Chapter 11. Utilizing Experience-Based Principles to Confirm the Suitability of a Process Design

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What You Will Learn

- There are experienced-based heuristics that can be used to estimate unknown parameters and validate calculated parameters used to design a chemical process.

Experienced chemical engineers possess the skills necessary to perform detailed and accurate calculations for the design, analysis, and operation of equipment and chemical processes. In addition, these engineers will have formulated a number of experienced-based shortcut calculation methods and guidelines useful for the following:

1. Checking new process designs
2. Providing equipment size and performance estimates
3. Helping troubleshoot problems with operating systems
4. Verifying that the results of computer calculations and simulations are reasonable
5. Providing reasonable initial values for input into a process simulator required to achieve program convergence
6. Obtaining approximate costs for process units
7. Developing preliminary process layouts

These shortcut methods are forms of heuristics that are helpful to the practicing engineer. All heuristics are, in the final analysis, fallible and sometimes difficult to justify. They are merely plausible aids or directions toward the solution of a problem [1]. Especially for the heuristics described in this chapter, the four characteristics of any heuristic should be kept in mind:

1. A heuristic does not guarantee a solution.
2. It may contradict other heuristics.
3. It can reduce the time to solve a problem.
4. Its acceptance depends on the immediate context instead of on an absolute standard.

The fact that one cannot precisely follow all heuristics all the time is to be expected, as it is with any set of technical heuristics. However, despite the limitations of heuristics, they are nevertheless valuable guides for the process engineer.

In Chapter 6, process units and stream conditions that were identified as areas of special concern were analyzed. These areas were highlighted in a series of informational tables. In this chapter, the analysis of chemical processes will be completed by checking the equipment parameters and stream conditions in the PFD for agreement with observations and experiences in similar applications.

The required information to start an analysis is provided in a series of **informational tables** containing shortcut calculation techniques. In this chapter, the use of these resources is demonstrated by checking the conditions given in the basic toluene hydrodealkylation PFD.

11.1. The Role of Experience in the Design Process

The following short narrative illustrates a situation that could be encountered early in your career as an engineer.

> *You are given an assignment that involves writing a report that is to be completed and presented in two weeks. You work diligently and feel confident you have come up with a respectable solution. You present the written report personally to your director (boss), who asks you to summarize only your final conclusions. Immediately after you provide this information, your boss declares that "your results must be wrong" and returns your report unopened and unread.*
>
> *You return to your desk angry. Your comprehensive and well-written report was not even opened and read. Your boss did not tell you what was wrong, and you did not receive any "partial credit" for all your work. After a while, you cool off and review your report. You find that you had made a "simple" error, causing your answer to be off by an order of magnitude. You correct the error and turn in a revised report.*
>
> *What remains is the nagging question, "How could your boss know you made an error without having reviewed your report or asking any questions?"*

The answer to this nagging question is probably a direct result of your director's experience with a similar problem or knowledge of some guideline that contradicted your answer. The ability of your boss to transfer personal experience to new situations is one reason why he or she was promoted to that position.

It is important to be able to apply knowledge gained through experience to future problems.

11.1.1. Introduction to Technical Heuristics and Shortcut Methods

A **heuristic** is a statement concerning equipment sizes, operating conditions, and equipment performance that reduces the need for calculations. A **shortcut method** replaces the need for extensive calculations in order to evaluate equipment sizes, operating conditions, and equipment performance. These are referred to as "back-of-the-envelope calculations." In this text, both of these experience-based tools are referred to as guidelines or heuristics.

The guidelines provided in this chapter are limited to materials specifically covered in this text (including problems at the end of the chapters). All such material is likely to be familiar to final-year B.S. chemical engineering students and new graduates as a result of their education. Upon entering the work force, engineers will develop guidelines that apply specifically to their area of responsibility.

Guidelines and heuristics must be applied with an understanding of their limitations. In most cases, a novice chemical engineer should have sufficient background to apply the rules provided in this text.

The narrative started earlier is now revisited. The assignment remains the same; however, the approach to solving the problem changes.

> *Before submitting your report, you apply a heuristic that highlights an inconsistency in your initial results. You then review your calculations, find the error, and make corrections before submitting your report. Consider two possible responses to this report:*
>
> 1. *Your boss accepts the report and notes that the report appears to be excellent and he or she looks forward to reading it.*
> 2. *Your boss expresses concern and returns the report as before. In this case, you have a reasoned response available. You show that your solution is consistent with the heuristic you used to check your work. With this supporting evidence your boss would have to rethink his or*

her response and provide you with an explanation regarding his or her concern.

In either case, your work will have made a good impression.

Guidelines and heuristics are frequently used to make quick estimates during meetings and conferences and are valuable in refreshing one’s memory with important information.

11.1.2. Maximizing the Benefits Obtained from Experience

No printed article, lecture, or text is a substitute for the perceptions resulting from experience. An engineer must be capable of transferring knowledge gained from one or more experiences to resolve future problems successfully.

To benefit fully from experience, it is important to make a conscious effort to use each new experience to build a foundation upon which to increase your ability to handle and to solve new problems.

An experienced engineer retains a body of information, made up largely of heuristics and shortcut calculation methods, that is available to help solve new problems.

The process by which an engineer uses information and creates new heuristics consists of three steps. These three steps are predict, authenticate, and re-evaluate, and they form the basis of the **PAR** process. The elements of this process are presented in Table 11.1, which illustrates the steps used in the PAR process.

Table 11.1. PAR Process to Maximize Benefits of Experience: *Predict, Authenticate, Reevaluate*

1. **Predict:** This is a precondition of the PAR process. It represents your best prediction of the solution. It often involves making assumptions and applying heuristics based on experience. Calculations should be limited to back-of-the-envelope or shortcut techniques.
2. **Authenticate/Analyze:** In this step, you seek out equations and relationships, do research relative to the problem, and perform the calculations that lead toward a solution. The ability to carry out this activity provides a necessary but not sufficient condition to be an engineer. When possible, information from actual operations is included in order to achieve the best possible solution.
3. **Reevaluate/Rethink:** The best possible solution from Step 2 is compared with the predicted solution in Step 1. When the prediction is not acceptable, it is necessary to correct the reasoning that led to the poor prediction. It becomes necessary to remove, revise, and replace assumptions made in Step 1. This is the critical step in learning from experience.

Example 11.1.

Evaluate the film heat transfer coefficient for water at 93°C (200°F) flowing at 3.05 m/s (10 ft/s) inside a 38 mm (1.5 in) diameter tube. From previous experience, you know that the film heat transfer coefficient for water, at 21°C (70°F) and 1.83 m/s (6 ft/s), in these tubes is 5250 W/m^2°C. Follow the PAR process to establish the heat transfer coefficient at the new conditions.

Step 1—Predict: Assume that the velocity and temperature have no effect. Predicted Heat Transfer Coefficient = 5250 W/m^2°C

Step 2—Authenticate/Analyze: Using the properties given below, it is found that the Reynolds number for the water in the tubes is

$$\mathrm{Re} = u\rho D_{pipe}/\mu = (1.83)(997.4)(1.5)(0.0254)/(9.8 \times 10^{-4}) = 71 \times 10^3 \rightarrow \text{Turbulent Flow}$$

Use the Sieder-Tate equation [2] to check the prediction:

$$hD/k = (0.023)(Du\rho/\mu)^{0.8}(C_p\mu/k)^{1/3} \tag{11.1}$$

Property	21°C (70°F)	93°C (200°F)	Ratio of (New/Old)
ρ (kg/m^3)	997.4	963.2	0.966
k (W/m°C)	0.604	0.678	1.12
C_p (kJ/kg°C)	4.19	4.20	1.00
μ (kg/m/s)	9.8×10^{-4}	3.06×10^{-4}	0.312

Take the ratio of Equation (11.1) for the two conditions given above, and rearrange and substitute numerical values. Using ’ to identify the new condition at 93°C,

$$h'/h = (D/D)^{0.2}(u'/u)^{0.8}(\rho'/\rho)^{0.8}(\mu/\mu')^{0.47}(C_p'/C_p)^{0.33}(k'/k)^{0.67} \tag{11.2}$$

$$= (1)(1.50)(0.973)(1.73)(1.00)(1.08) = 2.725 \tag{11.3}$$

$$h' = (2.725)(5250)\ \mathrm{W/m^{2}{}^\circ C} = 14{,}300\ \mathrm{W/m^{2}{}^\circ C}$$

The initial assumption that the velocity and temperature do not have a significant effect is incorrect. Equation (11.3) reveals a velocity effect of a factor of 1.5 and a viscosity effect of a factor of 1.73. All other factors are close to 1.0.

Step 3—Reevaluate/Rethink: The original assumptions that velocity and temperature had no effect on the heat transfer coefficient have been rejected. Improved assumptions for future predictions are as follows:

1. The temperature effect on viscosity must be evaluated.
2. The effects of temperature on C_p, ρ, and k are negligible.
3. Pipe diameter has a small effect on h (all other things being equal).
4. Results are limited to the range where the Sieder-Tate equation is valid.

With these assumptions, the values for water at 21°C are substituted into Equation (11.2). This creates a useful heuristic for evaluating the heat transfer coefficients for water.

$$h'(\mathrm{W/m^2{}^\circ C}) = 125u'^{0.8}/\mu'^{0.47} \text{ for } u'(\mathrm{m/s}),\ \mu'\ (\mathrm{kg/m/s})$$

Although it takes longer to obtain a solution when you start to apply the PAR process, the development of the heuristic and the addition of a more in-depth understanding of the factors that are important offer substantial long-term advantages.

There are hundreds of heuristics covering areas in chemical engineering—some general, and others specific to a given application, process, or material. The next section presents a number of these rules that can be used to make predictions to start the PAR analysis.

11.2. Presentation of Tables of Technical Heuristics and Guidelines

A number of these guidelines are provided in this section. The information given is limited to operations most frequently encountered in this text. Most of the information was extracted from a collection presented in Walas [3]. In addition, this excellent reference also includes additional guidelines for the following equipment:

1. Conveyors for particulate solids
2. Cooling towers

3. Crystallization from solution
4. Disintegration
5. Drying of solids
6. Evaporators
7. Size separation of particles

The heuristics or rules are contained in a number of tables and apply to operating conditions that are most often encountered. The information provided is used in Example 11.2 and should be used to work problems at the end of the chapter and to check information on any PFD.

Example 11.2.

Refer to the information given in Chapter 1 for the toluene hydrodealkylation process, namely, Figure 1.7 and Tables 1.5 and 1.7. Using the information provided in the tables in this chapter, estimate the size of the equipment and other operating parameters for the following units:

a. V-102
b. E-105
c. P-101
d. C-101
e. T-101
f. H-101

Compare your findings with the information given in Chapter 1.

a. V-102 High-Pressure Phase Separator

From Table 11.6, the following heuristics are used:

Rule 3 → Vertical vessel

Rule 4 → L/D between 2.5 and 5 with optimum at 3.0

Rule 5 → Liquid holdup time is 5 min based on 1/2 volume of vessel

Rule 9 → Gas velocity u is given by

$$u = k\sqrt{\frac{\rho_l}{\rho_v} - 1}\ \text{m/s}$$

where $k = 0.0305$ for vessels without mesh entrainers

Rule 12 → Good performance obtained at 30%–100% of u from Rule 9; typical value is 75%

From Table 1.5,

Vapor flow = Stream 8 = 9200 kg/h, $P = 23.9$ bar, $T = 38°\text{C}$

Liquid flow = Streams 17 + 18 = 11,570 kg/h, $P = 2.8$ bar, $T = 38°\text{C}$

$\rho_v = 8\ \text{kg/m}^3$ and $\rho_l = 850\ \text{kg/m}^3$ (estimated from Table 1.7)

From Rule 9, $u = 0.0305[850/8 - 1]^{0.5} = 0.313$ m/s

Use $u_{act} = (0.75)(0.313) = 0.23$ m/s

Now mass flowrate of vapor = $u\rho_v\pi D^2/4 = 9200/3600 = 2.56$ kg/s

Solving for D, $D = 1.33$ m

From Rule 5, the volume of liquid = $0.5\,L\pi D^2/4 = 0.726L\ \text{m}^3$

5 min of liquid flow = (5)(60)(11,570)/850/3600 = 1.13 m^3

Equating the two results above, $L = 1.56$ m

From Rule 4, L/D should be in the range 2.5 to 5. For this case $L/D = 1.56/1.33 = 1.17$

Because this is out of range, change to $L = 2.5D = 3.3$ m.

