.1. Other components might include the following.

Ejector: c/s installed, \$7 700 at gas handling capacity 0.02 kg/s with $n = 0.32$ for the range 0.005–0.05. Alloy factors, c/s = 1; s/s × 1.6; Ni × 2.3. (See also steam ejector, Section 2.2.)

Injector/ejector: c/s FOB, \$4000 at suction = discharge diameter of 7.6 cm with $n = 1.07$ for the range 3.8–25. L+M* = 2.0; L/M = 0.13.

Burner: FOB including blower, motor, automatic ignited pilot, fresh air system, \$1800 at 0.5 MW with $n = 0.16$ for range 0.15–0.5 and $n = 0.85$ for the range 0.5–3. L+M* = 2.45.

Section 6.5
PFTR: Pipe/Tube, Empty Pipe for Fluid Systems

Costs for pipes are given in Section 2.7. Here are some details specifically for reactors.

Pipe/tubes including tube loop, c/s: Installed cost excluding pumps: \$6000 at surface area = 10 m^2, $n = 1$; correlated with the product of (volume, m^3) (pipe diam., cm)$^{-1.5}$ = 0.015; $n = 1$ for range 0.0002–0.05. Alloy cost factors: c/s × 1.0; galvanized × 0.92; red brass × 0.87; monel × 1.8; nickel × 2.1; chrome moly × 1.8; PVC × 0.87; polypropylene × 1.06.

For **fire tube**, see thermal furnaces, Section 3.2.

Double pipe, c/s in c/s, < 4 MPa, FOB excluding pumps: \$3500 at surface area = 10 m^2 with $n = 0.14$ for the range 0.15–30. Alloy factors: c/s = 1.0; admiralty in c/s × 1.3; s/s inside c/s × 2; glass in c/s × 2.5. Pressure factors: 6.2 MPa × 1.1; 10.3 MPa × 1.3; 20.5 MPa, × 2; 30 MPa, × 3. L+M* = 2.6; L/M = 0.42.

Cascade exchanger (pipe loop with water flowing over outside), cast iron, FOB excluding pumps: \$3500 at surface area = 10 m^2 with $n = 1.0$ for the range 4–25. L+M* = 2.4; L/M = 0.41. Alloy FOB factors: cast iron × 1.00; glass × 5.0. For karbate construction, FOB excluding pump: \$7500 at surface area = 5 m^2 with $n = 0.61$ for the range 2–5 m^2 and $n = 0.82$ for the range 5–35 m^2.

Cascade/trombone cooler: cast iron FOB cost \$3300 at 10 m^2 heat transfer area with $n = 0.8$ for the range 1–30. L+M* = 2.35–2.8. L/M = 0.35–0.37.

For ejector into a tube; add injector: c/s installed, \$7,700 at gas handling capacity 0.02 kg/s with $n = 0.32$ for the range 0.005–0.05. Alloy factors, c/s = 1; s/s × 1.6; Ni × 2.3.

Injector/ejector used with a tube, injector only: c/s FOB, $4000 at suction = discharge diameter of 7.6 cm with $n = 1.07$ for the range 3.8–25. L+M* = 2.0; L/M = 0.13.

Section 6.6
PFTR: Static Mixer in Tube

Static mixer, c/s, FOB $4000 for 10 cm pipe diameter with $n = 1.38$ for the range 2.5–55 cm. Alloy factors: c/s × 1.00; s/s × 3.0; nickel alloy × 6.2; titanium, × 6.9. Jacketed × 1.5. L+M* = 2.0; L/M = 0.27.

Section 6.7
PFTR: Empty Pipe/Tube for Fluids and Solids

The costs are basically the cost of the pipe plus the auxiliaries required to make the system work. The basic cost of the pipe is given in Section 2.7. Costs for systems that might be considered to be similar to these types of reactors are given elsewhere: for GS transported bed, Sections 2.6 or 5.6.

Section 6.8
PFTR: Empty Multitube, Nonadiabatic

Cost as a fixed tube sheet heat exchanger, Section 3.3.

Section 6.9
PFTR: Fixed Bed Catalyst in Tube or Vessel: Adiabatic

Gas catalytic reactors: FOB, 1 MPa, cylindrical, dished ends, usual nozzles, access hole, support, internal supports for single bed of catalyst, but excluding catalyst, c/s, $110 000 for vessel mass of 8 Mg mass, $n = 0.58$; range 0.4–200 Mg; for the product of (height, m) (diameter, m)$^{1.5}$ = 20, $n = 0.81$ for range 0.5–1000; for total internal volume = 20 m^3, $n = 0.52$ for the range 1–500 m^3. Pressure adjustment: 1 MPa × 1.0; 5 MPa × 1.6; 10 MPa, × 2.3; 20 MPa, × 4.35; 30 MPa × 6.1; 40 MPa × 7.8. Alloy factors: c/s × 1.0; 316 s/s × 3.6; 316 s/s/clad × 2.5; 304 s/s × 2.75; 304 s/s clad × 2.5; 310 s/s × 3.25; 410 s/s × 2.1; nickel × 8; monel × 6.5; monel clad × 4.0; Hastalloy × 15; titanium × 8; titanium clad × 4.2. L+M* = 2.3. L/M = 0.4.
For other reactor configurations see process vessels, Section 10.1.

Section 6.10
PFTR: Multibed Adiabatic with Inter-bed Quench or Heating

FOB c/s including multibed supports, intercoolers but excludes catalyst, insulation, foundation, taxes: $1 300 000 for 100 m^3 catalyst volume, $n = 0.4$ for the range 10–180. L+M* = 2.2. L/M = 0.37. Reactor cost increases with pressure and specialty alloys. FOB cost of catalyst: depends on the type: vanadium pentoxide, \$20 000/m^3.

Section 6.11
PFTR: Fixed Bed with Radial Flow

Cost similar to Sections 6.9 and 6.10.

Section 6.12
PFTR: Multitube Fixed Bed Catalyst or Bed of Solid Inerts: Nonadiabatic

Cost fixed tube heat exchanger, Section 3.3.
FOB c/s cost \$350 000 at 3 m^3 catalyst volume, $n = 0.68$; at 1200 m^2 surface area, $n = 0.68$. L+M* = 2.2–2.8. L/M = 0.35–0.37. For alloy factors see Section 3.3.

