James R. Couper • W. Roy Penney • James R. Fair • Stanley M. Walas

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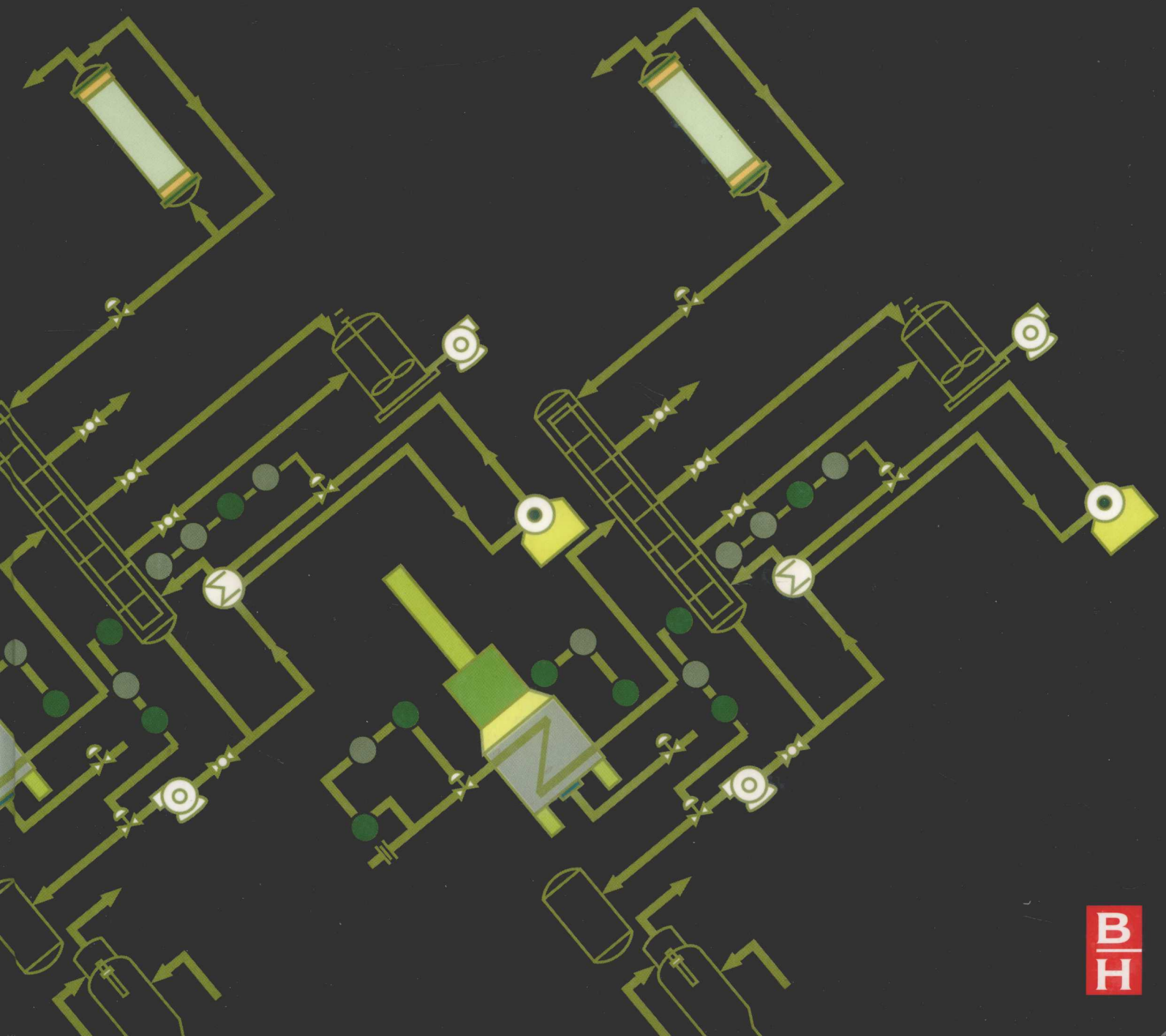
Chemical Process Equipment

Selection and Design

Third Edition



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Chemical Process Equipment

This book is dedicated to the memory of Dr James R. Fair, who passed away in October 2010. Dr Fair was responsible for the material in Chapters 13 and 15 as well as providing advice to the authors.

Dr Fair was a colleague at Monsanto of both Dr Roy Penney and Dr James R. Couper. He will be sorely missed since we relied on his advice and counsel during the preparation of this book's manuscript.

Preface to the Third Edition

This edition of the book contains revised and updated information from both the second edition and the revised second edition, as well as new material as of early 2010. The authors and collaborators have included information essential to the design and specification of equipment needed for the ultimate purchasing of equipment. The vast amount of literature has been screened so that only time-tested practical methods that are useful in the design and specification of equipment are included. The authors and collaborators have used their judgment about what to include based upon their combined industrial and academic experience. The emphasis is on design techniques and practice as well as what is required to work with vendors in the selection and purchase of equipment. This material would be especially helpful to the young engineer entering industry, thus bridging the gap between academia and industry. Chapters 10, 13, 14, 15, and 16 have been extensively updated and revised compared to the second and revised second editions of the book.

Dr Wayne J. Genck, President of Genck International, a renowned international expert on crystallization has joined the contributors, replacing John H. Wolf, Retired President of Swenson Process Equipment Company.

Older methods and obsolete equipment for the most part have been removed. If the reader has an interest in older material, he or she might consult previous editions of this book.

This book is not intended as a classroom text, however, with some modifications and addition of examples and problems, it could be used for teaching purposes.

James R. Couper
W. Roy Penney

Preface to the Second Edition

The editors of the revised edition are in agreement with the philosophy and the approach that Professor Stanley Walas presented in the original edition. In general, the subject headings and format of each chapter have been retained but the revised edition has been corrected to eliminate errors and insofar as possible update the contents of each chapter. Material that we consider superfluous or beyond the scope and intent of the revised edition has been eliminated. Most of the original text has been retained, since the methods have stood the test of time and we felt that any revision had to be a definite improvement.

Chapter 3, Process Control, and Chapter 10, Mixing and Agitation, have been completely revised to bring the content of these chapters up to date. Chapter 18, Process Vessels, has been expanded to include the design of bins and hoppers. Chapter 19, Membrane Separations, is an entirely new chapter. We felt that this topic has gained considerable attention in recent years in chemical processing and deserved to be a chapter devoted to this important material. Chapter 20, Gas-Solid Separation and Other Topics, consists of material on gas-solid handling as well as the remainder of the topics in Chapter 19 of the original edition. Chapter 21, Costs of Individual Equipment, is a revision of Chapter 20 in the original edition and the algorithms have been updated to late 2002. Costs calculated from these algorithms have been spot-checked with equipment suppliers and industrial sources. They have been found to be within 20 to 25% accurate.

