Chapter 0

RULES OF THUMB: SUMMARY

COMPRESSORS, FANS, BLOWERS AND VACUUM PUMPS

1. *Fans* are used to raise the pressure by about 3% [12 in. (30 cm) water], *blowers* raise to less than 2.75 barg (40 psig), and *compressors* to higher pressures, although the blower range is commonly included in the compressor range.
2. For vacuum pumps use the following:

Reciprocating piston Type	down to 133.3 Pa (1 torr)
Rotary piston type	down to 0.133 Pa (0.001 torr)
Two lobe rotary type	down to 0.0133 Pa (0.0001 torr)
Steam jet ejectors	1 stage down to 13.3 kPa (100 torr) 3 stage down to 133.3 Pa (1 torr) 5 stage down to 6.7 Pa (0.05 torr)

3. A three-stage ejector needs 100 kg steam/kg air to maintain a pressure of 133.3 Pa (1 torr).
4. In-leakage of air to evacuated equipment depends on the absolute pressure (torr) and the volume of the equipment, V in m^3 (ft^3), according to $W = kV^{2/3}$ kg/h (lb/h), with $k = 0.98$ (0.2) when $P > 90$ torr, $k = 0.39$ (0.08) when P is between 0.4 and 2.67 kPa (3 and 20 torr), and $k = 0.12$ (0.025) at p less than 133.3 Pa (1 torr).
5. Theoretical adiabatic horsepower

$$\text{THP} = \frac{(\text{SCFM})\,T_1}{8130a}\left[\left(\frac{P_2}{P_1}\right)^a - 1\right]$$

where T_1 is inlet temperature in Rankine, $R = {}^\circ\text{F} + 460$ and $a = (k-1)/k, k = C_p/C_v$. Theoretical reversible adiabatic power $= mz_1RT_1[(\{P_2/P_1\}^a - 1)]/a$ Where T_1 is inlet temperature, $R =$ Gas Constant, $z_1 =$ compressibility factor, $m =$ molar flow rate, $a = (k-1)/k$ and $k = C_p/C_v$. Values of $R = 8.314\,\text{J/mol}K = 1.987\,\text{Btu/lbmol}\,^\circ\text{R} = 0.7302\,\text{atm ft}^3/\text{lb mol}\,^\circ\text{R}$.

6. Outlet temperature for reversible adiabatic process

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^a$$

7. To compress air from 37.8° C (100° F), $k = 1.4$, compression ratio = 3, theoretical power required = 62 hp/million ft^3/day, outlet temperature 152.2° C (306° F).
8. Exit temperature should not exceed 167–204° C (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 reciprocating compressors: 65% at compression ratio of 1.5, 75% at 2.0, and 80–85% at 3–6.
11. Efficiencies of large centrifugal compressors, 2.83–47.2 m^3/s (6000–100,000 acfm) at suction, are 76–78%.
12. Rotary compressors have efficiencies of 70%, except liquid liner type which have 50%.

CONVEYORS FOR PARTICULATE SOLIDS

1. *Screw conveyors* are suited to transport of even sticky and abrasive solids up inclines of 20° or so. They are limited to distances of 3.81 m (150 ft) or so because of shaft torque strength. A 304.8 mm (12 in.) diameter conveyor can handle 28.3–84.95 m^3/h (1000–3000 ft^3/h), 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 609.6-mm (24 in.) wide belt can carry 84.95 m^3/h (3000 ft^3/h) at a speed of 0.508 m/s (100 ft/min), but speeds up to 3.048 m/s (600 ft/min) are suited to some materials. Power consumption is relatively low.
3. *Bucket elevators* are suited to vertical transport of sticky and abrasive materials. With 508 x 508-mm (20 x 20-in.) buckets, capacity can reach 28.3 m^3/h (1000 ft^3/h) at a speed of 0.508 m/s (100 ft/min), but speeds up to 1.524 m/s (300 ft/min) are used.
4. *Drag-type conveyors* (Redler) are suited to short distances in any direction and are completely enclosed. Units range in size from 19.4 x 10^{-4} to 122.6 x 10^{-4} m^2 (3–19 in.^{2}) and may travel from 0.15 m/s (30 ft/min) (fly ash) to 1.27 m/s (250 ft/min) (grains). Power requirements are high.
5. *Pneumatic conveyors* are for high capacity, short distance (122 m (400 ft)) transport simultaneously from several sources to several destinations. Either vacuum or low pressure 0.4–0.8 barg (6–12 psig) is used with a range of air velocities from 10.7 to 36.6 m/s (35–120 ft/s); depending on the material and pressure and air requirements, 0.03–0.2 m^3/m^3 (1–7 ft^3/ft^3) of solid is 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 the 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 497.6 Pa (2 in. of water).
5. Water circulation rate is 48.9–195.7 L/min m^2 (1–4 gpm/ft^2) and air rate is 6344–8784 kg/h m^2 (1300–1800 lb/h ft^2) or 1.52–2.03 m/s (300–400 ft/min).
6. Chimney-assisted natural draft towers are hyperboloidally shaped because they have greater strength for a given thickness; a tower 76.2 m (250 ft) high has concrete walls 127–152.4 mm (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.

