7

Fluid Flow, Pumps, and Liquid Handling and Gas Handling

This will be the first of the chapters related to the technical aspects of chemical engineering. As stated earlier, we tend to group chemical engineering studies and analyses by the term "unit operations." Fluid flow will be the first of these to be discussed.

Let's first define what we mean by a fluid flow. It is the flow of material through a *bounded* region (i.e., pipe) as opposed to the flow of a liquid or gas in an uncontrolled way, such as a vapor release or leaking tank. The behavior and properties of fluids affect how pumps, reactors, compressors, valves, and relief valves are designed and operated.

Fluid Properties

There are a number of fluid properties that affect how fluids behave as well as how much energy is required to move them:

Density is the weight per unit volume of a fluid. Water has a density of $62.4 \, \#/\text{ft}^3$ or $1000 \, \text{kg/m}^3$. There is a widespread in various fluid densities, as seen in Table 7.1 with approximate density values.

Table 7.1 Densities of common fluids.

Gasoline	$720 \, \text{kg/m}^3$
Liquid ammonia	$682 \, \text{kg/m}^3$
Liquid chlorine	$1442 \, \text{kg/m}^3$
Liquid bromine	$3100 \, \text{kg/m}^3$
Crude oils	$816\text{–}880 \, \text{kg/m}^3$
Milk	$1035 \, \text{kg/m}^3$
Blood	$1065 \, \text{kg/m}^3$
Mercury	$13\,500 \, \text{kg/m}^3$

Source: Public literature sources, averaged.

The density of gases is several orders of magnitudes less. The density of air at atmospheric conditions is around $1.25\,kg/m^3$. Increased pressure will raise these numbers. Some approximate additional gas densities are shown in Table 7.2.

Table 7.2 Density of common gases.

Ammonia	$0.73\,kg/m^3$
Chlorine	$3.20\,kg/m^3$
Bromine gas	$4.4\,kg/m^3$
Propane	$1.9\,kg/m^3$
Methane	$0.7\,kg/m^3$
Carbon dioxide	$1.9\,kg/m^3$
Steam	$0.59\,kg/m^3$
Hydrogen	$0.09\,kg/m^3$

Source: Public literature sources, averaged.

The higher the density of a fluid, the more energy is required to move or pump it. The densities of most fluids and gases commercially used are readily available online, in handbooks, or from manufacturers of the materials.

Viscosity is an important physical property, often overlooked in fluid flow calculations. It is stated in a number of ways. The *dynamic viscosity* is a measure of a fluid's resistance to flow. We can envision this with a fluid between two solid surfaces and we move one of the surfaces. How much force does it take to cause the fluid to move? It is basically a measure of a fluid's resistance to shear and has the units of #/ft s. 1 #/ft s. is one *poise*. It is represented in equations and calculations by the symbol μ. Many common fluids have viscosities in the range of 1 centipoise (0.01 poise), normally designated as 1 cP. As opposed to density, the viscosity of a fluid changes dramatically (orders of magnitude in some cases) with temperature. As a reference, the viscosity of water at room temperature is about 1 cP. Table 7.3 gives some ranges of viscosities of some common fluids.

Table 7.3 Dynamic viscosities of common fluids.

Gasoline	0.4–0.9 cP
Liquid ammonia	0.27 cP
Liquid chlorine	0.33 cP
Conc. Sulfuric acid	24 cP
Motor oils	65–315 cP
Molasses	5–10 000 cP
Blood	3–4 cP
Catsup	50–100 000 cP

Source: Public literature sources, averaged.

An increase in viscosity will make the liquid more resistant to flow (and thus harder to pump) and the converse is true. As opposed to density, viscosity is greatly affected by temperature. Table 7.4 gives the data for water.

Table 7.4 Viscosity of water versus temperature.

Water viscosity (cP)	Temperature (°C)
1.31	10
1.00	20
0.65	40
0.55	50
0.40	70
0.32	90
0.28	100

Source: Public literature sources, averaged.

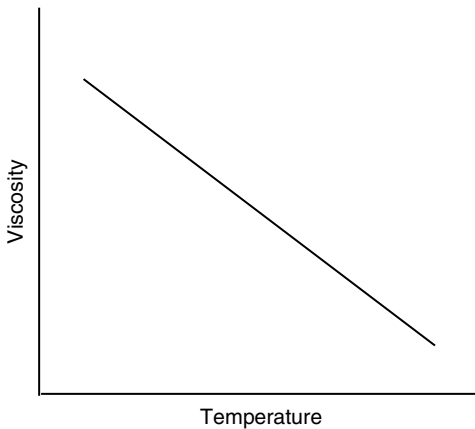In general, the viscosity of a fluid is logarithmic with temperature, as shown in Figure 7.1.

Figure 7.1 General response of viscosity to temperature.

This graph mirrors the dramatic drop in viscosity seen in the tabular data.

Another factor that affects actual viscosity is the response of viscosity to shear. In other words, how does a fluid's viscosity change (if at all) to the effect of the fluid being put under shear? Examples would include agitation, pumping, or mixing. There are four different classes of fluids:

1) Newtonian. A Newtonian fluid is one whose viscosity changes little with shear. Water, gasoline, and alcohols are examples of such fluids. Remember it still responds to a change in temperature!

2) Thixotropic. A thixotropic (shear thickening) fluid is one whose viscosity *decreases* with increasing shear but then returns to its higher viscosity state when the shear is removed. Examples include many inks (flow when applying but then stay where they're put), as well as paints, solder pastes, and quicksand.

3) Dilatant. A dilatant fluid is one whose viscosity increases with shear. Examples include a corn starch/water suspension or a transmission fluid.

4) Bingham plastic. This is an unusual fluid type whose viscosity versus shear curve is similar to a Newtonian fluid but not until a certain stress level is reached. In other words, the fluid is semisolid until a certain level of shear is applied, and then it begins to flow as a Newtonian fluid. Examples include drilling fluids and muds and catsup (ever tried to get catsup to flow out of a bottle?). A graphical display of these different classes of fluids is shown in Figure 7.2.
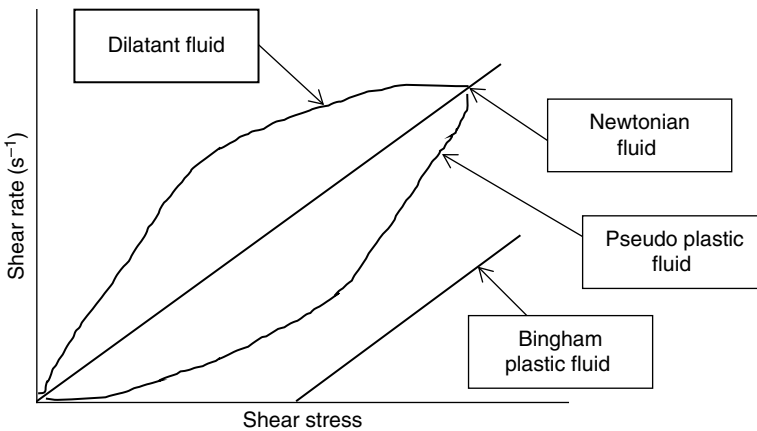

Figure 7.2 Shear versus stress for a variety of fluid types.

From this overview, it is obvious how important it is, when designed a fluid handling system, to be aware of the types of fluids being handled as well as well as their response to process conditions.

Kinematic viscosity is the ratio of dynamic viscosity to density, thus taking into account the density of the fluid.

The addition of solids to a liquid (creating a slurry) adds additional complexity to fluid behavior and analysis. The addition of solids can change the shape of the response curve for shear versus stress and needs to be carefully measured over the entire range of solids expected to be handled. In most cases, the addition of solids, creating a slurry, will increase the solution's viscosity. The exact change will be affected by solids concentration, particle size, and nature of starting liquid's viscosity.

As opposed to liquids, gas viscosities *rise* with temperature and generally follow an equation of the following type:

$$\mu = \mu_0 + \alpha T + \beta T^2$$

These constants, alpha and beta, must be experimentally determined or found in literature sources. Gas viscosity is also affected by pressure, whereas in liquid systems, this is not usually the case. Since processing of gases is very common in the hydrocarbon area and there is a large range of pressures and temperatures, it is important to have the knowledge of the gas viscosity response to temperature. Table 7.5 shows this type of data for air.

Table 7.5 Air and water viscosities versus temperature.

	Temperature (°F)	0	20	60	100
Air viscosity	# s/ft^2	3.38	3.50	3.60	3.94

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Characterizing Fluid Flow

One of the key ways we characterize a fluid is how *turbulent* its flow is in a pipeline (there are some analogous ways of analyzing turbulence in a vessel, which we will cover in Chapter 16). If a fluid is not mixed thoroughly within a pipeline, there is insufficient kinetic energy to overcome the fluid adhesion to the wall of the pipe; if the velocity is high enough, the flow (kinetic) energy is sufficient to overcome the fluid/wall adhesion. If we were to look at the velocity profiles across the pipe for these two types of flow, we would see profiles as shown in Figure 7.3. The linear profiles shown for turbulent flow are never an exact straight line as there is always a small amount of wall adhesion no matter what the velocity of the fluid is.

The flow with uneven distribution of flow velocity is called *laminar* flow, while the well-mixed flow distribution at a higher velocity is called *turbulent* flow.
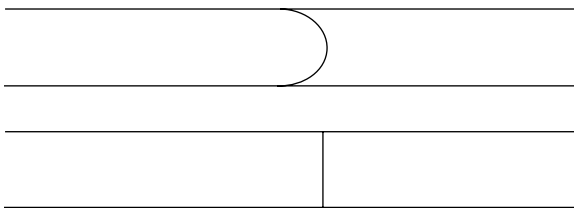

Figure 7.3 Velocity profiles: laminar versus turbulent flow.

Velocity is not the only parameter affecting which flow domain we are in but also the liquid physical properties and the diameter of the pipe. We can calculate what we call the *Reynolds number* for any fluid in a pipe with this equation:

$$N_{Re} = \frac{DV\rho}{\mu}$$

Where D is the pipe diameter, V is the velocity in the pipe, ρ is the density of the fluid, and μ is the liquid viscosity. Remember that we need to be consistent in the units we use in this calculation. This is a *dimensionless* number (and there are many in chemical engineering). In other words, if we plug numbers and units into this equation, we should have a number without any units. For example, if we have a fluid of 60 #/ft^3 density and a viscosity of 0.002 #/ft s. (2 cP) flowing at a rate of 5 ft/s in a ½ ft (6″ pipe), we would calculate the Reynolds number to be

$$\frac{0.5 \ ft. \times 5 \ ft./s \times 60 \ \#/ft.^3}{0.002 \ \#/ft. \ s}$$

or 75 000 (and that number would have no units as all unit values would cancel out in the equation). We know from our experiments with flow in glass pipe studies that a Reynolds number below 2 000 implies laminar flow while a Reynolds number above 4 000 ensures turbulent flow. In between these numbers, things are not so clear and additional study may be needed to determine the flow regime. If we just look at the Reynolds number equation, we can think through some practical aspects of flow:

1) Increasing velocity will increase turbulence and the Reynolds number (but also increase pressure drop). Decreasing pipe diameter will have the same effect.
2) Increasing the density of a fluid will decrease the velocity and Reynolds number. Higher density fluid takes more energy to move.
3) Increasing viscosity (think maple syrup vs. water) will decrease the Reynolds number and velocity, thus making it more difficult to mix in a pipeline.

An additional general area of importance in sizing piping and pumps is the pressure drop through process piping. When process piping is new, there are no special pressure drop concerns other than to do the initial calculations correctly. However, over time additional friction loss can develop due to corrosion or buildup of materials on the inner surface of process piping.