Heuristics from Table 11.6 suggest that V-102 should be a vertical vessel with $D = 1.33$ m, $L = 3.3$ m

From Table 1.7, the actual V-102 is a vertical vessel with $D = 1.1$ m, $L = 3.5$ m

It should be concluded that the design of V-102 given in Chapter 1 is consistent with the heuristics given in Table 11.6. The small differences in *L* and *D* are to be expected in a comparison such as this one.

b. E-105 Product Cooler

From Table 11.11 use the following heuristics:

Rule 1: Set $F = 0.9$

Rule 6: min. $\Delta T = 10°C$

Rule 7: Water enters at 30°C and leaves at 40°C

Rule 8: $U = 850\ W/m^2°C$

It is observed immediately from Table 1.5 and Figure 1.5 that Rule 6 has been violated because $\Delta T_{min} = 8°C$.

For the moment, ignore this and return to the heuristic analysis:

$\Delta T_{lm} = [(105 - 40) - (38 - 30)]/\ln[(105 - 40)/(38 - 30)] = 27.2°C$

$Q = 1085$ MJ/h = 301 kW (from Table 1.7)

$A = Q/U\Delta T_{lm}F = (301{,}000)/(850)/(27.2)/(0.90) = 14.46\ m^2$

From Rule 9, Table 11.11, this heat exchanger should be a double-pipe or multiple-pipe design.

Comparing this analysis with the information in Table 1.7 shows

Heuristic: Double-pipe design, area = 14.5 m^2

Table 1.7: Multiple-pipe design, area = 12 m^2

Again, the heuristic analysis is close to the actual design. The fact that the minimum approach temperature of 10°C has been violated should not cause too much concern, because the actual minimum approach is only 8°C and the heat exchanger is quite small, suggesting that a little extra area (due to a smaller overall temperature driving force) is not very costly.

c. P-101

From Table 11.9, use the following heuristics:

Rule 1: Power(kW) = (1.67)[Flow(m^3/min)]ΔP(bar)/ε

Rules 4–7: Type of pump based on head

From Figure 1.5 and Tables 1.5 and 1.7,

Flowrate (Stream 2) = 13,300 kg/h

Density of fluid = 870 kg/m^3

$\Delta P = 25.8 - 1.2 = 24.6$ bar = 288 m of liquid (head = $\Delta P/\rho g$)

Volumetric flowrate = (13,300)/(60)/(870) = 0.255 m^3/min

Fluid pumping power = (1.67)(0.255)(24.6) = 10.5 kW

From Rules 4–7, pump choices are multistage centrifugal, rotary, and reciprocating. Choose reciprocating to be consistent with Table 1.7. Typical $\varepsilon = 0.75$.

Power (shaft power) = 10.5/0.75 = 14.0 kW → compares with 14.2 kW from Table 1.7.

d. C-101

From Table 11.10, use the following heuristics:

Rule 2: $W_{rev\ adiab} = mz_1RT_1[(P_2/P_1)^a - 1]/a$

From Table 1.7, flow = 6770 kg/h, T_1 = 38°C = 311 K, mw = 8.45, P_1 = 23.9 bar, P_2 = 25.5

$k = 1.41$ (assume) and $a = 0.2908$

$m = (6770)/(3600)/(8.45) = 0.223$ kmol/s

$W_{rev\ adiab} = (223)(1.0)(8.314)(311)\{\ (25.5/23.9)^{0.2908} - 1)/0.2908 = 37.7$ kW using a compressor efficiency of 75%

$W_{actual} = (37.7)/(0.75) = 50.3$ kW → This checks with the shaft power requirement given in Table 1.7.

e. T-101

From Table 11.13, use the following heuristics:

Rule 5: Optimum reflux in the range of 1.2–1.5R_{min}

Rule 6: Optimum number of stages approximately 2N_{min}

Rule 7: $N_{min} = \ln\{\ [x/(1-x)]_{ovhd}/[x/(1-x)]_{bot}\}/\ln\alpha$

Rule 8: $R_{min} = \{F/D\}/(\alpha - 1)$

Rule 9: Use a safety factor of 10% on number of trays.

Rule 14: L_{max} = 53 m and $L/D < 30$

From Table 11.14, use the following heuristics:

Rule 2: $F_s = u\rho_\upsilon^{\ 0.5} = 1.2 \rightarrow 1.5\text{m/s(kg/m}^3)^{\ 0.5}$

Rule 3: $\Delta P_{tray} = 0.007$ bar

Rule 4: $\varepsilon_{tray} = 60 - 90$ %

$x_{ovhd} = 0.9962$, $x_{ovhd} = 0.0308$, $\alpha_{ovhd} = 2.44$, $\alpha_{bot} = 2.13$, $\alpha_{geom\ ave} = (\alpha_{ovhd}\alpha_{bot})^{0.5} = 2.28$

$N_{min} = \ln\{\ [0.9962/(1-0.9962)]/[0.0308/(1-0.0308)]\}/\ln(2.28) = 10.9$

$R_{min} = \{142.2/105.6\}/(2.28 - 1) = 1.05$

Range of $R = (1.2 \rightarrow 1.5)R_{min} = 1.26 \rightarrow 1.58$

$N_{theoretical} \approx (2)(10.9) = 21.8$

$\varepsilon_{tray} = 0.6$

$N_{actual} \approx (21.6/0.6)(1.1) = 40$ trays

$\rho_\upsilon = 6.1$ kg/m^3

$u = (1.2 \rightarrow 1.5)/6.1^{0.5} = 0.49 \rightarrow 0.60$ m/s

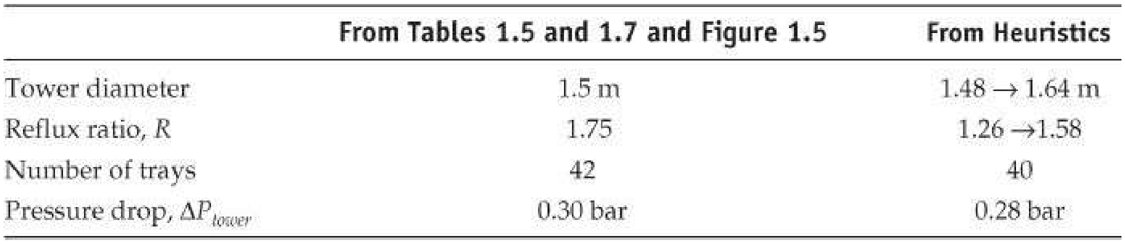
Vapor flowrate (Stream 13) = 22,700 kg/h

Vol. flowrate, $v = 1.03 \text{ m}^3/\text{s}$

$D_{tower} = [4v/\pi u]^{0.5} = [(4)(1.03)/(3.142)/(0.49 \rightarrow 0.60)]^{0.5} = 1.64 – 1.48 \text{ m}$

$\Delta P_{tower} = (N_{actual})(\Delta P_{tray}) = (40)(0.007) = 0.28 \text{ bar}$

A comparison of the actual equipment design and the predictions of the heuristic methods are given below.



	From Tables 1.5 and 1.7 and Figure 1.5	From Heuristics
Tower diameter	1.5 m	1.48 → 1.64 m
Reflux ratio, R	1.75	1.26 →1.58
Number of trays	42	40
Pressure drop, ΔP_{tower}	0.30 bar	0.28 bar

f. H-101

From Table 11.11, use the following heuristics:

Rule 13: Equal heat transfer in radiant and convective sections

Radiant rate = 37.6 kW/m^2, convective rate = 12.5 kW/m^2

Duty = 27,040 MJ/h = 7511 kW

Area radiant section = $(0.5)(7511)/(37.6) = 99.9 \text{ m}^2$ (106.8 m^2 in Table 1.7)

Area convective section = $(0.5)(7511)/(12.5) = 300.4 \text{ m}^2$ (320.2 m^2 in Table 1.7)

From the earlier worked examples, it is clear that the sizing of the equipment in Table 1.7 agrees well with the predictions of the heuristics presented in this chapter. Exact agreement is not to be expected. Instead, the heuristics should be used to check calculations performed using more rigorous methods and to flag any inconsistencies.

11.3. Summary

In this chapter, a number of heuristics have been introduced that allow the reasonableness of the results of engineering calculations to be checked. These heuristics or guidelines cannot be used to determine absolutely whether a particular answer is correct or incorrect. However, they are useful guides that allow the engineer to flag possible errors and help focus attention on areas of the process that may require special attention. Several heuristics, provided in the tables at the end of this chapter, were used to check the designs provided in Table 1.5 for the toluene hydrodealkylation process.