CRYSTALLIZATION FROM SOLUTION

1. 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.
2. Growth rates and ultimate sizes of crystals are controlled by limiting the extent of supersaturation at any time.
3. The ratio $S = C/C_{\mathrm{sat}}$ of prevailing concentration to saturation concentration is kept near the range 1.02–1.05.
4. In crystallization by chilling, the temperature of the solution is kept atmost 1–2° F below the saturation temperature at the prevailing concentration.
5. Growth rates of crystals under satisfactory conditions are in the range of 0.1–0.8 mm/h. The growth rates are approximately the same in all directions.
6. Growth rates are influenced greatly by the presence of impurities and of certain specific additives, which vary from case to case.

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 the design of air classifiers. Closed circuit is most common with ball and roller mills.
3. Jaw crushers take lumps of several feet in diameter to 102 mm (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 to slabby feeds and make a more rounded product.
4. Roll crushers are made either smooth or with teeth. A 610-mm (24-in.) toothed roll can accept lumps of 356 mm (14 in.) diameter. Smooth rolls affect reduction ratios up to about 4. Speeds are 50–90 rpm. Capacity is about 25% of the maximum, corresponding to a continuous ribbon of material passing through the rolls.
5. 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.
6. 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 in diameter. The 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.
7. 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. The 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 find grinding. Pebble mills have ceramic grinding elements, used when contamination with metal is to be avoided.
8. Roller mills employ cylindrical or tapered surfaces that roll along flatter surfaces and crush nipped particles. Products of 20–200 mesh are made.

TOWERS

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 pressure, $\alpha_{12} = P_2/P_1$.
3. Tower operating pressure is most often determined by the temperature of the available condensing medium, 38–50° C (100–120° F) if cooling water, or by the maximum allowable reboiler temperature, 10.34 barg (150 psig) steam, 186° C (366° F) to avoid chemical decomposition/degradation.
4. 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. And 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.
5. The economically optimum reflux ratio is about 1.2–1.5 times the minimum reflux ratio R_{m}.
6. The economically optimum number of theoretical trays is near twice the minimum value N_{m}.
7. The minimum number of trays is found with the Fenske–Underwood equation:

$$N_{\mathrm{m}} = \frac{\log\{[x/(1-x)]_{\mathrm{ovhd}} / [x/(1-x)]_{\mathrm{btms}}\}}{\log\alpha}$$

8. Minimum reflux for binary or pseudobinary mixtures is given by the following when separation is essentially complete ($x_{\mathrm{D}} \cong 1$) and D/F is the ratio of overhead product to feed rate:

$$\text{when feed is at the bubble point } \frac{R_{\mathrm{m}}D}{F} = \frac{1}{\alpha-1}$$

$$\text{when feed is at the dew point } \frac{(R_{\mathrm{m}}+1)D}{F} = \frac{\alpha}{\alpha-1}$$

9. A safety factor of 10% of the number of trays calculated by the best means is advisable.
10. Reflux pumps are made at least 10% oversize.
11. The optimum value of the Kremser—Brown absorption factor $A = (L/VK)$ is in the range 1.25–2.0.
12. 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 0.15 m/s (0.5 ft/s) minimum diameter of 406.4 mm (16 in.).
13. For towers about 914 mm (3 ft) diameter, add 1219 mm (4 ft) at the top for vapor disengagement and 1829 mm (6 ft) at the bottom for liquid level and reboiler return.
14. Limit the tower height to about 53 m (175 ft) maximum because of wind load and foundation considerations. An additional criterion is that L/D be less than 30 ($20 < L/D < 30$ often will require special design).

TRAY TOWERS

1. For reasons of accessibility, tray spacings are made 0.5–0.6 m (20–24 in.).
2. Peak efficiency of trays is at values of the vapor factor $F_{\mathrm{s}} = \mu(\rho_{\mathrm{v}})^{0.5}$ in the range of 1.2–1.5 m/s $(\mathrm{kg/m^3})^{0.5}$ $\left[1\text{–}1.2\,\mathrm{ft/s}\ (\mathrm{lb/ft^3})^{0.5}\right]$. This range of F_{s} establishes the

diameter of tower. Roughly, linear velocities are 0.6 m/s (2 ft/s) at moderate pressures and 1.8 m/s (6 ft/s) in vacuum.

3. Pressure drop per tray is of the order of 747 Pa (3 in. water) or 689.5 Pa (0.1 psi).
4. Tray efficiencies for distillation of light hydrocarbons and aqueous solutions are 60–90%; for gas absorption and stripping, 10–20%.
5. Sieve trays have holes of 6–7 mm (0.25–0.50 in.) diameter, hole area being 10% of the active cross section.
6. Valve trays have holes of 38 mm (1.5 in.) diameter, each provided with a liftable cap, with 130–150 caps per square meter (12–14 caps per square feet) of active cross section. Valve trays are usually cheaper than sieve trays.
7. Bubblecap trays are used only when liquid level must be maintained at low turndown ratio; they can be designed for lower pressure drop than either sieve or valve trays.
8. Weir heights are 50 mm (2 in.), weir lengths are about 75% of trays diameter, and liquid rate a maximum of about 1.2 m^3/min-m of weir (8 gpm/in. of weir); multi-pass arrangements are used at higher liquid rates.

