Chapter 20. Tools for Evaluating Process Performance

What You Will Learn

- There are important relationships, probably taught in earlier classes, that are used to evaluate process performance.

Several important computational and graphical tools used to analyze plant operations and changes in process design are developed and demonstrated in this chapter. Many of these tools are keyed to actual system performance. Tools presented are used extensively in future chapters.

Intuitive understanding is emphasized over computational complexity. All problems can be solved using a calculator without special functions. Graphical representations are also emphasized. They illustrate the characteristic behavior of a unit or process over a wide range of operations. Graphical presentations reveal critical operating regions that demand careful assessment.

20.1. Key Relationships

In analyzing equipment performance, there are certain key relationships that are used over and over again. These are shown in Table 20.1. Although these should be familiar to the reader, they are important enough to be reviewed here.

Table 20.1. Typical Key Performance Relationships

Situation	Equation	Trends	Comments
Frictional loss for fluid flow	$\Delta P = \dfrac{2\rho f L_{eq} u^2}{D}$	$\lvert \Delta P \rvert \propto u^2$ $\lvert \Delta P \rvert \propto D^{-5}$ $\lvert \Delta P \rvert \propto L$	Assumes fully developed turbulent flow, i.e., constant friction factor; for laminar flow $\Delta P \propto D^{-4}$.
Heat transfer	Of form $\left(\dfrac{hD}{k}\right) = c\left(\dfrac{Du\rho}{\mu}\right)^a \left(\dfrac{\mu C_p}{k}\right)^b$	$h_i \propto v^{0.8}$ inside closed channels $h_o \propto v^{0.6}$ cross flow outside pipes	Equations given are for no phase change; if phase change, weak flow dependence, but some ΔT dependence.
Kinetics	$r = k\Pi c_i^{a_i}$ $k = k_o e^{-\left(\frac{E}{RT}\right)}$	$\ln k$ vs $1/T$ is linear	As $T\uparrow, k\uparrow$ for ideal gases $P\uparrow, c_i\uparrow$, so $r\uparrow$.
Reactor	Mixed flow: $\dfrac{V}{F_{A0}} = \dfrac{\tau}{C_{A0}} = \dfrac{X}{-r_A}$ Plug flow: $\dfrac{V}{F_{A0}} = \dfrac{\tau}{C_{A0}} = \displaystyle\int_0^X \dfrac{dX}{-r_A}$	$\tau \propto V$ as $\tau\uparrow$ or $V\uparrow, X\uparrow$	τ is space time, V is reactor volume, X is conversion of limiting reactant, A assumes one reaction and constant volumetric flowrate.
Separator using mass separating agent	Not necessarily described by a single equation	As flow of mass separating agent $\uparrow$, or as number stages or height of packed tower $\uparrow$, degree of separation $\uparrow$	For certain cases, there are limitations to the effect of increasing number of stages or packed tower height.
Distillation	Not necessarily described by a single equation	As reflux ratio $\uparrow$, degree of separation $\uparrow$	Complicated analysis; see Chapter 21.

The first entry deals with the pressure drop due to frictional losses in a pipe. The key relationship is the proportionality between pressure drop and the square of the velocity, and the proportionality between pressure drop and length (or equivalent length) of pipe. Although it is intuitive that the pressure drop should increase with length of pipe and with increasing velocity, the quantitative relationship reveals the square dependence on velocity. Similarly, although it is intuitive that a larger pipe diameter should reduce frictional losses, the negative fifth-power dependence is revealed only by the equation describing the actual physical situation. Similarly, the general trends for heat transfer coefficients and for rate constants may be intuitive, but the equation describing the actual physical situation shows that quantitative dependence. For reactors and separators, only the intuitive trends can be shown because the exact, quantitative dependence is either situation specific or not easily quantifiable using a closed-form equation.

The relationships in Table 20.1 will be used extensively in Chapters 21, 22, and 23.

20.2. Thinking with Equations

It is possible to quantify equipment performance without resorting to extensive, detailed calculations. This involves using equations to understand trends. The first step is to identify the equations necessary to quantify a given situation. Wales and Stager [1] have termed this "thinking with equations" and have used the acronym GENI to describe the associated problem-solving strategy. The second step involves predicting trends from equations. These methods are described and then illustrated in an

example.

20.2.1. GENI

GENI is a method for solving quantitative problems. The name GENI is an acronym for the four steps in the method.

1. Goal: Identify the goal. This is usually the unknown that needs to be calculated.

2. Equation: Identify the equation that relates the unknown to known values or properties.

3. Need: Identify additional relationships that are needed to solve the equation in Step 2.

4. Information: List additional information that is available to determine whether what is needed in Step 3 is known. If the correct information is not known, the need becomes the new goal and the process is repeated.

20.2.2. Predicting Trends

The following method can be used to predict trends from equations known to apply to a given physical situation. In this method, there are four possible modifiers to a term in an equation:

1. ¢: value remains constant.