List of Informational Tables

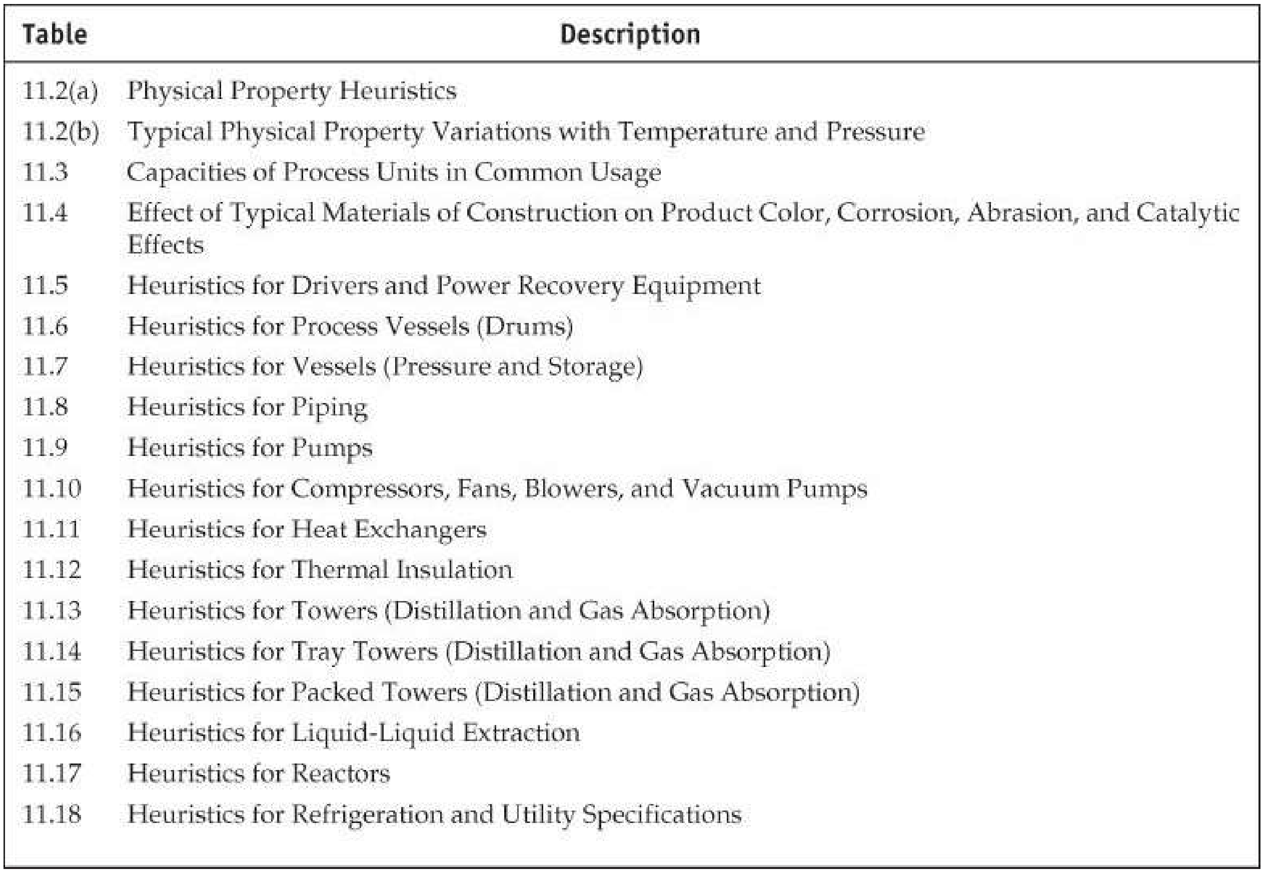
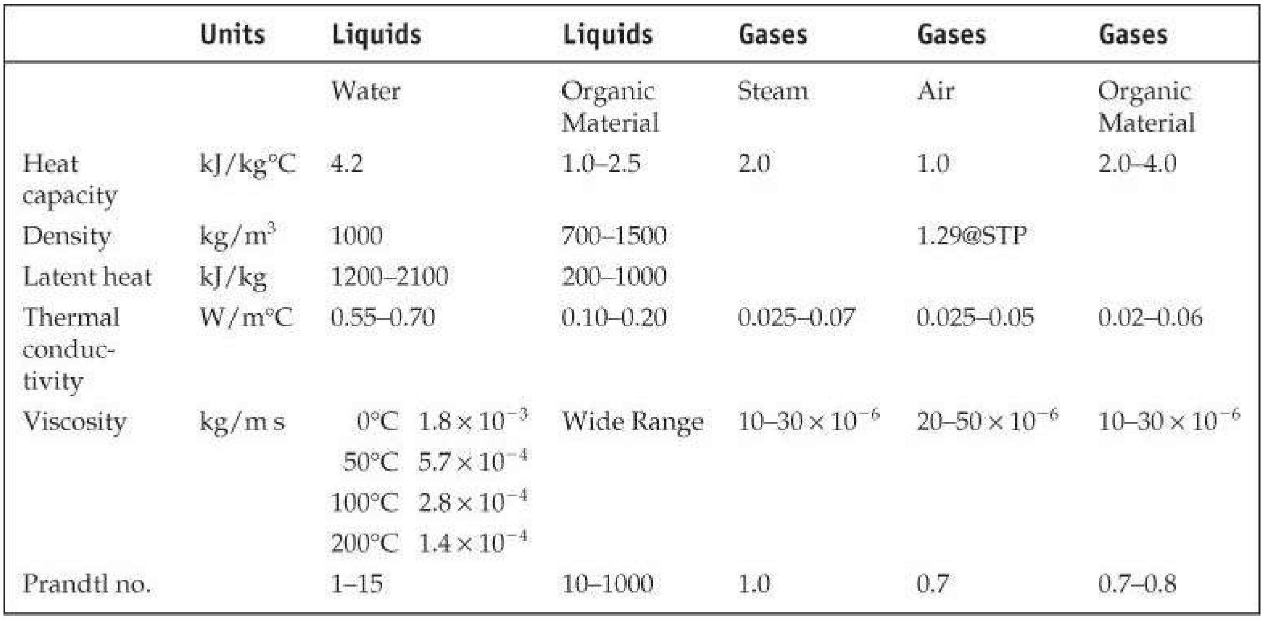


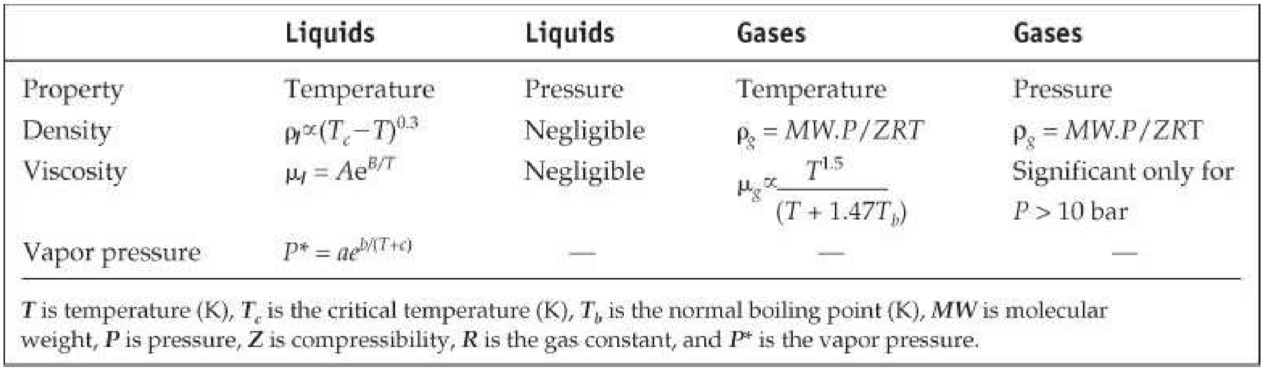
Table	Description
11.2(a)	Physical Property Heuristics
11.2(b)	Typical Physical Property Variations with Temperature and Pressure
11.3	Capacities of Process Units in Common Usage
11.4	Effect of Typical Materials of Construction on Product Color, Corrosion, Abrasion, and Catalytic Effects
11.5	Heuristics for Drivers and Power Recovery Equipment
11.6	Heuristics for Process Vessels (Drums)
11.7	Heuristics for Vessels (Pressure and Storage)
11.8	Heuristics for Piping
11.9	Heuristics for Pumps
11.10	Heuristics for Compressors, Fans, Blowers, and Vacuum Pumps
11.11	Heuristics for Heat Exchangers
11.12	Heuristics for Thermal Insulation
11.13	Heuristics for Towers (Distillation and Gas Absorption)
11.14	Heuristics for Tray Towers (Distillation and Gas Absorption)
11.15	Heuristics for Packed Towers (Distillation and Gas Absorption)
11.16	Heuristics for Liquid-Liquid Extraction
11.17	Heuristics for Reactors
11.18	Heuristics for Refrigeration and Utility Specifications

Table 11.2(a) 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@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/m s	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

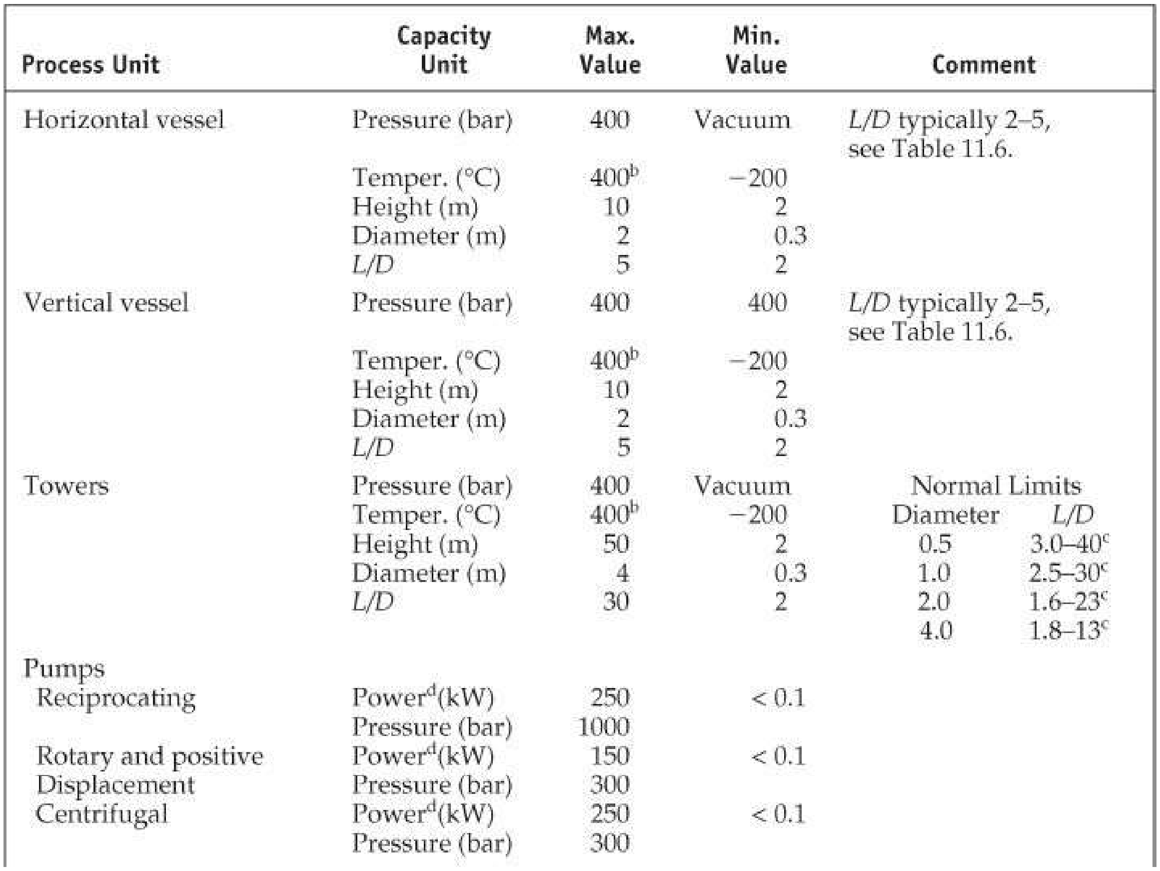
Table 11.2(b) Typical Physical Property Variations with Temperature and Pressure