Section 6.13
PFTR: Bubble Reactor

Cost as a process vessel, Section 10.1, plus the components used for the specific design; sparger, circulating pump, Section 2.3, ejector, Section 6.4, agitator, Section 7.1.
Pachuca: see Section 5.15.
Ozone generation from air, with air preparation equipment, ozone generator, dissolution equipment, off-gas recycling or destruction equipment, safety and monitoring equipment. FOB cost = \$545 000 at ozone production rate of 0.46 g/s with $n = 0.67$ for the range 0.09–30. Factors: air feed, × 1.00; oxygen feed, × 0.5. L+M = 1.2–1.35.
Ozone contact chamber, reinforced concrete, baffles and cover, installed excluding ozone generation. PM cost = \$ 82 000 at liquid volume = 90 m^3 with $n = 0.61$ for the range 13–2600.
Gas sparger, air diffuser only: unit price for 5.3 m sections of 23 cm diameter sparger including fittings to connect into gallery but excluding pipe to compressor or blower, FOB cost \$12 000 for sparger surface area = 3.5 m^2 , $n = 1.0$; \$12 000 for gas flow rate = 94 dm^3/s, $n = 1$.
Aeration, sparger diffused air system: including blowers (including one standby blower to ensure reliability), drives, building, air piping, air diffusers but excluding the vessel, installed cost \$475 000 at reliable air flow rate of 1.4 m^3/s, $n = 0.66$ for flow rate 0.05–1.4 and $n = 0.93$ for flow rate 1.4–23.
Diffused aeration system, installed including all piping, diffusers, blowers, air filters and blower house. Fully installed cost \$820 000 at air flow rate = 0.7 m^3/s with $n = 0.73$ for the range 0.25–15.
Aeration basin, concrete excluding aeration: PM cost \$1 360 000 at volume = 2000 m^3 with $n = 0.74$ for the range 90–10 000 000 m^3. Factors, no aeration, × 1.00; mechanical aeration, × 2.70; diffused aeration excluding blower house, × 2.75; diffused aeration including blower house, × 3.75.

Section 6.14
PFTR: Spray Reactor and Jet Nozzle Reactor

Costs of gravity spray and venturi, see Section 5.2.

Section 6.15
PFTR: Trays

Costs, see Section 4.2.

Section 6.16
PFTR: Packing

For packed column see Section 4.2.
Trickling filter, including earthwork, structure, underdrain, rotary feed distributor and rock media. PM cost \$545 000 at volume = 1000 m^3 with $n = 0.60$ for the range 100–1000 and $n = 0.88$ for the range 1000–23000 m^3.
Trickling filter, including earthwork, structure, underdrain, rotary feed distributor and plastic media. PM cost \$1 450 000 at volume = 130 m^3 with $n = 0.60$ for the range 100–8600 m^3.
Rotating biological contactor, including rotating mechanism, motor and drive but excluding concrete structure, FOB cost \$815 000 at design flow rate = 11.5 L/s with $n = 0.56$ for the range 0.5–12.5 L/s.
Rotating biological contactor, including rotating mechanism, motor, drive, concrete structure, installed. PM cost \$46 000 000 at design flow rate = 230 L/s with $n = 0.77$ for the range 9–3000 L/s.

Section 6.17
PFTR: Trickle Bed

See Section 10.1 for pressure vessel.

Section 6.18
PFTR: Monolithic

Cubic/monolithic reactor: graphite in c/s shell. FOB cost = \$14 000 for heat transfer area = 6.5 m^2 with $n = 0.71$ for the range 1–20 m^2. L+M* = 2.2–2.8. L/M = 0.35–0.37.

Section 6.19
PFTR: Thin Film

See Section 10.1 for pressure vessel.

Section 6.20
PFTR: Scraped Surface Reactor

See Section 4.6 scraped surface crystallizer.

Section 6.21
PFTR: Multiple Hearth

Multiple hearth furnace: FOB furnace including drive and motor, gas blower, exit screw conveyor and inlet feeder, \$6 000 000 at total effective area = 100 m^2 with n = 0.44 for range 15–800 m^2; at 1.8 kg/s of dry sludge incinerated with n = 0.40 for range 0.08–10 kg/s. L+M* = 2–2.05. L/M = 0.23. Alloy FOB factors: c/s × 1.00; 316 s/s × 2.7; monel × 3.3; nickel × 3.6.
Multiple hearth furnace: for regeneration of adsorbent carbon: furnace only including drive and motor, exit screw conveyor and inlet feeder. FOB cost = \$6 325 000 at carbon feed rate = 1 kg/s with n = 0.60 for the range 0.02–10 kg/s. TM = 2.1–2.2. L/M = 0.3.

Section 6.22
PFTR: Traveling Grate

Installed sintering unit, \$4 000 000 at capacity 10 kg/s with n = 0.62 for range 1–100 kg/s.

Section 6.23
PFTR: Rotary Kiln

Rotary kiln for incineration of low hazard material, c/s. FOB cost = \$3 000 000 at heat load of 2000 kW with n = 0.49 for the range 300–35 000 kW. Alloy factors c/s, × 1.0; s/s × 2.7; monel, × 3.3; nickel, × 3.5. Factors for hazard: low hazard, × 1.0; corrosive, × 1.5; hazardous, × 2. L+M* = 2.15.
Rotary kiln, for activated carbon regeneration, FOB cost = \$3 000 000 at carbon load of 0.15 kg/s with n = 0.62 for range 0.025–0.3 kg/s. L+M* = 2.1; TM = 3.8.
Rotary kiln, direct fired, flue gas for incineration, ore roasting, solid waste disposal (at 10.3 MJ/kg). Installed unit. PM cost = \$1 200 000 at feed rate = 1 kg wet solids/s with n = 0.84 for the range 0.4–6 kg/s.
Tunnel kiln for bricks. FOB cost = \$1 500 000 for brick capacity = 12 g/s with n = 0.98 for the range 6–12. L+M* = 1.7. L/M = 0.15.

