18

VALVES AND FITTINGS

As indicated in Chapter 13, pipes, tubing and other conduits are used for the transportation of gases, liquids and slurries. These ducts are often connected and may also contain a variety of valves and fittings, including expansion and contraction joints. Types of connecting conduits include:

1. Threaded.
2. Bell-and-spigot.
3. Flanged.
4. Welded.

Extensive information on these classes of connections is available in the literature.[1]

Details on valves, fittings, and changes in cross-sectional area are provided below.

18.1 VALVES[2]

Because of the diversity of the types of systems, fluids, and environments in which valves must operate, a vast array of valve types have been developed. Examples of the common types are the globe valve, gate valve, ball valve, plug valve, pinch valve, butterfly valve, and check valve. Each type of valve has been designed to meet specific needs. Some valves are capable of throttling flow, other valve types can only stop flow, others work well in corrosive systems, and others handle high pressure fluids. Each valve type has advantages and disadvantages. Understanding

Fluid Flow for the Practicing Chemical Engineer. By J. Patrick Abulencia and Louis Theodore

these differences and how they effect the valve's application or operation is necessary for the successful operation of a facility.

Valves have two main functions in a pipeline: to control the amount of flow or to stop the flow completely. There are many different types of valves; the most commonly used are the gate valve and the globe valve. The gate valve contains a disk that slides at right angles to the flow direction. This type of valve is used primarily for on–off control of a liquid flow. Because small lateral adjustments of the disk can cause extreme changes in the flow cross-sectional area, this type of valve is not suitable for accurately adjusting flow rates. As the fluid passes through the gate valve, only a small amount of turbulence is generated; the direction of flow is not altered and the flow cross-sectional area inside the valve is only slightly smaller than that of the pipe. As a result, the valve causes only a minor pressure drop. Problems with abrasion and erosion of the disk arise when the valve is used in positions other than fully open or fully closed.

Unlike the gate valve, the globe valve—so called because of the spherical shape of the valve body—is designed for more sensitive flow control. In this type of valve, the liquid passes through the valve in a somewhat circuitous route. In one form, the seal is a horizontal ring into which a plug with a slightly beveled edge is inserted when the stem is closed. Good control of flow is achieved with this type of valve, but at the expense of a higher pressure loss than a gate valve.

Stop valves are used to shut off or, in some cases, partially shut off the flow of fluid. Stop valves are controlled by the movement of the valve stem. Stop valves can be divided into four general categories: globe, gate, butterfly, and ball valves. Plug valves and needle valves may also be considered stop valves.

Ball valves, as the name implies, are stop valves that use a ball to stop or start the flow of fluid. The ball performs the same function as the disk in the globe valve. When the valve handle is operated to open the valve, the ball rotates to a point where the hole through the ball is in line with the valve body inlet and outlet. When the valve is shut, which requires only a 90-degree rotation of the handwheel for most valves, the ball is rotated so the hole is perpendicular to the flow openings of the valve body and flow is stopped.

A plug valve is a rotational motion valve used to stop or start fluid flow. The name is derived from the shape of the disk, which resembles a plug. The simplest form of a plug valve is the petcock. The body of a plug valve is machined to receive a tapered or cylindrical plug. The disk is a solid plug with a bored passage at a right angle to the longitudinal axis of the plug. In the open position, the passage in the plug lines up with the inlet and outlet ports of the valve. When the plug is turned 90° from the open position, the solid part of the plug blocks the ports and stops fluid flow.

The relatively inexpensive pinch valve is the simplest in any valve design. Pinch valves are suitable for on–off and throttling services. However, the effective throttling range is usually between 10% and 95% of the rated flow capacity. Pinch valves are ideally suited for the handling of slurries, liquids with large amounts of suspended solids, and systems that convey solids pneumatically. Because the operating mechanism is completely isolated from the fluid, these valves also find application where corrosion or metal contamination of the fluid might be a problem.

The pinch control valve consists of a sleeve molded of rubber or other synthetic material and a pinching mechanism. All of the operating portions are completely external to the valve.

A butterfly valve is a rotary motion valve that is used to stop, regulate, and start fluid flow. Butterfly valves are easily and quickly operated because a 90° rotation of the handle moves the disk from a fully closed to a fully opened position. Larger butterfly valves are actuated by hand wheels connected to the stem through gears that provide mechanical advantage at the expense of speed. Butterfly valves possess many advantages over gate, globe, plug, and ball valves, especially for large valve applications. Savings in weight, space, and cost are the most obvious advantages. The maintenance costs are usually low because there are a minimal number of moving parts and there are no pockets to trap fluids.