2. ↑: value increases.

3. ↓: value decreases.

4. ?: value change not known.

Each variable in an expression has one of these identifiers appended. If x is a constant, then $x \to x(¢)$. The symbol in parentheses identifies the effect the variable has on the term; that is, reducing a value in the denominator of a term increases the term.

The application of the techniques described in is illustrated in .

Example 20.1.

For a bimolecular, elementary, gas-phase reaction, the rate expression is known to be $-r_A = kC_A C_B$.

a. What is the effect on the reaction rate of increasing the reaction pressure by 10% while maintaining constant temperature?

b. What is the effect on the reaction rate of increasing the reaction temperature by 10% while maintaining constant pressure?

The **goal** is to determine the effect of increasing pressure on the reaction rate. The **equation** containing the unknown value, which is the reaction rate, r_A, is given. A relationship is needed between pressure and at least one variable in the equation. The ideal gas law states that $C_i = P_i/RT$, where i is A or B.

Now that the necessary relationships are known, an intuitive understanding can be obtained by predicting trends.

a. First, examine the ideal gas relationship. If the pressure increases with the temperature remaining constant, then the ideal gas relationship can be written as

$$C_i(\uparrow) = y_i(¢)P(\uparrow)/R(¢)T(¢) = P_i(\uparrow)/R(¢)T(¢)$$

Therefore, the concentration increases because the pressure increases while the temperature and the gas constant remain constant. Intuitively, if the pressure increases by 10%, the concentration

must increase by 10%.

Moving to the rate expression, because the rate constant is not affected by pressure, the resulting trend is predicted by

$$r_A(\uparrow) = k(\text{¢})C_A(\uparrow)C_B(\uparrow)$$

which means that the reaction rate increases. Intuitively, because each concentration increases by 10%, then the reaction rate changes by a factor of $(1.1)^2 = 1.21$, an increase of 21%.

b. In this case, from the ideal gas relationship,

$$C_i(\downarrow) = y_i(\text{¢})P(\text{¢})/R(\text{¢})T(\uparrow) = P_i(\text{¢})/R(\text{¢})T(\uparrow)$$

From the rate expression, because the rate constant is a function of temperature,

$$r_A(?) = k(\uparrow)C_A(\downarrow)C_B(\downarrow)$$

Because the concentrations decrease and the rate constant increases, it cannot be determined, a priori, whether the rate increases or decreases. If the activation energy in the rate constant were known, a quantitative evaluation could be made.

20.3. Base-Case Ratios

The calculation tool provided in this section combines use of fundamental relationships with plant operating data to form a basis for predicting changes in system behavior.

The ability to predict changes in a process design or in plant operations is improved by anchoring an analysis to a base case. For design changes, it is desirable to identify a design proven in practice as the base case. For operating plants, actual data are available and are chosen as the base case. It is important to put this base case into perspective. Assuming that there are no instrument malfunctions and the operating data are correct, then these data represent a real operating point at the time the data were taken. As the plant ages, the effectiveness of process units changes and operations is altered to account for these changes. As a consequence, recent data on plant operations should be used in setting up the base case.

Establish predictions of process changes on known operating data, not on design data.

The base-case ratio integrates the "best available" information from the operating plant with design relationships to predict process changes. It is an important and powerful technique with wide application. The base-case ratio, X, is defined as the ratio of a newcase system characteristic, x_2, to the base-case system characteristic, x_1.

$$X \equiv x_2/x_1 \qquad\qquad (20.1)$$

Using a base-case ratio often reduces the need for knowing actual values of physical and transport properties (physical properties refer to thermodynamic and transport properties of fluids), equipment, and equipment characteristics. The values identified in the ratios fall into three major groups. They are defined below and applied in Example 20.2.

1. **Ratios Related to Equipment Sizes** (L_{eq}, equivalent length; diameter, D; surface area, A): Assuming that the equipment is not modified, these values are constant, the ratios are unity, and these terms cancel out.

2. **Ratios Related to Physical Properties** (such as density, ρ; viscosity, μ): These values can be functions of material composition, temperature, and pressure. Absolute values are not needed,

only the functional relationships. Quite often, for small changes in composition, temperature, or pressure, the properties are unchanged, and the ratio is unity and cancels out. An exception to this is gas-phase density.

3. **Ratios Related to Stream Properties:** These usually involve velocity, flowrate, concentration, temperature, and pressure.

Using the base-case ratio eliminates the need to know equipment characteristics and reduces the amount of physical property data needed to predict changes in operating systems.

The base-case ratio is a powerful and straightforward tool to analyze and predict process changes. This is illustrated in Example 20.2.

Example 20.2.

It is necessary to scale up production in an existing chemical plant by 25%. It is your job to determine whether a particular pump has sufficient capacity to handle the scale-up. The pump's function is to provide enough pressure to overcome frictional losses between the pump and a reactor.