We have removed almost all the Fortran computer program listings, since every engineer has his or her own methods for solving such problems. There is one exception and that is the fired heater design Fortran listing in Chapter 8, Heat Transfer and Heat Exchangers. Our experience is that the program provides insight into a tedious and involved calculation procedure.

Although the editors of this text have had considerable industrial and academic experience in process design and equipment selection, there are certain areas in which we have limited or no experience. It was our decision to ask experts to serve as collaborators. We wish to express our profound appreciation to those colleagues and they are mentioned in the List of Contributors.

We particularly wish to acknowledge the patience and understanding of our wives, Mary Couper, Merle Fair, and Annette Penney, during the preparation of this manuscript.

James R. Couper
James R. Fair
W. Roy Penney

Preface to the First Edition

This book is intended as a guide to the selection or design of the principal kinds of chemical process equipment by engineers in school and industry. The level of treatment assumes an elementary knowledge of unit operations and transport phenomena. Access to the many design and reference books listed in Chapter 1 is desirable. For coherence, brief reviews of pertinent theory are provided. Emphasis is placed on shortcuts, rules of thumb, and data for design by analogy, often as primary design processes but also for quick evaluations of detailed work.

All answers to process design questions cannot be put into a book. Even at this late date in the development of the chemical industry, it is common to hear authorities on most kinds of equipment say that their equipment can be properly fitted to a particular task only on the basis of some direct laboratory and pilot plant work. Nevertheless, much guidance and reassurance are obtainable from general experience and specific examples of successful applications, which this book attempts to provide. Much of the information is supplied in numerous tables and figures, which often deserve careful study quite apart from the text.

The general background of process design, flowsheets, and process control is reviewed in the introductory chapters. The major kinds of operations and equipment are treated in individual chapters. Information about peripheral and less widely employed equipment in chemical plants is concentrated in Chapter 19 with references to key works of as much practical value as possible. Because decisions often must be based on economic grounds, Chapter 20, on costs of equipment, rounds out the book. Appendixes provide examples of equipment rating forms and manufacturers' questionnaires.

Chemical process equipment is of two kinds: custom designed and built, or proprietary "off the shelf." For example, the sizes and performance of custom equipment such as distillation towers, drums, and heat exchangers are derived by the process engineer on the basis of established principles and data, although some mechanical details remain in accordance with safe practice codes and individual fabrication practices.

Much proprietary equipment (such as filters, mixers, conveyors, and so on) has been developed largely without benefit of much theory and is fitted to job requirements also without benefit of much theory. From the point of view of the process engineer, such equipment is predesigned and fabricated and made available by manufacturers in limited numbers of types, sizes, and capacities. The process design of proprietary equipment, as considered in this book, establishes its required performance and is a process of selection from the manufacturers' offerings, often with their recommendations or on the basis of individual experience. Complete information is provided in manufacturers' catalogs. Several classified lists of manufacturers of chemical process equipment are readily accessible, so no listings are given here.

Because more than one kind of equipment often is suitable for particular applications and may be available from several manufacturers, comparisons of equipment and typical applications are cited liberally. Some features of industrial equipment are largely arbitrary and may be standardized for convenience in particular industries or individual plants. Such aspects of equipment design are noted when feasible.

Shortcut methods of design provide solutions to problems in a short time and at small expense. They must be used when data are limited or when the greater expense of a thorough method is not justifiable. In particular cases they may be employed to obtain information such as:

1. an order of magnitude check of the reasonableness of a result found by another lengthier and presumably accurate computation or computer run,
2. a quick check to find if existing equipment possibly can be adapted to a new situation,
3. a comparison of alternate processes,
4. a basis for a rough cost estimate of a process.

Shortcut methods occupy a prominent place in such a broad survey and limited space as this book. References to sources of more accurate design procedures are cited when available.

Another approach to engineering work is with rules of thumb, which are statements of equipment performance that may obviate all need for further calculations. Typical examples, for instance, are that optimum reflux ratio is 20% greater than minimum, that a suitable cold oil velocity in a fired heater is 6 ft/sec, or that the efficiency of a mixer-settler extraction stage is 70%. The trust that can be placed in a rule of thumb depends on the authority of the propounder, the risk associated with its possible inaccuracy, and the economic balance between the cost of a more accurate evaluation and suitable safety factor placed on the approximation. All experienced engineers have acquired such knowledge. When applied with discrimination, rules of thumb are a valuable asset to the process design and operating engineer, and are scattered throughout this book.

Design by analogy, which is based on knowledge of what has been found to work in similar areas, even though not necessarily optimally, is another valuable technique. Accordingly, specific applications often are described in this book, and many examples of specific equipment sizes and performance are cited.

For much of my insight into chemical process design, I am indebted to many years' association and friendship with the late Charles W. Nofsinger, who was a prime practitioner by analogy, rule of thumb, and basic principles. Like Dr. Dolittle of Puddleby-on-the-Marsh, "he was a proper doctor and knew a whole lot".

Stanley M. Walas

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Chapter 0

RULES OF THUMB: SUMMARY

Although experienced engineers know where to find information and how to make accurate computations, they also keep a minimum body of information readily available, made largely of shortcuts and rules of thumb. This compilation is such a body of information from the material in this book and is, in a sense, a digest of the book.

Rules of thumb, also known as *heuristics*, are statements of known facts. The word *heuristics* is derived from Greek, to discover or to invent, so these rules are known or discovered through use and practice but may not be able to be theoretically proven. In practice, they work and are most safely applied by engineers who are familiar with the topics. Such rules are of value for approximate design and preliminary cost estimation, and should provide even the inexperienced engineer with perspective and whereby the reasonableness of detailed and computer-aided design can be appraised quickly, especially on short notice, such as a conference.

Everyday activities are frequently governed by rules of thumb. They serve us when we wish to take a course of action but we may not be in a position to find the best course of action.

Much more can be stated in adequate fashion about some topics than others, which accounts, in part, for the spottiness of the present coverage. Also, the spottiness is due to the ignorance and oversights on the part of the authors. Therefore, every engineer undoubtedly will supplement or modify this material (Walas, 1988).