PACKED TOWERS

1. Structured and random packings are suitable for packed towers less than 0.9 m (3 ft) when low pressure drop is required.
2. Replacing trays with packing allows greater throughput and separation in existing tower shells.
3. For gas rates of 14.2 m^3/min (500 ft^3/min), use 25.4-mm (1-in.) packing; for 56.6 m^3/min (2000 ft^3/min) or more use 50-mm (2-in.) packing.
4. Ratio of tower diameter/packing diameter should be >15/1.
5. Because of deformability, plastic packing is limited to 3–4 m (10–15 ft) and metal packing to 6.0–7.6 m (20–25 ft) unsupported depth.
6. Liquid distributors are required every 5–10 tower diameters with pall rings and at least every 6.5 m (20 ft) for other types of dumped packing.
7. Number of liquid distributions should be >32–55/m^2 (3–5/ft^2) in towers greater than 0.9 m (3 ft) diameter and more numerous in smaller columns.
8. Packed towers should operate near 70% of the flooding rate (evaluated from Sherwood and Lobo correlation).
9. Height Equivalent to a Theoretical Stage (HETS) for vapor–liquid contacting is 0.4–0.56 m (1.3–1.8 ft) for 25-mm (1-in.) pall rings and 0.76–0.9 m (2.5–3.0 ft) for 50-mm (2-in.) pall rings.
10.

Generalized pressure drops	**Design Pressure Drops (cm of H_2O/m of packing)**	**Design Pressure Drops (in. of H_2O/ft of packing)**
Absorbers and Regenerators (non-foaming systems)	2.1–3.3	0.25–0.40
Absorbers and Regenerators	0.8–2.1	0.10–0.25
Atmospheric/Pressure Stills and Fractionators	3.3–6.7	0.40–0.80
Vacuum Stills and Fractionators	0.8–3.3	0.10–0.40
Maximum value	8.33	1.0

DRIVERS AND POWER RECOVERY EQUIPMENT

1. Efficiency is greater for larger machines. Motors, 85–95%; steam turbines, 42–78%; gas engines and turbines, 28–38%.
2. For under 74.6 kW (100 hp), electric motors are used almost exclusively. They are made for up to 14,900 kW (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 are available, from weather-proof to explosion-proof.
4. Steam turbines are competitive above 76.6 kW (100 hp). They are speed-controllable. They are frequently used 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 pressure reduction in a process is done with throttling valves.
7. The following useful definitions are given:

$$\text{shaft power} = \frac{\text{theoretical power to pump fluid (liquid or gas)}}{\text{efficiency of pump or compressor, } \varepsilon_{sh}}$$

$$\text{drive power} = \frac{\text{shaft power}}{\text{efficiency of drive, } \varepsilon_{dr}}$$

$$\text{Overall efficiency, } \varepsilon_{ov} = \varepsilon_{sh} \cdot \varepsilon_{dr}$$

DRYING OF SOLIDS

1. Drying times range from a few seconds in spray dryers to 1 h 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 1.52–3.05 m/s (5–10 ft/s), sometimes up to 10.67 m/s (35 ft/s) 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 s, and produce flakes 1–3 mm thick with evaporation rates of 15–30 kg/m^2-h. Diameters are in the range of 1.5–5.0 ft; and rotation rate is 2–10 rpm. The greatest evaporative capacity is of the order of 1360.7 kg/h (3000 lb/h) in commercial units.
5. Pneumatic conveying dryers normally take particles 1–3 mm diameter but up to 10 mm when the moisture is mostly on the surface. Air velocities are 10–30 m/s. Single-pass residence times are 0.5–3.0 s, but with normal recycling the average residence time is brought up to 60 s. Units in use range from 0.2 m in diameter by 1 m long to 0.3 m in diameter by 38 m long. Air requirement is several SCFM per lb of dry product/h.
6. Fluidized bed dryers work best on particles of a few tenths of a mm in diameter, but particles of up to 4 mm in diameter 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 h.
7. Spay dryers: Surface moisture is removed in about 5 s, and most drying is completed in less than 60 s. Parallel flow of

air and stock is most common. Atomizing nozzles have openings 3–3.8 mm (0.012–0.15 in.) and operate at pressures of 21–276 bar (300–4000 psi). Atomizing spray wheels rotate at speeds of 20,000 rpm with peripheral speeds of 76.2–183 m/s (250–600 ft/s). 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 diameter should be made.