Section 6.24
PFTR, Shaft Furnace

Installed unit including burden equipment, gas cleaning, blowers, conveyors, cowpers, cooling system, furnace gun but excluding bins and slag granulation, \$38 000 000 at capacity of 30 kg/s iron with n = 0.63 for range 4.5–200 kg/s.

Section 6.25
PFTR, Melting Cyclone Burner

Installed incinerator unit \$5 500 000 at nominal hearth area 20 m^2 with $n = 0.49$ for the range 13.5–40 m^2.

Section 6.26
PFTR via Multistage CSTR

Aerated lagoon including earthwork, embankment, concrete on embankment and apron excluding aeration. PM cost \$1 360 000 at volume = 10 000 m^3 with $n = 0.72$ for the range 380–760 000 m^3.
Aerated lagoon including earthwork, embankment, concrete on embankment and apron, aeration equipment, piping, electrical, control and instrumentation. PM cost \$1 900 000 at volume = 10 000 m^3 with $n = 0.72$ for the range 380–760 000 m^3.

Section 6.27
STR: Batch (Backmix)

Open tank, jacketed with agitation: FOB c/s cost \$37 500 for nominal working volume = 3 m^3, $n = 0.53$, range 0.3–75. L+M* = 2.36–2.61. L/M = 0.37. Alloy cost factor: c/s × 1.0; s/s × 1.7; glass lined × 1.6.
Pressure vessel, jacketed with agitation, 0.3 MPa: vertical cylinder, dished ends, jacketed agitated vessel, jacket rated at 0.8 MPa, 175 °C, top entry agitator with packed seal, 1–2 kW/m^3, 9 nozzles, 4 baffles. FOB c/s cost including jacket, top entry agitator and motor. \$75 000 for nominal volume = 3 m^3, with $n = 0.4$ for range 0.3–3 and $n = 0.53$; range 3–90 m^3. L+M* = 2.25–2.52, L/M = 0.41–0.59. Alloy factors: c/s, × 1.00; 304s/s × 1.8; 316 s/s, × 2.0; 321/347 s/s, × 2.25; nickel, × 2.6; glass-lined × 3.5. Pressure factors: 0.34 kPa g, × 1.00; 2.1 MPa, × 1.25; 4 MPa g, × 2.4; 10 MPa, × 8.2; 20 MPa × 11; 35 MPa × 12. High pressure reactors are often called autoclaves.
Hydrogenator, 304s/s, agitator, cooling coils, 2.5 MPa, FOB \$1 250 000 at Mg of oil to hydrogenate in the batch = 10 Mg. with $n = 0.38$ for range 10–30. L+M* = 1.78; L/M = 0.3. BM = 2.5.
Inoculation tank, 316 s/s with agitator, aerator and jacket, FOB \$40 000 at nominal volume = 0.3 m^3 with $n = 0.5$ for the range 0.07–0.8. Alloy factors 316 s/s × 1.0; 304 s/s × 0.82.
Fermenter, 316 s/s, 0.18 kPa g, cooling coil, agitator and motor drive, sparger, \$420 000 at nominal volume = 10 m^3 with $n = 0.51$ for the range 2–40. Alloy factors 316 s/s × 1.0; 304 s/s × 0.82; c/s × 0.24.
See also Section 6.29.

Section 6.28
STR: Semibatch

See Section 6.27.

Section 6.29
CSTR: Mechanical Mixer (Backmix)

See Section 6.27.
Conventional activated sludge process including basin, aeration system, recycle pumping and secondary clarifier. PM cost \$8 150 000 for design flow rate = 120 L/s with $n = 0.71$ for the range 0.5–4400 L/s.
Aeration basin, concrete excluding aeration: PM cost \$1 360 000 at volume = 2000 m^3 with $n = 0.74$ for the range 90–10 000 000 m^3. Factors, no aeration, × 1.00; mechanical aeration, × 2.70; diffused aeration excluding blower house, × 2.75; diffused aeration including blower house, × 3.75.

Section 6.30
STR: Fluidized Bed (Backmix)

Sludge or coal incineration via BFB. FOB excluding preheater, feed preparation/dewatering, ash disposal. FOB cost = \$14 000 000 at dry solids feed rate = 1 kg/s with $n = 0.53$ for the range 0.1–4. FOB cost = \$4 200 000 at cross sectional area = 10 m^2 with $n = 0.25$ for the range 3–10 and $n = 0.63$ for the range 10–50 or fluidized bed volume = 12 m^3 with $n = 0.67$ for the range 1–50 m^3. TM = 1.5–1.75. Factors: BFB only, × 1.00; BFB plus preheater, feed preparation and ash handling excluding steam recovery, × 1.3; BFB plus preheater, feed, ash and steam recovery, × 1.4. As incinerators, the cost of fluidized bed = 0.33 of rotary and 0.70 of multiple hearth.
Gaseous reactions catalyzed by solid catalyst: BFB. FOB cost = \$4 200 000 at fluidized bed volume = 12 m^3 with $n = 0.67$ for the range 1–500 m^3. TM = 2. **CFB**. including riser, separator, downcomer. FOB cost = \$5 000 000 at fluidized bed volume in riser = 12 m^3 with $n = 0.67$ for the range 1–500 m^3. TM = 1.7.
Gas reacting with solid: (roasting, reduction, calcination) via BFB or series of BFB. FOB including feed injection and gas preparation. FOB cost = \$14 000 000 at dry solids feed rate = 1 kg/s with $n = 0.53$ for the range 0.1–100. TM = 2.

Section 6.31
TR: Tank Reactor

Mechanical surface aeration, including aerator, motor, drive and supports. FOB cost \$190 000 at drive power = 75 kW with $n = 0.55$ for the range 0.75–75 and $n = 1.00$ for the range 75–3700. L+M* = 1.48.

Anaerobic or **facultative lagoon**, including earthwork but excluding liner. PM cost \$90 000 at volume = 10 000 m^3 with $n = 0.69$ for the range 4000–300 000. Factors: liner costs polyethylene, \$45/m^2; hypalon (0.94 mm), \$54/m^2, (1.14 mm), \$72/m^2; EPDM, \$36/m^2. Lagoon depth 1–3 m BOD 0.0007–0.0054 kg/d m^2 or 0.008–0.0625 mg/s m^2.