COMPRESSORS AND VACUUM PUMPS

1. *Fans* are used to raise the pressure about 3% (12 in. water), *blowers* raise to less than 40 psig, and *compressors* to higher pressures, although the blower range commonly is included in the compressor range.
2. Vacuum pumps: reciprocating piston type decrease the pressure to 1 Torr; rotary piston down to 0.001 Torr, two-lobe rotary down to 0.0001 Torr; steam jet ejectors, one stage down to 100 Torr, three stage down to 1 Torr, five stage down to 0.05 Torr.
3. A three-stage ejector needs 100 lb steam/lb air to maintain a pressure of 1 Torr.
4. In-leakage of air to evacuated equipment depends on the absolute pressure, Torr, and the volume of the equipment, V cuft, according to $w = kV^{2/3}$ lb/hr, with $k = 0.2$ when P is more than 90 Torr, 0.08 between 3 and 20 Torr, and 0.025 at less than 1 Torr.
5. Theoretical adiabatic horsepower (THP) = $[(\text{SCFM})T_1/8130a][(P_2/P_1)^a - 1]$, where T_1 is inlet temperature in °F + 460 and $a = (k-1)/k$, $k = C_p/C_v$.
6. Outlet temperature $T_2 = T_1(P_2/P_1)^a$.
7. To compress air from 100°F, $k = 1.4$, compression ratio = 3, theoretical power required = 62 HP/million cuft/day, outlet temperature 306°F.
8. Exit temperature should not exceed 350–400°F; for diatomic gases ($C_p/C_v = 1.4$) this corresponds to a compression ratio of about 4.
9. Compression ratio should be about the same in each stage of a multistage unit, ratio = $(P_n/P_1)^{1/n}$, with n stages.
10. Efficiencies of fans vary from 60–80% and efficiencies of blowers are in the range of 70–85%.
11. Efficiencies of reciprocating compressors: 65–70% at compression ratio of 1.5, 75–80% at 2.0, and 80–85% at 3–6.
12. Efficiencies of large centrifugal compressors, 6000–100,000 ACFM at suction, are 76–78%.
13. Rotary compressors have efficiencies of 70–78%, except liquid-liner type which have 50%.
14. Axial flow compressor efficiencies are in the range of 81–83%.

CONVEYORS FOR PARTICULATE SOLIDS

1. *Screw conveyors* are used to transport even sticky and abrasive solids up inclines of 20° or so. They are limited to distances of 150 ft or so because of shaft torque strength. A 12 in. dia conveyor can handle 1000–3000 cuft/hr, at speeds ranging from 40 to 60 rpm.
2. *Belt conveyors* are for high capacity and long distances (a mile or more, but only several hundred feet in a plant), up inclines of 30° maximum. A 24 in. wide belt can carry 3000 cuft/hr at a speed of 100 ft/min, but speeds up to 600 ft/min are suited for some materials. The number of turns is limited and the maximum incline is 30 degrees. Power consumption is relatively low.
3. *Bucket elevators* are used for vertical transport of sticky and abrasive materials. With buckets 20 × 20 in. capacity can reach 1000 cuft/hr at a speed of 100 ft/min, but speeds to 300 ft/min are used.
4. *Drag-type conveyors* (Redler) are suited for short distances in any direction and are completely enclosed. Units range in size from 3 in. square to 19 in. square and may travel from 30 ft/min (fly ash) to 250 ft/min (grains). Power requirements are high.
5. *Pneumatic conveyors* are for high capacity, short distance (400 ft) transport simultaneously from several sources to several destinations. Either vacuum or low pressure (6–12 psig) is employed with a range of air velocities from 35 to 120 ft/sec depending on the material and pressure. Air requirements are from 1 to 7 cuft/cuft of solid transferred.

COOLING TOWERS

1. Water in contact with air under adiabatic conditions eventually cools to the wet bulb temperature.
2. In commercial units, 90% of saturation of the air is feasible.
3. Relative cooling tower size is sensitive to the difference between the exit and wet bulb temperatures:

ΔT(°F)	5	15	25
Relative volume	2.4	1.0	0.55

4. Tower fill is of a highly open structure so as to minimize pressure drop, which is in standard practice a maximum of 2 in. of water.
5. Water circulation rate is 1–4 gpm/sqft and air rates are 1300–1800 lb/(hr)(sqft) or 300–400 ft/min.
6. Chimney-assisted natural draft towers are of hyperboloidal shapes because they have greater strength for a given thickness; a tower 250 ft high has concrete walls 5–6 in. thick. The enlarged cross section at the top aids in dispersion of exit humid air into the atmosphere.
7. Countercurrent induced draft towers are the most common in process industries. They are able to cool water within 2°F of the wet bulb.

8. Evaporation losses are 1% of the circulation for every 10°F of cooling range. Windage or drift losses of mechanical draft towers are 0.1–0.3%. Blowdown of 2.5–3.0% of the circulation is necessary to prevent excessive salt buildup.
9. Towers that circulate cooling water to several process units and are vulnerable to process intrusion should not use film fill due to the risk of fouling and fill failure (Huchler, 2009).
10. Sites with nearby obstructions or where there is the risk that the tower plume or combustion exhaust may be entrained should use a couterflow configuration, and may need special air intake designs (Huchler, 2009).
11. If the facility, like a power plant, has very high heat loads requiring high recirculating water rates and large cooling loads, it may require the use of natural-draft towers with hyperbolic concrete shells (Huchler, 2009).
12. The use of variable-frequency fan drives increase capital costs and provide operating flexibility for towers of two or more cells (Huchler, 2009).

CRYSTALLIZATION FROM SOLUTION

1. The feed to a crystallizer should be slightly unsaturated.
2. Complete recovery of dissolved solids is obtainable by evaporation, but only to the eutectic composition by chilling. Recovery by melt crystallization also is limited by the eutectic composition.
3. Growth rates and ultimate sizes of crystals are controlled by limiting the extent of supersaturation at any time.
4. Crystal growth rates are higher at higher temperatures.
5. The ratio $S = C/C_{sat}$ of prevailing concentration to saturation concentration is kept near the range of 1.02–1.05.
6. In crystallization by chilling, the temperature of the solution is kept at most 1–2°F below the saturation temperature at the prevailing concentration.
7. Growth rates of crystals under satisfactory conditions are in the range of 0.1–0.8 mm/hr. The growth rates are approximately the same in all directions.
8. Growth rates are influenced greatly by the presence of impurities and of certain specific additives that vary from case to case.
9. Batch crystallizers tend to have a broader crystal size distribution than continuous crystallizers.
10. To narrow the crystal size distribution, cool slowly through the initial crystallization temperature or seed at the initial crystallization temperature.