The relationship for frictional pressure drop is given in Table 20.1. This relationship is now written as the ratio of two base cases as follows:

$$\frac{\Delta P_2}{\Delta P_1} = \frac{2\rho_2 f_2 L_{eq2} u_2^2 D_1}{2\rho_1 f_1 L_{eq1} u_1^2 D_2}$$

Because the pipe has not been changed, the ratios of diameters (D_2/D_1) and lengths (L_{eq2}/L_{eq1}) are unity. Because a pump is used only for liquids, and liquids are (practically) incompressible, the ratio of densities is unity. If the flow is assumed to be fully turbulent, which is usually true for process applications, the friction factor is not a function of Reynolds number. (This fact should be checked for a particular application.) Therefore, the friction factor is constant, and the ratio of friction factors is unity. The above ratio reduces to

$$\frac{\Delta P_2}{\Delta P_1} = \frac{u_2^2}{u_1^2} = \frac{\dot{m}_2^2/A_2^2\rho_2^2}{\dot{m}_1^2/A_1^2\rho_1^2} = \frac{\dot{m}_2^2}{\dot{m}_1^2}$$

where the second equality is obtained by substituting for u_i in numerator and denominator using the mass balance $\dot{m}_i = \rho_i A_i u_i$, canceling the ratio of densities for the same reason as above, and canceling the ratio of cross-sectional areas because the pipe has remained unchanged. Therefore, by assigning the base-case mass flow to have a value of 1, for a 25% scale-up, the new case has a mass flow of 1.25, and the ratio of pressure drops becomes

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{\dot{m}_2}{\dot{m}_1}\right)^2 = \left(\frac{1.25}{1}\right)^2 = 1.56$$

Thus, the pump must be able to deliver enough head to overcome 56% additional frictional pressure drop while pumping 25% more material.

It is important to observe that Example 20.2 was solved without knowing any details of the system. The pipe diameter, length, and number of valves and fittings were not known. The liquid being pumped, its temperature, and its density were not known. Yet the use of base-case ratios along with simple assumptions permitted a solution to be obtained. This illustrates the power and simplicity of base-case ratios.

20.4. Analysis of Systems Using Controlling Resistances

Design relationships for many operations such as fluid flow, heat transfer, mass transfer, and chemical reactors all involve rate equations of the general form

$$\text{Rate} = \text{Driving Force/Resistance.} \tag{20.2}$$

For resistances in series,

$$R_T \text{ (Total Resistance)} = R_1 + R_2 + R_3 + \cdots + R_N \tag{20.3}$$

For certain situations, one resistance dominates all other resistances. For example, if resistance R_1 dominates, then

$$R_1 \gg R_2 + R_3 + \cdots + R_N \tag{20.4}$$

and

$$R_T \approx R_1 \tag{20.5}$$

where R_1 represents the "controlling resistance." Other resistances have little impact on the rate. Only those factors that impact R_1 have a significant impact on the rate.

As an example, an overall heat transfer coefficient for a clean (nonfouling) service, U_o, can be expressed as

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{D_o \ln\left(\frac{D_o}{D_i}\right)}{2k} + \frac{D_o}{D_i h_i} \tag{20.6}$$

where D_o and D_i are the outer and inner tube diameters, respectively, k is the thermal conductivity of the tube material, and h_o and h_i are the outer and inner heat transfer coefficients. It is assumed that Equation (20.6) can be simplified by assuming $D_o \approx D_i$, and that the conduction resistance is negligible, so that

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_i} \tag{20.7}$$

Suppose that it is desired to use a base-case ratio of a new overall heat transfer coefficient, U_{o2}, to an original overall heat transfer coefficient, U_{o1}. For a situation when no phase change is occurring on either side of a shell-and-tube heat exchanger, from Equation (20.7), this ratio would be

$$\frac{\left(\dfrac{1}{U_{o1}}\right)}{\left(\dfrac{1}{U_{o2}}\right)} = \frac{U_{o2}}{U_{o1}} = \frac{\dfrac{1}{\alpha u_{i1}^{0.8}} + \dfrac{1}{\beta u_{o1}^{0.6}}}{\dfrac{1}{\alpha u_{i2}^{0.8}} + \dfrac{1}{\beta u_{o2}^{0.6}}} \tag{20.8}$$

where the individual heat transfer coefficients have been expressed as indicated in Table 20.1, and the proportionality factors α and β contain the lead constant and all of the properties contained in the dimensionless groups other than the heat transfer coefficient and the velocity. From Equation (20.8), it would not be possible, as it was in Example 20.2, to determine quantitatively how the overall heat transfer coefficient changes with changing velocity (i.e., mass flowrate) without knowing values for all of the physical properties. However, if it could be assumed that one resistance were dominant, the problem would be greatly simplified. For example, assume that a heat transfer fluid in the shell is heating a gas in the tubes. It is likely that the resistance in the tubes would dominate, given the low film heat transfer coefficient for gases. Therefore, the base-case ratio would reduce to

$$\frac{U_{o2}}{U_{o1}} = \frac{h_{i2}}{h_{i1}} = \left(\frac{u_{i2}}{u_{i1}}\right)^{0.8} \tag{20.9}$$

and it would be possible to predict a new heat transfer coefficient without having values for the physical properties.