This additional friction loss is accounted for by what is known as the Fanning friction factor, or "f." It is basically the percentage increase in pressure drop over time, determined through knowledge of the Reynolds number (degree of turbulence) and the relative roughness of the inner pipe surface. This can change over time due to corrosion products and contamination. These two factors are plotted in logarithmic fashion against each other, and we see a
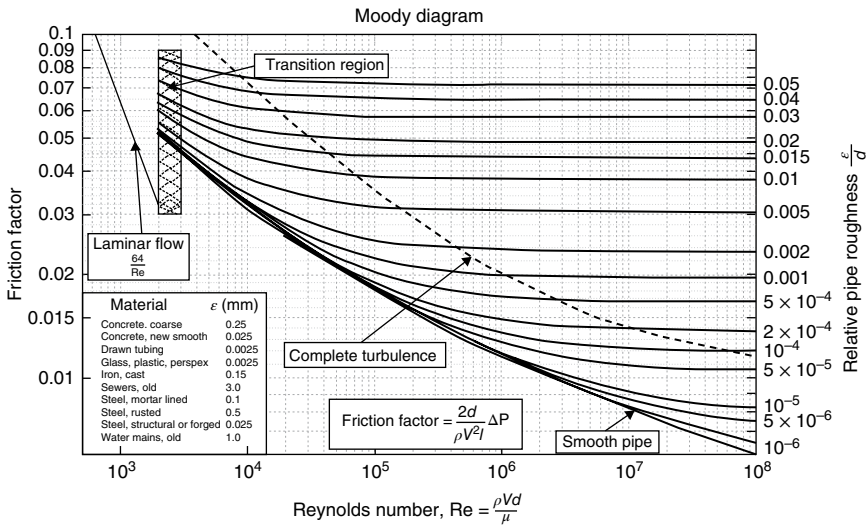
Moody diagram

Figure 7.4 Friction factor versus Reynolds number. Source: Beck and Collins, https://commons.wikimedia.org/wiki/File:Moody_diagram.jpg. Used under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/deed.en

logarithmic estimate of the friction factor that needs to be added to take into account the anticipated loss of pipe diameter. As seen in Figure 7.4, the net results are typically in the area of a few percent and are shown on a Moody diagram. Whether this is important or not depends upon how close the design was initially, the type of piping material, and the surface roughness. Figure 7.4 also shows some relative roughness factors for such materials as concrete, glass, and steel.

Figure 7.5 shows a simple pumping system moving a fluid from one tank to another.
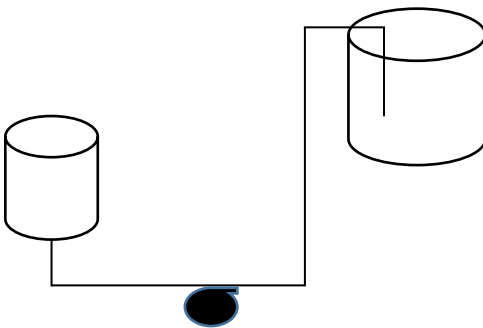

Figure 7.5 Pumping from one tank to higher level tank.

Review Figure 7.5 and make a list of all the pressure drop causes that would have to be taken into account in sizing the pump.

Sources of pressure drop:

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

We should consider, first of all, the level differences between the two vessels. Second, the rate at which we desire to pump the liquid (e.g., gal/min or GPM). Third, the total length of the process piping. Fourth, each time the piping makes a directional change, there is an added pressure drop. In this case there are four elbows that will add to the pressure drop. This diagram has no valves or in-line measuring devices, but if it did, they would also be major sources of pressure drop.

We would also consider the fluid properties. This would include its density and viscosity, both of which will affect the pressure drop significantly. If these properties changed over time, the pressure drop would also change with time.

Pump Types

There are two general classifications of fluid pumps: centrifugal and positive displacement. Within these two general classifications, there are many subsets of design.

If we were to open up a centrifugal pump and view it in a cross section, we would see something similar to that shown in Figure 7.6.
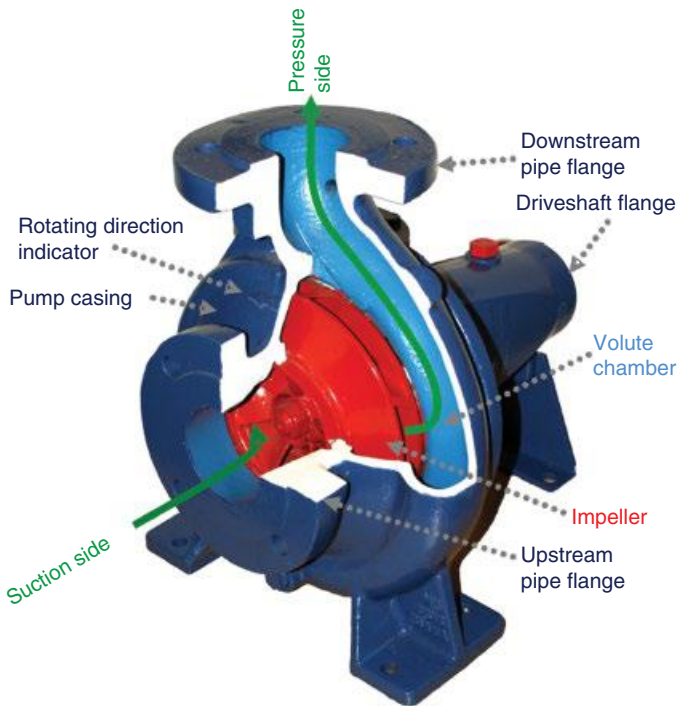
Figure 7.6 Internal view of a centrifugal pump. Source: Fantagu, https://commons. wikimedia.org/wiki/File:Centrifugal_Pump.png

The rotation of the blades converts the electrical power supplied to the pump to a "velocity head" or its equivalent pressure. The impeller is the rotational device internal to the pump, which rotates and transfers the motor's electrical energy into rotational energy. This type of pump does NOT produce constant flow under all conditions; it supplies a certain amount of energy via its rotational energy. The "head" for all fluids will not be the same. For example, the head or pressure produced by this type of pump will be higher for a low density fluid and lower for a high density fluid. Head and pressure are interchangeable and are related by the density of the fluid.

Any particular centrifugal pump will have what is referred to as a *characteristic curve*, supplied by its manufacturer, and it will look similar to that shown in Figure 7.7.
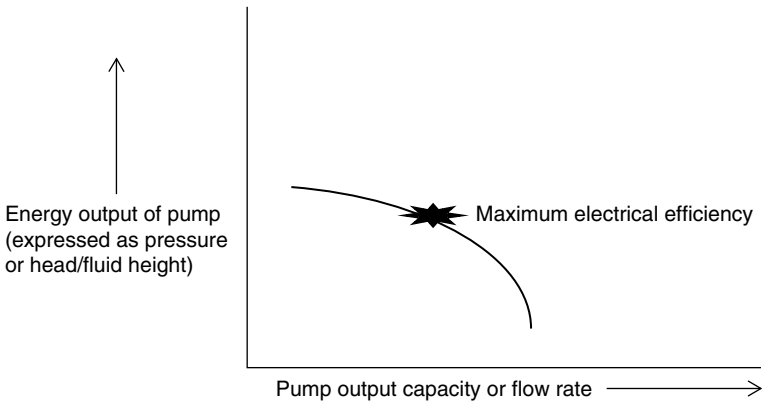
Figure 7.7 General pump curve.

As we can see, the head (or pressure) produced by this pump is inverse to its output. It is not possible to have both high flow and high head or pressure output with this type of pump. The pump will operate anywhere along this curve by controlling or varying process conditions, and the vendor usually indicates on the curve the highest electrical efficiency point for the pump's operation. At the extremes of this curve, maximum flow is achieved at minimum pressure or head output, and maximum flow is seen at minimum head or pressure output. It is not necessary to operate the pump here, but it is best to come as close to it as possible from an energy efficiency standpoint. This curve is unique to this pump with a specific size impeller (this is the diameter of the circulating veins in the pump shown earlier) in it. The shape of this curve can be shifted by changing the impeller size, internal to the pump, as shown in Figure 7.8.

The higher the flow or head generated by the pump, the more horsepower is required to drive it. Let's take a look at the centrifugal pump from an energy use standpoint (see Figure 7.9).

The hydraulic power needed by any given pump, P_h, will be a function of the flow rate (q), density of the fluid (ρ), and the differential height (including other pressure drop). "g" is the gravitational conversion constant in the units required. Note again the previous comments about unit consistency to ensure accurate calculations:

$$P_h(kW) = \frac{q\rho g h}{3.6 \times 10^6}$$

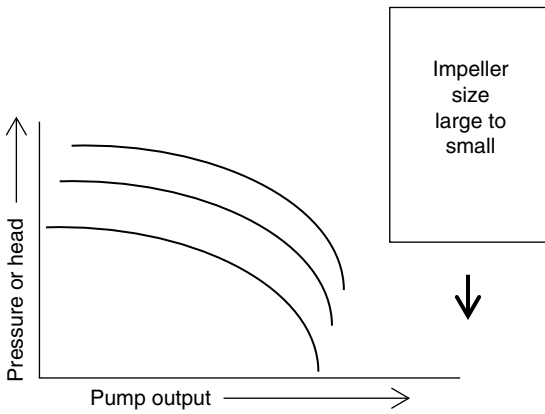where P_z, the electrical power supply, is the $P_h/0.746$.

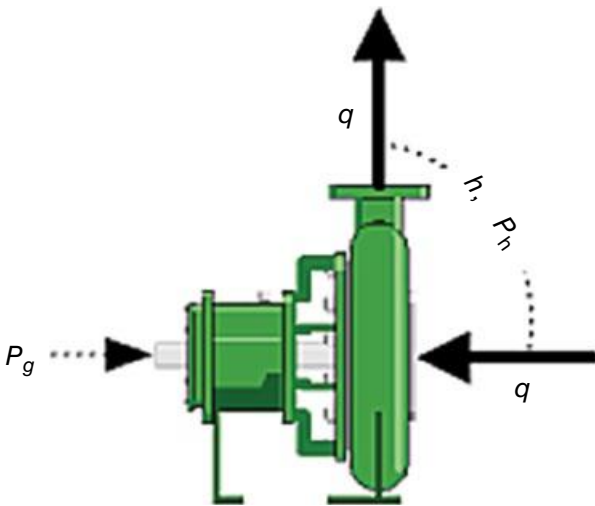**Figure 7.8** Pump output versus impeller size.

Figure 7.9 Energy use in a centrifugal pump. Source: Reproduced with permission of Engineering Toolbox.

Figure 7.10 shows a general representation of power requirements across a broad range of conditions.

The point of this analysis is not to memorize the equations (unless you are in the pump business) but to understand the variables that can affect a pump's performance. We can see, for example, that if a fluid's density is increased, the power requirements will increase proportionally, as will an increase in height difference.
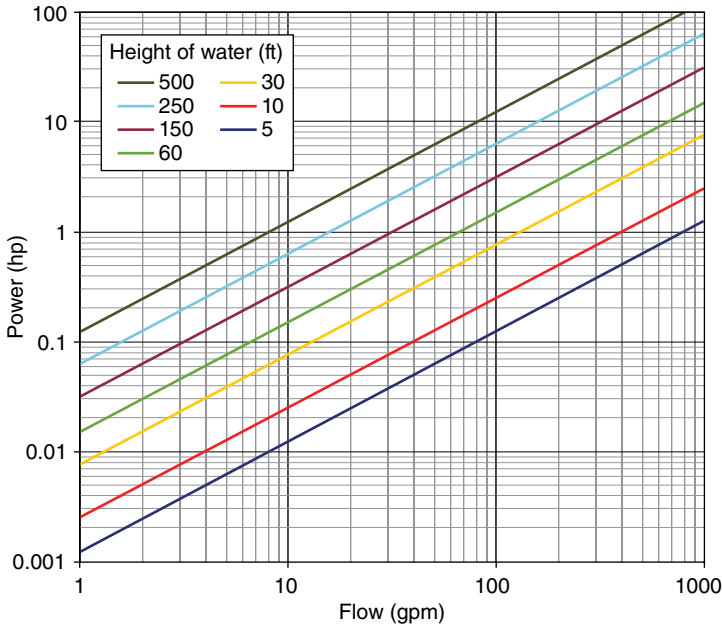
Figure 7.10 Shaft HP versus flow and height. Source: Reproduced with permission of Engineering Toolbox.