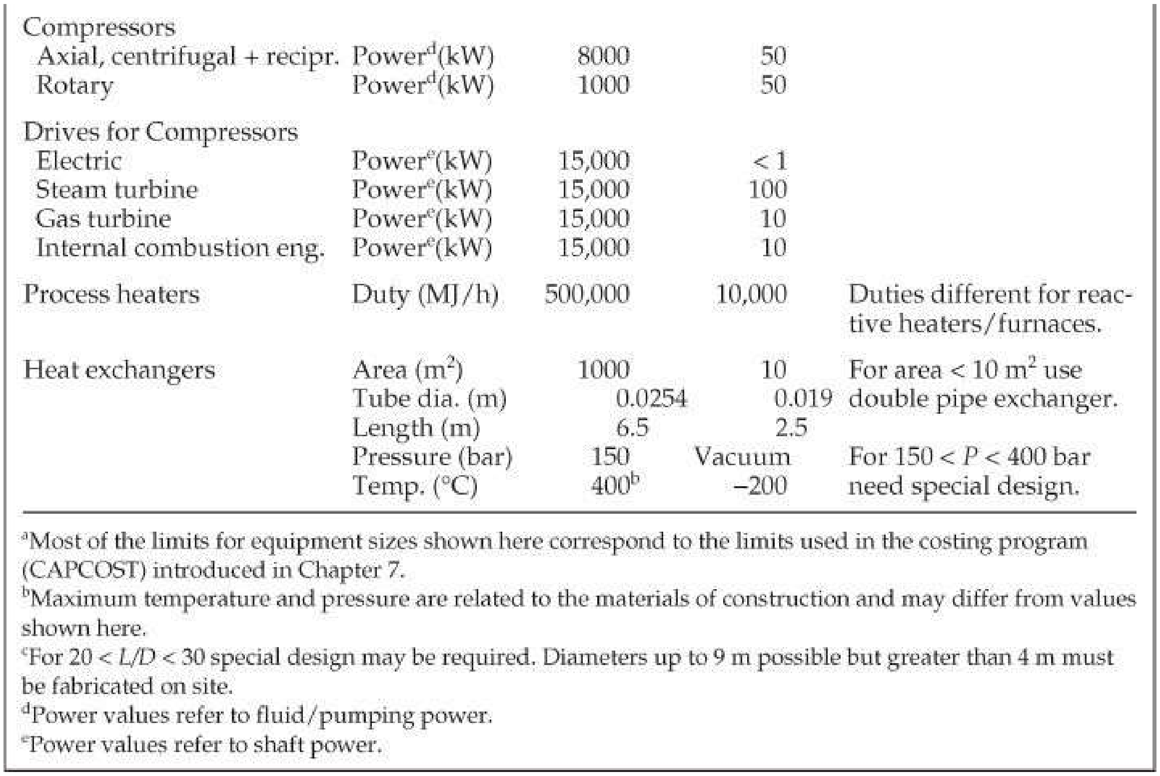
	Liquids	**Liquids**	**Gases**	**Gases**
Property	Temperature	Pressure	Temperature	Pressure
Density	$\rho_l \propto (T_c - T)^{0.3}$	Negligible	$\rho_g = MW.P/ZRT$	$\rho_g = MW.P/ZRT$
Viscosity	$\mu_l = Ae^{B/T}$	Negligible	$\mu_g \propto \frac{T^{1.5}}{(T + 1.47T_b)}$	Significant only for $P > 10$ bar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

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.

Table 11.3. Capacities of Process Units in Common Usage[a]



Process Unit	**Capacity Unit**	**Max. Value**	**Min. Value**	**Comment**
Horizontal vessel	Pressure (bar)	400	Vacuum	L/D typically 2–5, see Table 11.6.
	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, see Table 11.6.
	Temper. (°C)	400[b]	−200	
	Height (m)	10	2	
	Diameter (m)	2	0.3	
	L/D	5	2	
Towers	Pressure (bar)	400	Vacuum	Normal Limits
	Temper. (°C)	400[b]	−200	Diameter L/D
	Height (m)	50	2	0.5 3.0–40[c]
	Diameter (m)	4	0.3	1.0 2.5–30[c]
	L/D	30	2	2.0 1.6–23[c]
				4.0 1.8–13[c]
Pumps				
Reciprocating	Power[d](kW)	250	< 0.1	
	Pressure (bar)	1000		
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)	8000	50	
Rotary	Power[d](kW)	1000	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)	1000	10	For area < 10 m^2 use
	Tube dia. (m)	0.0254	0.019	double pipe exchanger.
	Length (m)	6.5	2.5	
	Pressure (bar)	150	Vacuum	For 150 < P < 400 bar
	Temp. (°C)	400[b]	–200	need special design.

[a] Most of the limits for equipment sizes shown here correspond to the limits used in the costing program (CAPCOST) introduced in Chapter 7.

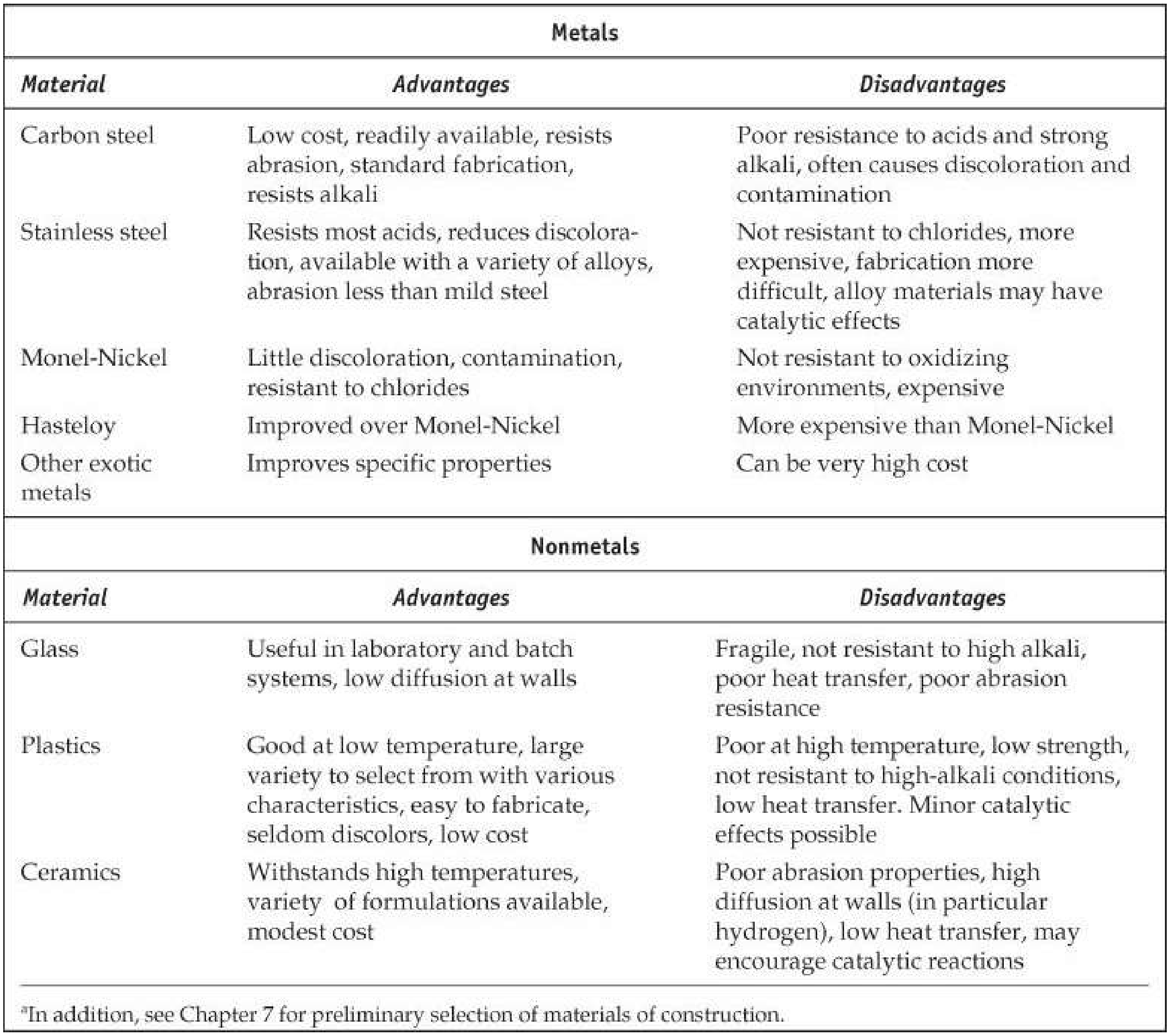
[b] Maximum temperature and pressure are related to the materials of construction and may differ from values shown here.

[c] For 20 < L/D < 30 special design may be required. Diameters up to 9 m possible but greater than 4 m must be fabricated on site.

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

[e] Power values refer to shaft power.

Table 11.4. Effect of Typical Materials of Construction on Product Color, Corrosion,[a] Abrasion, and Catalytic Effects

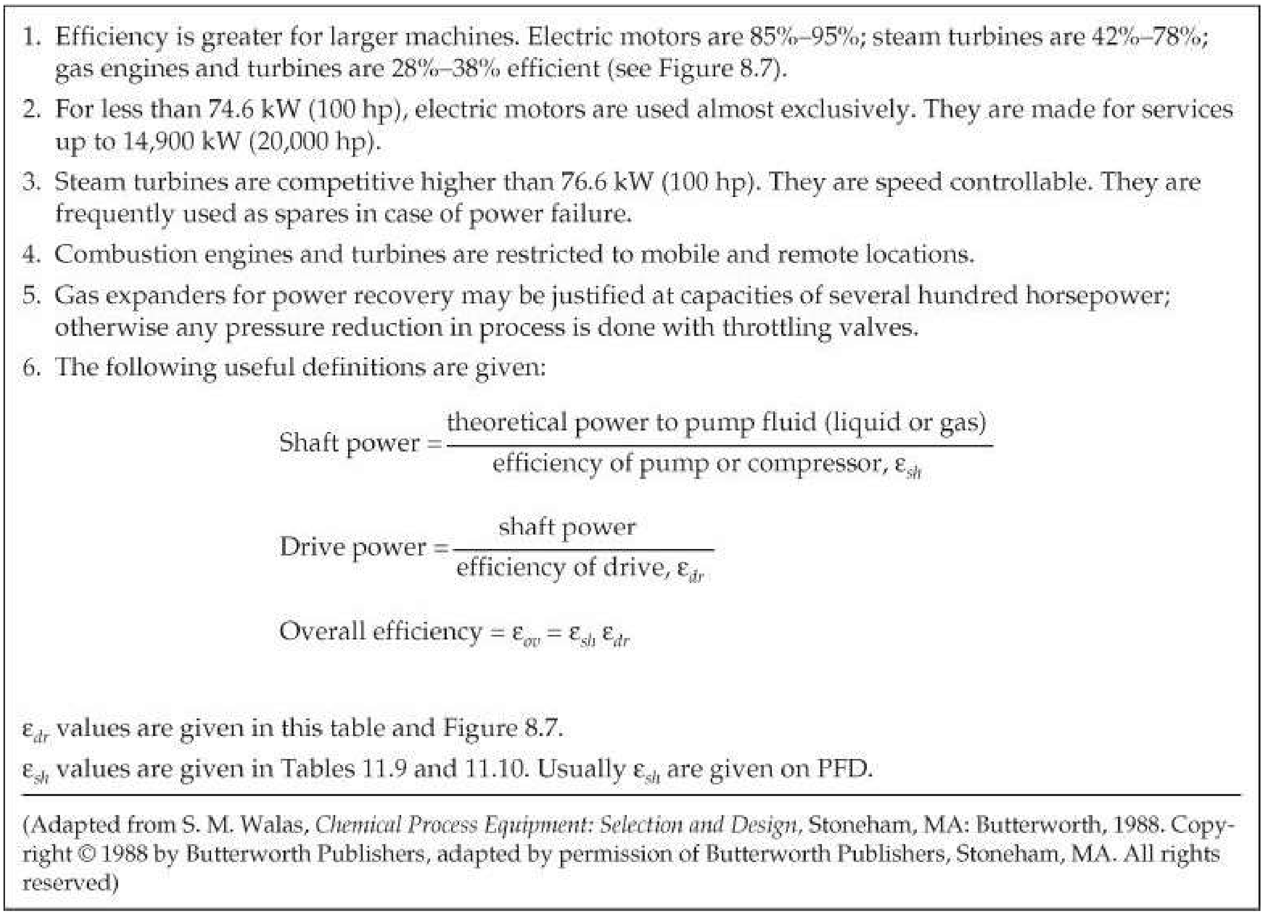


Metals		
Material	*Advantages*	*Disadvantages*
Carbon steel	Low cost, readily available, resists abrasion, standard fabrication, resists alkali	Poor resistance to acids and strong alkali, often causes discoloration and contamination
Stainless steel	Resists most acids, reduces discoloration, available 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	Can be very high cost

Nonmetals		
Material	*Advantages*	*Disadvantages*
Glass	Useful in laboratory and batch systems, 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, low cost	Poor at high temperature, low strength, not resistant to high-alkali conditions, low heat transfer. Minor catalytic effects possible
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

[a] In addition, see Chapter 7 for preliminary selection of materials of construction.