Section 6.32
Mix of CSTR, PFTR with Recycle

Conventional activated sludge process including basin, aeration system, recycle pumping and secondary clarifier. PM cost \$8 150 000 for design flow rate = 120 L/s with $n = 0.71$ for the range 0.5–4400 L/s.

Extended aeration package plant including pumps, aeration basins, air system and secondary clarifier. PM cost \$325 000 at design flow rate = 0.45 L/s with $n = 0.63$ for the range 0.1–44. (L+M* = 1.78)

Contact stabilization package palnt including pumps, aeration basin, air system and secondary clarifier. PM cost \$1 360 000 at design feed rate = 11.5 L/s with $n = 0.46$ for the range 4.4–90. (L+M* = 1.78).

Oxidation ditch including concrete basin, aeration equipment and secondary clarifier, installed. PM cost \$2 450 000 at design flow rate = 46 L/s with $n = 0.44$ for the range 2.2–46 and $n = 0.76$ for the range 46–440 L/s.

Conventional activated sludge process including basin, aeration system, recycle pumping and secondary clarifier. PM cost \$8 150 000 for design flow rate = 120 L/s with $n = 0.71$ for the range 0.5–4400 L/s.

Extended aeration package plant including pumps, aeration basins, air system and secondary clarifier. PM cost \$325 000 at design flow rate = 0.45 L/s with $n = 0.63$ for the range 0.1–44. (L+M* = 1.78)

Contact stabilization package plant including pumps, aeration basin, air system and secondary clarifier. PM cost \$1 360 000 at design feed rate = 11.5 L/s with $n = 0.46$ for the range 4.4–90. (L+M* = 1.78).

Oxidation ditch including concrete basin, aeration equipment and secondary clarifier, installed. PM cost \$2 450 000 at design flow rate = 46 L/s with $n = 0.44$ for the range 2.2–46 and $n = 0.76$ for the range 46–440 L/s.

Section 6.33
STR: PFTR with Large Recycle

See PFTR costs.

Section 6.34
Reaction Injection Molding and Reactive Extrusion

See Section 9.11.

Section 6.35
Reactive Distillation, Extraction, Crystallization

See Section 4.2.

Section 6.36
Membrane Reactors

See Sections 10.1 and 4.22.

6.37
Liquid Piston Reactor

See Section 2.2.

Section 7.1
Liquids

Turbines: c/s open tank, supported at the top, 50–100 rpm, single impeller including TEFC motor, gear reduction unit excluding starter, wiring. FOB cost \$19 000 at 10 kW drive power, $n = 0.45$ for the range 1.7–88 kW. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; s/s × 1.8; Monel × 1.9. Rpm factors: 50–100 rpm, × 1.00; 30–45 rpm, × 1.7; 110–230 rpm, × 0.68. No. of impellers on the same shaft, 1, × 1.00 and kW range up to 22 kW; two, × 1.3 and kW range up to 44 kW; three × 1.55 and kW range up to 66 kW; four, × 1.9 and kW range up to 88 kW.

Turbines: c/s closed tank, with mechanical seal, 50–100 rpm, single impeller including TEFC motor, gear reduction unit excluding starter, wiring. FOB cost \$20 000 at 5 kW drive power, $n = 0.30$ for the range 0.7–5 kW and $n = 0.56$ for the range 5–400 kW. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; s/s × 1.8; Monel × 1.9. Rpm factors: 50–100 rpm, × 1.00; 30–45 rpm, × 1.7; 110–230 rpm, × 0.68. No. of impellers on the same shaft, 1, × 1.00 and kW range up to 100 kW; two, × 1.3 and kW range up to 200 kW; three × 1.55 and kW range up to 300 kW; four, × 1.9 and kW range up to 400 kW. Includes bottom bearing when needed.

Propellers: c/s portable, clamp-on, including TEFC motor, drive and gear reduction. FOB \$3 800 at 1 kW drive with $n = 0.58$ for the range 0.15–5.5 kW. Alloy factors c/s × 1.0; s/s × 1.19; rubber covered, × 1.36; monel, × 1.37. Other factors, gear drive, × 1.0; direct drive × 0.75.

Propellers: c/s side entry, including TEFC motor, gear reducer, fixed plate, mechanical seal, FOB \$16 000 at 3.5 kW with $n = 0.19$ for the range 0.7–3.5 kW and $n = 0.48$ for the range 3.5–150 kW.

Propellers: c/s top entry, open tank, including impeller, shaft, TEFC motor and gear reduction unit but excluding starter, wiring, taxes, and duties. FOB cost \$6000 at 1.75 kW drive power, $n = 0.42$ for the range 0.15–1.75 and $n = 0.52$

for the range 1.75–75 kW. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; s/s × 1.19; Monel × 1.4. Configuration, 1 impeller × 1.00; 2 impellers, × 1.22.

Mechanical agitators: bioreactor: cost of mixer = (maximum impeller shear rate)$^{-2.3}$. The power required being about 20 to 40 % less than would be required to mix liquid.

Anchor: c/s closed tank including TEFC motor, gear reduction, stuffing box, FOB cost $10 000 at 2 kW drive power, n = 0.41 for the range 0.7–8 kW. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; s/s × 1.19; Monel × 1.4.

Gas sparger, air diffuser only: unit price for 5.3 m sections of 23 cm diameter sparger including fittings to connect into gallery but excluding pipe to compressor or blower, FOB cost $12 000 for sparger surface area = 3.5 m^2 , n = 1.0; $12 000 for gas flow rate = 94 dm^3/s, n = 1.

For double arm kneaders, edge mills and Banbury mixers see Section 7.4. For static mixers, see Section 6.6.

Section 7.2
Liquid–Liquid

See Section 7.1. For static mixers, see Section 6.6.

Section 7.3
Liquid–Solid

See Sections 7.1 and 6.27.

Section 7.3.1
Solids Suspension

See Sections 7.1 and 6.27.

Mechanism only for thickener, c/s including drive, access platform, central shaft, bridge, rake and scraping arm, handrail, surface skimmer, excluding inlet pipe and overflow launders, FOB cost $98 000 for cross-sectional area = 100 m^2 with n = 0.62 for the range 60–7000. Factors: sandblast and paint, × 1.2. L+M* = 1.35.