The reduction of the heat transfer coefficient ratio using a limiting resistance described above is very powerful but must be used with care. It is not valid for all situations. It is most likely valid when one resistance is for a boiling liquid or condensing steam and the other resistance is for a liquid or gas without phase change. In other situations, the base-case ratio can be determined from Equation (20.8) only if the relative magnitude for each resistance is known for the base case, as is illustrated in Example 20.4. It is also important to understand that Equations (20.8) and (20.9) do not represent all possible base-case ratios arising in heat transfer. Each situation must be analyzed individually to ensure that a correct solution is obtained. Problems of this type are given at the end of the chapter.

Situations in which the simplifications leading to Equation (20.9) are valid, along with situations that require a form for the base-case ratio similar to Equation (20.8), will be applied to heat-exchanger performance in Chapter 21. Examples of how Equations (20.8) and (20.9) can be applied are presented in Examples 20.3 and 20.4.

Example 20.3.

It is desired to scale down process capacity by 25%. In a particular heat exchanger, process gas in the tubes is heated by condensing steam in the shell. By how much will the overall heat transfer coefficient for the heat exchanger change after scale-down?

Using the subscript 2 for the new, scaled-down operation and the subscript 1 for the original conditions, a scale-down of the mass flowrate of the process stream by 25% means that $u_{i2} = 0.75u_{i1}$. For a process gas heated by condensing steam, it is certain that the heat transfer coefficient for condensing steam will be at least 100 times as large as that for the process gas. Although Equation (20.9) is applicable, it is not derived from Equation (20.8) because of the phase change. The correct derivation is assigned in Problem 20.5 at the end of the chapter. The result is $U_{o2}/U_{o1} = (u_{i2}/u_{i1})^{0.8} = (0.75)^{0.8} = 0.79$, and the overall heat transfer coefficient is reduced by 21%.

Example 20.4.

In a similar process as in Example 20.3, there is a heat exchanger between two process streams, neither of which involves a phase change. It is known that the resistances on the shell-and-tube sides are approximately equal before scale-down. By how much will the overall heat transfer coefficient for the heat exchanger change after scale-down by 25%?

Here, Equation (20.7) is required. Because both original resistances are equal, both original heat transfer coefficients will be denoted h_1. In the tubes, $h_{i2}/h_1 = (u_{i2}/u_{i1})^{0.8}$, and in the shell $h_{o2}/h_1 = (u_{o2}/u_{o1})^{0.6}$. Both velocity ratios are 0.75. Therefore, Equation (20.7) reduces to

$$\frac{U_2}{U_1} = \frac{\dfrac{1}{h_1} + \dfrac{1}{h_1}}{\dfrac{1}{h_1\left(\dfrac{u_{i2}}{u_{i1}}\right)^{0.8}} + \dfrac{1}{h_1\left(\dfrac{u_{o2}}{u_{o1}}\right)^{0.6}}} = \frac{2}{\dfrac{1}{(0.75)^{0.8}} + \dfrac{1}{(0.75)^{0.6}}} = 0.82$$

and the new heat transfer coefficient is reduced by 18%.

20.5. Graphical Representations

At times, graphical representations are useful descriptions of physical situations. They provide a means to an intuitive understanding of a problem rather than a computational tool. Probably the best-known example of this is the McCabe-Thiele diagram for distillation. Even though no one would design a distillation column nowadays using this method, the McCabe-Thiele diagram provides a means for an intuitive understanding of distillation. Another example is the reactor profiles illustrated in Chapter 23.

In this section, three graphical representations that will be used to analyze performance problems are discussed.