Net Positive Suction Head (NPSH) for Centrifugal Pumps

Another key mechanical design parameter in choosing a centrifugal pump for a particular application is to ensure that the pump's NPSH is at least what the system requires. NPSH is the minimum suction head (the sum of all the hydraulic pressure drops *ahead* of the pump's suction minus the vapor pressure of the fluid being pumped). Let's take the example of a tank holding 10 ft of liquid having a density of 0.8 (compared to water) and the equivalent of 2 ft of piping pressure drop between the tank and the pump. Let's also assume that the fluid in the tank is at a temperature where its vapor pressure is the equivalent of 1 ft of liquid $(1/14.7 \times 0.8)$ feet. This means that the head available to the pump is $(10 \times 0.8) - 2 - 0.05 \times 0.8$ or just under 6 ft. The pump purchased for this service must be able to function on this amount of suction head. Otherwise, the energy supplied to the pump will be sufficient to boil the fluid in the pump, causing severe mechanical damage to the pump, including severe vibration and the pump potentially coming off its support base. Every pump

purchased from a vendor will include this information. Because of unique and sometimes proprietary pump designs, it is possible for different pumps in the same general service area to require different NPSHs.

There are two frequently overlooked aspects of centrifugal pump design that occur. The first is a simple change in tank levels, either on the intake or discharge side of the pump, changing the pump output and its efficiency or allowing the operating conditions to go below the minimum NPSH required. The second is ignoring changes in the temperature of the fluid. An increase in fluid temperature feeding the pump will reduce the inlet pressure and its output and energy efficiency and affect the NPSH available. Fluids inside pumps with insufficient NPSH will boil (energy balance: the energy going into the pump needs to go somewhere), potentially causing significant stress and possible breakage of piping connections.

Positive Displacement Pumps

These are pump designs that generate a fixed amount of *flow* relatively independent of suction head available. These are usually piston or diaphragm pumps, which act on the principle of positive volume displacement versus generation of pressure or head. A gear pump is an example of such a pump:
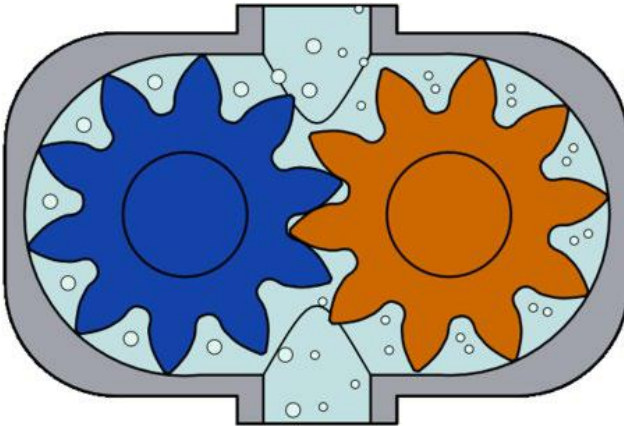
Figure 7.11 Gear pump. Source: https://commons.wikimedia.org/wiki/File:Gear_pump_ animation.gif. Used under CC0 1.0, https://creativecommons.org/publicdomain/zero/1.0/ deed.en. © Wikipedia.

Another example would be a diaphragm pump (Figure 7.12). The two diaphragms pulsate out of phase 180°, so if more continuous flow is desired, several of these pumps must be installed and operated out of phase with each
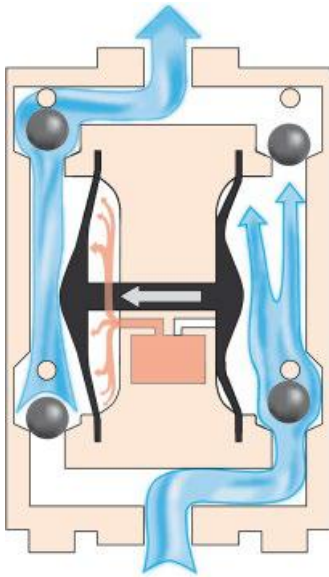
Figure 7.12 Diaphragm pump. Source: Samtar, https://commons.wikimedia.org/wiki/ File:Diaphragm_pump_animated.gif. Used under CC BY-SA 4.0, https://creativecommons.org/licenses/by- sa/4.0/deed.en. © Wikipedia.
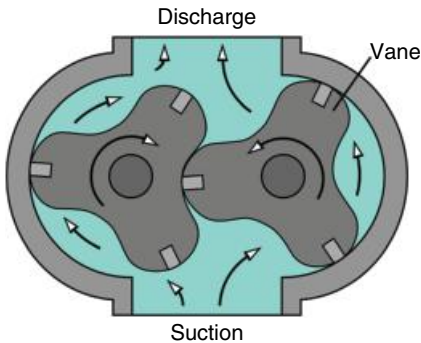
Figure 7.13 Rotary lobe pump. Source: https://commons.wikimedia.org/wiki/ File:LobePump_en.svg. Used under CC0 1.0, https://creativecommons.org/publicdomain/ zero/1.0/deed.en. © Wikipedia.

other. In order to have this type of pumping system deliver a more constant flow, one of more of them must be out of phase with each other to fill in the gaps and even out the flow.

A rotary lobe pump is another example of such a pump (Figure 7.13). There is one special safety aspect of positive displacement pumps that needs to be considered, and that is that they have the capability, since they are delivering constant flow, of creating vacuum on the suction side of the pump and the feed vessel must be designed to survive under vacuum or some kind of safety

system must be in use to prevent a vacuum from being created. Also, since there is constant delivery of pressure output, the piping and all downstream equipment must be capable of handling the maximum potential pressure output of this kind of pump.

Variable Speed Drive Pumps

Another approach to varying and controlling the flow output from the pump is to use a variable speed drive motor, instead of constant speed motor whose output is typically throttled by a control valve on either sides of the pump. Their typically higher capital cost may be offset by energy savings in situations where there is constant valve cycling to control flow.

Water "Hammer"

Regardless of the type of pump being used, a general safety rule is not to make sudden changes in valving downstream of the pump, especially with positive displacement pumps. If we shut a valve suddenly downstream of the pump, preventing flow, the energy being put into the fluid must go somewhere (energy balance) and in this case will cause large vibration in the piping system possibly causing pipe breakage and, in rare cases, cause the pump to leave its support stand—all very dangerous situations.

Piping and Valves

The pump is only one part of a fluid handling system. Other parts include piping, valves, metering, and instrumentation. The diameter and type of piping (metal, plastic, plastic lined, etc.) will be chosen based on cost, corrosion properties, and pressure drop, and as mentioned several times already, there will seldom be one right choice. Piping is rarely simply just a straight line of pipe of one size in one direction. There will be elbows, joints, and connections of various types. Examples include tees (one line splitting into two), elbows (change in direction), couplings, reducing couplings, unions (straight line connection to allow access), and caps and plugs to allow access. From a practical standpoint, these are chosen for maintenance reasons, but each has a different impact on flow pressure drop and must be taken into account in sizing the pumping system.

Valves are chosen to control or modify flow and can be gate valves, butterfly valves, globe valves, and others. We will discuss these in more detail in our chapter on process control. But as with piping and valves, the pressure drop across valves must also be considered in the design of the liquid handling system and the choice of the pump.

Flow Measurement

There are many different ways of measuring flow, either as a mass unit or as a volume unit. If the density of the fluid is known to be constant, then volumetric flow measurement may be sufficient. In this case, there are several types of measuring devices commonly used.

One of the most commonly used is the orifice plate as shown in Figure 7.14.

The flow in the pipe goes through a fixed plate with a hole in it within the piping system. Based on the density of the fluid, the ΔP across the hole, and the ratio of the plate hole size to the pipe size, the volumetric flow rate can be calculated. The pressure in the pipeline will eventually recover. Another approach is to use a venturi meter as shown in Figure 7.15.
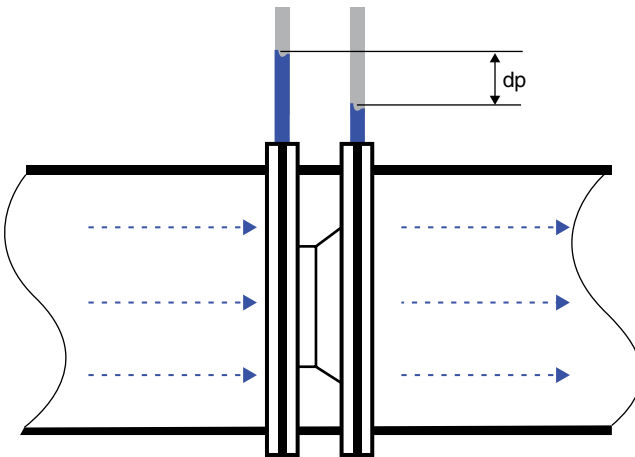

Figure 7.14 Orifice flow meter. Source: Reproduced with permission of Engineering Toolbox.
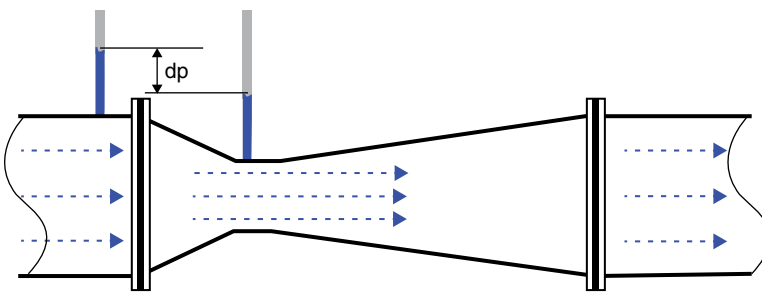

Figure 7.15 Venturi meter. Source: Reproduced with permission of Engineering Toolbox.

This type of meter operates under the same principle as the orifice meter, but since its geometry reduction is gradual on both sides of the ultimate hole, its pressure drop is less and the measurement is more accurate. But as you might expect, the cost is higher. Again, choices!

When it is important to know the actual mass (as opposed to volume) of flow, a Coriolis meter is frequently used:
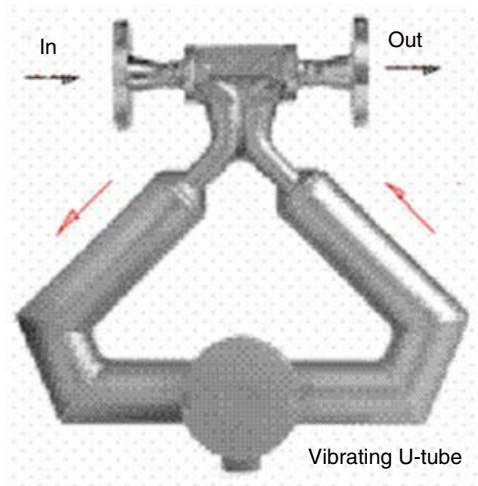
Figure 7.16 Coriolis meter. Source: https://commons.wikimedia.org/wiki/File:Coriolis_meter.png. Used under CC0 1.0, https://creativecommons.org/publicdomain/zero/1.0/deed.en. © Wikipedia.

This is a meter with a fixed amount of fluid volume going through it, but two parallel tubes containing liquid also vibrated at a fixed frequency. The change in frequency caused by a change in density allows this meter to compensate for this change and report out actual mass flow.

Gas Laws

When our systems involve the handling of gases, there are some unique differences in thinking about physical properties. Gases, unlike solids and liquids, change volume as a function of pressure. Solids and liquids do also, but to such a small degree, that it is usually not relevant in a practical sense. The equation used to describe the behavior of *ideal* gases is

$$PV = nRT$$

where
P is the absolute pressure of the system
V is the volume occupied by the gas
n is the number of moles of gas present
R is the universal gas constant
T is the temperature (in absolute, K or °R)

As we have discussed earlier, it is critical to use the value of *R* to match the units of the other variables.