Section 7.3.2
Solids Dispersion

See Sections 7.1 and 6.27.

Section 7.3.3
Solids Dissolving

See Sections 7.1 and 6.27.

Section 7.3.4
Solids Flocculating

See Section 9.3.

Section 7.4
Dry Solids

Double cone: including TEFC motor and drive. FOB c/s cost \$60 000 at a working capacity = 3 m^3 with $n = 0.42$ for the range 0.8–7. L+M* = 1.3–2.25. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.9. Factors: including motor, × 1.00; excluding motor, × 0.75.
Ribbon: FOB c/s cost \$66 000 at working capacity = 3 m^3 with $n = 0.6$ for the range 0.9–7; at drive power = 15 kW, $n = 0.6$. L+M* = 1.3–2.25. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.9.
Twin shell: FOB c/s cost \$48 000 at working capacity= 3 m^3 with $n = 0.5$ for the range 0.4–7; L+M* = 1.3–2.25. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.5.
Edge mill (Muller mixer; Planetary action vertical, pan mixer): including TEFC motor c/s FOB cost \$200 000 at a drive power = 50 kW (with working capacity about 1 m^3) with $n = 0.71$ for the range 3–400 kW. L+M* = 2.1–2.3. L/M = 0.27.
Kneader, double arm (sigma kneader): horizontal, c/s, jacketed, tilting, non-vacuum, including TEFC motor and gear reduction, drive. FOB cost = \$170 000 at drive power = 33 kW with $n = 0.70$ for the range 2–50 and at working volume 0.55 m^3 with $n = 0.42$ for the range 0.1–0.55 and $n = 0.53$ for the range 0.55–3. L+M* = 1.3–2.25. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.6; 316 s/s, × 1.7; monel, × 2.1.
Kneader, double arm (sigma kneader): horizontal, c/s, jacketed, tilting, vacuum, including TEFC motor, gear reduction, drive and vacuum equipment. FOB cost = \$230 000 at working capacity = 0.55 m^3 with $n = 0.31$ for the range 0.15–0.55 and $n = 0.62$ for the range 0.55–2. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.7; 316 s/s, × 2.2 and monel, × 2.5.
Kneader Double arm (sigma kneader): vertical, c/s, jacketed, tilting, non-vacuum, including TEFC motor and gear reduction, drive. FOB cost = \$150 000 at working volume = 0.55 m^3 with $n = 0.75$ for the range 0.4–3. L+M* = 2.1–2.3. L/M = 0.27. Alloy cost factors: c/s × 1.0; 304 s/s × 1.6, 316 s/s, × 1.9; monel, × 2.2.
Banbury: including motor, gear reduction. FOB cost = \$600 000 at working capacity = 200 L with $n = 0.62$ for the range 30–600 L. L+M* = 1.8.

Section 8.1
Gas in Liquid (Foams)

No costs related to this topic.

Section 8.2
Liquid in Gas (Sprays)

Mechanical surface aeration, including aerator, open drip proof motor, drive and supports. FOB cost \$190 000 at drive power = 75 kW with *n* = 0.55 for the range 0.75–75 and *n* = 1.00 for the range 75–3700. L+M* = 1.48. L/M = 0.25.

Section 8.3
Liquid–Liquid

Homogenizer, high pressure, 7 MPa, 316 s/s, with baseplate, gears but excluding motor. FOB cost = \$95 000 at the liquid feed = 0.1 L/s with *n* = 0.43 for the range 0.01–14. L+M* = 2.5. L/M = 0.42.
Colloid mill: s/s with open drip-proof motor and drive. FOB cost = \$45 000 for a drive power = 7.5 kW with *n* = 0.61 for the range 3–25. L+M* = 2.5. L/M = 0.45.

Section 8.4
Cell Disintegration

Homogenizer, see Section 8.3.

Section 8.5
Solids: Crushing and Grinding

Jaw crusher: c/s with drive but excluding motor. FOB cost = \$110 000 for a solid capacity = 10 Mg/h with *n* = 0.58 for the range 0.5–30; FOB cost = \$800 000 for a solids capacity = 350 Mg/h with *n* = 1.11 for the range 350–1000 (two different capacity ranges); FOB cost = \$80 000 for a drive power = 7.5 kW with *n* = 0.65 for the range 0.7–40; FOB cost = \$675 000 for a drive power = 75 kW with *n* = 0.81 for the range 45–280 (two different power ranges). FOB cost = \$555 000 for a feed opening = 1 m^2 with *n* = 1.28 for the range 0.2–1.9. L+M* = 2–2.8. L/M = 0.25.
Gyratory crusher: c/s with lubrication system but excluding drive and motor. FOB cost = \$2 500 000 for a solids capacity = 1000 Mg/h with *n* = 0.92 for the range 150–4000. Crusher, c/s with lubrication system and drive but excluding motor. FOB cost = \$1 270 000 for a receiver opening mantle diameter = 1 m^2 with *n* = 0.95 for the range 0.5–1.3. FOB cost = \$2 400 000 for a receiver opening mantle diameter = 2 m^2 with *n* = 1.41 for the range 1.1–4. L+M* = 1.7–2.8. L/M = 0.23.
Roll crusher, twin, smooth roll: c/s for light duty but cost excludes drive or motor. FOB cost = \$20 000 for a drive power = 1 kW with *n* = 0.94 for the range 0.5–15 kW. L+M* = 1.7–2.8. L/M = 0.23.
Roll crusher, twin, smooth roll: c/s for heavy duty but cost excludes drive or motor. FOB cost = \$65 000 for a drive power = 10 kW with *n* = 0.61 for the range 0.75–200 kW. FOB cost = \$75 000 for a solids grinding capacity = 10 Mg/h with *n* = 0.61 for the range 1–60 Mg/h. L+M* = 1.7–2.8. L/M = 0.23.

Roll crusher, sawtooth: c/s for crusher only excludes drive or motor. FOB cost = \$20 000 for a drive power = 10 kW with n = 0.59 for the range 3–30 kW. L+M* = 1.7-2.8. L/M = 0.23.