Table 11.5. Heuristics for Drivers and Power Recovery Equipment



1. Efficiency is greater for larger machines. Electric motors are 85%–95%; steam turbines are 42%–78%; gas engines and turbines are 28%–38% efficient (see Figure 8.7).
2. For less than 74.6 kW (100 hp), electric motors are used almost exclusively. They are made for services up to 14,900 kW (20,000 hp).
3. Steam turbines are competitive higher than 76.6 kW (100 hp). They are speed controllable. They are frequently used as spares in case of power failure.
4. Combustion engines and turbines are restricted to mobile and remote locations.
5. Gas expanders for power recovery may be justified at capacities of several hundred horsepower; otherwise any pressure reduction in process is done with throttling valves.
6. The following useful definitions are given:

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

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

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

ε_{dr} values are given in this table and Figure 8.7.

ε_{sh} values are given in Tables 11.9 and 11.10. Usually ε_{sh} are given on PFD.

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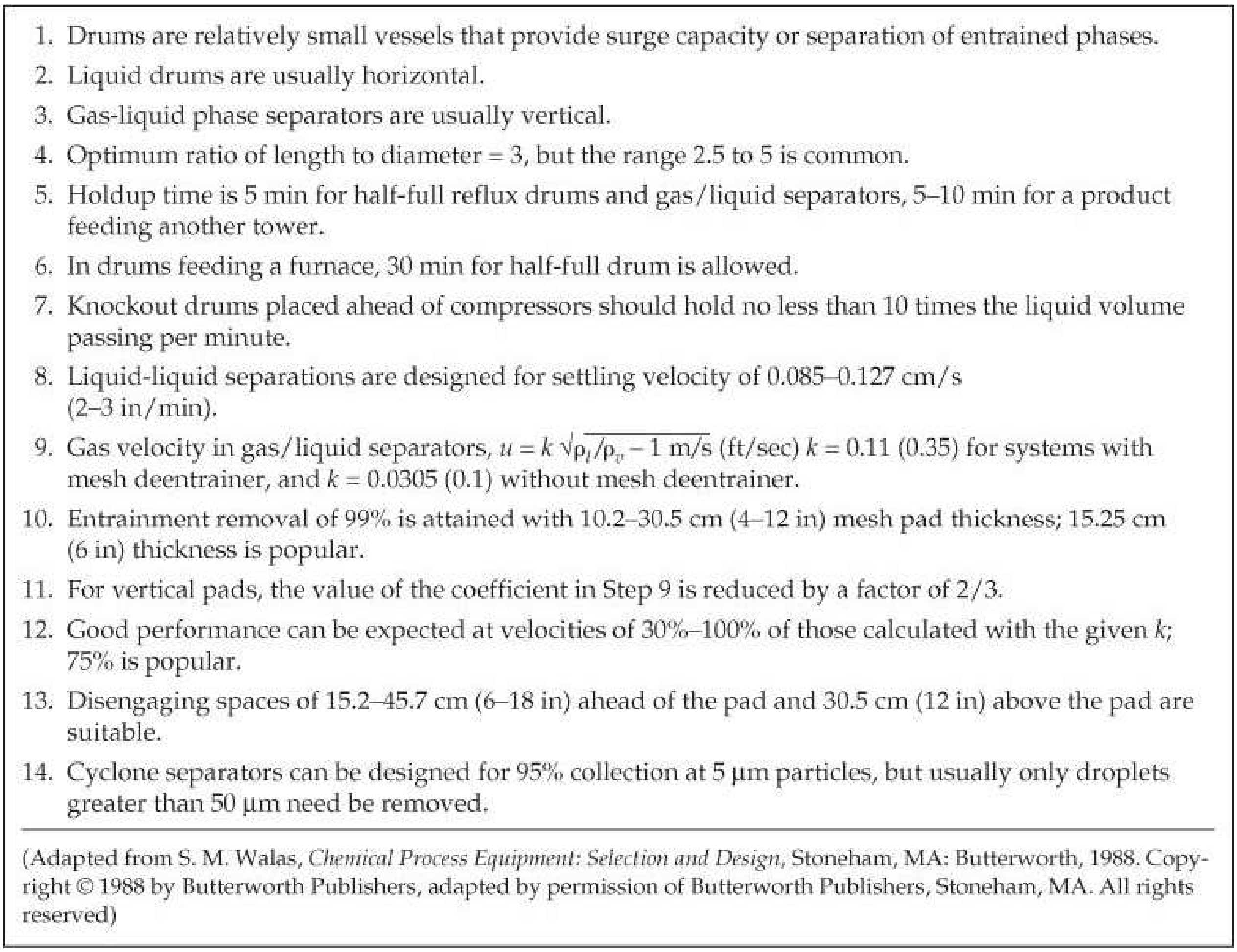
Table 11.6. Heuristics for Process Vessels (Drums)



1. Drums are relatively small vessels that provide surge capacity or separation of entrained phases.
2. Liquid drums are usually horizontal.
3. Gas-liquid phase separators are usually vertical.
4. Optimum ratio of length to diameter = 3, but the range 2.5 to 5 is common.
5. Holdup time is 5 min for half-full reflux drums and gas/liquid separators, 5–10 min for a product feeding another tower.
6. In drums feeding a furnace, 30 min for half-full drum is allowed.
7. Knockout drums placed ahead of compressors should hold no less than 10 times the liquid volume passing per minute.
8. Liquid-liquid separations are designed for settling velocity of 0.085–0.127 cm/s (2–3 in/min).
9. Gas velocity in gas/liquid separators, $u = k\sqrt{\rho_l/\rho_v - 1}$ m/s (ft/sec) $k = 0.11$ (0.35) for systems with mesh deentrainer, and $k = 0.0305$ (0.1) without mesh deentrainer.
10. Entrainment removal of 99% is attained with 10.2–30.5 cm (4–12 in) mesh pad thickness; 15.25 cm (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 15.2–45.7 cm (6–18 in) ahead of the pad and 30.5 cm (12 in) above the pad are suitable.
14. Cyclone separators can be designed for 95% collection at 5 µm particles, but usually only droplets greater than 50 µm need be removed.

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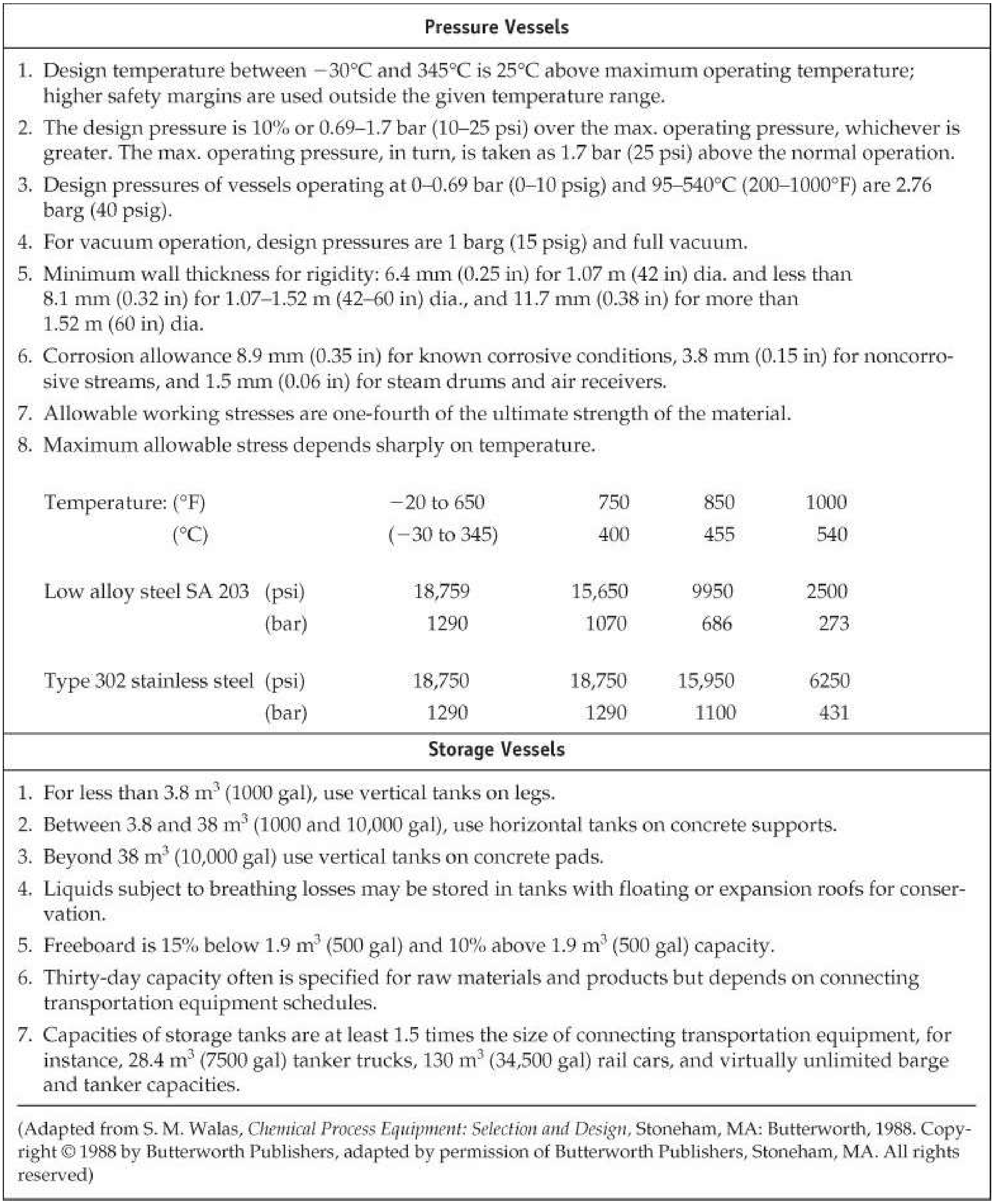
Table 11.7. Heuristics for Vessels (Pressure and Storage)



Pressure Vessels

1. Design temperature between −30°C and 345°C is 25°C 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 max. operating pressure, whichever is greater. The max. 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 bar (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) dia. and less than 8.1 mm (0.32 in) for 1.07–1.52 m (42–60 in) dia., and 11.7 mm (0.38 in) for more than 1.52 m (60 in) dia.
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 of the ultimate strength of the material.
8. Maximum allowable stress depends sharply on temperature.

Temperature: (°F)		−20 to 650	750	850	1000
(°C)		(−30 to 345)	400	455	540
Low alloy steel SA 203	(psi)	18,759	15,650	9950	2500
	(bar)	1290	1070	686	273
Type 302 stainless steel	(psi)	18,750	18,750	15,950	6250
	(bar)	1290	1290	1100	431

Storage Vessels

1. For less than 3.8 m^3 (1000 gal), use vertical tanks on legs.
2. Between 3.8 and 38 m^3 (1000 and 10,000 gal), use horizontal tanks on concrete supports.
3. Beyond 38 m^3 (10,000 gal) use vertical tanks on concrete pads.
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. Thirty-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.