EVAPORATORS

1. Long tube vertical evaporators with either natural or forced circulation are most popular. Tubes are 19–63 mm (0.75–24.8 in.) in diameter and 3.66–9.14 m (12–30 ft) long.
2. In forced circulation, linear velocities in the tubes are in the range of 4.57–6.09 m/s (15–20 ft/s).
3. Elevation of boiling point by dissolved solids results in temperature differences of 3–10° F between solution and saturated vapor.
4. When the boiling point rise is appreciable, the economic number of effects in series with forward feed is 4–6.
5. When the boiling point rise is small, minimum cost is obtained with 8–10 effects in series.
6. 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.
7. The steam economy of an N-stage battery is approximately 0.8 N-lb evaporation/lb of outside steam.
8. 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 back-mixing 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 is greater, that phase should be made up of the less expensive or less hazardous material.
2. There are no known commercial applications of reflux to extraction processes, although the theory is favorable.
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 in diameter. In open vessels, residence times of 30–60 min or superficial velocities of 0.15–0.46 m/min (0.5–1.5 ft/min) are provided in settlers. Extraction-stage efficiencies commonly are taken as 80%.
4. Spray towers as tall as 6–12 m (20–40 ft) cannot be depended on to function as more than a single stage.
5. Packed towers are employed when 5–10 stages suffice. Pall rings 25–38 mm (1–1.5 in.) in size are best. Dispersed-phase loadings should not exceed 10.2 $m^3/min\text{-}m^2$ (25 gal./min-ft^2). And HETS of 1.5–3.0 m (5–10 ft) may be realized. The dispersed phase must be redistributed every 1.5–2.1 m (5–7 ft). Packed towers are not satisfactory when the surface tension is more than 10 dyne/cm.
6. Sieve tray towers have holes of only 3–8 mm diameter. Velocities through the holes are kept below 0.24 m/s (0.8 ft/s) to avoid formation of small drops. Re-dispersion of either phase at each tray can be designed for. Tray spacings are 152–600 mm (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 tower, 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 of 150 mm (9/16 in.) diameter, 50–60% open area, stroke length 190 mm (0.75 in.), 100–150 strokes/min, and plate spacing normally 50 mm (2 in.) but in the range of 25.0–150 mm (1–6 in.). In a 760-mm (30-in.) diameter tower, HETS is 500–650 mm (20–25 in.) and throughput is 13.7 $m^3/min\text{-}m^2$ (2000 gal./h-ft^2). Power requirements are much less than those of pulsed towers.
9. Rotating disk contractors or other rotary agitated towers realize HETS in the range of 0.1–0.5 m (0.33–1.64 ft). The especially efficient Kuhni with perforated disks of 40% free cross section has HETS of 0.2 m (0.66 ft) and a capacity of 50 m^3/m^2-h (164 ft^3/ft^2-h).

FILTRATION

1. Processes are classified by their rate of cake buildup in a laboratory vacuum leaf filter: rapid, 0.1–10.0 cm/s; medium, 0.1–10.0 cm/min; and slow, 0.1–10.0 cm/h.
2. Continuous filtration should not be attempted if 1/8 in. cake thickness cannot be formed in less than 5 min.
3. Rapid filtering is accomplished with belts, top feed drums, or pusher centrifuges.
4. Medium rate filtering is accomplished with vacuum drums or disks or peeler centrifuges.
5. Slow-filtering slurries are handled in pressure filters or sedimenting centrifuges.
6. Clarification with negligible cake buildup is accomplished with cartridges, precoat drums, or sand filters.
7. 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, and when precoating may be needed.
8. For finely ground ores and minerals, rotary drum filtration rates may be 15,000 lb/day-ft^2 at 20 rev/h and 18–25 in. Hg vacuum.
9. Coarse solids and crystals may be filtered at rates of 6000 lb/day-ft^2 at 20 rev/h and 2–6 in. Hg vacuum.

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 of 50–500 μm diameter, and 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, and 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 are typified by coarse sand and glass beads, both of which have been the subject of much laboratory investigation. Their sizes are in the range of 150–500 μm, densities 1.5–4.0 g/ml, have small bed expansion and about the same magnitudes of minimum bubbling and minimum fluidizing velocities, and they 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 driers, the fine particles dry most quickly so the entrained material need not be recycled.

HEAT EXCHANGERS

1. For conservative estimate set $F = 0.9$ for shell and tube exchangers with no phase changes, $q = UAF\Delta T_{\text{lm}}$. When ΔT at exchanger ends differ greatly then check F, reconfigure if F is less than 0.85.
2. Take true countercurrent flow in a shell-and-tube exchanger as a basis.
3. Standard tubes are 19.0 mm (3/4 in.) outer diameter (OD), 25.4 mm (1 in.) triangular spacing, 4.9 m (16 ft) long.

   A shell of 300 mm (1 ft) diameter accommodates 9.3 m^2 (100 ft^2);
   600 mm (2 ft) diameter accommodates 37.2 m^2(400 ft^2);
   900 mm (3 ft) diameter accommodates 102 m^2 (1100 ft^2).

4. Tube side is for corrosive, fouling, scaling, and high-pressure fluids.
5. Shell side is for viscous and condensing fluids.
6. Pressure drops are 0.1 bar (1.5 psi) for boiling and 0.2–0.62 bar (3–9 psi) for other services.
7. Minimum temperature approach is 10° C(20° F) for fluids and 5° C (10° F) for refrigerants.
8. Cooling water inlet temperature is 30° C (90° F), maximum outlet temperature 49° C (120° F).
9. Heat-transfer coefficients for estimating purposes, $W/m^{2\circ}C$ ($Btu/h\text{-}ft^2\text{-}^\circ F$): water to liquid, 850 (150); condensers, 850 (150); liquid to liquid, 280 (50); liquid to gas, 60 (10); gas to gas, 30 (5); and reboiler 1140 (200). Maximum flux in reboiler is 31.5 kW/m^2 (10,000 $Btu/h\text{-}ft^2$). When phase changes occur, use a zoned analysis with appropriate coefficients for each zone.
10. Double-pipe exchanger is competitive at duties requiring 9.3–18.6 m^2 (100–200 ft^2).
11. Compact (plate and fin) exchangers have 1150 m^2/m^3 (350 ft^2/ft^3), and about 4 times the heat transfer per cut of shell-and-tube units.
12. Plate and frame exchangers are suited to high sanitation services and are 25–50% cheaper in stainless steel construction than shell-and-tube units.
13. Air coolers: Tubes are 0.75–1.00 in. OD., total finned surface 15–20 ft^2/ft^2 bare surface, $U = 450\text{–}570\ W/m^{2\circ}C$ (80–100 $Btu/hr\text{-}ft^2$(bare surface)-° F). Minimum approach temperature = 22° C (40° F). Fan input power = 1.4–3.6 kW/(MJ/h) [2–5 hp/(1000 Btu/h)].
14. Fired heaters: radiant rate, 37.6 kW/m^2 (12,000 $Btu/h\text{-}ft^2$), convection rate, 12.5 kW/m^2 (4000 $Btu/h\text{-}ft^2$); cold oil tube velocity = 1.8 m/s (6 ft/s); approximately equal heat transfer in the two sections; thermal efficiency, 70–75%; flue gas temperature, 140–195° C (250–350° F) above feed inlet; and stack gas temperature, 345–510° C (650–950° F).