DISINTEGRATION

1. Percentages of material greater than 50% of the maximum size are about 50% from rolls, 15% from tumbling mills, and 5% from closed circuit ball mills.
2. Closed circuit grinding employs external size classification and return of oversize for regrinding. The rules of pneumatic conveying are applied to design of air classifiers. Closed circuit is most common with ball and roller mills.
3. Jaw and gyratory crushers are used for coarse grinding.
4. Jaw crushers take lumps of several feet in diameter down to 4 in. Stroke rates are 100–300/min. The average feed is subjected to 8–10 strokes before it becomes small enough to escape. Gyratory crushers are suited for slabby feeds and make a more rounded product.
5. Roll crushers are made either smooth or with teeth. A 24 in. toothed roll can accept lumps 14 in. dia. Smooth rolls effect reduction ratios up to about 4. Speeds are 50–900 rpm. Capacity is about 25% of the maximum corresponding to a continuous ribbon of material passing through the rolls.
6. Hammer mills beat the material until it is small enough to pass through the screen at the bottom of the casing. Reduction ratios of 40 are feasible. Large units operate at 900 rpm, smaller ones up to 16,000 rpm. For fibrous materials the screen is provided with cutting edges.
7. Rod mills are capable of taking feed as large as 50 mm and reducing it to 300 mesh, but normally the product range is 8–65 mesh. Rods are 25–150 mm dia. Ratio of rod length to mill diameter is about 1.5. About 45% of the mill volume is occupied by rods. Rotation is at 50–65% of critical.
8. Ball mills are better suited than rod mills to fine grinding. The charge is of equal weights of 1.5, 2, and 3 in. balls for the finest grinding. Volume occupied by the balls is 50% of the mill volume. Rotation speed is 70–80% of critical. Ball mills have a length to diameter ratio in the range 1–1.5. Tube mills have a ratio of 4–5 and are capable of very fine grinding. Pebble mills have ceramic grinding elements, used when contamination with metal is to be avoided.
9. Roller mills employ cylindrical or tapered surfaces that roll along flatter surfaces and crush nipped particles. Products of 20–200 mesh are made.
10. Fluid energy mills are used to produce fine or ultrafine (submicron) particles.

DISTILLATION AND GAS ABSORPTION

1. Distillation usually is the most economical method of separating liquids, superior to extraction, adsorption, crystallization, or others.
2. For ideal mixtures, relative volatility is the ratio of vapor pressures $\alpha_{12} = P_2/P_1$.
3. For a two-component, ideal system, the McCabe-Thiele method offers a good approximation of the number of equilibrium stages.
4. Tower operating pressure is determined most often by the temperature of the available condensing medium, 100–120°F if cooling water; or by the maximum allowable reboiler temperature, 150 psig steam, 366°F.
5. Sequencing of columns for separating multicomponent mixtures: (a) perform the easiest separation first, that is, the one least demanding of trays and reflux, and leave the most difficult to the last; (b) when neither relative volatility nor feed concentration vary widely, remove the components one by one as overhead products; (c) when the adjacent ordered components in the feed vary widely in relative volatility, sequence the splits in the order of decreasing volatility; (d) when the concentrations in the feed vary widely but the relative volatilities do not, remove the components in the order of decreasing concentration in the feed.
6. Flashing may be more economical than conventional distillation but is limited by the physical properties of the mixture.
7. Economically optimum reflux ratio is about 1.25 times the minimum reflux ratio R_m.
8. The economically optimum number of trays is nearly twice the minimum value N_m.
9. The minimum number of trays is found with the Fenske-Underwood equation

$$N_m = \log \{[(x/(1-x)]_{ovhd}/[x/(1-x)]_{btms}\}/\log \alpha.$$

10. Minimum reflux for binary or pseudobinary mixtures is given by the following when separation is essentially complete ($x_D \approx 1$) and D/F is the ratio of overhead product and feed rates:

$R_m D/F = 1/(\alpha-1)$, when feed is at the bubblepoint,

$(R_m + 1)D/F = \alpha/(\alpha-1)$, when feed is at the dewpoint.

11. A safety factor of 10% of the number of trays calculated by the best means is advisable.
12. Reflux pumps are made at least 25% oversize.
13. For reasons of accessibility, tray spacings are made 20–30 in.
14. Peak efficiency of trays is at values of the vapor factor $F_s = u\sqrt{\rho_v}$ in the range 1.0–1.2 (ft/sec) $\sqrt{\text{lb/cuft}}$. This range of F_s establishes the diameter of the tower. Roughly, linear velocities are 2 ft/sec at moderate pressures and 6 ft/sec in vacuum.
15. The optimum value of the Kremser-Brown absorption factor $A = K\,(V/L)$ is in the range 1.25–2.0.
16. Pressure drop per tray is of the order of 3 in. of water or 0.1 psi.
17. Tray efficiencies for distillation of light hydrocarbons and aqueous solutions are 60–90%; for gas absorption and stripping, 10–20%.
18. Sieve trays have holes 0.25–0.50 in. dia, hole area being 10% of the active cross section.
19. Valve trays have holes 1.5 in. dia each provided with a liftable cap, 12–14 caps/sqft of active cross section. Valve trays usually are cheaper than sieve trays.
20. Bubblecap trays are used only when a liquid level must be maintained at low turndown ratio; they can be designed for lower pressure drop than either sieve or valve trays.
21. Weir heights are 2 in., weir lengths about 75% of tray diameter, liquid rate a maximum of about 8 gpm/in. of weir; multipass arrangements are used at high liquid rates.
22. Packings of random and structured character are suited especially to towers under 3 ft dia and where low pressure drop is desirable. With proper initial distribution and periodic redistribution, volumetric efficiencies can be made greater than those of tray towers. Packed internals are used as replacements for achieving greater throughput or separation in existing tower shells.
23. For gas rates of 500 cfm, use 1 in. packing; for gas rates of 2000 cfm or more, use 2 in.
24. The ratio of diameters of tower and packing should be at least 15.
25. Because of deformability, plastic packing is limited to a 10–15 ft depth unsupported, metal to 20–25 ft.
26. Liquid redistributors are needed every 5–10 tower diameters with pall rings but at least every 20 ft. The number of liquid streams should be 3–5/sqft in towers larger than 3 ft dia (some experts say 9–12/sqft), and more numerous in smaller towers.
27. Height equivalent to a theoretical plate (HETP) for vapor-liquid contacting is 1.3–1.8 ft for 1 in. pall rings, 2.5–3.0 ft for 2 in. pall rings.
28. Packed towers should operate near 70% of the flooding rate given by the correlation of Sherwood, Lobo, et al.
29. Reflux drums usually are horizontal, with a liquid holdup of 5 min half full. A takeoff pot for a second liquid phase, such as water in hydrocarbon systems, is sized for a linear velocity of that phase of 0.5 ft/sec, minimum diameter of 16 in.
30. For towers about 3 ft dia, add 4 ft at the top for vapor disengagement and 6 ft at the bottom for liquid level and reboiler return.
31. Limit the tower height to about 175 ft max because of wind load and foundation considerations. An additional criterion is that L/D be less than 30.

DRIVERS AND POWER RECOVERY EQUIPMENT

1. Efficiency is greater for larger machines. Motors are 85–95%; steam turbines are 42–78%; gas engines and turbines are 28–38%.
2. For under 100 HP, electric motors are used almost exclusively. They are made for up to 20,000 HP.
3. Induction motors are most popular. Synchronous motors are made for speeds as low as 150 rpm and are thus suited for example for low speed reciprocating compressors, but are not made smaller than 50 HP. A variety of enclosures is available, from weather-proof to explosion-proof.
4. Steam turbines are competitive above 100 HP. They are speed controllable. They are used in applications where speeds and demands are relatively constant. Frequently they are employed as spares in case of power failure.
5. Combustion engines and turbines are restricted to mobile and remote locations.
6. Gas expanders for power recovery may be justified at capacities of several hundred HP; otherwise any needed pressure reduction in process is effected with throttling valves.
7. Axial turbines are used for power recovery where flow rates, inlet temperatures or pressure drops are high.
8. Turboexpanders are used to recover power in applications where inlet temperatures are less than 1000°F.