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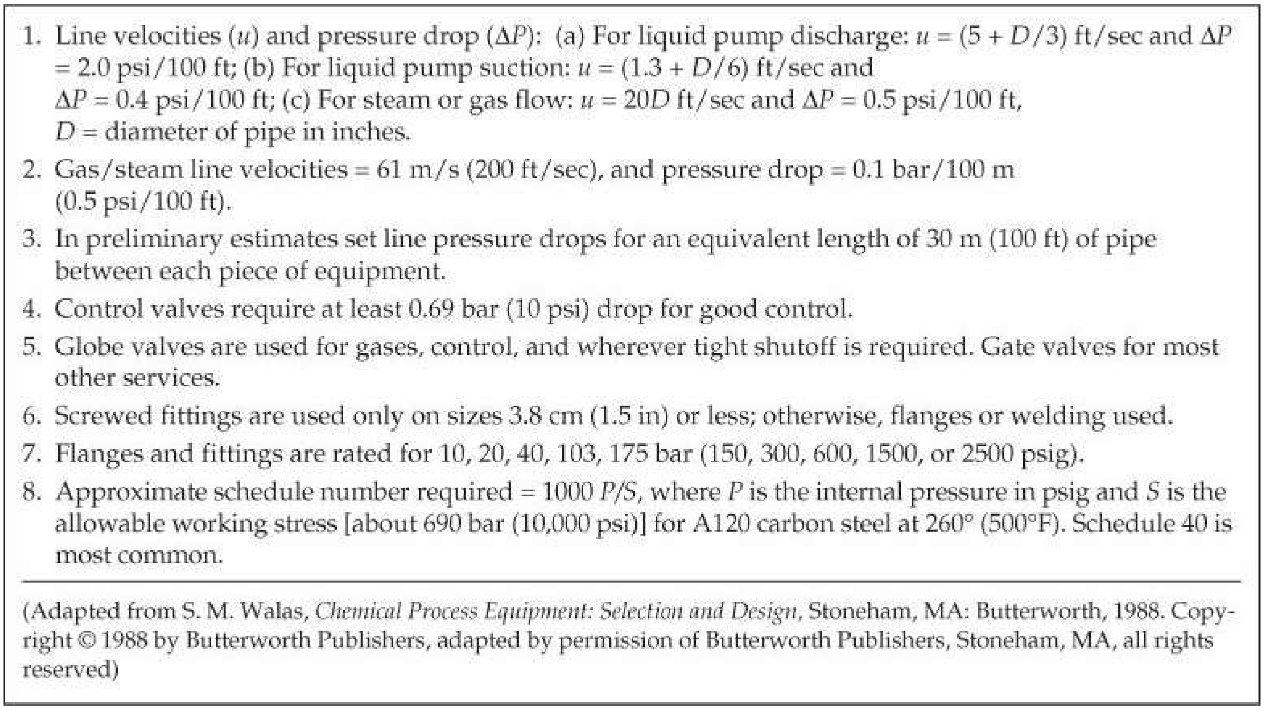
Table 11.8. Heuristics for Piping



1. Line velocities (u) and pressure drop (ΔP): (a) For liquid pump discharge: $u = (5 + D/3)$ ft/sec and $\Delta P = 2.0$ psi/100 ft; (b) For liquid pump suction: $u = (1.3 + D/6)$ ft/sec and $\Delta P = 0.4$ psi/100 ft; (c) For steam or gas flow: $u = 20D$ ft/sec and $\Delta P = 0.5$ psi/100 ft, D = diameter of pipe in inches.
2. Gas/steam line velocities = 61 m/s (200 ft/sec), 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 m (100 ft) of pipe between each piece of equipment.
4. Control valves require at least 0.69 bar (10 psi) drop for good control.
5. Globe valves are used for gases, control, and wherever tight shutoff is required. Gate valves for most other services.
6. Screwed fittings are used only on sizes 3.8 cm (1.5 in) or less; otherwise, flanges or welding used.
7. Flanges and fittings are rated for 10, 20, 40, 103, 175 bar (150, 300, 600, 1500, or 2500 psig).
8. Approximate schedule number required = 1000 P/S, where P is the internal pressure in psig and S is the allowable working stress [about 690 bar (10,000 psi)] for A120 carbon steel at 260° (500°F). Schedule 40 is most common.

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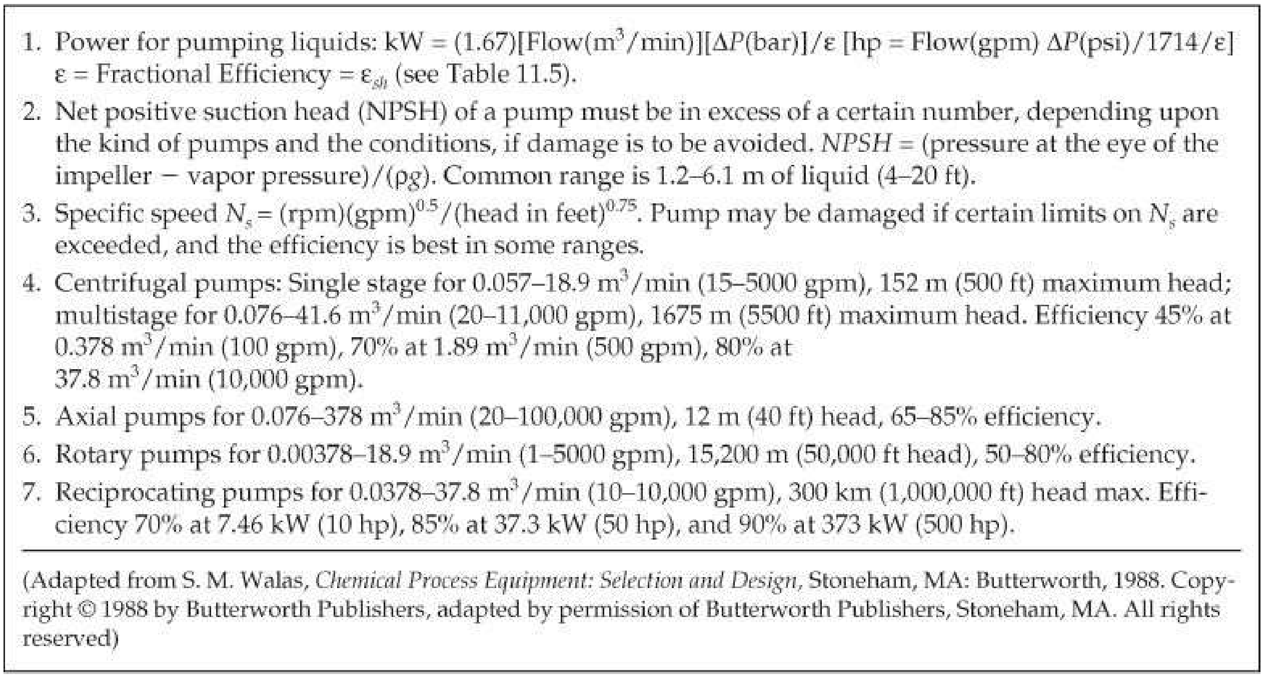
Table 11.9. Heuristics for Pumps



1. Power for pumping liquids: kW = (1.67)[Flow(m^3/min)][ΔP(bar)]/ε [hp = Flow(gpm) ΔP(psi)/1714/ε] ε = Fractional Efficiency = ε_{sh} (see Table 11.5).
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 of liquid (4–20 ft).
3. Specific speed N_s = (rpm)(gpm)$^{0.5}$/(head in feet)$^{0.75}$. Pump may be damaged if certain limits on N_s are exceeded, and the 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), 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) head max. Efficiency 70% at 7.46 kW (10 hp), 85% at 37.3 kW (50 hp), and 90% at 373 kW (500 hp).

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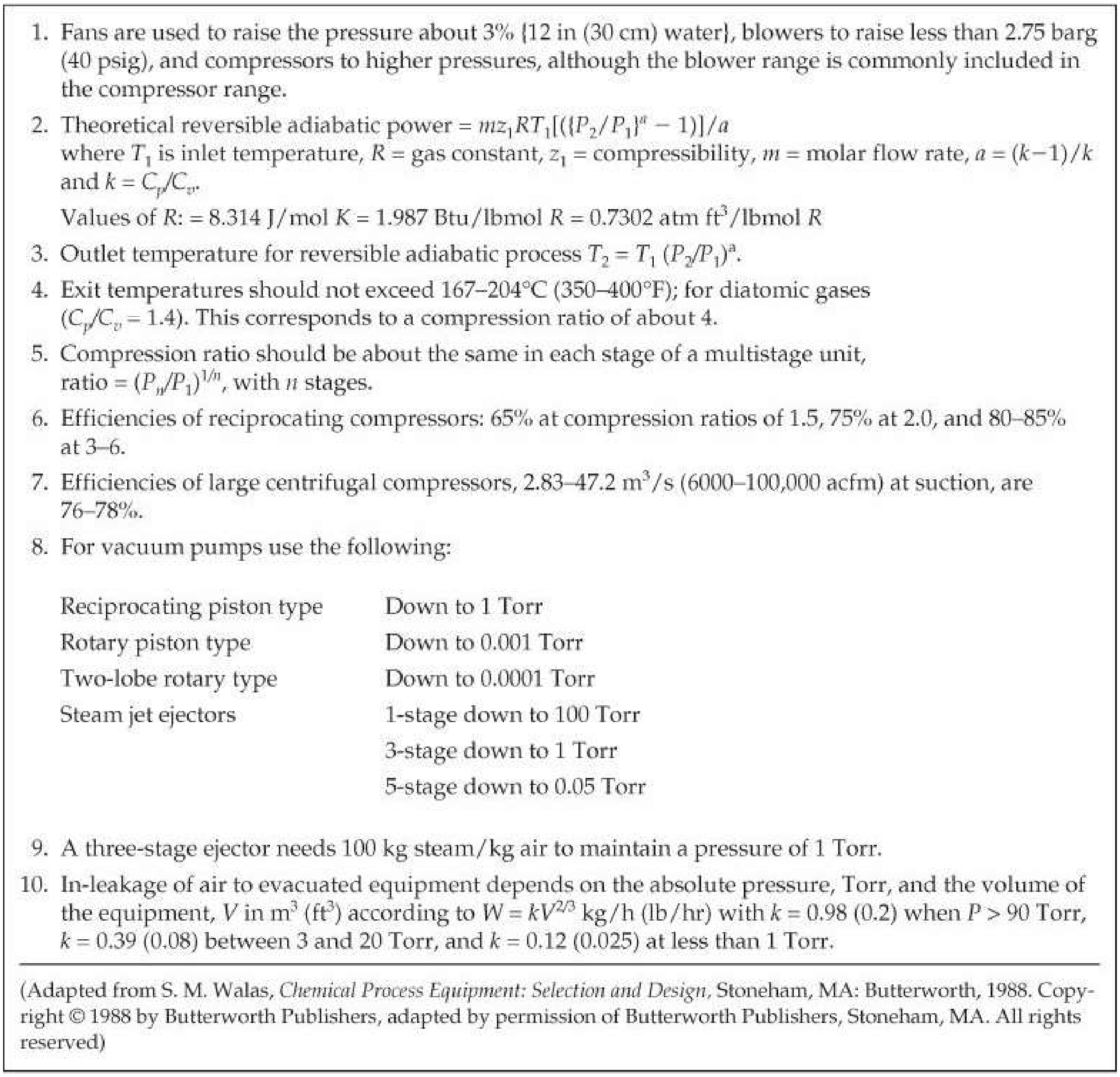
Table 11.10. Heuristics for Compressors, Fans, Blowers, and Vacuum Pumps



1. Fans are used to raise the pressure about 3% {12 in (30 cm) water}, blowers to raise less than 2.75 barg (40 psig), and compressors to higher pressures, although the blower range is commonly included in the compressor range.
2. 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, m = molar flow rate, $a = (k-1)/k$ and $k = C_p/C_v$.