Notice that the amount of gas present is represented by "*n*," the number of moles, not the mass or weight of the gas. That's because, as counterintuitive as it may seem, the volume is independent of mass and depends only on the number of moles. A gram mole of hydrogen, 2 grams, occupies the same volume as one gram mole of chlorine, 71 grams.

This simple law allows us to calculate and conceptualize the effect of changes in pressure and temperature. This equation applies only to an ideal gas, or as an approximation to a real gas that behaves sufficiently like an ideal gas. There are in fact many different forms of this gas law reflecting both molecular size and intermolecular attractions, and it is most accurate for monatomic gases at high temperatures and low pressures. The neglect of molecular size becomes less important for lower densities, that is, for larger volumes at lower pressures, because the average distance between adjacent molecules becomes much larger than the molecular size. The primary point here is that gases are different than liquids and gases, and chemical engineering calculations involving gases must take into account changes in pressure and volume.

Recalling Le Chatlier's principle, we can see how, in a system involving gases reacting or being generated, the equilibrium of the reaction changes by changing pressure. For example, if we have four moles of gases reacting generating two moles of gases, such as in the ammonia reaction

$$N_2 + 3H_2 \rightarrow 2NH_3$$
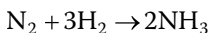
we would assume that a higher pressure during the reaction would shift the reaction to the right, increasing the amount of ammonia formed. This is in fact the case, as the ammonia reaction is usually run at pressures greater than 1000 psig to promote the forward reaction.

Since this reaction is also exothermic in nature, it also has an equilibrium constant (K_e), which dramatically decreases with temperature, providing a true paradox. We want the reaction rate to be high, but when we raise the temperature to do this, we reduce the amount of ammonia we make. At the same time, we want high pressure to shift the reaction in favor of the product with fewer gas moles than the feed gases. High pressure equipment costs money. A typical ammonia process runs at several hundred degrees Celsius and at least 1000 psig

to deal with this contradiction. Reducing the temperature and pressure of this reaction is one of the "holy grails" of chemical engineering. This same challenge has been with us for over 100 years, and along with the safety aspects of such a process is the subject of large annual meetings of chemical engineers and the companies that design and run ammonia plants.

Gas Flows

One of the more common ways of measuring gas flows is with a simple pitot tube, shown in Figure 7.17.
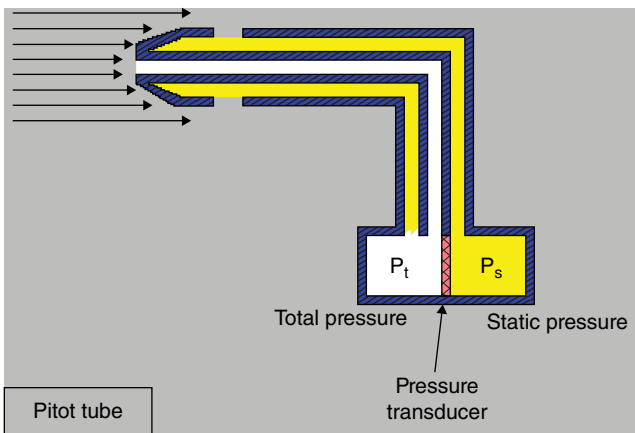
Figure 7.17 Pitot tube meter for gas flow. Source: Mendel, https://commons.wikimedia.org/wiki/File:Pitot_tube_diagram.png. Used under CC BY-SA 3.0, https://creativecommons.org/licenses/by-sa/3.0/deed.en. © Wikipedia.

These are seen occasionally on airplane wings as they are typically used to measure airplane speed.

The other measurement devices discussed earlier can also be used.

Gas Compression

Gases are normally moved by compressors (at high pressure) and fans (at low pressure). As with liquids, all the sources of pressure drop must be considered in sizing the compressor or fan. Gas flow rates are more complicated to deal with as their density will change with pressure. This requires an integrative type of flow calculations based on the changes in pressure and temperatures.

A gas compressor's work will dramatically increase the temperature of the gas (remember the differences in heat capacities between liquids and gases?), in turn affecting the efficiency of the compressor. The thermal conductivity of the gas being compressed will also change as the temperature changes. Though more capital intensive, compressing a gas isothermally (meaning cooling as the gas is compressed) will consume less energy.

As with liquid flow systems, we must take into account the following factors:

- Average versus peak flow.
- Pressure drop—have all items been considered?
- Source pressure.
- Piping design, elbows, tees.
- Capability of causing vacuum.

Compressors are usually "sealed" against atmospheric interaction either mechanically or with a sealing fluid. If the latter is used, its vapor pressure must be considered at the operating temperature as that will limit its sealing capability. In addition the solubility of the compressed gas in the fluid must be considered.

In summary, liquid and gas flows and metering are affected by many physical property variables that must be taken into account as their temperature and pressure change. Fluids and slurries have many different responses to shear, which must be taken into account. Flows, pumping, and compression can be done in numerous ways depending upon the requirements of the system. In positive displacement systems, it is important to consider the possibility of creating vacuum and the possible safety consequences.

Fluid Flow and Coffee Brewing

Let's go back to our case study again. When are fluids moving, when might their properties change, and what might be the impact? There are several different ways of brewing, but let's start with the most often used process, drip filtration. In this case, hot water is dispersed over the top of ground coffee particles, usually driven by a small pump not seen by the user, and the water flows through "extracting" or "leaching" (more on these unit operations later) flavor ingredients from the ground coffee beans and then dripping into a container. The majority of the ground bean raw material remains behind, trapped by a filter (more on this unit operation as well later) of some sort but usually a paper element. It can also be a permanent filament wound filter, expected to be washed and reused. What are the fluid issues here?

(Continued)

(Continued)

We discussed the significant impact of temperature on liquid viscosity. Is the temperature produced by the machine constant? If not, then its viscosity will be different every time a cup of coffee is brewed. If the viscosity is higher or lower, the flow rate through the ground coffee and the filter medium will also change, affecting the time that the water has to leach the flavor ingredients. The coffee will be weaker or stronger depending on the viscosity. It is unlikely that there will be any significant density differences, so this aspect can probably be ignored.

What is the nature of the pump feeding water into the coffee machine? Most likely a small positive displacement pump that "precisely" delivers the amount of water needed, but how do we know unless we check?

Water, as with any other fluid, has a surface tension, a property also affected by dissolved salts and temperature. How long does it "cling" to the coffee ground particles? How big are these particles? Are they all the same size? What is their particle size distribution? Is the water softened, adding sodium and removing calcium? Is it in the middle of a regeneration cycle? How does this affect the surface tension?

Coffee brewing is beginning to sound a bit complicated, isn't it? And we still have a long way to go!

Discussion Questions

1 What is the nature of the fluids in your process? Have all of their physical properties been measured? Is the information readily available?

2 Do you have this data over the *entire* range of actual operating conditions?

3 How were the pumps you use chosen? Is there any basis now for revisiting that decision?

4 How close to the minimum NPSH for your centrifugal pumps are you running? What would happen if you reached this point? Has that been discussed in a HAZOP or any other type of safety or process review?

5 Is there a new centrifugal pump available that would satisfy your NPSH and flow demands, should it be installed? Why or why not?

6 If you are using positive displacement pumps, what would be the consequences of the pump being "dead headed?" How long would this situation need to exist before a fluid decomposition occurred? A reactive chemical incident?

7 What types of flow meters are being used? What was the basis for choosing them originally? Has anything changed that would warrant a change? (Accuracy needed, type of fluid, pressure drop, cost?)

8 Is volumetric flow rate sufficient or would mass flow rate be more useful information? For what reason?

Review Questions (Answers in Appendix with Explanations)

1 Total fluid pressure is measured by the sum of:
   A __Static pressure and dynamic pressure
   B __Dynamic pressure and fluid density
   C __Static pressure and anticipated friction loss
   D __All of the above

2 Laminar flow implies:
   A __Pressure drop for the fluid flow is high
   B __Fluid is wandering around with no direction
   C __Pipes are made from plastic laminates
   D __Little or no mixing across the cross-sectional area of a pipe

3 Turbulent flow implies:
   A __Fluid is well mixed across the cross-sectional area of the pipe
   B __Pressure drop will be higher than laminar flow
   C __There is little or no adhesion between the fluid and the piping wall
   D __All of the above

4 Turbulent versus laminar flow will affect all but:
   A __Pressure drop in the pipeline
   B __Mixing in the pipe
   C __Cost of the piping materials
   D __Pressure drop across valves and instrumentation

5 Key fluid properties affecting fluid handling systems include all except:
   A __Density
   B __Viscosity
   C __Residence time in tank prior to pumping
   D __Temperature and vapor pressure

6 Viscosity characterizes a fluid's resistance to:
  A __Being pumped
  B __Being held in storage
  C __Price change
  D __Shear

7 The viscosity of a fluid is most affected by:
  A __Density
  B __Pressure
  C __Index of refraction
  D __Temperature

8 The viscosity of an ideal (Newtonian) fluid reacts to a change in shear at constant temperature by:
  A __Remaining the same
  B __Increasing
  C __Decreasing
  D __Need more information to answer

9 A dilatant fluid's viscosity _____ with shear:
  A __Increases
  B __Decreases
  C __Stays the same
  D __Depends on what kind of shear

10 A thixotropic fluid responds to shear by _____ its viscosity:
  A __Increasing
  B __Decreasing
  C __Not affecting
  D __Depending on what kind of shear

11 In general, adding solids to a liquid (converting it into a slurry) will _____ its viscosity:
  A __Increase
  B __Decrease
  C __Not affect
  D __Can't be known

12 The Reynolds number is:
  A __Dimensionless
  B __A measure of turbulence in flow
  C __The ratio of diameter × density × velocity
  D __All of the above

13 A dimensionless number in chemical engineering:
   A __Provides a simple way of characterizing an aspect of design
   B __Has no units (if calculated correctly)
   C __Allows a chemical engineer to estimate relative behavior of an engineering system
   D __All of the above

14 Friction in fluid flow is influenced by all but:
   A __Fluid properties
   B __Flow rate
   C __Piping design characteristics
   D __Cost of energy to pump the fluid

15 Pressure drop in a fluid system can be affected by:
   A __Length of piping
   B __Number and nature of connections and valves
   C __Degree of corrosion on walls
   D __All of the above

16 The difference between a centrifugal and positive displacement pumps is:
   A __Centrifugal pumps are less expensive
   B __Positive displacement pumps have a characteristic curve
   C __Centrifugal pumps generate constant pressure; positive displacement pumps put out constant flow
   D __It is harder to "dead head" a positive displacement pump versus a centrifugal pump

17 Centrifugal pumps require a minimum net positive suction head (NPSH) to operate; otherwise they will cavitate. This can be caused by all but:
   A __Improper placement of the pump on an engineering drawing
   B __Reducing the level of the liquid feeding the pump
   C __Raising the level of a tank into which the pump is discharging
   D __Raising the temperature of the feed liquid and raising its vapor pressure

18 If the process needs to exceed the minimum NPSH available, what options are available?
   A __Raise the height of inlet stream to the pump
   B __Lower the temperature of the inlet feed
   C __Increase the size of the piping in the system
   D __Any of the above

19 The choice of a flow meter will depend upon:
   A __Accuracy required
   B __Pressure drop tolerance
   C __Cleanliness of fluid
   D __All of the above

Additional Resources

Collins, D. (2012) "Choosing Process Vacuum Pumps" *Chemical Engineering Progress*, 8, pp. 65–72.

Corbo, M. (2002) "Preventing Pulsation Problems in Piping Systems" *Chemical Engineering Progress*, 2, pp. 22–31.

Fernandez, K.; Pyzdrowski, B.; Schiller, D. and Smith, M. (2002) "Understanding the Basics of Centrifugal Pump Selection" *Chemical Engineering Progress*, 5, pp. 52–56.

James, A. and Greene, L. (2005) "Pumping System Head Estimation" *Chemical Engineering Progress*, 2, pp. 40–48.