Rotary crusher: c/s, crusher without drive or motor. FOB cost = \$20 000 for a drive power = 10 kW with n = 0.65 for the range 1–100 kW. L+M* = 1.7–2.8. L/M = 0.23.

Cone or shorthead crusher: c/s with drive but excluding motor. FOB cost = \$275 000 for a solids grinding capacity = 100 Mg/h with n = 0.64 for the range 25–1000 Mg/h; FOB cost = \$400 000 for a drive power = 100 kW with n = 0.92 for the range 20–200 kW; FOB cost = \$260 000 for a diameter of discharge annulus = 1 m with n = 1.8 for the range 0.6–2.1. L+M* = 2.1–2.6. L/M = 0.23.

Pulverizer crusher: c/s crusher only excluding drive and motor: FOB cost = \$40 000 for a drive power = 7.5 kW with n = 0.33 for the range 1.5–750 kW. L+M* = 1.6. L/M = 0.25. Alloy factors: c/s, × 1.00; 340 s/s, × 2.28.

Lump breaker: breaker only excluding drive and motor. FOB cost = \$8000 for a drive power = 7.5 kW with n = 1.1 for the range 4.5–15 kW. L+M* = 1.7–2.8. L/M = 0.23.

Mills, cage mill (impactor; micropulverizer): c/s excluding drive and motor. FOB cost = \$87 000 for a grinding solids capacity = 90 Mg/h with n = 0.60 for the range 9–360 Mg/h. L+M* = 1.70. L/M = 0.34. Alloy factors: c/s, × 1.00; 316 s/s, × 2.28.

Mills, swing hammer: including mill, motor, classifier, fan and filter. FOB cost = \$63 000 for a drive power = 15 kW with n = 0.81 for the range 2–150 kW. L+M* = 2.7–2.8. L/M = 0.34. Factor: mill plus auxiliaries, × 1.00; mill only, × 0.70.

Mills, attrition: mill including drive but excluding motor. FOB cost = \$30 000 for a drive power = 23 kW with n = 0.63 for the range 4.5–280 kW. L+M* = 2.7–2.8. L/M = 0.34.

Mills, fluid energy: mill including all auxiliary equipment (compressor, bag filter). FOB cost = \$330 000 for an air-jet flow of 500 dm^3/s with n = 0.88 for the range 400–700. L+M* = 1.7. L/M = 0.4.

Mills, roller (twin or ring roller): mill only excluding drive and motor. FOB cost \$260 000 for a drive power = 75 kW with n = 0.62 for the range 7–450 kW. L+M* = 2.7–2.8. L/M = 0.34.

Mills, ball: c/s excluding liner, drive, motor, guard and ball load. FOB cost = \$285 000 for a drive power = 75 kW with n = 0.70 for the range 4.5–4500 kW. L+M* = 2.7–2.8. L/M = 0.34.

Mills, rod: c/s excluding liner, drive, motor, guard and ball load. FOB cost = \$290 000 for a drive power = 75 kW with n = 0.74 for the range 4.5–4500 kW. L+M* = 2.7–2.8. L/M = 0.34.

Mills, autogenous, semi autogenous: rubber backing and lining, mill plus drive but excluding motor and starter. FOB cost \$1 700 000 for a drive power = 300 kW with n = 0.71 for the range 38–300 and n = 0.31 for the range 300–4500. L+M* = 1.7–2.0. L/M = 0.34. TM = 2.4–3.2.

Mills, grinding circuits: open circuit ball mill, dry with 100 Mesh product, including classifier, motors, drives, mill, installation and erection within the BL but excluding dust collection, feeder and solids handling. PM cost = \$460 000 for a capacity of 4.5 Mg/h with $n = 0.65$ for the range 0.7–150. Factors: open circuit, dry, × 1.00; open, wet, × 1.00; closed circuit, dry, × 1.00; closed circuit, wet, × 0.90. Product size: 325 Mesh, closed circuit wet or dry, × 1.8; 48 Mesh, open dry or wet, × 0.65; closed dry, × 0.75; closed wet, × 0.6; 10 Mesh, open circuit, dry or wet, × 0.35.

Comminutor, with gear reduction unit, motor, steel cutters, FOB cost \$45 000 at design flow rate = 90 L/s with $n = 0.29$ for the range 4–90 L/s and $n = 0.54$ for the range 90–1000. L+M* = 1.4.

Section 9.1
Size Enlargement: Liquid–Gas: Demisters

Demister pads: Standard glass fibers, s/s construction, medium pressure drop, fine drops. Includes gaskets, cap screws, washer and polygon frame but excluding vessel or tank. FOB cost = \$95 000 for an inlet gas capacity = 4700 Ndm^3/s with $n = 0.72$ for the range 4000–90 000. Factors: medium Δp, fine drops, × 1.00; low Δp, coarse drops, × 0.6; high Δp, fine drops, high efficiency, × 3–4.

Section 9.2
Size Enlargement: Liquid–Liquid: Coalescers

Coalescer pads: estimate as a fraction of the cost of the vessel. 10–30 % c/s cost of pressure vessel.

Section 9.3
Size Enlargement: Solid in Liquid: Coagulation/Flocculation

Flocculation basin including reinforced concrete basin, motors, variable speed drive, horizontal paddle flocculators, excluding upstream rapid mix and downstream settling basin, installed. PM cost \$545 000 at volume = 1000 m^3 with $n = 0.45$ for the range 50–1000 and $n = 0.77$ for the range 1000–20 000.

Flocculation basin including reinforced concrete basin, motors, variable speed drive, vertical turbine flocculators (20–80 1/s) excluding upstream rapid mix and downstream settling basin, installed. PM cost \$205 000 at volume = 1000 m^3 with $n = 0.59$ for the range 20–1000.

Section 9.4
Size Enlargement: Solids: Fluidization

See Sections 5.6 and 6.30.

Section 9.5
Size Enlargement: Solids: Spherical Agglomeration

Data not available.

Section 9.6
Size Enlargement: Solids: Disc Agglomeration

Cone agglomerator: variable speed, variable angle with drive but excluding motor. FOB cost = $100 000 for a solids capacity = 4 Mg/h with $n = 0.58$ for the range 0.9–32 Mg/h (0.05–8.9 kg/s). L+M* = 2.5. L/M = 0.3.