   Values of R: = 8.314 J/mol K = 1.987 Btu/lbmol R = 0.7302 atm ft^3/lbmol R
3. Outlet temperature for reversible adiabatic process $T_2 = T_1\,(P_2/P_1)^a$.
4. Exit temperatures 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.
5. Compression ratio should be about the same in each stage of a multistage unit, ratio = $(P_n/P_1)^{1/n}$, with n stages.
6. Efficiencies of reciprocating compressors: 65% at compression ratios of 1.5, 75% at 2.0, and 80–85% at 3–6.
7. Efficiencies of large centrifugal compressors, 2.83–47.2 m^3/s (6000–100,000 acfm) at suction, are 76–78%.
8. For vacuum pumps use the following:

Reciprocating piston type	Down to 1 Torr
Rotary piston type	Down to 0.001 Torr
Two-lobe rotary type	Down to 0.0001 Torr
Steam jet ejectors	1-stage down to 100 Torr 3-stage down to 1 Torr 5-stage down to 0.05 Torr

9. A three-stage ejector needs 100 kg steam/kg air to maintain a pressure of 1 Torr.
10. 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/hr) with $k = 0.98$ (0.2) when $P > 90$ Torr, $k = 0.39$ (0.08) between 3 and 20 Torr, and $k = 0.12$ (0.025) at less than 1 Torr.

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Table 11.11. Heuristics for Heat Exchangers

1. For conservative estimate set $F = 0.9$ for shell-and-tube exchangers with no phase changes, $q = UAF\Delta T_{\mathrm{lm}}$. When ΔT at exchanger ends differ greatly, then check F, and reconfigure if F is less than 0.85.
2. Standard tubes are 1.9 cm (3/4 in) OD, on a 2.54 cm (1 in) triangle spacing, 4.9 m (16 ft) long.

   A shell 30 cm (1 ft) dia. accommodates 9.3 m^2 (100 ft^2)
   60 cm (2 ft) dia. accommodates 37.2 m^2 (400 ft^2)
   90 cm (3 ft) dia. accommodates 102 m^2 (1100 ft^2)
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 0.1 bar (1.5 psi) for boiling and 0.2–0.62 bar (3–9 psi) for other services.
6. Minimum temperature approach is 10°C (20°F) for fluids and 5°C (10°F) for refrigerants.
7. Cooling water inlet is 30°C (90°F), maximum outlet 45°C (115°F).
8. Heat transfer coefficients for estimating purposes, W/m$^{2\circ}$C (Btu/hr ft$^{2\circ}$F): water to liquid, 850 (150); condensers, 850 (150); liquid to liquid, 280 (50); liquid to gas, 60 (10); gas to gas 30 (5); reboiler 1140 (200). Maximum flux in reboiler 31.5 kW/m^2 (10,000 Btu/hr ft^2).

   When phase changes occur, use a zoned analysis with appropriate coefficient for each zone.
9. Double pipe exchanger is competitive at duties requiring 9.3–18.6 m^2 (100–200 ft^2).
10. 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.
11. Plate and frame exchangers are suited to high-sanitation services and are 25–50% cheaper in stainless steel construction than shell-and-tube units.
12. Air coolers: Tubes are 0.75–1.0 in. OD, total finned surface 15–20 m^2/m^2 (ft^2/ft^2 bare surface), U = 450–570 W/m$^{2\circ}$C (80–100 Btu/hr 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/hr)].
13. Fired heaters: Radiant rate, 37.6 kW/m^2 (12,000 Btu/hr ft^2); convection rate, 12.5 kW/m^2 (4000 Btu/hr ft^2); cold oil tube velocity = 1.8 m/s (6 ft/sec); approximately equal transfer in the two sections; thermal efficiency 70–90% based on lower heating value; flue gas temperature 140–195°C (250–350°F) above feed inlet; stack gas temperature 345–510°C (650–950°F).

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Table 11.12. Heuristics for Thermal 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 (refractory) linings at higher temperature.
4. Cryogenic equipment −130°C (−200°F) employs insulation with fine pores of trapped air, e.g., Perlite.
5. Optimal thickness varies with temperature: 1.27 cm (0.5 in) at 95°C (200°F), 2.54 cm (1.0 in) at 200°C (400°F), 3.2 cm (1.25 in) at 315°C (600°F).
6. Under windy conditions 12.1 km/h (7.5 miles/hr), 10–20% greater thickness of insulation is justified.

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Table 11.13. Heuristics for Towers (Distillation and Gas Absorption)

1. Distillation is usually the most economical method for separating liquids, superior to extraction, absorption crystallization, or others.
2. For ideal mixtures, relative volatility is the ratio of vapor pressures $\alpha_{12} = P_1^*/P_2^*$.
3. Tower operating pressure is most often determined by the temperature of the condensing media, 38–50°C (100–120°F) if cooling water is used, or by the maximum allowable reboiler temperature to avoid chemical decomposition/degradation.
4. Sequencing of columns for separating multicomponent mixtures:[a]
   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 composition varies widely, remove 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 order of decreasing volatility.
   d. When the concentrations in the feed vary widely but the relative volatilities do not, remove the components in order of decreasing concentration.
5. Economical optimum reflux ratio is in the range of 1.2 to 1.5 times the minimum reflux ratio, R_{min}.
6. The economically optimum number of theoretical trays is near twice the minimum value N_{min}.
7. The minimum number of trays is found with the Fenske-Underwood equation
   $N_{min} = \ln\{[x/(1-x)]_{ovhd}/[x/(1-x)]_{btms}\}/\ln \alpha$.
8. 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 to feed rate:
   $R_{min}D/F = 1/(\alpha-1)$, when feed is at the bubble point
   $(R_{min}+1)\ D/F = \alpha/(\alpha-1)$, when feed is at the dew point
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 absorption factor $A = (L/mV)$ is in the range of 1.25 to 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 1.3 m/s (0.5 ft/sec), minimum diameter is 0.4 m (16 in).
13. For towers about 0.9 m (3 ft) dia., add 1.2 m (4 ft) at the top for vapor disengagement, and 1.8 m (6 ft) at bottom for liquid level and reboiler return.
14. Limit the tower height to about 53 m (175 ft) max. 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).

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[a] Additional information on sequencing is given in Table 12.2.

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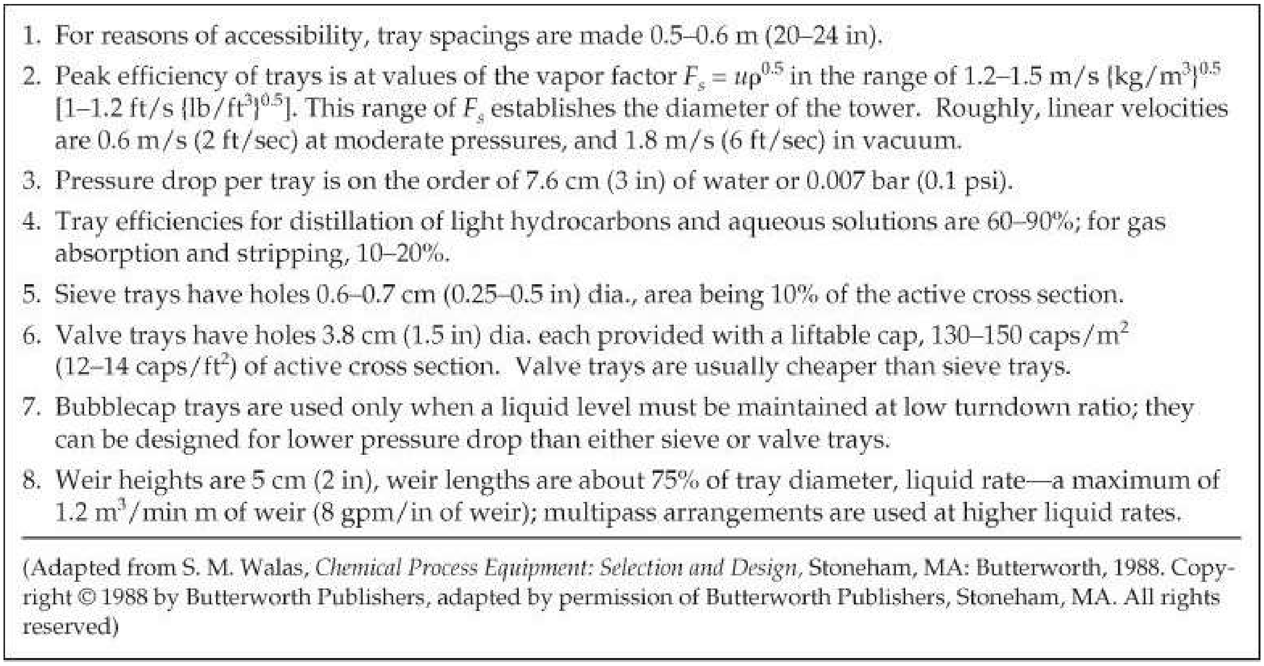
Table 11.14. Heuristics for Tray Towers (Distillation and Gas Absorption)



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 $F_s = u\rho^{0.5}$ in the range of 1.2–1.5 m/s {kg/m^3}$^{0.5}$ [1–1.2 ft/s {lb/ft^3}$^{0.5}$]. This range of F_s establishes the diameter of the tower. Roughly, linear velocities are 0.6 m/s (2 ft/sec) at moderate pressures, and 1.8 m/s (6 ft/sec) in vacuum.
3. Pressure drop per tray is on the order of 7.6 cm (3 in) of water or 0.007 bar (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 0.6–0.7 cm (0.25–0.5 in) dia., area being 10% of the active cross section.
6. Valve trays have holes 3.8 cm (1.5 in) dia. each provided with a liftable cap, 130–150 caps/m^2 (12–14 caps/ft^2) of active cross section. Valve trays are usually cheaper than sieve trays.
7. 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.
8. Weir heights are 5 cm (2 in), weir lengths are about 75% of tray diameter, liquid rate—a maximum of 1.2 m^3/min m of weir (8 gpm/in of weir); multipass arrangements are used at higher liquid rates.