Kelley, J.H. (2010) "Understanding the Fundamentals of Centrifugal Pumps" *Chemical Engineering Progress*, 10, pp. 22–28.

Kernan, D. (2011) "Learn How to Effectively Operate and Maintain Pumps" *Chemical Engineering Progress*, 12, pp. 26–31.

Livelli, G. (2013) "Selecting Flowmeters to Minimize Energy Costs" *Chemical Engineering Progress*, 5, pp. 35–39.

https://commons.wikimedia.org/wiki/File:Viscosity_video_science_museum.ogv (accessed on August 30, 2016).

8

Heat Transfer and Heat Exchangers

A second major subject for chemical engineering practice is the study of energy transfer, most often the use of equipment to transfer heat, either heating or cooling. We use the term refrigeration when we are discussing cooling below ambient temperatures. We may want to heat or cool for a variety of reasons:

1) Preheat a material entering a chemical reaction system.
2) Cool a process vessel or reaction system that is generating heat in an exothermic reaction.
3) Heat a reaction to sustain its reaction if it is an endothermic reaction.
4) Condense vapors from an evaporator or distillation column.
5) Reboil liquid at the bottom of a distillation column.
6) Refrigerate a material that might decompose at a very low temperature in a reaction system. When we are cooling below room temperature, the heat exchanger is often referred to as a "chiller."
7) Collect or remove radiative heat. Solar collectors are examples of such devices. High temperature cracking furnaces are another.

The equipment and fluids used in this unit operation vary widely according to the requirements and the resource availability. For example, if it is necessary to cool a material in South Texas to 70°F in the summer, this will not be possible with lake or river water. Some kind of refrigeration will be required. If this same system were in Minnesota or the upper peninsula of Michigan, there would be no such need. Conversely, if there is a need to heat a material, the pressure of the steam available will put limits on what is possible as steam temperature and pressure go hand in hand.

As in the other topics we have covered, there are two fundamental principles that we need to remember:

1) Heat flows from high temperature to low temperature.
2) Heating or cooling can be used to increase or decrease the temperature of a material or to change its phase, that is, melt/freeze or boil/condense. When a material is undergoing a phase change, there is no change in temperature.

There are also two different types of heat transfer, convective and conductive. *Convective* heat transfer involves bulk transfer of heat *between* materials. Mixing of hot and cold fluids together or the heating or cooling of a mass of fluid are such examples. *Conductive* heat transfer involves the flow of heat *through* a material with no temperature change. An example here is the loss of heat from the interior of a house to the outside. Even though there is no apparent bulk movement of the materials (say, in a rod or in the insulation inside the walls of the house), the molecules inside these materials are vibrating and moving, transporting the energy from hot to cold.

The conductivity of materials is measured by a property known as the thermal conductivity or k, whose units are BTU/h/ft/°F or cal/s/m/°C or some other combination of heat, time, and distance that are consistent. The higher a material's k value, the more rapid thermal energy (heating or cooling) moves through it. If we want to prevent heat flow, we choose a material with a low k; if we want to maximize the rate at which heating or cooling leaves a system, we choose a material with a high k.

The thermal conductivity values for some materials are shown in Table 8.1. You can think about these numbers in the context of cooking and the pots and pans we use every day. Many of the more expensive (since copper is more expensive than steel or aluminum) pans are copper plated or made entirely of copper to provide quick, even heat. Aluminum is a compromise between the low k of steel and the high k of copper as well as the prices of each of these. It would be wonderful if we could afford to make cooking pans made out of silver (or process heat exchangers!). As you can see, brick has a very low k, making it an insulating material.

Table 8.2 shows some additional k values that provide some interesting insights. Notice the large difference between a hydrocarbon, such as hexane, and water. The use of water in a heat exchanger would require significantly less material to transfer the same amount of heat. Note that the gases have relatively low k's, meaning that it would take less heat input to raise their temperature versus solids and liquids. Notice also the extremely large k value for sodium

Table 8.1 Thermal conductivities of common materials.

Aluminum	115–120 (BTU/h ft °F)
Copper	215–225
Iron/steel	25–40
Silver	240
Brick	0.08–0.12

Source: Average of public sources.

Table 8.2 Thermal conductivities of materials.

N-Hexane	0.08 (BTU/h ft^2 °F)
Water	0.36
Sodium metal	45
Hydrogen	0.11
Methane	0.02
Air	0.016
Argon	0.010

Source: Average of public information.

metal, meaning that a small amount of sodium can absorb tremendous quantities of heat. This is the primary reason that liquid sodium is used as an emergency coolant in nuclear power plant reactors.

In most storm windows, there is an insulating layer of air between the glass panes to inhibit the loss of heat. In far northern climates, it can pay to inject and seal argon (an expensive gas) between the panes of glass to further inhibit heat flow. Its *k* is 40% less than air.

When we have bulk material flow and heat transfer is involved, we have *convective* heat transfer. This can be, as mentioned before, the bulk mixing of a hot and cold fluid, but in the chemical engineering world, it is usually referring to two fluids (liquids or gases) being heated or cooled with a metal barrier between them in the form of a *heat exchanger*.

Types of Heat Exchangers

Though not an all-inclusive list, the following are the primary types of heat exchange equipment in use in the chemical industry:

1) Shell and tube exchangers. These types of exchangers are the workhorse of the chemical industry. An illustration of such an exchanger, in a typical countercurrent flow design, is shown in Figure 8.1.

   In this type of equipment, a cooling fluid outside the tubes is being used to cool a hot process stream inside the tubes. The flow inside the tubes and outside the tubes is where the convective heat transfer is occurring. There is conductive heat transfer across the metal walls of the tubes. Though this illustration shows a "one-pass" configuration, the tubes can be of a "U tube" configuration and have a multi-pass configuration. The baffles are added to increase the turbulence of the fluid on the shell side of the exchanger, increasing the heat transfer rate.
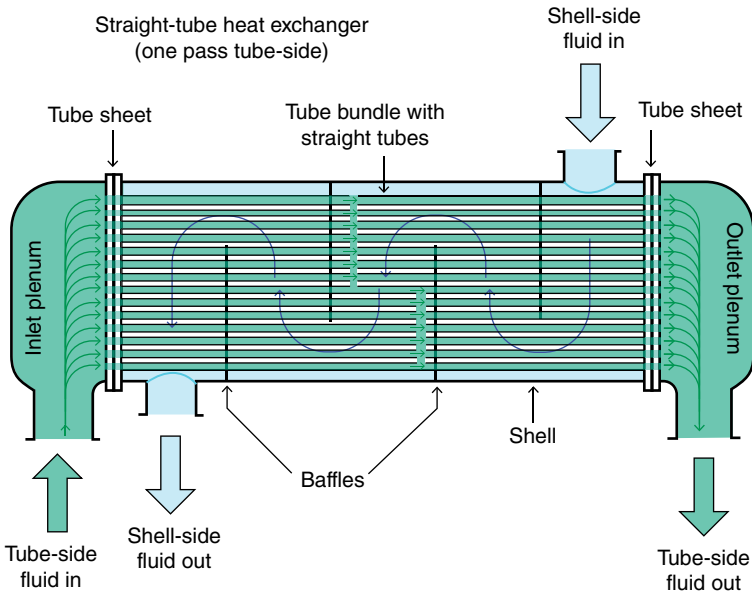
Straight-tube heat exchanger
(one pass tube-side)

Shell-side
fluid in

Tube sheet

Tube bundle with
straight tubes

Tube sheet

Inlet plenum

Outlet plenum

Shell

Baffles

Shell-side
fluid out

Tube-side
fluid in

Tube-side
fluid out

Figure 8.1 Conventional shell and tube heat exchanger. Source: Pedlackas, https://commons.wikimedia.org/wiki/File:Straight-tube_heat_exchanger_1-pass.PNG.

2) Jacketed Pipe Exchangers (see Figure 8.2).

Shell-side
fluid in

Flange

Tube-side
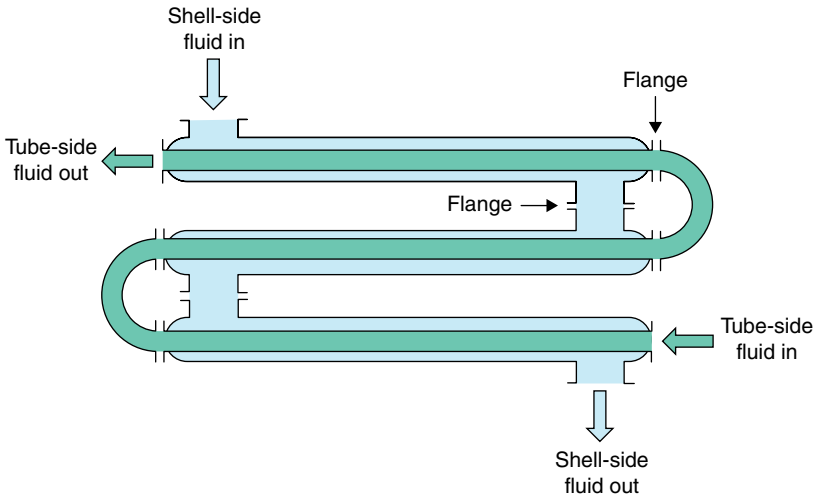fluid out

Flange

Tube-side
fluid in

Shell-side
fluid out

Figure 8.2 Jacketed pipe heat exchanger. Source: https://commons.wikimedia.org/wiki/File:Double-Pipe_Heat_Exchanger.png. Used under CC BY-SA 4.0, https://creativecommons.org/licenses/by-sa/4.0/. © Wikipedia.

These are simply pipes with jackets wrapped around them (similar to insulation) that either cool or heat. Due to the area and time limitations, these can be used only for minimal amounts of heat transfer.

3) Chillers. This terminology refers to any kind of heat exchanger operating below normal ambient temperatures. Usually its purpose is to condense low boiling point compounds and use a refrigerant such as ammonia, low boiling hydrocarbon, or a fluorinated hydrocarbon. It could refer to any number of mechanical configurations.

4) Condensers. This refers to a heat exchanger being used to condense a vapor stream into a liquid. It could refer to any number of mechanical configurations. It is most frequently seen used to condense the overhead vapor from a distillation column (distillation will be discussed in detail in Chapter 10) as seen in Figure 8.3.
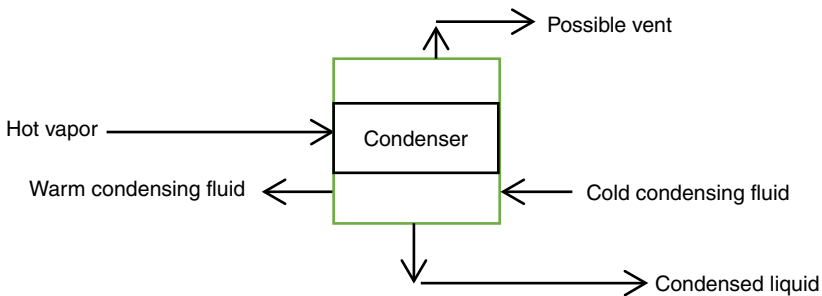

Figure 8.3 Condenser.

This type of heat exchanger can also be used to condense and remove volatile organic carbons (VOCs) from a gaseous vent stream. Depending upon the composition of the incoming stream, not all of the incoming vapor will condense, and a vent may be necessary and further handling of the vent stream required. If only part of the stream is condensed, this type of condenser would be referred to as a partial condenser.

5) Reboilers. This refers to a heat exchanger (again, could be a number of mechanical configurations) that is being used to "reboil" liquid at the bottom of a distillation column (more later on this unit operation in Chapter 10) as shown in Figure 8.4.