Section 9.7
Size Enlargement: Solids: Drum Granulator

Drum granulator: FOB c/s cost $25 000 for a solids capacity = 3.5 Mg/h with $n = 0.05$ for the range 0.5–3.5 and $n = 0.28$ for the range 3.5–23 Mg/h. FOB cost = $40 000 for a solids capacity = 23 Mg/h with $n = 0.68$ for the range 23–60. L+M* = 3. L/M = 0.25. Alloy cost factors: c/s × 1.0; s/s × 1.1; nickel alloy × 1.3.

Section 9.8
Size Enlargement: Solids: Briquetting

Briquetter: FOB cost $100 000 for a solids capacity = 15 Mg/h with $n = 0.58$ for the range 3.5–55. L+M* = 3. L/M = 0.25. Alloy cost factors: c/s × 1.0; s/s × 1.2; nickel alloy × 1.4.

Section 9.9
Size Enlargement: Solids: Tabletting

Tabletter: FOB cost $80 000 for a solids capacity = 0.39 Mg/h with $n = 0.3$ for the range 0.09–0.39 and $n = 0.44$ for the range 0.39–3.8. L+M* = 3. L/M = 0.25. Alloy cost factors: c/s × 1.0; s/s × 1.2; nickel alloy × 1.4.

Section 9.10
Size Enlargement: Solids: Pelleting

Pellet mill. FOB cost = $30 000 for a solids capacity = 3 Mg/h with $n = 0.12$ for the range 0.35–45. L+M* = 2. L/M = 0.25. Alloy factors: c/s × 1.0; s/s × 1.2; nickel alloy × 1.4.

Section 9.11
Solids: Modify Size and Shape: Extruders, Food Extruders, Pug Mills and Molding Machines

Injection molding machine: FOB, shot size 1.88 kg polystyrene, hydraulic machine, $600 000 for a clamp force of 5000 MPa with $n = 0.78$ for the range 125–20 000 MPa. L+M* = 1.2.
Extruders for polymers: c/s excluding drive and motor. FOB cost = $70 000 for a drive power = 10 kW with $n = 0.47$ for the range 1.5–220. L+M* = 3. L/M = 0.27.

Alloy cost factors: c/s × 1.0; s/s × 1.19, monel × 1.4. Factor: including variable speed drive, × 1.5. Results depend on barrel diameter and L/D ratio.
Pug mill-extruder: FOB cost = \$38 000 for a solids capacity = l Mg/h with $n = 0.15$ for the rane 0.1–18 solids capacity, $n = 0.15$. L+M* = 1.5–3. L/M = 0.27. Alloy cost factors: c/s, × 1.0; s/s, × 1.19, Monel, × 1.4.

Section 9.12

Solids: Solidify Liquid to Solid: Flakers, Belts and Prill towers

Flaker: c/s standard single roll, feed pan, knife and holder, variable speed drive FOB cost \$175 000 at drum surface area = 2.5 m^2 with $n = 0.60$ for the range 0.1–18. L+M* = 2.6–2.75. L/M = 0.3–0.36. Alloy cost factors: c/s, × 1.00.
Prilling tower: installed tower, spray unit, scrubber, pump, sump, ductwork and piping excluding air pollution control devices. PM cost = \$14 250 000 for a prilled capacity of 1000 Mg/d with $n = 0.57$ for the range 300–1200. Factor: include wet scrubber for the vent gas, × 1.22.

Section 9.13

Coating

Costs are very specialized.

Section 10.1

Process Vessels

Vertical cylinder, atmospheric, open tank or flat roof: flat bottom including access hole, one 12 cm nozzle, one 15 cm nozzle and four 5 cm nozzles, excluding foundation, FOB c/s cost \$17 000 for volume = 1.5 m^3 with $n = 0.93$ for the range 0.03–7; for a mass = 1.3 Mg with $n = 0.51$ for the range 0.2–10. L+M* = 2.3. L/M = 0.4. Alloy cost factors: c/s, × 1.0; aluminum, × 1.4; lead lined, × 1.5; redwood, × 0.5; glass lined, × 4.3; 304 s/s clad, × 1.5, alloy, × 3; 316 s/s clad, × 2.5, alloy, × 2.5; Inconel clad, × 3, alloy, × 5.8; nickel clad, × 3, alloy, × 5.9; Monel clad, × 3, alloy, × 5.1; fiberglas reinforced, filament wound, × 0.75; plus 40 mil vinyl ester coating, × 1.68; plus 6.5 mm rubber lined, × 1.83; plus 6.5 mm chloroprene lined, × 2.04; plus fluorinated polymer lining, × 6.3. Other factors, non-jacketed, × 1; jacketed, × 1.2; no agitator, × 1.00; side-entry mixer including motor, × 1.7.
Vertical cylinder, atmospheric, open, c/s tank for sedimentation or aeration excluding internals and painting. FOB cost \$132 000 at horizontal cross-sectional area = 325 m^2 with $n = 0.49$ for the range 60–500 m^2.
Vertical cylinder, atmospheric, open, reinforced concrete tank for sedimentation or aeration excluding earthwork and mechanism, installed cost \$240 000 at horizontal cross-sectional area = 325 m^2 with $n = 0.55$ for the range 60–325 m^2, with $n = 0.84$ for the range 325–650, with $n = 0.74$ for the range 650–10000.

Pressure vessel, horizontal or vertical: FOB, 1 MPa, cylindrical, dished ends, usual nozzles, access hole, support, excluding internals, c/s, \$100 000 for vessel mass of 8 Mg mass with $n = 0.58$ range 0.4–200 Mg; for the product of (height, m) (diameter, m)$^{1.5}$ = 20, $n = 0.81$ for range 0.5–1000; for total internal volume = 20 m^3 with $n = 0.52$ for the range 1–500 m^3. Pressure adjustment: 1 MPa × 1.0; 5 MPa × 1.6; 10 MPa, × 2.3; 20 MPa, × 4.35; 30 MPa, × 6.1; 40 MPa, × 7.8. Alloy factors: c/s, × 1.0; 316 s/s, × 3.6; 316 s/s clad, × 2.5; 304 s/s, × 2.75; 304 s/s clad, × 2.5; 310 s/s, × 3.25; 410 s/s, × 2.1; nickel, × 8; Monel, × 6.5; Monel clad, × 4.0; Hastalloy, × 15; titanium, × 8; titanium clad, × 4.2. L+M* = 2.3. L/M = 0.4.