DRYING OF SOLIDS

1. Drying times range from a few seconds in spray dryers to 1 hr or less in rotary dryers and up to several hours or even several days in tunnel shelf or belt dryers.
2. Continuous tray and belt dryers for granular material of natural size or pelleted to 3–15 mm have drying times in the range of 10–200 min.
3. Rotary cylindrical dryers operate with superficial air velocities of 5–10 ft/sec, sometimes up to 35 ft/sec when the material is coarse. Residence times are 5–90 min. Holdup of solid is 7–8%. An 85% free cross section is taken for design purposes. In countercurrent flow, the exit gas is 10–20°C above the solid; in parallel flow, the temperature of the exit solid is 100°C. Rotation speeds of about 4 rpm are used, but the product of rpm and diameter in feet is typically between 15 and 25.
4. Drum dryers for pastes and slurries operate with contact times of 3–12 sec, produce flakes 1–3 mm thick with evaporation rates of 15–30 kg/m^2 hr. Diameters are 1.5–5.0 ft; the rotation rate is 2–10 rpm. The greatest evaporative capacity is of the order of 3000 lb/hr in commercial units.
5. Pneumatic conveying dryers normally take particles 1–3 mm dia but up to 10 mm when the moisture is mostly on the surface. Air velocities are 10–30 m/sec. Single pass residence times are 0.5–3.0 sec but with normal recycling the average residence time is brought up to 60 sec. Units in use range from 0.2 m dia by 1 m high to 0.3 m dia by 38 m long. Air requirement is several SCFM/lb of dry product/hr.
6. Fluidized bed dryers work best on particles of a few tenths of a mm dia, but up to 4 mm dia have been processed. Gas velocities of twice the minimum fluidization velocity are a safe prescription. In continuous operation, drying times of 1–2 min are enough, but batch drying of some pharmaceutical products employs drying times of 2–3 hr.
7. Spray dryers are used for heat sensitive materials. Surface moisture is removed in about 5 sec, and most drying is completed in less than 60 sec. Parallel flow of air and stock is most common. Atomizing nozzles have openings 0.012–0.15 in. and operate at pressures of 300–4000 psi. Atomizing spray wheels rotate at speeds to 20,000 rpm with peripheral speeds of 250–600 ft/sec. With nozzles, the length to diameter ratio of the dryer is 4–5; with spray wheels, the ratio is 0.5–1.0. For the final design, the experts say, pilot tests in a unit of 2 m dia should be made.

EVAPORATORS

1. Long tube vertical evaporators with either natural or forced circulation are most popular. Tubes are 19–63 mm dia and 12–30 ft long.
2. In forced circulation, linear velocities in the tubes are 15–20 ft/sec.
3. Film-related efficiency losses can be minimized by maintaining a suitable temperature gradient, for instance 40–45°F. A reasonable overall heat transfer coefficient is 250 Btu/(h)(ft^2).
4. Elevation of boiling point by dissolved solids results in differences of 3–10°F between solution and saturated vapor.
5. When the boiling point rise is appreciable, the economic number of effects in series with forward feed is 4–6.
6. When the boiling point rise is small, minimum cost is obtained with 8–10 effects in series.
7. In countercurrent evaporator systems, a reasonable temperature approach between the inlet and outlet streams is 30°F. In multistage operation, a typical minimum is 10°F.
8. In backward feed the more concentrated solution is heated with the highest temperature steam so that heating surface is lessened, but the solution must be pumped between stages.
9. The steam economy of an N-stage battery is approximately $0.8N$ lb evaporation/lb of outside steam.
10. Interstage steam pressures can be boosted with steam jet compressors of 20–30% efficiency or with mechanical compressors of 70–75% efficiency.

EXTRACTION, LIQUID-LIQUID

1. The dispersed phase should be the one that has the higher volumetric rate except in equipment subject to backmixing where it should be the one with the smaller volumetric rate. It should be the phase that wets the material of construction less well. Since the holdup of continuous phase usually is greater, that phase should be made up of the less expensive or less hazardous material.
2. Although theory is favorable for the application of reflux to extraction columns, there are very few commercial applications.
3. Mixer-settler arrangements are limited to at most five stages. Mixing is accomplished with rotating impellers or circulating pumps. Settlers are designed on the assumption that droplet sizes are about 150 μm dia. In open vessels, residence times of 30–60 min or superficial velocities of 0.5–1.5 ft/min are provided in settlers. Extraction stage efficiencies commonly are taken as 80%.
4. Spray towers even 20–40 ft high cannot be depended on to function as more than a single stage.
5. Packed towers are employed when 5–10 stages suffice. Pall rings of 1–1.5 in. size are best. Dispersed phase loadings should not exceed 25 gal/(min) (sqft). HETS of 5–10 ft may be realizable. The dispersed phase must be redistributed every 5–7 ft. Packed towers are not satisfactory when the surface tension is more than 10 dyn/cm.
6. Sieve tray towers have holes of only 3–8 mm dia. Velocities through the holes are kept below 0.8 ft/sec to avoid formation of small drops. At each tray, design for the redistribution of each phase can be provided. Redispersion of either phase at each tray can be designed for. Tray spacings are 6–24 in. Tray efficiencies are in the range of 20–30%.
7. Pulsed packed and sieve tray towers may operate at frequencies of 90 cycles/min and amplitudes of 6–25 mm. In large diameter towers, HETS of about 1 m has been observed. Surface tensions as high as 30–40 dyn/cm have no adverse effect.
8. Reciprocating tray towers can have holes 9/16 in. dia, 50–60% open area, stroke length 0.75 in., 100–150 strokes/min, plate spacing normally 2 in. but in the range 1–6 in. In a 30 in. dia tower, HETS is 20–25 in. and throughput is 2000 gal/(hr)(sqft). Power requirements are much less than of pulsed towers.
9. Rotating disk contactors or other rotary agitated towers realize HETS in the range 0.1–0.5 m. The especially efficient Kuhni with perforated disks of 40% free cross section has HETS 0.2 m and a capacity of 50 m^3/m^2 hr.