The overall heat transfer coefficient of a heat exchanger is normally referred to as U. Given the basic equation of $Q = UA\Delta T$, the heat transfer area required is simply $A = Q/U\Delta T$. The Q is simply the amount of energy required and can be calculated by multiplying the fluid rate times its heat capacity times the temperature change (and latent heat of vaporization if applicable) and then dividing by the estimated heat transfer coefficient.
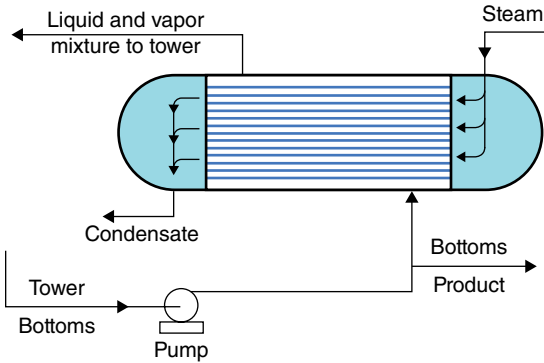
Figure 8.4 Reboiler. Source: Baychok, https://commons.wikimedia.org/wiki/
File:ForcedCirculation.png. Used under CC BY-SA 3.0 https://creativecommons.org/licenses/
by-sa/3.0/deed.en. © Elesvier.

Countercurrent versus Cocurrent Flow Design

1) It is possible to configure a heat exchanger in two different ways usually
   described as cocurrent (sometimes referred to as parallel flow) and counter-
   current (sometimes referred to as counterflow). An example of a typical
   countercurrent exchanger was shown in Figure 8.1. In cocurrent flow, both
   hot and colder streams enter at the same end of the heat exchanger as shown
   in Figure 8.5.
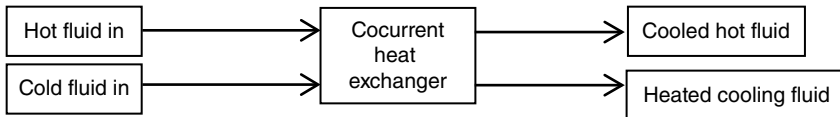
Figure 8.5 Flows in a cocurrent heat exchanger.

2) The difference in profiles of the fluid temperatures will be quite different,
   since with cocurrent flow, it is not possible for either the hot or cold fluid to
   achieve more than their "average" temperature. The temperature profiles
   within these two different types of exchangers would be as shown in
   Figure 8.6.
3) A countercurrent flow arrangement will always allow for a colder exiting
   temperature of the fluid being cooled.

Figure 8.6 Cocurrent versus countercurrent temperature profiles.

Heat Transfer Coefficient

The overall heat transfer coefficient, U in BTU/h ft^2 or similar metric units, is a sum of three different heat transfer coefficients:
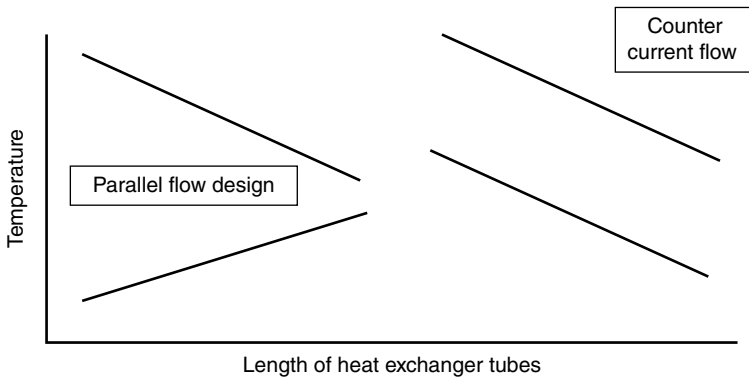
1) Convective heat transfer from the cooling fluid to the wall
2) Conductive heat transfer through the wall
3) Convective heat transfer from the inner cooling wall surface to the process fluid

The overall heat transfer coefficient, U, is the sum of these three individual heat transfer coefficients, $h_{outerwall} + h_{tube} + h_{innerwall}$. In many situations where the Reynolds number is high (turbulence is high) on both the inner tube and outer tube, the h across the tube is the highest number, meaning that it provides the least resistance to heat flow. The normal challenge is getting the heat to and from the wall. However, this should not be assumed if the fluids have a low Reynolds number. The individual h's can be calculated (see Table 8.3), and the h of the tube calculated from its thermal conductivity, thickness, and the temperature difference across the tube. These rough calculations will tell us whether the h across the tube is small enough to be ignored.

The amount of energy transferred is equal to the overall heat transfer coefficient (actually a sum of three sub-coefficients) times the area of the tubing times the temperature differential at any point.

Approximate ranges for these overall heat transfer coefficients are shown in Table 8.3.

Table 8.3 Approximate heat transfer coefficients.

Outside fluid	Inside fluid	Contact material	Overall U
Air	Water	Metal	1.5–2.5
Water	Water	Metal	40–80
Steam	Water	Metal	120–180

Source: Reproduced with permission of Engineering Toolbox.

Heat transfer coefficients are a function of a number of fluid physical properties as well as flow conditions. One of the equations used to calculate these in more detail uses a grouping of dimensionless numbers (we have already been introduced to the Reynolds number, which is a measure of turbulence of flow) along with the geometry of the piping used in the heat exchange equipment:

$$\frac{hD}{k} = 0.023 \left(\frac{DV\rho}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.3}$$

where h is the heat transfer coefficient we have been referring to, D is the pipe diameter, k is the thermal conductivity of the fluid, $DV\rho/\mu$ is the Reynolds number, and $C_p\mu/k$ is a dimensionless number that we know as the Prandtl number, which is a measure of the physical properties of the material, independent of whether the fluid or gas is flowing. It is basically the ratio of the fluid's ability to absorb heat (C_p) versus transfer heat (k) and the rate at which heat can be moved, as indirectly indicated by its viscosity. One only needs to think about the difference in moving heat through a low-viscosity fluid such as water versus a high-viscosity fluid such as maple syrup. If we rearrange this equation to solve for h, we see a relationship like the following:

$$h = \frac{0.023 \left(DV\rho/\mu \right)^{0.8} \left(C_p\mu/k \right)^{0.3} (k)}{D}$$

Without worrying about the exact numbers, we can look at the variables and how this equation predicts how the heat transfer coefficient would respond to a change in conditions or physical properties:

1) If the Reynolds number increases, the heat transfer will *increase* by the 0.8 power. The greater the turbulence, the more efficient the heat transfer, but it does not increase linearly.
2) If the pipe diameter increases, the heat transfer will *decrease* by the 0.2 power (the smaller the pipe diameter, the lower the velocity and less turbulent is the flow).

3) If the viscosity increases, the heat transfer will decrease by the 0.5 power (if the fluid is "thicker," the Reynolds number decreases and the ability to mix the fluid drops). Again, think about water versus maple syrup.
4) If the thermal conductivity of the fluid increases, the heat transfer will increase by the 0.7 power.

The point here is not to memorize the equation, but just to reinforce the natural logic that heat transfer will change in response to variables that can be affected and changed in the chemical engineering design of not only the heat exchanger but also the choice of fluids and their physical properties. This kind of general knowledge can also assist in estimating changes in heat transfer efficiency when changes to process systems are made.

Utility Fluids

It is easy to overfocus on the process stream that needs to be heated or cooled, but the utility fluid (water, steam, refrigerant, or heat transfer fluid) is equally important. Their properties and availability may not be under complete control of the user, especially if they are supplied by a public utility. Even though we may specify 150 psig steam on a process flow sheet as well as on our calculations, the chances of the steam being at exactly 150 psig at any given time are slim to none, despite the best intentions of the utility manager or supplier. What happens if it's 140 psig? 160 psig? Can the process fluid overheat? Are there any consequences to this? (Recall our discussions about HAZOP thinking earlier.) If the process fluid is not heated sufficiently, does the reactor it may be feeding slow down in reaction rate? Is this a problem? If so, what kind of problem? How do you counteract? What happens if the steam supply is totally lost?

If the utility fluid is water (used as a cooling fluid), what are the consequences if its temperature is too hot or too cold? Is it cooling an exothermic reaction? Could there be a runaway reactive chemicals incident? How many layers of protection are needed? What is the backup plan, especially if the cooling water is coming from a public utility over which you have no direct control? How do you decide? Is the output from this "cooled" reactor feeding some other process? What are the consequences of losing this flow?

In a chiller, low boiling compounds such as hydrocarbons, fluorinated hydrocarbons, and liquid ammonia are used as coolants. Since these materials, when vaporized, generate pressure, it is critical to make sure that valves within the heat exchanger system are not closed inappropriately, potentially causing the rupture of a heat exchanger that was not designed to be a pressure vessel.

Air Coolers

If there is a shortage of cold cooling water, air coolers are frequently used:

Figure 8.7 Air-cooled heat exchanger. Source: Reproduced with permission of Engineering Toolbox.

These types of heat exchangers have much lower heat transfer coefficients than those using fluids, but they use a "free" resource. Ambient air has its limits in terms of temperature, so it is important to consider the worst-case air temperature in designing the required area.

Scraped Wall Exchangers

When the materials that need to be heated or cooled have high viscosities, the tube fouling may be so severe that continuous scraping and clearing of the walls may be required, as seen in the illustration of a commercial scraped wall exchanger in Figure 8.8.

Figure 8.8 Scraped wall exchanger. Source: Reproduced with permission of Sulzer. © Elsevier.
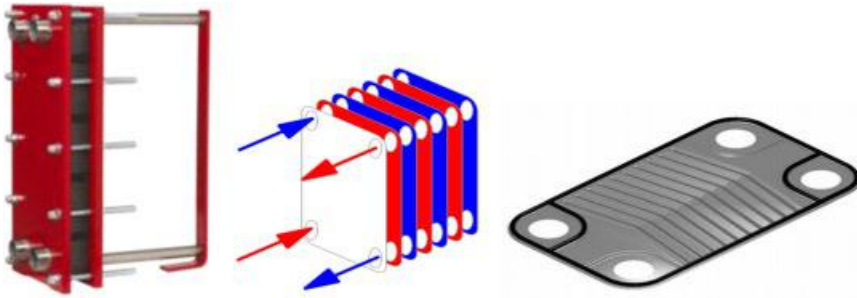
Figure 8.9 Plate and frame heat exchanger. Source: Varem, https://commons.wikimedia. org/wiki/File:Plate_heat_exchanger.png. © Wikipedia.

Plate and Frame Heat Exchangers

These are shell and tube exchangers with very tight clearance between sides of the exchanger and high turbulence between the layers (Figure 8.9). They typically have high heat transfer efficiencies but, due to close clearances, are not the first choices for slurries. Their major advantage is high heat transfer rates in a small area.

Leaks

Any heat exchanger will eventually leak between the shell and tube side. It's just a question of when. The important issue of concern is when this happens which way do we want the exchanger to leak? Shell to tube, or tube to shell? This will be primarily controlled by the pressure values on either side, which can be considered in the design. If several tubes break off the tube sheet (see section "Mechanical Design Concerns"), massive leaks are possible. What kind of safety, shutdown, and environmental protections need to be in place not only for the heat exchanger but also for its downstream flow, and its use?

Mechanical Design Concerns

Though the detailed mechanical design, including welding and meeting vessel codes, is typically done by mechanical and welding engineers, there a few basic points to remember when operating an exchanger, especially one that undergoes a large temperature change:

1) Thermal Expansion. Metals have coefficients of expansion and will stretch or contract as their temperature rises or falls. Since metals are typically

joined by welding, too rapid a change in temperature may produce sufficient force to rupture the weld.

2) Fouling. Heat exchangers will foul or develop coatings on the tube and shell surfaces over time due to a variety of reasons including contamination, impurities in flow streams, and corrosion products from the reactions of the process and utility fluids with the materials in the heat exchanger.

3) Placement of Fluids. There may be specific reasons we might want the process or utility fluid to be either on the shell or tube side, but there are also some general suggestions that are helpful:

   a) Pressure drop will normally be lower on the shell side, so if flow pressure has some limitations, this may be a consideration.

   b) Cleaning the tubes is easier than taking the assembly apart, so if fouling is expected, it would be better to put that fluid on the tube side.

4) Chiller Pressure Development. If a refrigerant such as ammonia is being used, we must remember that the cold liquid can vaporize and generate pressure, so it is critical in maintenance procedures to remember that the heat exchanger can turn into a pressurized vessel, which it was not designed to be.