INSULATION

1. Up to 345° C (650° F), 85% magnesia is used.
2. Up to 870–1040° C (1600–1900° F), a mixture of asbestos and diatomaceous earth is used.
3. Ceramic refractories at higher temperatures.
4. Cryogenic equipment −130° C (−200° F) employs insulations with fine pores of trapped air, for example, Perlite™.
5. Optimum thickness varies with temperature: 12.7 mm (0.5 in.) at 95° C (200° F), 25.4 mm (1.0 in.) at 200° C (400° F), 32 mm (1.25 in.) at 315° C (600° F).
6. Under windy conditions, 12.1 km/h (7.5 miles/h), 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 30.48–60.9 mm/s (0.1–0.2 ft/s), and intense agitation at 213.4–304.8 mm/s (0.7–1.0 ft/s).
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)**	**Tip speed (m/s)**
Blending	0.2–0.5		
Homogeneous reaction	0.5–1.5	7.5–10	0.038–0.051
Reaction with heat transfer	1.5–5.0	10–15	0.051–0.076
Liquid–liquid mixtures	5	15–20	0.076–0.10
Liquid–gas mixtures	5–10	15–20	0.076–0.10
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 with a maximum of 457.2-mm (18-in.) turbine impellers to 2.74 m (9 ft).
5. Gas bubbles sparged at the bottom of the vessel will result in mild agitation at a superficial gas velocity of 0.0051 m/s (1 ft/min), severe agitation at 0.02 m/s (4 ft/min).
6. Suspension of solids with a settling velocity of 0.009 m/s (0.03 ft/s) is accomplished with either turbine or propeller impellers, but when the settling velocity is above 0.05 m/s (0.15 ft/s) 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 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 10–20 rpm, pitch as much as 10°. Size is controlled by speed, residence time, and amount of binder; 2–5 mm diameter is common.
3. Rotary disk granulators produce a more nearly uniform product than drum granulators: fertilizer, 1.5–3.5 mm diameter; iron ore 10–25 mm diameter.
4. Roll compacting and briquetting is done with rolls ranging from 130 mm diameter by 50 mm wide to 910 mm diameter 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 tableting machines or to dryers.

5. Tablets are made in rotary compression machines that convert powders and granules into uniform sizes. The usual maximum diameter is about 38.1 mm (1.5 in.), but special sizes up to 101.6 mm (4 in.) diameter 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. A 203.2-mm (8-in.) screw has a capacity of 907.2 kg/h (2000 lb/h) of molten plastic and is able to extrude tubing at 0.76–1.52 m/s (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 are in the range of 30–200 lb/h-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 (196.9 ft) 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 diameter in the 5–95% range.
8. Fluidized bed granulation is conducted in shallow beds 304.8–609.6 mm (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 s. One product has a size range 0.7–2.4 mm diameter.

PIPING

1. Line velocities (v) and pressure drops (ΔP): (a) For a liquid pump discharge, $v = (5 + D/3)$ ft/s and $\Delta P = 0.45$ bar/100 m (2.0 psi/100 ft); (b) For liquid pump suction, $v = (1.3 + D/6)$ ft/s, $\Delta P = 0.09$ bar/100 m (0.4 psi/100 ft); (c) for steam or gas flow: $v = 20D$ ft/s and $\Delta P = 0.113$ bar/100 m (0.5 psi/100 ft), $D =$ diameter of pipe in inches.
2. Gas/steam line velocities = 61 m/s (200 ft/s) and pressure drop = 0.1 bar/100 m (0.5 psi/100 ft).
3. In preliminary estimates set line pressure drops for an equivalent length of 30.5 m (100 ft) of pipe between each of piece of equipment.
4. Control valves require at least 0.69 bar (10 psi) pressure drop for good control.
5. Globe valves are used for gases, control and wherever tight shut-off is required. Gate valves are for most other services.
6. Screwed fittings are used only on sizes 38 mm (1.5 in.) or less, flanges or welding used otherwise.
7. Flanges and fittings are rated for 10, 20, 40, 103, 175 bar (150, 300, 600, 900, 1500, or 2500 psig).
8. Approximate schedule number required = 1000 P/S, where P is the internal pressure psig and S is the allowable working stress [about 690 bar (10,000 psi)] for A120 carbon steel at 260° C (500° F). Schedule (Sch.) 40 is most common.