20.5.1. The Moody Diagram for Friction Factors

An example of a graphical representation commonly used for illustrative and for computational purposes is the Moody diagram, which gives the friction factor as a function of Reynolds number for varying roughness factors. It is illustrated in Figure 20.1. Although this diagram is often used for numerical calculations, it also provides an intuitive understanding of frictional losses. For example, it is observed that the friction factor increases as the pipe roughness increases. It is also observed that the friction factor becomes constant at high Reynolds numbers, and the dashed line represents the boundary between variable and constant friction factor.
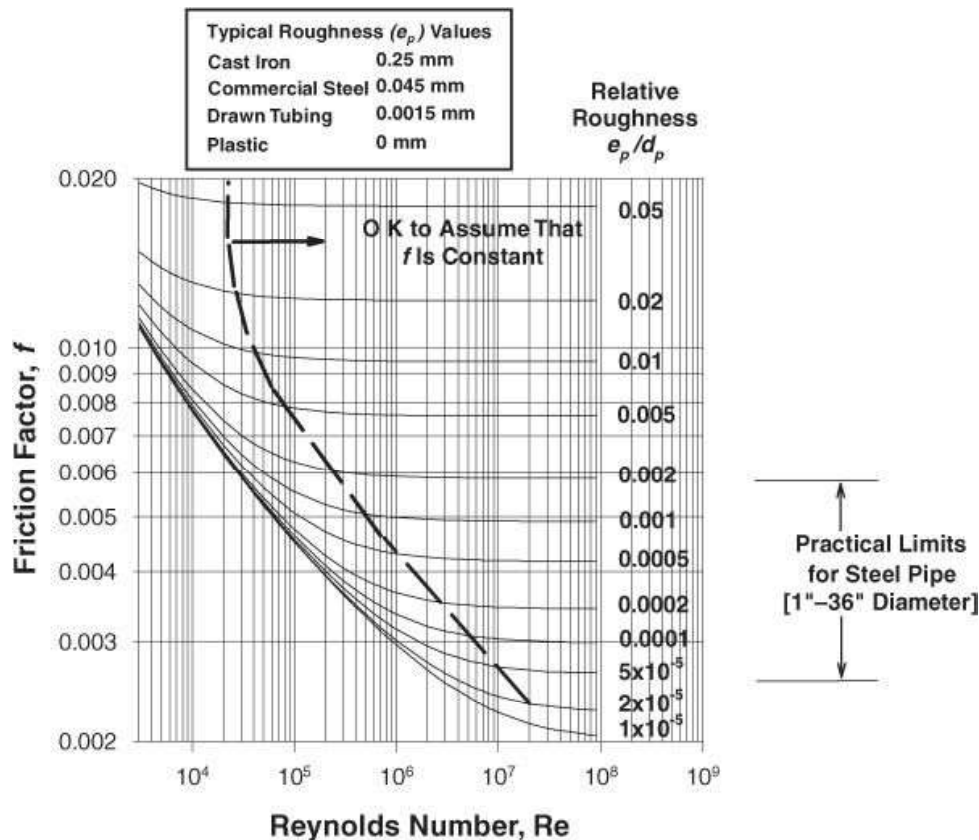

Figure 20.1. Moody Plot for Turbulent Flow in Pipes

20.5.2. The System Curve for Frictional Losses

In Table 20.1, an equation was given for frictional losses in a pipe. This equation is derived from the mechanical energy balance for constant density.

$$\frac{\Delta P}{\rho g} + \Delta z + \Delta \frac{u^2}{2g} - \frac{W_s}{g} + \frac{F_d}{g} = 0 \qquad (20.10)$$

In Equation (20.10), Δ means out $-$ in, and the specific energy dissipation due to drag, F_d, is a positive number. For a constant diameter length of pipe with no pump at constant elevation, $\Delta z = 0$, there is no work, the kinetic energy term is zero, and, using the expression for frictional losses, the result is

$$\Delta P = -\rho F_d = -\frac{2\rho f L_{eq} u^2}{D} \qquad (20.11)$$

If fully developed turbulent flow is assumed, the friction factor, f, is constant. For process changes involving the same fluid, the density remains constant, and if the pipe is unchanged, the equivalent length and diameter are unchanged. Therefore, Equation (20.11) describes how the pressure drop in a length of pipe changes with flowrate or velocity. This can be plotted as ΔP versus velocity, and the result is a parabola passing through the origin. This is called the **system curve** and will be shown in Chapter 21 to be a useful tool in evaluating pump performance.

If, for example, there were an elevation change over the length of pipe in question, there would be an additional term in Equation (20.11), and the result would be a parabola with a nonzero intercept. Examples 20.5 and 20.6 illustrate how a system curve is obtained.

Example 20.5.

Develop the system curve for flow of water at approximately 10 kg/s through 100 m of 2-in schedule-40 commercial steel pipe oriented horizontally.

The density of water will be taken as 1000 kg/m^3, and the viscosity of water will be taken as 1 mPa s (0.001 kg/m s). The inside diameter of the pipe is 0.0525 m. The Reynolds number can be determined to be 2.42×10^5. For a roughness factor of 0.001, $f = 0.005$. Equation (20.11) reduces to