5) Leaks. At some time point in time, an exchanger will leak between the shell and the tube sides. It is not a matter of if; it is when. This requires that we think about the consequences of this event. Which way do we want the fluid to leak? Tube into shell? Or shell into tube? What are the consequences of these choices from the standpoint of reactive chemicals, product contamination, or environmental release?

Cleaning Heat Exchangers

All heat exchangers, regardless of type of design or service, will need cleaning. There are a number of ways that this is done. First, mechanically. Tubes can be "rodded" out mechanically and the waste disposed of properly. Second, ultrahigh pressure water jet cleaning can be used. It must be shown that the high pressure will not cause some other rupture in the equipment. It is also important to provide education on the danger of high pressure water jets, which can amputate fingers and toes. Third, chemical cleaning methods can be used. There are inhibited acid solutions available that, for a period of time, will dissolve the corrosion product without corroding the base steel metal. In addition to ensuring that the proper conditions are maintained, the proper safety equipment must be worn while handling these acid streams.

Radiation Heat Transfer

Every "thing" or person emits radiative energy, but at room temperatures, the amount of this energy is extremely small and is not considered in normal heat transfer calculations. But we all are concerned about sunburn in the summer time from a star emitting radiation over 90 million miles away. Even at this distance the extremely high temperature makes this a serious heat transfer issue.

In the real world, temperatures need to exceed 1000°C for radiation heat transfer to be of a significant amount that needs to be considered. This does occur in hydrocarbon cracking furnaces and in carbon black plants. In high temperature hydrocarbon cracking furnaces, high molecular weight hydrocarbons are "cracked" into lighter, more valuable materials such as gasoline, ethylene, propane, diesel fuel, and aromatics. Side issues with these types of furnaces include the need for high temperature insulation materials and the carburization of tubes requiring eventual cleaning.

High Temperature Transfer Fluids

In some processes it is desired to heat materials to 300–600°C. If this is done with steam, extremely high pressure steam is required, normally beyond the capability of conventional boilers. A class of organic compounds, with low vapor pressure at high temperatures, has been developed over the years by a number of manufacturers to meet this need. These compounds are typically organic fluids with very low boiling points and low viscosities, allowing them to be used to supply heat input at very high temperature at significantly less pressure than the same temperature supplied by steam. Many of these fluids are mineral oils or diphenyl oxides, but many have proprietary formulations. Since these fluids are typically organic liquids, the addition of a fire hazard must be considered. Figure 8.10 shows the range of usability of these fluids from one manufacturer.

At one extreme, the fluid will freeze, and at the other extreme, it will decompose rapidly. The chemical synthesis and composition of these various fluids are controlled by their manufacturers to meet specific customer needs.

Since these fluids are organic, they will decompose slowly over time via oxidation or thermal decomposition and are monitored by the customer and supplier and, at some point in time, will have to be disposed of and replaced. Decomposition of these fluids takes the form of caking inside the heat transfer piping as shown in Figure 8.11.
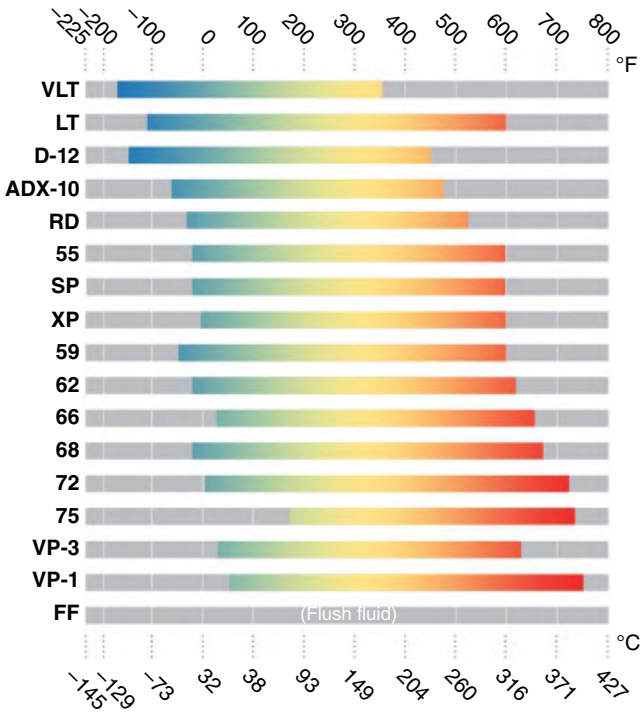
Figure 8.10 Thermal ranges for heat transfer fluids. Source: Courtesy of Eastman Chemical Company. © Elsevier.

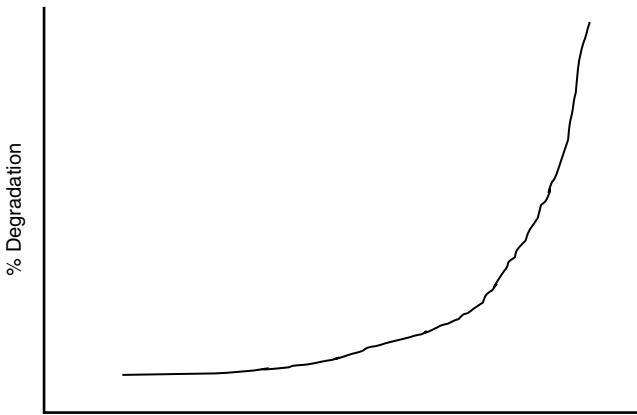Figure 8.11 Pipe plugged with decomposed heat transfer fluid.

Figure 8.12 Heat transfer fluid degradation time and temperature.

In practice, the provider of these fluids works with the user to develop a systematic sampling process to measure the degradation rate, and at an appropriate time, the fluid will be flushed and replaced (Figure 8.12).

Another key aspect of virtually all of these fluids is that, unlike steam, they are flammable to varying degrees. This requires users of these fluids to have on-site firefighting and fire safety as part of their overall safety programs.

Summary

Heat transfer and the equipment required to transfer heat are integral parts of a chemical process and a chemical complex. There are numerous types of equipment that operate under basic heat transfer equations but have advantages and disadvantages depending upon the nature of the fluid requiring heating or cooling, the utility fluids available, the consideration for radiative heat transfer, and the necessity for equipment cleaning.

Coffee Brewing: Heat Transfer

Back to our coffee brewing with our chemical engineering hats on. Do we want coffee brewed with cold water? Maybe REALLY cold water if we want iced coffee, but let's stay focused on normal hot coffee. We need to heat the water. How do we do this? By using the $U = QA\Delta T$ equation. What is the U? Well, how much water do we want to heat? What is the starting temperature? How hot do we want it to be? That's the ΔT. How much water? We decide this

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(Continued)

(Continued)

when we decide how many cups we are brewing. What's the *A*? What is the heat transfer area inside the coffee pot? We don't really know, but someone who worked for the coffee brewing machine manufacturing company decided that.

What about the "hot plate?" It has a surface area and the manufacturer has decided on a temperature to be sustained. We will discuss evaporators later, but that's what a hot plate is; while it is maintaining a temperature, some of the water is evaporating, concentrating the coffee, AND supplying heat input that causes the coffee flavor ingredients to degrade into not so tasty materials including aldehydes. This is no different than the kinetic rate material we discussed earlier. What is another alternative that we have seen in home coffee brewers? A sealed vacuum receiver without a hot plate. While there is still some degradation going on, its rate is lower since there is not constant heat input.

And your coffee cup? It can be a simple cup (which will lose heat at the $Q = UA \Delta T$ rate). What affects this? What is the area of the cup? What is the temperature difference between the coffee and the room? What is the thermal resistance across the wall of the cup? Was the initial temperature affected by the addition of cold cream? How much? Sugar? How much? We have seen practical attempts to minimize this by insulated cup holders and small hot plates in an office. Keep thinking about this process!

Discussion Questions

1 What is the heat balance around your process or area you are involved in? Is it calculated by an online process control computer? If so, what aspects of the operation could change that may cause errors in the calculation?

2 Do you have thermal property data over the entire range of your process? What situations could cause the process to go outside this range? Are the thermal properties taken into account?

3 If the temperature of your feed into a reactor increases, what happens?

4 If the temperature of the feed decreases, what happens?

5 If you are using high temperature heat transfer fluids, do you know their decomposition point? How often are they sampled? What happens if their process lines totally plug? Do you have adequate fire protection? On-site? Off-site?

6 If you have a shell and tube heat exchanger, which direction will it leak? Shell to tube? Tube to shell? What happens when either fluid contaminates the other? Safety issues? Quality issues? Reactive chemicals issues?

7 If you are using a refrigerant or some other fluid under pressure on one side of the exchanger, what happens if the outlet flow of the liquid under pressure is blocked? Is the exchanger designed to handle the pressure that results? What does the energy balance look like in this situation? How much heat is entering? How fast does the other side of the exchanger heat up? To what pressure? Is there an environmental issue?

8 How did you decide on the heat exchanger equipment and design that you now have? Has anything changed that would warrant a technical review?

9 What is the source of your utility fluid? Is it reliable? What happens if its flow stops? How does its temperature and pressure affect the operation of your heat exchangers?

Review Questions (Answers in Appendix with Explanations)

1 An energy balance around a process or piece of equipment requires knowledge of all but:
   A __Flow rates and temperatures of flows in and out
   B __The speed of the pump feeding the vessel
   C __Heat generated by any reaction occurring
   D __Heat capacities of streams in and out

2 The three methods of heat transfer are all but:
   A __Conductive
   B __Convective
   C __Convoluted
   D __Radiation

3 Conductive heat transfer refers to heat moving:
   A __Above
   B __Below
   C __Around
   D __Through

4 Convective heat transfer refers to heat moving:
  A __In a bulk fashion
  B __Only as a function of convective currents
  C __On its own
  D __None of the above

5 Variables that affect the rate of heat transfer are:
  A __Flow rates
  B __Physical properties of fluids
  C __Turbulence within the heat transfer area or volume
  D __All of the above

6 If the pipe diameter is increased and all other variables remain the same, the rate of heat transfer:
  A __Will increase
  B __Will decrease
  C __Will stay the same
  D __Can't tell without more information

7 If the viscosity of fluids on the shell side is increased, the heat transfer rate:
  A __Will increase
  B __Will decrease
  C __Will stay the same
  D __Can't tell without more information

8 The utility fluid is:
  A __The fluid that costs less since it is asked to do anything
  B __A fluid that can move in either direction
  C __The non-process fluid in a heat exchanger
  D __A utility that is a fluid

9 The overall heat transfer coefficient includes the resistance to heat transfer through:
  A __The pipe wall
  B __The barrier layer on the shell side
  C __The barrier layer on the tube side
  D __All of the above

10 Design issues with heat exchangers include all but:
  A __Area required
  B __Corrosion resistance to the fluids
  C __Leakage possibilities
  D __The dollar to euro conversion at the time of design

11   The primary design limitation of air cooled heat exchangers is:
    A __Fan speed
    B __Distance from a river or lake
    C __Temperature of outside air
    D __Contractor's ability to raise or lower the heat exchanger

12   Fouling and scaling on a heat exchanger can be caused by:
    A __Deposition of hard water salts
    B __Softness of the heat exchanger material
    C __Use of distilled water as a coolant
    D __Poor maintenance

13   Radiative heat transfer can be an important concern in:
    A __Sunburns while working in a chemical plant in Houston
    B __Chemicals that are red or yellow
    C __Insufficient heat transfer on a cloudy day
    D __High temperature processing in the oil and petrochemical industry

14   High temperature heat transfer fluids are used when:
    A __Cold ones are not available
    B __It is necessary to transfer heat at high temperature and low pressure
    C __Hot water is not available
    D __The plant manager owns stock in a company that makes and sells them

15   The downside of high temperature heat transfer fluids include all but:
    A __Flammability
    B __Possible degradation and need to recharge
    C __Potential chemical exposure to the process fluid
    D __Ability to transfer high temperature heat at low pressure

Additional Resources

Arsenault, G. (2008) "Safe Handling of Heat Transfer Fluids" *Chemical Engineering Progress*, 3, pp. 42–47.