PUMPS

1. Power for pumping liquids: kW = (1.67)[Flow (m^3/min)] [ΔP(bar)]/ε[hp = Flow (gpm) ΔP (psi)/(1, 714)(ε)]. (ε = fractional efficiency).
2. Net positive suction head (NPSH) of a pump must be in excess of a certain number, depending upon the kind of pumps and the conditions, if damage is to be avoided. NPSH = (pressure at the eye of the impeller-vapor pressure)/(ρg). Common range is 1.2–6.1 m (4–20 ft) of liquid.
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 0.057–18.9 m^3/min (15–5000 gpm), 152 m (500 ft) maximum head; multistage for 0.076–41.6 m^3/min (20–11,000 gpm), 1675 m (5500 ft) maximum head. Efficiency: 45% at 0.378 m^3/min (100 gpm), 70% at 1.89 m^3/min (500 gpm), and 80% at 37.8 m^3/min (10,000 gpm).
5. Axial pumps for 0.076–378 m^3/min (20–100,000 gpm), 12 m (40 ft) head, 65–85% efficiency.
6. Rotary pumps for 0.00378–18.9 m^3/min (1–5000 gpm), 15,200 m (50,000 ft) head, 50–80% efficiency.
7. Reciprocating pumps for 0.0378–37.8 m^3/min (10–10,000 gpm), 300 km (1,000,000 ft) maximum head. Efficiency: 70% at 7.46 kW (10 hp), 85% at 37.3 kW (50 hp), and 90% at 373 kW (500 hp).

REACTORS

1. 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 from a pilot plant.
2. Dimensions of catalyst particles are 0.1 mm (0.004 in.) in fluidized beds, 1 mm in slurry beds, and 2–5 mm (0.078–0.197 in.) in fixed beds.
3. The optimum proportions of stirred tank reactors are with liquid level equal to the tank diameter, but at high pressures slimmer proportions are economical.
4. Power input to a homogeneous reaction stirred tank is 0.1–0.3 kw/m^3 (0.5–1.5 hp/1000 gal.) but three times this amount when heat is to be transferred.
5. Ideal CSTR (continuous stirred tank reactor) behavior is approached when the mean residence time is 5–10 times the length needed to achieve homogeneity, which is accomplished with 500–2000 revolutions of a properly designed stirrer.
6. 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 programed in some way.
7. Relatively slow reactions of liquids and slurries are conducted in continuous stirred tanks. A battery of four or five in series is most economical.
8. Tubular flow reactors are suited to high production rates at short residence times (seconds or minutes) and when substantial heat transfer is needed. Embedded tubes or shell-and-tube constructions then are used.
9. In granular catalyst packed reactors, the residence time distribution is often no better than that of a five-stage CSTR battery.
10. For conversions under about 95% of equilibrium, the performance of a five-stage CSTR battery approaches plug flow.
11. The effect of temperature on chemical reaction rate is to double the rate every 10° C.
12. The rate of reaction in a heterogeneous system is more often controlled by the rate of heat or mass transfer than by the chemical reaction kinetics.
13. The value of a catalyst may be to improve selectivity more than to improve the overall reaction rate.

REFRIGERATION

1. A ton of refrigeration is the removal of 12,700 kJ/h (12,000 Btu/h) of heat.
2. At various temperature levels: −18 to −10° C (0–50° F), chilled brine and glycol solutions; −45 to −10° C (−50 to −40° F), ammonia, Freon, and butane; −100 to −45° C (−150 to −50° F), ethane or propane.
3. Compression refrigeration with 38° C (100° F) condenser requires kW/tonne (hp/ton) at various temperature levels; 0.93 (1.24) at −7° C (20° F), 1.31 (1.75) at −18° C (0° F); 2.3 (3.1) at −40° C (−40° F); 3.9 (5.2) at −62° C (−80° F).

4. Below −62° C (−80° F), cascades of two or three refrigerants are used.
5. In single-stage compression, the compression ratio is limited to 4.
6. In multistage compression, economy is improved with interstage flashing and recycling, the so-called "economizer operation."
7. Absorption refrigeration: ammonia to −34° C (−30° F) and lithium bromide to 7° C (45° F) is economical when waste steam is available at 0.9 barg (12 psig).