$$\Delta P = -19u^2$$

with ΔP in kPa and u in m/s. This is the equation of a parabola, and it is plotted in Figure E20.5. Therefore, from either the equation or the graph, the pressure drop is known for any velocity.
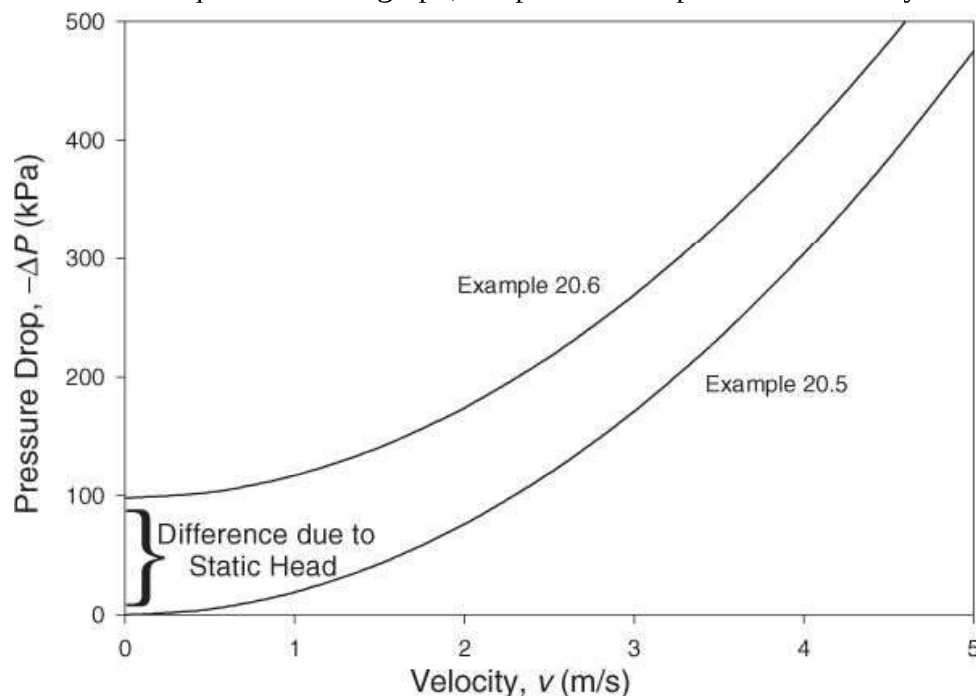
Example 20.6.

Repeat [Example 20.5](#) for pipe with a 10 m vertical elevation change, with the flow from lower to higher elevation.

Here, the potential energy term from the mechanical energy balance must be included. The magnitude of this term is 10 m of water, so $\rho g \Delta z = 98$ kPa. Equation ([20.10](#)) reduces to

$$\Delta P = -(98 + 19u^2)$$

with ΔP in kPa and u in m/s. This equation is also plotted in [Figure E20.5](#). It is observed that the system curve has the same shape as that in [Example 20.5](#). This means that the frictional component is unchanged. The difference is that the entire curve is shifted up by the constant, static pressure difference.

20.5.3. The *T-Q* Diagram for Heat Exchangers

Another example of a useful diagram that illustrates the behavior of a piece of equipment is the *T-Q* diagram for a heat exchanger. [Figure 20.2](#) illustrates a *T-Q* diagram for the countercurrent heat exchanger with no phase change shown in the figure.
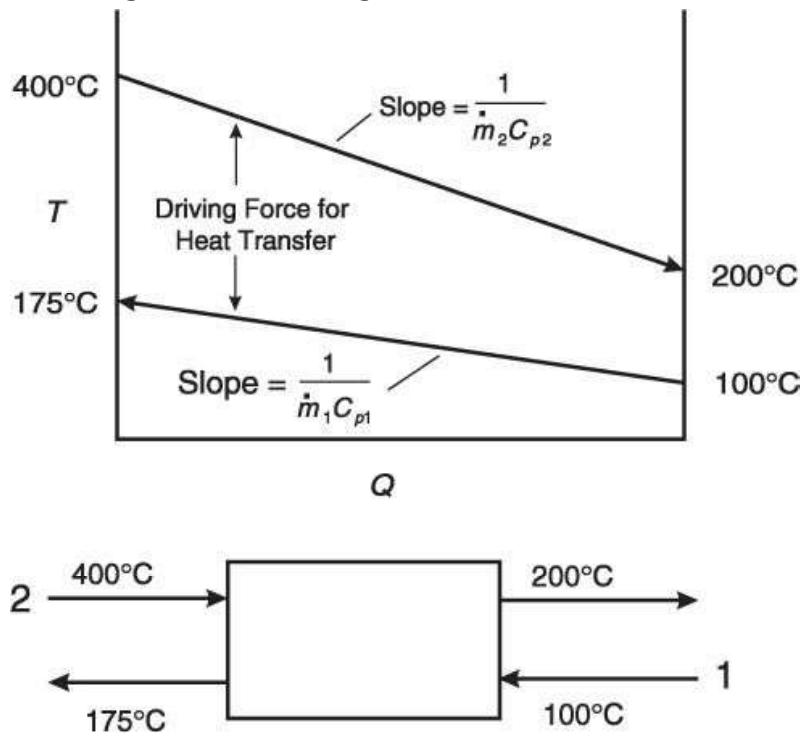

Figure 20.2. Example of *T-Q* Diagram

A *T-Q* diagram is a visual representation of the energy balance equation for each stream. Because, for single-phase streams with constant C_p and no pressure effect on the enthalpy,

$$Q = \dot{m}C_p\Delta T \tag{20.12}$$

process streams that undergo no phase change are represented by a line with a slope of $1/(\dot{m}C_p)$.