Beain, A.; Heidari, J. and Gamble, C. (2001) "Properly Clean Out Your Organic Heat Transfer System" *Chemical Engineering Progress*, 5, pp. 74–77.

Bennett, C.; Kistler, R. and Lestina, T. (2007) "Improving Heat Exchanger Designs" *Chemical Engineering Progress*, 4, pp. 40–45.

Beteta, O. (2015) "Cool Down with Liquid Nitrogen" *Chemical Engineering Progress*, 9, pp. 30–35.

Bouhairie, S. (2012) "Selecting Baffles for Shell and Tube Heat Exchangers" *Chemical Engineering Progress*, 2, pp. 27–32.

Chu, C. (2005) "Improved Heat Transfer Predictions for Air Cooled Heat Exchangers" *Chemical Engineering Progress*, 11, pp. 46–48.

Gamble, C. (2006) "Cost Management in Heat Transfer Fluid Systems" *Chemical Engineering Progress*, 7, pp. 22–26.

Garvin, J. (2002) "Determine Liquid Specific Heat for Organic Compounds" *Chemical Engineering Progress*, 5, pp. 48–50.

Krishna, K.; Rogers, W. and Mannan, M.S. (2005) "Consider Aerosol Formation When Selecting Heat Transfer Fluids" *Chemical Engineering Progress*, 7, pp. 25–28.

Laval, A. and Polley, G. (2002) "Designing Plate-and-Frame Heat Exchangers" (3 part series), *Chemical Engineering Progress*, 9, pp. 32–37; 10, pp. 48–51, and 11, pp. 46–51.

Lestina, T. (2011) "Selecting a Heat Exchanger Shell" *Chemical Engineering Progress*, 6, pp. 35–38.

Nasr, M. and Polley, G. (2002) "Should You Use Enhanced Tubes?" *Chemical Engineering Progress*, 4, pp. 44–50.

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9

Reactive Chemicals Concepts

This chapter is a collection of issues relating to reactivity and control of heat-generating chemical reactions, both of which, if not properly considered and accommodated in design, can cause significant consequences, including loss of life and property. There are many inherently unstable families of chemicals (i.e., peroxides) that are well known to be thermally unstable and must be stored under refrigeration. In these cases, it is essential to provide backup utility supply to the refrigeration system. The separation of oxidizing and reducing gas cylinders is also a common practice to minimize the possibility of these types of materials interacting with each other, producing a large release of energy. Chemicals that have known degradation rates to hazardous by-products must be monitored on a regular basis, especially if in storage situations where they are not seen regularly.

The safety and operational concepts in the processing of materials that could generate uncontrolled release of energy are the most important in chemical engineering. It concerns the balance of cooling to remove energy released and an exothermic chemical reaction, mixing, or degradation process, which is heat generating. We have discussed the two key aspects within this area already—kinetics and heat transfer. One is a logarithmic function of temperature (kinetics, $k = Ae^{-E/RT}$) and the other a linear function ($Q = UA\Delta T$). Let's look at a typical rate expression as a graph as we reviewed earlier (Figure 9.1).

If we superimpose a heat transfer (a linear function) line on top of this, we see a graph such as that shown in Figure 9.2.

When the rate of energy generation from the reaction is greater than the system's ability to remove the heat, we have a runaway chemical reaction. It is absolutely critical that this point be known for any exothermic chemical reaction system and to think seriously about how to minimize the possibility of reaching this point, how to monitor and shut off feeds, how to provide supplementary cooling, or other means to minimize the consequences.

The shapes of these curves, as well as their response to temperature and other process conditions, have been covered in the previous chapters (4 and 8)
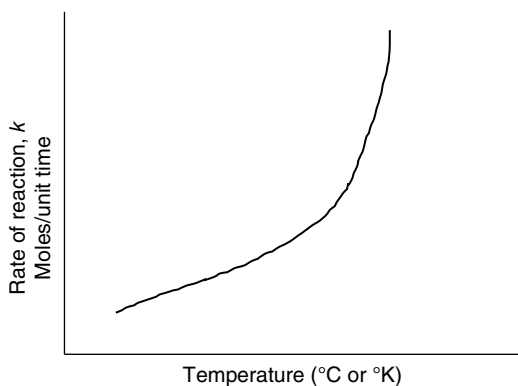
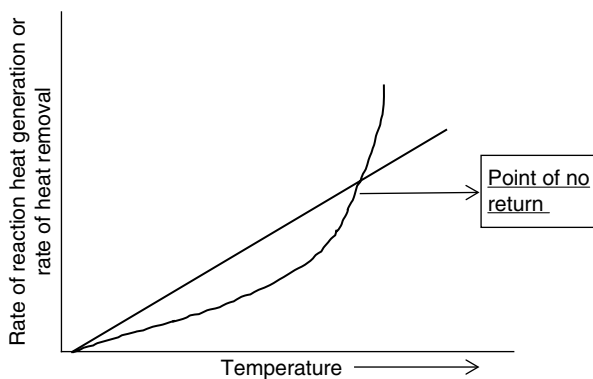**Figure 9.1** Rate of reaction versus temperature.

Figure 9.2 Point of no return for a runaway reaction.

on kinetics/reaction engineering and heat transfer. Reactive chemicals analysis includes a full knowledge of the nature of the chemicals being handled and the integration of kinetics and heat transfer to provide a complete view of the safety implications of running any exothermic reaction. This knowledge can also be used to design appropriate backup utility supplies as well as the control systems needed to ensure proper shutdown of feeds to an exothermic reaction.

As a suggested review on this topic, the Chemical Safety Board video on the T-2 explosion that occurred in Jacksonville, FL is recommended:

http://www.csb.gov/t2-laboratories-inc-reactive-chemical-explosion/

In this case, in addition to the unawareness of the general hazard, the scale-up of this known exothermic chemical reaction to larger and larger reaction volumes, moved the system along the curve as seen in Figure 9.2. The cooling capability was limited by both the reactor jacket heating area and the temperature of the cooling water. As the reaction scale was increased, the

heat generation increased beyond the capability of the heat removal system, causing excessive pressure generation and the release of hydrogen gas (a reaction by-product).

There have been many reactive chemicals incidents in the chemical industry over the past few decades caused by one or more of the following:

1) Insufficient data on reaction rates and their change with process conditions
2) Insufficient heat transfer area to remove the heat of an exothermic chemical reaction, especially beyond the normal operating conditions
3) Lack of backup cooling water supply, especially if primary cooling is from a public utility
4) Lack of communication of KNOWN information to plant operating personnel
5) Insufficient numbers of layers of protection in the event of failure of primary means of controlling feeds, pressure, or cooling
6) Multiple charging of materials
7) Mechanical shock or extremes in cold or heat
8) Unrecognized side reactions
9) Insufficient or sudden loss of agitation or mixing
10) Friction and shock

Summary

Though one of the shortest chapters in this book, it is the most important. It is at the intersection of chemistry, chemical engineering, and mechanical engineering. The lack of complete knowledge of this topic has been the cause of many injuries, deaths, and huge property losses in the chemical industry. The topics reviewed here need to be at the heart of any comprehensive safety and loss prevention program. They are frequently included in most HAZOP and FMEA reviews, but if not, a separate and focused review is recommended.

Coffee Brewing: A Potential Reactive Chemical Process?

Since we are not running a reaction in the classical sense, the short answer to this is probably not. However if we put all of our ChE hats on, there are a few questions we might ask. If and when the water overflows, is there anything in your kitchen it could react with? Could it short out an electrical circuit? We usually put the spent grounds down the sink drain without thinking. Could something be in the sink or drain (left by someone previously) that it could react with? Most of the time, there's also a waste grinder below our sinks. It is putting in grinding energy. Where does that energy go? Could it cause a reaction through its heat generation? You may be putting cream, artificial cream, creams with flavorings, sugar, and sugar substitutes (what kind?). Any reactive chemical possibilities?

Discussion Questions

1 For any exothermic reactions, is the amount of heat release as a function of reaction temperature? How is this affected by any change in stoichiometry in the reaction?

2 Has the "runaway" or point of no return been clearly defined for the reaction?

3 What variables, in addition to stoichiometry, could affect it? Are they measured?

4 What is the emergency response plan for a possible runaway?

5 If the reaction produces a gas, where does it vent? Does this cause additional areas of concern?

6 How does a potential loss of agitation or mixing affect the rates of reaction and heat removal? How many layers of protection are appropriate?

7 Has a formal reactive chemicals review been made of the process? How long ago? What has changed?

8 If the cooling in the process is supplied by a public utility, what is the effect of its loss? What is the communication process between plant operations and the utility supplier?

9 What other utility losses could cause a reactive chemical release? Air? Electricity? What are the backup plans? How many layers of protection are needed?

10 Has all known reactive chemicals information been communicated to all personnel in the manufacturing plant?

11 For any endothermic reactions, what are the consequences of a loss of energy input if the feeds to the reaction continue?

Review Questions (Answers in Appendix with Explanations)

1 Reactive chemicals reviews start with an understanding of:
   A __How reactive management is to safety incidents
   B __A summary of last quarter's reactive chemicals incident reviews
   C __The chemical stability of all chemicals being handled
   D __The cost of changing storage conditions for gas cylinders

2 Reactive chemicals analysis would include all but the following:
   A __Management's reaction to a reactive chemicals incident
   B __Shock sensitivity
   C __Temperature sensitivity
   D __Heat generation during any processing

3 When considering the reactive chemicals potential of an exothermic chemical reaction, the key consideration is:
   A __The cost of cooling versus heating
   B __The cost of relief devices and environmental permits relating to an over-pressured reactor
   C __The rate of heat generation versus the rate of cooling required
   D __The possible rise in cost of processing

4 The reason there is a basic conflict between kinetics and heat transfer is that heat transfer is a linear function and kinetics or reaction rates are typically:
   A __Logarithmic with temperature
   B __Inversely proportional to pressure
   C __Subject to residence times in the reactor
   D __Vary with the square root of the feed ratios

5 A rise in reactor temperature will:
   A __Increase the rate of heat removal from the reactor
   B __Increase the rate of any chemical reaction occurring
   C __Lower the viscosity of any liquids in the reactor, increasing the heat transfer rate
   D __All of the above

6 An increase in volume used within a chemical reactor will have what effect on the potential for a reactive chemical incident?

   A __None

   B __Make the system less susceptible

   C __Make the system more susceptible

   D __Need additional information to answer

7 A drop in temperature within the reactor will _____ the probability of a runaway reaction.

   A __Increase

   B __Decrease

   C __Make no difference

   D __Need additional information

8 Improper storage of materials in warehouses can be a source of reactive chemicals incidents if:

   A __Moisture-sensitive materials are stored under a leaky roof

   B __Oxidizers and reducers are stored next to each other

   C __Known compound stability time limits are exceeded

   D __Any or all of the above

Additional Resources

Baybutt, P. (2015) "Consider Chemical Reactivity in Process Hazard Analysis" *Chemical Engineering Progress* 1, pp. 25–31.

Chastain, J.; Doerr, W.; Berger, S. and Lodal, P. (2005) "Avoid Chemical Reactivity Incidents in Warehouses" *Chemical Engineering Progress* 2, pp. 35–39.

Crowl, D. and Keith, J. (2013)"Characterize Reactive Chemicals with Calorimetry" *Chemical Engineering Progress* 7, pp. 26–33.

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Murphy, J. and Holmstrom, D. (2004) "Understanding Reactive Chemical Incidents" *Chemical Engineering Progress* 3, pp. 31–33.

Richardson, K. (2015) "Tool Helps Predict Reactivity Hazards" *Chemical Engineering Progress* 4, p. 21.

Saraf, S.; Rogers, W. and Mannan, M.S. (2004) "Classifying Reactive Chemicals" *Chemical Engineering Progress* 3, pp. 34–37.