SIZE SEPARATION OF PARTICLES

1. Grizzlies that are constructed of parallel bars at appropriate spacings are used to remove products larger than 50 mm in diameter.
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, 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 of 30–1000 strokes/min and handle sizes 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–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 ft^3/min and can remove particles in the range of 300–5 μm from dilute suspensions. In one case, a 20-in. diameter 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: 1–2 bar (15–30 psig), 121–135° C (250–275° F); 10 barg (150 psig), 186° C (366° F); 27.6 barg (400 psig), 231° C (448° F); 41.3 barg (600 psig), 252° C (488° F) or with 55–85° C (100–150° F) superheat.
2. Cooling water: For design of cooling tower use, supply at 27–32° C (80–90° F); from cooling tower, return at 45–52° C (115–125° F); return seawater at 43° C (110° F); return tempered water or steam condensate above 52° C (125° F).
3. Cooling air supply at 29–35° C (85–95° F); temperature approach to process, 22° C (40° F).
4. Compressed air at 3.1 (45), 10.3 (150), 20.6 (300), or 30.9 barg (450 psig) levels.
5. Instrument air at 3.1 barg (45 psig), −18° C (0° F) dew point.
6. Fuels: gas of 37,200 kJ/m^3 (1000 Btu/SCF) at 0.35–0.69 barg (5–10 psig), or up to 1.73 barg (25 psig) for some types of burners; liquid at 39.8 GJ/m^3 (6 million British Thermal unit per barrel).
7. Heat-transfer fluids: petroleum oils below 315° C (600° F), Dowtherms below 400° C (750° F), fused salts below 600° C (1100° F), and direct fire or electricity above 232° C (450° F).
8. Electricity: 0.75–74.7 kW (1–100 hp), 220–550 V; 149–1864 kW (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 are usually horizontal.
3. Gas/liquid phase separators are usually vertical.
4. Optimum length/diameter = 3, but the range 2.5–5.0 is common.
5. Holdup time is 5 min half-full for reflux drums and gas/liquid separators, 5–10 min for a product feeding another tower.
6. In drums feeding a furnace, 30 min half-full drum is allowed.
7. Knockout drums placed ahead of compressors should hold no less than 10 times the liquid volume passing through per minute.
8. Liquid/liquid separators are designed for a setting velocity of 0.85–1.27 mm/s (2–3 in./min).
9. Gas velocity in gas/liquid separators, $v = k\sqrt{\rho_L/\rho_V - 1}$ m/s (ft/s), with $k = 0.11$ (0.35) for systems with a mesh deentrainer and $k = 0.0305$ (0.1) without a mesh deentrainer.
10. Entrainment removal of 99% is attained with 102–305 mm (4–12 in.) mesh pad thickness; 152.5 mm (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 152–457 mm (6–18 in.) ahead of the pad and 305 mm (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.

VESSEL (PRESSURE)

1. Design temperature between −30 and 345° C is 25° C (−20° F and 650° F if 50° F) above maximum operating temperature; higher safety margins are used outside the given temperature range.
2. The design pressure is 10% or 0.69–1.7 bar (10–25 psi) over the maximum operating pressure, whichever is greater. The maximum operating pressure, in turn, is taken as 1.7 bar (25 psi) above the normal operation.
3. Design pressures of vessels operating at 0–0.69 barg (0–10 psig) and 95–540° C (200–1000° F) are 2.76 barg (40 psig).
4. For vacuum operation, design pressures are 1 barg (15 psig) and full vacuum.
5. Minimum wall thickness for rigidity: 6.4 mm (0.25 in.) for 1.07 m (42 in.) diameter and under, 8.1 mm (0.32 in.) for 1.07–1.52 m (42–60 in.) diameter, and 9.7 mm (0.38 in.) for over 1.52 m (60 in.) diameter.
6. Corrosion allowance 8.9 mm (0.35 in.) for known corrosive conditions, 3.8 mm (0.15 in.) for noncorrosive streams, and 1.5 mm (0.06 in.) for steam drums and air receivers.
7. Allowable working stresses are one-fourth the ultimate strength of the material.
8. Maximum allowable stress depends sharply on temperature

Temperature (° F)	−20–650	750	850	1,000
(° C)	−30–345	400	455	540
Low-alloy steel, SA 203 (psi)	18,759	15,650	9,550	2,500
(bar)	1,290	1,070	686	273
Type 302 stainless (psi)	18,750	18,750	15,950	6,250
(bar)	1,290	1,290	1,100	431

VESSELS (STORAGE TANKS)

1. For less than 3.8 m^3 (1000 gal.), use vertical tanks on legs.
2. For 3.8–38 m^3 (1000–10,000 gal.), use horizontal tanks on concrete supports.
3. Beyond 38 m^3 (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 1.9 m^3 (500 gal.) and 10% above 1.9 m^3 (500 gal.) capacity.
6. A 30-day 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, 28.4-m^3 (7500 gal.) tanker trucks, 130-m^3 (34,500 gal.) rail cars, and virtually unlimited barge and tanker capacities.

Source: The above mentioned rules of thumb have been adapted from Walas, S.M., *Chemical Process Equipment: Selection and Design*, copyright 1988 with permission from Elsevier, all rights reserved.

Physical Property Heuristics

	Units	Liquids	Liquids	Gases	Gases	Gases
		Water	Organic Material	Steam	Air	Organic Material
Heat Capacity	kJ/kg° C	4.2	1.0–2.5	2.0	1.0	2.0–4.0
Density	kg/m^3	1000	700–1500		1.29 at STP	
Latent Heat	kJ/kg	1200–2100	200–1000			
Thermal Conductivity	W/m° C	0.55–0.70	0.10–0.20	0.025–0.07	0.025–0.05	0.02–0.06
Viscosity	kg/ms	0° C 1.8×10^{-3} 50° C 5.7×10^{-4} 100° C 2.8×10^{-4} 200° C 1.4×10^{-4}	Wide Range	$10–30 \times 10^{-6}$	$20–50 \times 10^{-6}$	$10–30 \times 10^{-6}$
Prandtl No.		1–15	10–1000	1.0	0.7	0.7–0.8

(*Source*: Turton, R. et al., *Analysis, Synthesis, and Design of Chemical Processes*, Prentice Hall International Series, 2001.)