Finally, check valves are designed to prevent the reversal of flow in a piping system. These valves are activated by the flowing material in the pipeline. The pressure of the fluid passing through the system opens the valve, while any reversal of flow will close the valve. Closure is accomplished by the weight of the check mechanism, by back pressure, by a spring, or by a combination of these means. The general types (classification) of check valves are swing, tilting-disk, piston, butterfly, and stop.

Valves are also sometimes classified according to the resistance they offer to flow. The low resistance class of valves includes the straight-through flow units; for example, gate, ball, plug, and butterfly valves. Valves having a change in direction are high resistance valves; examples include globe and angle valves.

18.2 FITTINGS[2]

A fitting is a piece of equipment that has for its function one or more of the following:

1. The joining of two pieces of straight pipe (e.g., couplings and unions).
2. The changing of pipeline direction (e.g., elbows and Ts).
3. The changing of pipeline diameter (e.g., reducers and bushings).
4. The terminating of a pipeline (e.g., plugs and caps).
5. The joining of two streams (e.g., Ts and Ys).

A coupling is a short piece of pipe threaded on the inside and used to connect straight sections of pipe with no change in direction or size. When a coupling is opened, a considerable amount of piping must usually be dismantled. A union is also used to connect two straight sections but differs from a coupling in that it can be opened conveniently without disturbing the rest of the pipeline. An elbow is an angle fitting used to change flow direction, usually by 90°, although 45° elbows are also available. In addition, a T (shaped like the letter T) can be used to change flow direction; this fitting is more often used to combine two streams into one; that is, when two branches of piping are to be connected at the same point. A reducer is a coupling for two pipe sections of different diameter. A bushing is also a connector for pipes of different diameter, but, unlike the reducer coupling, is threaded on both the inside and outside. The larger pipe screws onto the outside of the bushing and the smaller pipe screws into the inside of the bushing. Plugs, which are threaded on the outside, and caps, which are threaded on the inside, are used to terminate a pipeline. Finally, a Y (shaped like the letter Y) is similar to the T and is used to combine two streams.

Fittings may be classified as reducing, expanding, branching or deflecting. Reducing or expanding fittings are ones that change the area for flow; these include reducers, bushings, and sudden expansions and contractions. Branch fittings are Ts, crosses, or side outlet elbows. Deflecting fittings change the direction of flow, for example, elbows and bends.

18.3 EXPANSION AND CONTRACTION EFFECTS

If the cross-section of a conduit enlarges gradually so that the flowing fluid velocity does not undergo any disturbances, energy losses are minor and may be neglected. However, if the change is sudden, as in a rapid expansion, it can result in additional friction losses. For such sudden enlargement/expansion situations, the exit loss can be represented by

$$h_{f,e} = \frac{v_1^2 - v_2^2}{2g_c}; \quad e = \text{sudden expansion, SE} \tag{18.1}$$

where $h_{f,e}$ is the loss in head, v_2 is the velocity at the larger cross-section and v_1 is the velocity at the smaller cross-section. When the cross-section of the pipe is reduced suddenly (a contraction), the loss may be expressed by:

$$h_{f,c} = \frac{Kv_2^2}{2g_c}; \quad c = \text{sudden contraction, SC} \tag{18.2}$$

where v_2 is the velocity in the small cross-section and K is a dimensionless loss coefficient that is a function of the ratio of the two cross-sectional areas. Both of the above calculations receive additional treatment in the next section.

In addition to specifying the pipe, fitting and (where applicable) flange materials required, it is also necessary to specify the nuts and bolts and gasket material to be used in most joints. Information is available on steel nuts and bolts for various pressure and temperature services.[3] The choice of gaskets is wide and in general is determined by the material being handled in the pipe line; there are no generalized suggestions. The thickness of any insulation required must be considered in laying out pipe lines for accessibility, ease of maintenance, clearances, and supports. Anchors and supports may also have to be considered. Steam lines or hot process lines must be designed to either have inherent flexibility or to actually incorporate expansion loops or joints in their runs. Lines subject to appreciable expansion must also be adequately anchored at certain intervals so that the expansion joints function properly. Inherent flexibility can be designed in the piping systems by the inclusion of right angle bends in at least two directions. Care must also be taken that the stresses set up in a pipe system due to expansion are not transmitted to the nozzles on the pieces of equipment being connected by the piping. The magnitude of these stresses or forces is sufficient in many cases to distort or actually break these nozzles. In the case of pumps, the force may be sufficient to cause the rotating shaft to bind or cause the packing to wear out very rapidly and cause excessive maintenance.[3,4]