FILTRATION

1. Processes are classified by their rate of cake buildup in a laboratory vacuum leaf filter: rapid, 0.1–10.0 cm/sec; medium, 0.1–10.0 cm/min; slow, 0.1–10.0 cm/hr.
2. The selection of a filtration method depends partly on which phase is the valuable one. For liquid phase being the valuable one, filter presses, sand filters, and pressure filters are suitable. If the solid phase is desired, vacuum rotary vacuum filters are desirable.
3. Continuous filtration should not be attempted if 1/8 in. cake thickness cannot be formed in less than 5 min.
4. Rapid filtering is accomplished with belts, top feed drums, or pusher-type centrifuges.
5. Medium rate filtering is accomplished with vacuum drums or disks or peeler-type centrifuges.
6. Slow filtering slurries are handled in pressure filters or sedimenting centrifuges.
7. Clarification with negligible cake buildup is accomplished with cartridges, precoat drums, or sand filters.
8. Laboratory tests are advisable when the filtering surface is expected to be more than a few square meters, when cake washing is critical, when cake drying may be a problem, or when precoating may be needed.
9. For finely ground ores and minerals, rotary drum filtration rates may be 1500 lb/(day)(sqft), at 20 rev/hr and 18–25 in. Hg vacuum.
10. Coarse solids and crystals may be filtered by rotary drum filters at rates of 6000 lb/(day)(sqft) at 20 rev/hr, 2–6 in. Hg vacuum.
11. Cartridge filters are used as final units to clarify a low solid concentration stream. For slurries where excellent cake washing is required, horizontal filters are used. Rotary disk filters are for separations where efficient cake washing is not essential. Rotary drum filters are used in many liquid-solid separations and precoat units capable of producing clear effluent streams. In applications where flexibility of design and operation are required, plate-and-frame filters are used.

FLUIDIZATION OF PARTICLES WITH GASES

1. Properties of particles that are conducive to smooth fluidization include: rounded or smooth shape, enough toughness to resist attrition, sizes in the range 50–500 μm dia, a spectrum of sizes with ratio of largest to smallest in the range of 10–25.
2. Cracking catalysts are members of a broad class characterized by diameters of 30–150 μm, density of 1.5 g/mL or so, appreciable expansion of the bed before fluidization sets in, minimum bubbling velocity greater than minimum fluidizing velocity, and rapid disengagement of bubbles.
3. The other extreme of smoothly fluidizing particles is typified by coarse sand and glass beads both of which have been the subject of much laboratory investigation. Their sizes are in the range 150–500 μm, densities 1.5–4.0 g/mL, small bed expansion, about the same magnitudes of minimum bubbling and minimum fluidizing velocities, and also have rapidly disengaging bubbles.
4. Cohesive particles and large particles of 1 mm or more do not fluidize well and usually are processed in other ways.

5. Rough correlations have been made of minimum fluidization velocity, minimum bubbling velocity, bed expansion, bed level fluctuation, and disengaging height. Experts recommend, however, that any real design be based on pilot plant work.
6. Practical operations are conducted at two or more multiples of the minimum fluidizing velocity. In reactors, the entrained material is recovered with cyclones and returned to process. In dryers, the fine particles dry most quickly so the entrained material need not be recycled.

HEAT EXCHANGERS

1. Take true countercurrent flow in a shell-and-tube exchanger as a basis.
2. Standard tubes are 3/4 in. OD, 1 in. triangular spacing, 16 ft long; a shell 1 ft dia accommodates 100 sqft; 2 ft dia, 400 sqft, 3 ft dia, 1100 sqft.
3. Tube side is for corrosive, fouling, scaling, and high pressure fluids.
4. Shell side is for viscous and condensing fluids.
5. Pressure drops are 1.5 psi for boiling and 3–9 psi for other services.
6. Minimum temperature approach is 20°F with normal coolants, 10°F or less with refrigerants.
7. Water inlet temperature is 90°F, maximum outlet 120°F.
8. Heat transfer coefficients for estimating purposes, Btu/(hr)(sqft)(°F): water to liquid, 150; condensers, 150; liquid to liquid, 50; liquid to gas, 5; gas to gas, 5; reboiler, 200. Max flux in reboilers, 10,000 Btu/(hr)(sqft).
9. Usually, the maximum heat transfer area for a shell-and-tube heat exchanger is in the range of 5000 ft^2.
10. Double-pipe exchanger is competitive at duties requiring 100–200 sqft.
11. Compact (plate and fin) exchangers have 350 sqft/cuft, and about 4 times the heat transfer per cuft of shell-and-tube units.
12. Plate and frame exchangers are suited to high sanitation services, and are 25–50% cheaper in stainless construction than shell-and-tube units.
13. Air coolers: Tubes are 0.75–1.00 in. OD, total finned surface 15–20 sqft/sqft bare surface, U = 80–100 Btu/(hr)(sqft bare surface)(°F), fan power input 2–5 HP/(MBtu/hr), approach 50°F or more.
14. Fired heaters: radiant rate, 12,000 Btu/(hr)(sqft); convection rate, 4000; cold oil tube velocity, 6 ft/sec; approx equal transfers of heat in the two sections; thermal efficiency 70–75%; flue gas temperature 250–350°F above feed inlet; stack gas temperature 650–950°F.

INSULATION

1. Up to 650°F, 85% magnesia is most used.
2. Up to 1600–1900°F, a mixture of asbestos and diatomaceous earth is used.
3. Ceramic refractories at higher temperatures.
4. Cryogenic equipment (−200°F) employs insulants with fine pores in which air is trapped.
5. Optimum thickness varies with temperature: 0.5 in. at 200°F, 1.0 in. at 400°F, 1.25 in. at 600°F.
6. Under windy conditions (7.5 miles/hr), 10–20% greater thickness of insulation is justified.

MIXING AND AGITATION

1. Mild agitation is obtained by circulating the liquid with an impeller at superficial velocities of 0.1–0.2 ft/sec, and intense agitation at 0.7–1.0 ft/sec.
2. Intensities of agitation with impellers in baffled tanks are measured by power input, HP/1000 gal, and impeller tip speeds:

Operation	HP/1000 gal	Tip speed (ft/min)
Blending	0.2–0.5	
Homogeneous reaction	0.5–1.5	7.5–10
Reaction with heat transfer	1.5–5.0	10–15
Liquid-liquid mixtures	5	15–20
Liquid-gas mixtures	5–10	15–20
Slurries	10	

3. Proportions of a stirred tank relative to the diameter D: liquid level = D; turbine impeller diameter = $D/3$; impeller level above bottom = $D/3$; impeller blade width = $D/15$; four vertical baffles with width = $D/10$.
4. Propellers are made a maximum of 18 in., turbine impellers to 9 ft.
5. Gas bubbles sparged at the bottom of the vessel will result in mild agitation at a superficial gas velocity of 1 ft/min, severe agitation at 4 ft/min.
6. Suspension of solids with a settling velocity of 0.03 ft/sec is accomplished with either turbine or propeller impellers, but when the settling velocity is above 0.15 ft/sec intense agitation with a propeller is needed.
7. Power to drive a mixture of a gas and a liquid can be 25–50% less than the power to drive the liquid alone.
8. In-line blenders are adequate when a second or two contact time is sufficient, with power inputs of 0.1–0.2 HP/gal.