Because, for pure component streams undergoing a phase change process streams that involve constant temperature phase changes (pure component vaporizers and condensers) are represented by a

horizontal line.

$$Q = \dot{m}\lambda \qquad (20.13)$$

The temperature differences between the two streams shown on the *T-Q* diagram provide the actual temperature driving force throughout the exchanger. The greater the temperature separation, the larger the driving force (ΔT_{lm}), and the greater the heat transferred.

The representations described above are for simple situations commonly encountered. However, more complex cases exist. If the heat capacity is not constant, then the line for heat transfer without phase change is a curve. For phase changes involving multicomponent systems, because the bubble and dew points are at different temperatures, the line representing the phase change is not horizontal. For partial condensers and vaporizers, the representation on a *T-Q* diagram is a curve rather than a straight line.

The *T-Q* diagram reveals two important truths regarding heat transfer:

1. **Temperature Lines Cannot Cross:** This is an impossible situation. Temperature lines will never cross when dealing with operating equipment. If a temperature cross is encountered in doing a calculation, an error has been made.

2. **Temperature Lines Should Not Approach Each Other Too Closely:** As temperature lines approach each other, the area required for a heat exchanger approaches infinity. The point of closest approach is called the pinch point. When dealing with multiple heat exchangers, the pinch point is a key to heat-exchanger network integration, that is, determining the configuration for most efficient heat transfer between hot and cold streams. This concept was discussed in Chapter 15.

Example 20.7 illustrates the construction of *T-Q* diagrams.

Example 20.7.

Sketch a *T-Q* diagram for the following situations:

a. A single-phase process stream is heated from 100°C to 200°C by condensation of saturated steam to saturated liquid at 250°C in a countercurrent heat exchanger.

b. A single-phase process stream is heated from 120°C to 220°C by condensation of saturated steam at 250°C and subcooling of the condensate to 225°C in a countercurrent heat exchanger.

The solution to Part (a) is shown in Figure E20.7(a). The horizontal line at 250°C is for the steam condensing at constant temperature. The sloped line is for heating of the process stream. The arrow on the sloped line indicates the direction of flow of the process stream, because it is being heated. The arrow on the condensing steam line is opposite because of countercurrent flow.

The solution to Part (b) is shown in Figure E20.7(b). The difference from Part (a) is the subcooling zone. It is important to understand that when there is a pure-component phase change, there must be a horizontal portion of the line. It is incorrect to draw a single straight line between the two end temperatures. In fact, due to the amount of heat associated with phase changes relative to the heat in temperature changes, the horizontal portion associated with the phase change will almost always be the longer segment.
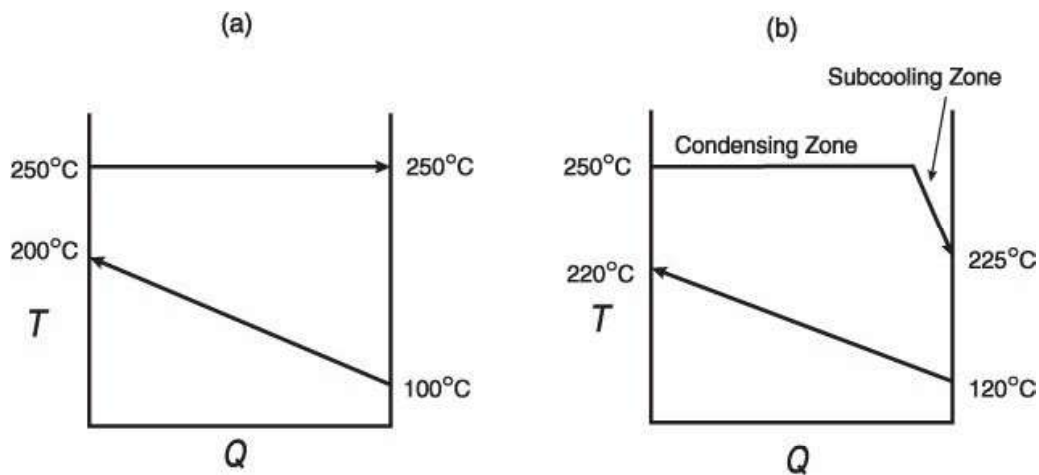
Figure E20.7. Solutions to Example 20.7

20.6. Summary

In this chapter, several important tools were introduced that are essential in analyzing equipment performance problems. Base-case ratios are the most important tool. They permit comparison of two cases, usually without complex calculations, and often without the need to know physical and transport properties. Under the circumstances for which it is valid, using a limiting resistance simplifies the base-case ratio. Finally, graphical representation of equipment performance is a useful tool in understanding the physical situation. All these techniques require a minimum of calculations. However, they do provide an intuitive understanding of equipment performance that is very rarely achieved from merely doing repetitive, complex computations.