Equalization basin, PM cost including fully installed concrete basin up to a volume of 3000 m^3. For larger size use a basin with liner. Cost is for basin only and excluding aeration. Installed cost \$270 000 at volume = 800 m^3 with $n = 0.52$ for the range 40–3000; at design flow rate = 16 L/s with $n = 0.52$ for the range 0.8–6170.

Section 10.2
Storage Vessels for Gases and Liquids

Horizontal pressure bullet: 1.7 MPa, 0.45 m access hole, five 7.5 cm diameter and four 5 cm diameter nozzles. No internals. FOB c/s cost \$100 000 for tank volumetric capacity = 70 m^3 with $n = 0.86$ for the range 50–150. L+M* = 1.9. L/M = 0.4.

Sphere: c/s, 0.2 MPa g, ASME construction including supports, ladders, walkways, relief valves, sampling and gauging devices, excluding foundations and dykes, field erected cost \$225 000 for tank volumetric capacity = 100 m^3 with $n = 0.70$ for the range 40–1500. L+M* = 1.9–2.85. L/M = 0.35–0.4. Pressure factors: 0.2 MPa g, × 1.00; 0.35 MPa, × 1.1; 0.5 MPa, × 1.2; 0.7 MPa, × 1.3; 1.4 MPa g, × 1.4.

Spheroid: c/s. 0.2 MPa g, including access holes, relief valves, staircase, instruments excluding foundation and dykes, field erected cost \$775 000 for volumetric capacity = 4000 m^3 with $n = 0.73$ for the range 1200–5000.

Underground cavity, salt dome, complete cost \$3 600 000 at nominal volume 30 000 m^3 with $n = 0.73$ for the range 8000–50 000.

Underground cavity, mined, complete cost \$11 000 000 at nominal volume 30 000 m^3 with $n = 0.58$ for the range 13 000–100 000.

Small, low pressure tank: vertical cylinder with usual nozzles, FOB c/s cost \$14 000 at tank volumetric capacity = 20 m^3 with $n = 0.71$ for the range 4–70. L+M* = 2.3–2.9. L/M = 0.4. Alloy cost factors: c/s, × 1.0; fiber glass open top, × 1.6; rubber-lined, × 1.5; lead-lined, × 1.6; s/s, × 2.0.

Cone roof API, < 100 m^3: API flat bottom, fixed cone roof, including access hole, one 10 cm nozzle, one 15 cm nozzle, four 5 cm nozzles, staircase excluding foundations and dyking, FOB c/s \$32 000 for tank volumetric capacity = 10 m^3 with $n = 0.32$ for the range 3–100. L+M* = 2.3–2.9. L/M = 0.4. Alloy cost factors: c/s, × 1.0; aluminum, × 1.4; rubber-lined, × 1.5; lead-lined, × 1.5; glass lined, × 4.3; s/s, × 2.0.

Cone roof API, > 100 m^3: API flat bottom, fixed cone roof, including access hole, one 10 cm nozzle, one 15 cm nozzle, four 5 cm nozzles, staircase excluding foundations and dyking: field erected c/s \$560 000 for tank volumetric capacity = 4000 m^3 with n = 0.58 for the range 300–40 000. Alloy cost factors: c/s, × 1.0; rubber-lined, × 1.5; lead-lined, × 1.6; 304 s/s, × 3.2; 316 s/s, × 3.5; nickel, × 5.9; inconel, × 5.8; Monel, × 5.1.
Vertical cylinder, API movable roof: c/s atmospheric pressure, lifter type, 1.5 m lift, liquid seal, including access holes, relief valves, roof supports, glide slides, spiral staircase, ladder, usual flanged connections excluding foundation and dyking. Field erected cost \$700 000 for tank volumetric capacity = 4000 m^3 with n = 0.63 for the range 1000–12 000. Factors, pontoon, × 0.85; 3 m lift, × 1.3.

Section 10.3
Bins and Hoppers for Bulk Solids

Bin/surge/catenary/pebble storage: FOB c/s cost \$350 000 for solids working volume = 350 m^3 with n = 0.65 for the range 10–10 000 m^3. L+M* = 1.4–2.5. L/M = 0.23. Factors, purchased new, × 1.00; used, × 0.3–0.4.
Conical hopper: FOB c/s cost \$500 for a working volume = 2.8 m^3 with n = 0.91. L+M* = 1.4–2.5. L/M = 0.23.
Vibrating bin activator: FOB \$27 000 for an activator of 13.5 cm diameter with n = 1.07 for the range 8–13.5 and n = 1.66 for the range 13.5–30 cm. L+M* = 1.8.

Section 10.4
Bagging Machines

Valve fill, single spout bagging machine at 5 bags per minute with 20–50 kg bags: FOB with auger fill including bag hangers, scales but excluding pant-leg hopper, conveyor \$75 000. Factor for other feeder: auger fill, × 1.00; air pack, × 1.3; gravity, × 0.53. L+M* = 2.0. Factors, electrically operated, × 1.0; mechanically operated, × 0.58.
Extra scales, FOB \$100 000; automatic bag placer: FOB \$150 000.
Bag sealer for kraft bags with polymer liner, FOB including preheater but excluding vacuum attachment to remove dust, cooler, conveyors and kiln section: \$85 000 at 65 heater length along the direction of bag movement, cm; n = 0.52 for range 40–180 cm.
Bag vibrating packers: FOB \$7000 at maximum bag width = 50 cm with n = 1.0 for the range 30–100 cm. For rigid container vibrating packer, × 2.0.
Automatic bulk weighing scales: for free flowing material, not dust enclosed, up to 2 weighings/min and capacity up to 0.06 m^3/s ± 1%, FOB cost \$28 000 for volume/weighing = 0.5 m^3 with n = 0.42 for the range 0.2–0.9 m^3.

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