Typical Physical Property Variations with Temperature and Pressure

	Liquids	Liquids	Gases	Gases
Property	Temperature	Pressure	Temperature	Pressure
Density	$\rho_l \propto (T_c - T)^{0.3}$	Negligible	$\rho_g = \mathrm{MW}\ P/ZRT$	$\rho_g = \mathrm{MW}\ P/ZRT$
Viscosity	$\mu_l = Ae^{B/T}$	Negligible	$\mu_g \alpha \frac{T^{1.5}}{(T + 1.47T_b)}$	Significant only for >10 bar
Vapor Pressure	$P^* = ae^{b/(T+c)}$	–	–	–

Note: T is temperature (K), T_c is the critical Temperature (K), T_b is the normal boiling point (K), MW is molecular weight, P is pressure, Z is compressibility, R is the gas constant, and P^* is the vapor pressure.

(*Source*: Turton, R. et al., *Analysis, Synthesis, and Design of Chemical Processes*, Prentice Hall International Series, 2001.)

Capacities of Process Units in Common Usage[a]

Process unit	Capacity Unit	Maximum Value	Minimum Value	Comment	
Horizontal Vessel	Pressure (bar)	400	Vacuum	L/D typically 2–5	
	Temper. (° C)	400[b]	−200		
	Height (m)	10	2		
	Diameter (m)	2	0.3		
	L/D	5	2		
Vertical Vessel	Pressure (bar)	400	400	L/D typically 2–5	
	Temperature (° C)	400[b]	−200		
	Height (m)	10	2		
	Diameter (m)	2	0.3		
	L/D	5	2		
Towers	Pressure (bar)	400	Vacuum	Normal Limits	
				Diameter	L/D
	Temperature (° C)	400[b]	−200	0.5	3.0–40[c]
	Height (m)	50	2	1.0	2.5–30[c]
	Diameter (m)	4	0.3	2.0	1.6–23[c]
	L/D	30	2	4.0	1.8–13[c]

Pumps				
Reciprocating	Power[d] (kW)	250	<0.1	
	Pressure (bar)	1,000		
Rotary and Positive Displacement	Power[d] (kW)	150	<0.1	
	Pressure (bar)	300		
Centrifugal	Power[d] (kW)	250	<0.1	
	Pressure (bar)	300		
Compressors				
Axial, Centrifugal + Recipr.	Power[d] (kW)	8,000	50	
Rotary	Power[d] (kW)	1,000	50	
Drives for Compressors				
Electric	Power[e](kW)	15,000	<1	
Steam Turbine	Power[e] (kW)	15,000	100	
Gas Turbine	Power[e](kW)	15,000	10	
Internal Combustion Eng.	Power[e](kW)	15,000	10	
Process Heaters	Duty (MJ/h)	500,000	10,000	Duties different for reactive heaters/furnaces.
Heat Exchangers	Area (m^2)	1,000	10	For Area < 10 m^2 use double-pipe exchanger.
	Tube Dia. (m)	0.0254	0.019	
	Length (m)	6.5	2.5	
	Pressure (bar)	150	Vacuum	For 150<P<400 bar need special design.
	Temperature (° C)	400[b]	−200	

[a] Most of the limits for equipment sizes shown here correspond to the limits used in the costing program (CAPCOST.BAS).

[b] Maximum temperature and pressure are related to the materials of construction and may differ from values shown here.

[c] For $20<L/D<30$ special design may be required. Diameter up to 7 m possible but over 4 m must be fabricated on site.

[d] Power values refer to fluid/pumping power.

[e] Power values refer to shaft power.

(*Source*: Turton, R. et al., *Analysis, Synthesis, and Design of Chemical Processes*, Prentice Hall International Series, 2001.)

Effect of Typical Materials of Construction on Product Color, Corrosion, Abrasion, and Catalytic Effects

Metals

Material	Advantages	Disadvantages
Carbon Steel	Low cost, readily available, resists abrasion, standard fabrication, resists alkali	Poor resistance to acids and strong alkali, often causes discoloration and contamination
Stainless Steel	Resists most acids, reduces discoloration, available with a variety of alloys, abrasion less than mild steel	Not resistant to chlorides, more expensive, fabrication more difficult, alloy materials may have catalytic effects
Monel-Nickel	Little discoloration, contamination, resistant to chlorides	Not resistant to oxidizing environments, expensive
Hasteloy	Improved over Monel-Nickel	More expensive than Monel-Nickel
Other Exotic Metals	Improves specific properties	Very high cost
Non-Metals		
Glass	Useful in laboratory and batch system, low diffusion at walls	Fragile, not resistant to high alkali, poor heat transfer, poor abrasion resistance
Plastics	Good at low temperature, large variety to select from with various characteristics, easy to fabricate, seldom discolors, minor catalytic effects possible	Poor at high temperature, low strength, not resistant to high alkali conditions, low heat transfer, low cost
Ceramics	Withstands high temperatures, variety of formulations available, modest cost	Poor abrasion properties, high diffusion at walls (in particular hydrogen), low heat transfer, may encourage catalytic reactions

(*Source*: Turton, R. et al., *Analysis, Synthesis, and Design of Chemical Processes*, Prentice Hall International Series, 2001.)