What You Should Have Learned

- There are important relationships, probably taught in earlier classes, that are used to evaluate process performance.
- For small variations in process parameters and physical properties, ratios are a powerful tool for analyzing chemical process performance.

Reference

1. Wales, C. E., and R. A. Stager, *Thinking with Equations* (Morgantown, WV: West Virginia University, 1990).

Problems

1. It is known that for a certain second-order, elementary, gas-phase reaction, the rate of reaction doubles when the temperature goes from 220°C to 250°C. If the rate of reaction is 5 mole/m^{3}s at the base conditions, which are 10 atm pressure and 225°C, and the feed is pure reactant (no inerts), answer the following questions:

   a. Compared to the base case, by how much does the rate of reaction (at inlet conditions) change if the temperature is increased to 245°C at constant pressure?

   b. Compared to the base case, by how much does the rate of reaction (at inlet conditions) change if the pressure is increased by 10%?

2. A storage tank is connected to a pond (at atmospheric pressure!) by a length of 3-in pipe and two gate valves. From previous operating experience, it has been found that when the tank is at a pressure of 3 atm, the flow through the pipe is 12.5 m^3/h, when both gate valves are fully open. If the pressure in the tank increases to 5 atm, what will be the maximum discharge rate from the tank?

3. In a single-pass shell-and-tube heat exchanger, cooling water is used to condense an organic vapor. Under present operating conditions, the heat transfer coefficients are h_o = 2000 W/m^2K (turbulent flow of cooling water), h_i = 700 W/m^2K. Fouling is negligible, and the tubes are 1.25-in 16-BWG carbon steel. Water flows in the shell. If the cooling water rate were to rise suddenly by 15%, estimate the change in overall heat transfer coefficient. Clearly state all assumptions made.

4. In a shell-and-tube heat exchanger, the overall and individual heat transfer coefficients are U = 300 W/m^2K, h_i = 1000 W/m^2K, and h_o = 500 W/m^2K. Both the shell-side and the tube-side fluids are liquids, and no change of phase occurs. The flow of both fluids is turbulent.

   a. Estimate the new value of U if the flowrate of the shell-side fluid is decreased by 20%.

   b. Estimate the new value of U if the flowrate of the tube-side fluid is decreased by 20%.

   c. Estimate the new value of U when both situations in Parts (a) and (b) exist.

5. Derive the relationship, identical to Equation (20.9), for the situation described in Example 20.3.

6. You are considering two pipes to connect liquid leaving a pump to the entrance to a reactor. For a given mass flowrate of liquid, how much operating cost would you save (or lose) by using 2.5-in schedule-40 pipe rather than 3-in schedule-40 pipe? The pump runs on electricity, and electricity costs $0.06/kWh. The pump efficiency is 80%.

7. For laminar flow of a Newtonian liquid in a pipe, determine the effect on flowrate of the following changes:

   a. The pressure drop triples (everything else remains constant).

   b. The pipe is changed from 1.25-in schedule-40 to 2-in schedule-40 (everything else remains constant).

   c. The viscosity of the fluid is increased by 50% (everything else remains constant).

   d. The equivalent length of pipe is decreased by an order of magnitude (everything else remains constant).

   e. (a) and (b)

   f. (a) and (c)

   g. (b) and (d)

8. Sketch T-Q diagrams for the following situations:

   a. The condenser on a distillation column; vapor condenses at 160°C and is sub-cooled to 130°C, cooling water enters at 30°C and exits at 40°C.

   b. The reboiler on the same distillation column; vapor is reboiled at 240°C, and saturated, high-pressure steam is condensing to saturated water.

   c. Methanol, initially at 30°C and atmospheric pressure, is vaporized to 150°C and atmospheric pressure, and saturated, medium-pressure steam is condensed to saturated water.

9. Air at approximately STP and 15 kg/s flows through 100 m of 8-in commercial steel schedule-40 pipe. Derive an expression for the system curve and sketch the system curve for this situation.

10. In a batch reactor, a first-order, irreversible, liquid-phase reaction, A → B, occurs. The initial concentration is C_{Ao}.

   a. By what percentage must the reaction time be increased to raise the conversion of A from 0.9 to 0.95?

   b. If the initial conversion is 0.8, what will the final conversion be if the reaction time is increased by 50%?

11. Repeat Problem 20.10 for a catalytic/enzymatic reaction with a rate expression of the form

$$-r_A = \frac{K_1 C_A}{1 + K_2 C_A}$$