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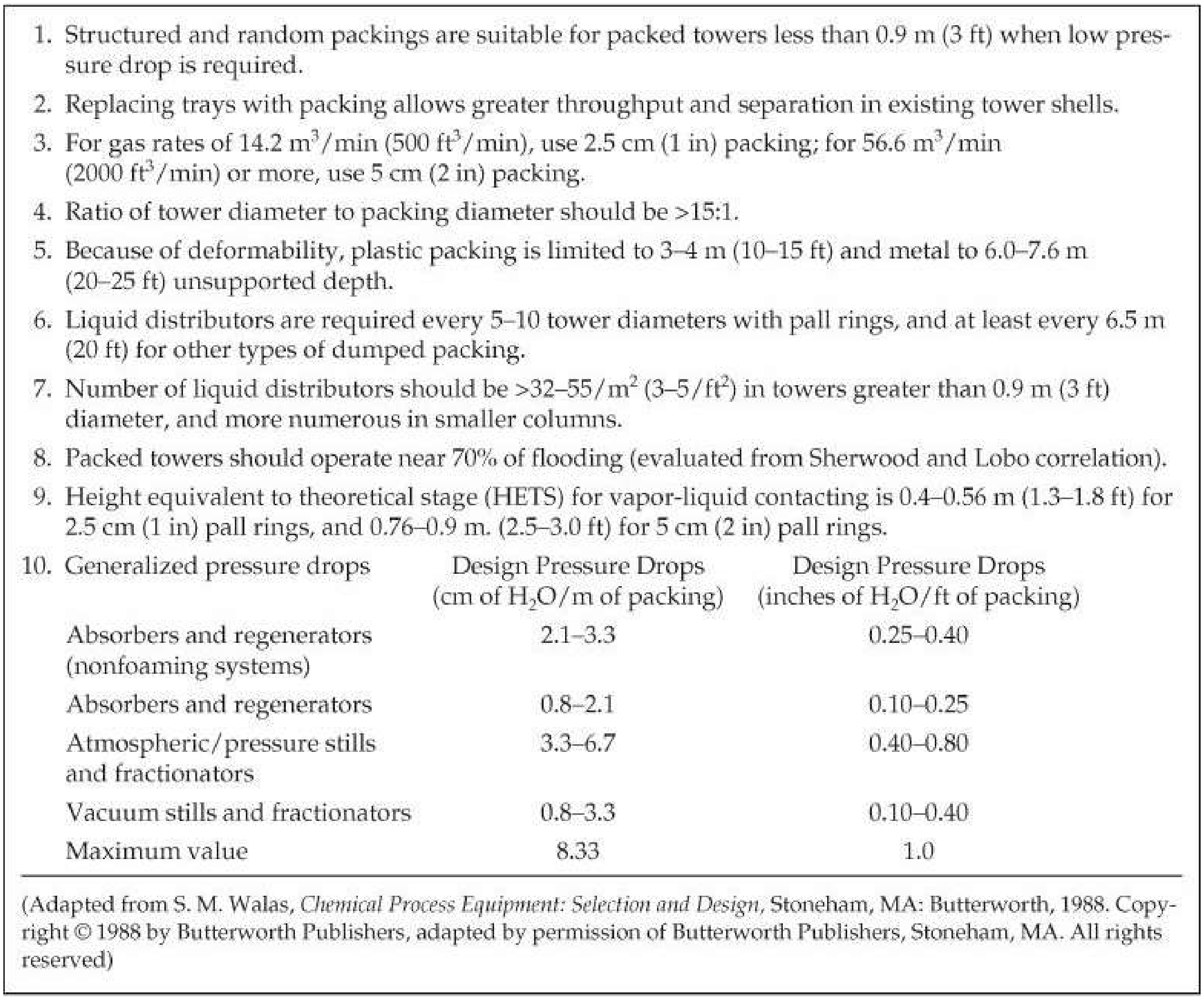
Table 11.15. Heuristics for Packed Towers (Distillation and Gas Absorption)



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 2.5 cm (1 in) packing; for 56.6 m^3/min (2000 ft^3/min) or more, use 5 cm (2 in) packing.
4. Ratio of tower diameter to packing diameter should be >15:1.
5. Because of deformability, plastic packing is limited to 3–4 m (10–15 ft) and metal 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 distributors 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 flooding (evaluated from Sherwood and Lobo correlation).
9. Height equivalent to theoretical stage (HETS) for vapor-liquid contacting is 0.4–0.56 m (1.3–1.8 ft) for 2.5 cm (1 in) pall rings, and 0.76–0.9 m. (2.5–3.0 ft) for 5 cm (2 in) pall rings.
10. Generalized pressure drops

10. Generalized pressure drops	Design Pressure Drops (cm of H_2O/m of packing)	Design Pressure Drops (inches of H_2O/ft of packing)
Absorbers and regenerators (nonfoaming 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

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Table 11.16. Heuristics for Liquid-Liquid Extraction

1. The dispersed phase should be the one with the higher volumetric flowrate 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 material of construction less well. Because 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 circulation 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 0.15–0.46 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 2.5–3.8 cm (1–1.5 in) size are best. Dispersed phase loadings should not exceed 10.2 $m^3/min\ m^2$ (25 $gal/min\ ft^2$). 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 dia. Velocities through the holes are kept less than 0.24 m/s (0.8 ft/sec) to avoid formation of small drops. Redispersion of either phase at each tray can be designed for. Tray spacings are 15.2 to 60 cm (6 to 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 have been observed. Surface tensions as high as 30–40 dyne/cm have no adverse effect.
8. Reciprocating tray towers can have holes 1.5 cm (9/16 in) dia., 50–60% open area, stroke length 1.9 cm (0.75 in), 100–150 strokes/min, plate spacing normally 5 cm (2 in) but in the range of 2.5–15 cm (1–6 in). In a 76 cm (30 in) diameter tower, HETS is 50–65 cm (20–25 in) and throughput is 13.7 $m^3/min\ m^2$ (2000 $gal/hr\ ft^2$). Power requirements are much less than that of pulsed towers.
9. Rotating disk contactors 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 $ft^3/ft^2\ hr$).

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Table 11.17. Heuristics for 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 to 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 programmed 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 construction then is 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 conversion less than 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.

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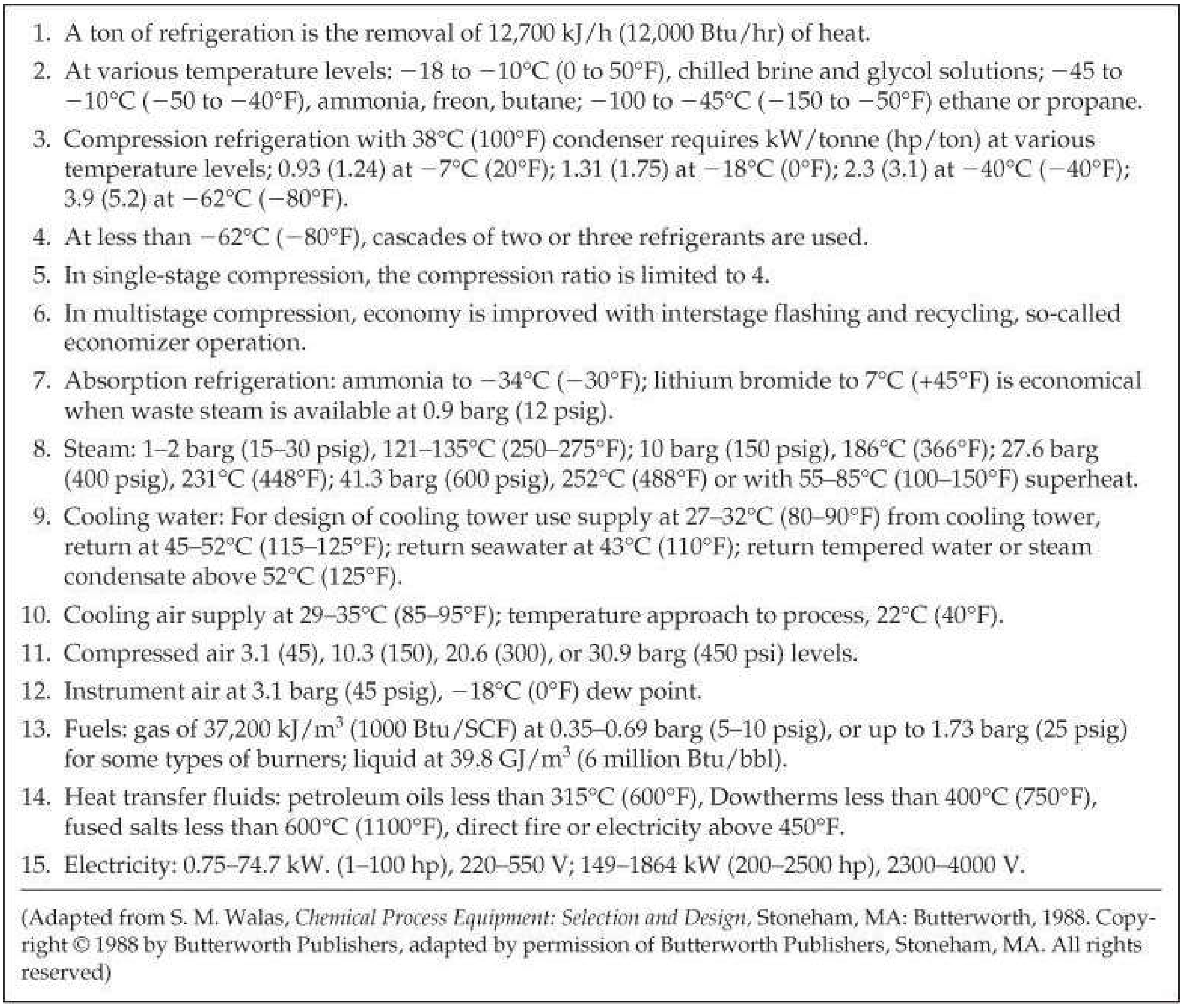
Table 11.18. Heuristics for Refrigeration and Utility Specifications



1. A ton of refrigeration is the removal of 12,700 kJ/h (12,000 Btu/hr) of heat.
2. At various temperature levels: −18 to −10°C (0 to 50°F), chilled brine and glycol solutions; −45 to −10°C (−50 to −40°F), ammonia, freon, 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. At less than −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, so-called economizer operation.
7. Absorption refrigeration: ammonia to −34°C (−30°F); lithium bromide to 7°C (+45°F) is economical when waste steam is available at 0.9 barg (12 psig).
8. Steam: 1–2 barg (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.
9. 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).
10. Cooling air supply at 29–35°C (85–95°F); temperature approach to process, 22°C (40°F).
11. Compressed air 3.1 (45), 10.3 (150), 20.6 (300), or 30.9 barg (450 psi) levels.
12. Instrument air at 3.1 barg (45 psig), −18°C (0°F) dew point.
13. 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 Btu/bbl).
14. Heat transfer fluids: petroleum oils less than 315°C (600°F), Dowtherms less than 400°C (750°F), fused salts less than 600°C (1100°F), direct fire or electricity above 450°F.
15. Electricity: 0.75–74.7 kW. (1–100 hp), 220–550 V; 149–1864 kW (200–2500 hp), 2300–4000 V.

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What You Should Have Learned

- This chapter is a resource of experienced-based heuristics that can be used to estimate unknown parameters and validate calculated parameters used to design a chemical process.

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2. Sieder, E. N., and G. E. Tate, “Heat Transfer and Pressure Drop of Liquids in Tubes,” *Ind. Eng. Chem.* 28 (1936): 1429–1435.
3. Walas, S. M., *Chemical Process Equipment: Selection and Design* (Stoneham, MA: Butterworth, 1988).

Problems

1. For the ethylbenzene process shown in Appendix B, check the design specifications for the following three pieces of equipment against the appropriate heuristics: P-301, V-302, T-302.

Comment on any significant differences that you find.

2. For the styrene process shown in Appendix B, check the design specifications for the following three pieces of equipment against the appropriate heuristics: E-401, C-401, T-402. Comment on any significant differences that you find.
3. For the drying oil process shown in Appendix B, check the design specifications for the following three pieces of equipment against the appropriate heuristics: V-501, P-501, H-501. Comment on any significant differences that you find.