PARTICLE SIZE ENLARGEMENT

1. The chief methods of particle size enlargement are: compression into a mold, extrusion through a die followed by cutting or breaking to size, globulation of molten material followed by solidification, agglomeration under tumbling or otherwise agitated conditions with or without binding agents.
2. Rotating drum granulators have length to diameter ratios of 2–3, speeds of 10–20 rpm, pitch as much as 10°. Size is controlled by speed, residence time, and amount of binder; 2–5 mm dia is common.
3. Rotary disk granulators produce a more nearly uniform product than drum granulators. Fertilizer is made 1.5–3.5 mm; iron ore 10–25 mm dia.
4. Roll compacting and briquetting is done with rolls ranging from 130 mm dia by 50 mm wide to 910 mm dia by 550 mm wide. Extrudates are made 1–10 mm thick and are broken down to size for any needed processing such as feed to tabletting machines or to dryers.
5. Tablets are made in rotary compression machines that convert powders and granules into uniform sizes. Usual maximum diameter is about 1.5 in., but special sizes up to 4 in. dia are possible. Machines operate at 100 rpm or so and make up to 10,000 tablets/min.
6. Extruders make pellets by forcing powders, pastes, and melts through a die followed by cutting. An 8 in. screw has a capacity of 2000 lb/hr of molten plastic and is able to extrude tubing at 150–300 ft/min and to cut it into sizes as small as washers at 8000/min. Ring pellet extrusion mills have hole diameters of 1.6–32 mm. Production rates cover a range of 30–200 lb/(hr)(HP).
7. Prilling towers convert molten materials into droplets and allow them to solidify in contact with an air stream. Towers as high as 60 m are used. Economically the process becomes competitive with other granulation processes when a capacity of 200–400 tons/day is reached. Ammonium nitrate prills, for example, are 1.6–3.5 mm dia in the 5–95% range.

8. Fluidized bed granulation is conducted in shallow beds 12–24 in. deep at air velocities of 0.1–2.5 m/s or 3–10 times the minimum fluidizing velocity, with evaporation rates of 0.005–1.0 kg/m^{2}sec. One product has a size range 0.7–2.4 mm dia.
9. Agglomerators give a loosely packed product and the operating costs are low.

PIPING

1. Line velocities and pressure drops, with line diameter D in inches: liquid pump discharge, (5 + D/3) ft/sec, 2.0 psi/100 ft; liquid pump suction, (1.3 + D/6) ft/sec, 0.4 psi/100 ft; steam or gas, 20D ft/sec, 0.5 psi/100 ft.
2. Control valves require at least 10 psi drop for good control.
3. Globe valves are used for gases, for control and wherever tight shutoff is required. Gate valves are for most other services.
4. Screwed fittings are used only on sizes 1.5 in. and smaller, flanges or welding otherwise.
5. Flanges and fittings are rated for 150, 300, 600, 900, 1500, or 2500 psig.
6. Pipe schedule number = 1000 P/S, approximately, where P is the internal pressure psig and S is the allowable working stress (about 10,000 psi for A120 carbon steel at 500°F). Schedule 40 is most common.

PUMPS

1. Power for pumping liquids: HP = (gpm)(psi difference)/(1714)(fractional efficiency).
2. Normal pump suction head (NPSH) of a pump must be in excess of a certain number, depending on the kind of pumps and the conditions, if damage is to be avoided. NPSH = (pressure at the eye of the impeller − vapor pressure)/(density). Common range is 4–20 ft.
3. Specific speed $N_s = (\text{rpm})(\text{gpm})^{0.5}/(\text{head in ft})^{0.75}$. Pump may be damaged if certain limits of N_s are exceeded, and efficiency is best in some ranges.
4. Centrifugal pumps: Single stage for 15–5000 gpm, 500 ft max head; multistage for 20–11,000 gpm, 5500 ft max head. Efficiency 45% at 100 gpm, 70% at 500 gpm, 80% at 10,000 gpm. They are used in processes where fluids are of moderate viscosity and the pressure increase is modest.
5. Axial pumps for 20–100,000 gpm, 40 ft head, 65–85% efficiency. These pumps are used in applications to move large volumes of fluids at low differential pressure.
6. Rotary pumps for 1–5000 gpm, 50,000 ft head, 50–80% efficiency.
7. Reciprocating pumps for 10–10,000 gpm, 1,000,000 ft head max. Efficiency 70% at 10 HP, 85% at 50 HP, 90% at 500 HP. These pumps are used if high pressures are necessary at low flow rates.
8. Turbine pumps are used in low flow and high pressure applications.
9. Positive displacement pumps are used where viscosities are large, flow rates are low, or metered liquid rates are required.

REACTORS

1. Inlet temperature, pressure and concentrations are necessary for specification of a reactor. An analysis of equilibrium should be made to define the limits of possible conversion and to eliminate impossible results.
2. Material and energy balances are essential to determine reactor size.
3. The rate of reaction in every instance must be established in the laboratory, and the residence time or space velocity and product distribution eventually must be found in a pilot plant.
4. Dimensions of catalyst particles are 0.1 mm in fluidized beds, 1 mm in slurry beds, and 2–5 mm in fixed beds.
5. The optimum proportions of stirred tank reactors are with liquid level equal to the tank diameter, but at high pressures slimmer proportions are economical.
6. Power input to a homogeneous reaction stirred tank is 0.5–1.5 HP/1000 gal, but three times this amount when heat is to be transferred.
7. Ideal CSTR (continuous stirred tank reactor) behavior is approached when the mean residence time is 5–10 times the length of time needed to achieve homogeneity, which is accomplished with 500–2000 revolutions of a properly designed stirrer.
8. Batch reactions are conducted in stirred tanks for small daily production rates or when the reaction times are long or when some condition such as feed rate or temperature must be programmed in some way.
9. Relatively slow reactions of liquids and slurries are conducted in continuous stirred tanks. A battery of four or five in series is most economical.
10. Tubular flow reactors are suited to high production rates at short residence times (sec or min) and when substantial heat transfer is needed. Embedded tubes or shell-and-tube construction then are used.
11. In granular catalyst packed reactors, the residence time distribution often is no better than that of a five-stage CSTR battery.
12. For conversions under about 95% of equilibrium, the performance of a five-stage CSTR battery approaches plug flow.

REFRIGERATION

1. A ton of refrigeration is the removal of 12,000 Btu/hr of heat.
2. At various temperature levels: 0 to 50°F, chilled brine and glycol solutions; −50 to 40°F, ammonia, freons, or butane; −150 to −50°F, ethane or propane.
3. Compression refrigeration with 100°F condenser requires these HP/ton at various temperature levels: 1.24 at 20°F; 1.75 at 0°F; 3.1 at −40°F; 5.2 at −80°F.
4. Below −80°F, cascades of two or three refrigerants are used.
5. In single stage compression, the compression ratio is limited to about 4.
6. In multistage compression, economy is improved with interstage flashing and recycling, so-called economizer operation.
7. Absorption refrigeration (ammonia to −30°F, lithium bromide to +45°F) is economical when waste steam is available at 12 psig or so.

SIZE SEPARATION OF PARTICLES

1. Grizzlies that are constructed of parallel bars at appropriate spacings are used to remove products larger than 5 cm dia.
2. Revolving cylindrical screens rotate at 15–20 rpm and below the critical velocity; they are suitable for wet or dry screening in the range of 10–60 mm.
3. Flat screens are vibrated or shaken or impacted with bouncing balls. Inclined screens vibrate at 600–7000 strokes/min and are used for down to 38 μm although capacity drops off sharply below 200 μm. Reciprocating screens operate in the range 30–1000 strokes/min and handle sizes down to 0.25 mm at the higher speeds.
4. Rotary sifters operate at 500–600 rpm and are suited to a range of 12 mm to 50 μm.

5. Air classification is preferred for fine sizes because screens of 150 mesh and finer are fragile and slow.
6. Wet classifiers mostly are used to make two product size ranges, oversize and undersize, with a break commonly in the range between 28 and 200 mesh. A rake classifier operates at about 9 strokes/min when making separation at 200 mesh, and 32 strokes/min at 28 mesh. Solids content is not critical, and that of the overflow may be 2–20% or more.
7. Hydrocyclones handle up to 600 cuft/min and can remove particles in the range of 300–5 μm from dilute suspensions. In one case, a 20 in. dia unit had a capacity of 1000 gpm with a pressure drop of 5 psi and a cutoff between 50 and 150 μm.

UTILITIES: COMMON SPECIFICATIONS

1. Steam: 15–30 psig, 250–275°F; 150 psig, 366°F; 400 psig, 448°F; 600 psig, 488°F or with 100–150°F superheat.
2. Cooling water: Supply at 80–90°F from cooling tower, return at 115–125°F; return seawater at 110°F, return tempered water or steam condensate above 125°F.
3. Cooling air supply at 85–95°F; temperature approach to process, 40°F.
4. Compressed air at 45, 150, 300, or 450 psig levels.
5. Instrument air at 45 psig, 0°F dewpoint.
6. Fuels: gas of 1000 Btu/SCF at 5–10 psig, or up to 25 psig for some types of burners; liquid at 6 million Btu/barrel.
7. Heat transfer fluids: petroleum oils below 600°F, Dowtherms, Therminol, etc. below 750°F, fused salts below 1100°F, direct fire or electricity above 450°F.
8. Electricity: 1–100 Hp, 220–660 V; 200–2500 Hp, 2300–4000 V.

VESSELS (DRUMS)

1. Drums are relatively small vessels to provide surge capacity or separation of entrained phases.
2. Liquid drums usually are horizontal.
3. Gas/liquid separators are vertical.
4. Optimum length/diameter = 3, but a range of 2.5–5.0 is common.
5. Holdup time is 5 min half full for reflux drums, 5–10 min for a product feeding another tower.
6. In drums feeding a furnace, 30 min half full is allowed.
7. Knockout drums ahead of compressors should hold no less than 10 times the liquid volume passing through per minute.
8. Liquid/liquid separators are designed for settling velocity of 2–3 in./min.
9. Gas velocity in gas/liquid separators, $V = k\sqrt{\rho_L/\rho_v - 1}$ ft/sec, with k = 0:35 with mesh deentrainer, k = 0:1 without mesh deentrainer.
10. Entrainment removal of 99% is attained with mesh pads of 4–12 in. thicknesses; 6 in. thickness is popular.
11. For vertical pads, the value of the coefficient in Step 9 is reduced by a factor of 2/3.
12. Good performance can be expected at velocities of 30–100% of those calculated with the given k; 75% is popular.
13. Disengaging spaces of 6–18 in. ahead of the pad and 12 in. above the pad are suitable.
14. Cyclone separators can be designed for 95% collection of 5 μm particles, but usually only droplets greater than 50 μm need be removed.

VESSELS (PRESSURE)

1. Design temperature between −20°F and 650°F is 50°F above operating temperature; higher safety margins are used outside the given temperature range.
2. The design pressure is 10% or 10–25 psi over the maximum operating pressure, whichever is greater. The maximum operating pressure, in turn, is taken as 25 psi above the normal operation.
3. Design pressures of vessels operating at 0–10 psig and 600–1000°F are 40 psig.
4. For vacuum operation, design pressures are 15 psig and full vacuum.
5. Minimum wall thicknesses for rigidity: 0.25 in. for 42 in. dia and under, 0.32 in. for 42–60 in. dia, and 0.38 in. for over 60 in. dia.
6. Corrosion allowance 0.35 in. for known corrosive conditions, 0.15 in. for non-corrosive streams, and 0.06 in. for steam drums and air receivers.
7. Allowable working stresses are one-fourth of the ultimate strength of the material.
8. Maximum allowable stress depends sharply on temperature.

Temperature (°F)	−20–650	750	850	1000
Low alloy steel SA203 (psi)	18,750	15,650	9550	2500
Type 302 stainless (psi)	18,750	18,750	15,900	6250

VESSELS (STORAGE TANKS)

1. For less than 1000 gal, use vertical tanks on legs.
2. Between 1000 and 10,000 gal, use horizontal tanks on concrete supports.
3. Beyond 10,000 gal, use vertical tanks on concrete foundations.
4. Liquids subject to breathing losses may be stored in tanks with floating or expansion roofs for conservation.
5. Freeboard is 15% below 500 gal and 10% above 500 gal capacity.
6. Thirty days capacity often is specified for raw materials and products, but depends on connecting transportation equipment schedules.
7. Capacities of storage tanks are at least 1.5 times the size of connecting transportation equipment; for instance, 7500 gal tank trucks, 34,500 gal tank cars, and virtually unlimited barge and tanker capacities.

MEMBRANE SEPARATIONS

1. When calculating mole fraction relationships (see Section 19.10), respective permeabilities in mixtures tend to be less, or much less, than measured pure permeabilities.
2. In calculating the degree of separation for mixtures between two components or key components, the permeability values used can be approximated as 50 percent of the values of the pure components.
3. In calculating membrane area, these same lower membrane permeability values may be used.
4. When in doubt, experimental data for each given mixture for a particular membrane material must be obtained.

MATERIALS OF CONSTRUCTION

1. The maximum use temperature of a metallic material is given by $T_{Max} = 2/3\ (T_{Melting\ Point})$
2. The coefficient of thermal expansion is of the order of 10×10^{-6}. Nonmetallic coefficients vary considerably.

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