18.4 CALCULATING LOSSES OF VALVES AND FITTINGS

Pipe systems, as mentioned above, include inlets, outlets, bends, and other devices (e.g., valves, fittings) that create a pressure drop. This drop, which results in energy loss, may be greater than that due to flow in a straight pipe. Thus, these additional so-called minor losses may not be so minor in some applications. Pressure loss data for a wide variety of valves and fittings have been compiled in terms of either the loss (or resistance) coefficient, K, or the "equivalent-length," L_{eq}. Details on these two concepts follow.

The dimensionless loss coefficient is defined as:

$$K = \frac{h_{f,m}}{v^2/2g_c} \tag{18.3}$$

where $h_{f,m}$ is the minor head loss due to the device and $v^2/2g_c$ is defined as the dynamic or velocity head. This equation may be rewritten as

$$h_{f,m} = K\frac{v^2}{2g_c} \tag{18.4}$$

The units of $h_{f,m}$ must have units consistent with $v^2/2g_c$ (e.g., $\text{ft} \cdot \text{lb}_f/\text{lb}$) for K to be dimensionless. A pipe system may have several valves and fittings. The minor losses of all of them can therefore be expressed in terms of the aforementioned velocity (dynamic) head. Then, they can all be summed, i.e.,

$$\sum h_{f,m} = \frac{v^2}{2g_c}\sum K \tag{18.5}$$

The resistance coefficient, K, for open valves, elbows and tees are listed in Table 18.1. The listed K values depend on the nominal diameter, the valve or fitting type, and whether it is screwed or flanged. The tabulated valve loss coefficients are for *fully open* valves. To account for *partially open* valves, the following ratio is employed

$$\frac{K \text{ of partially open valve}}{K \text{ of fully open valve}} \tag{18.6}$$

Table 18.1 Resistance coefficients *K* for open valves, elbows, and tees

Nominal diameter, inch	Screwed				Flanged				
	1/2	1	2	4	1	2	4	8	20
Valves (fully open):									
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03
Swing check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0
Elbows:									
45° regular	0.39	0.32	0.30	0.29					
45° long radius					0.21	0.20	0.18	0.16	0.14
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20
180° long radius					0.40	0.30	0.21	0.15	0.10
Tees:									
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.07
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41

Values for gate and globe valves are given in Table 18.2 for estimation purposes.

The loss coefficient K_{SE} due to a sudden expansion (SE) between two different sizes of pipes D_1 and D_2 ($D_1 < D_2$) for Equation (18.7)

$$h_{f,e} = K_{SE} \frac{v_1^2}{2g_c} \tag{18.7}$$

is given by (see Fig. 18.1)

$$K_{SE} = \left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2 \tag{18.8}$$

Combining Equations (18.7) and (18.8) gives

$$h_{f,e} = \left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2 \frac{v_1^2}{2g_c} \tag{18.9}$$

Table 18.2 Increased losses of partially open valves

Condition		Ratio K/K (Fully Open Condition)	
		Gate Valve	Globe Valve
Open		1.0	1.0
Closed	25%	3.0–5.0	1.5–2.0
	50%	12.0–22.0	2.0–3.0
	75%	70–120.0	6.0–8.0

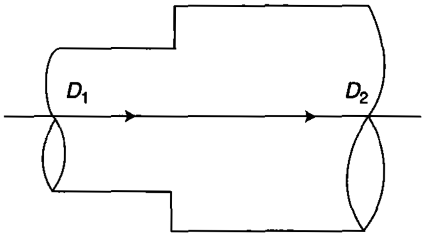

Figure 18.1 Sudden expansion.

Illustrative Example 18.1 Calculate K_{SE} if there is a sudden expansion in which the diameter D_1 doubles to D_2, that is, $D_2 = 2D_1$.

Solution Apply Equation (18.8).

$$K_{SE} = \left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2$$

Set

$$D_2 = 2D_1$$

Thus,

$$K_{SE} = \left[1 - \left(\frac{1}{2}\right)^2\right]^2$$
$$= 9/16$$
$$= 0.562$$

Note that the loss coefficient K_{SE} is based on the velocity head of the smaller pipe.

A sudden contraction (see Fig. 18.2) generally leads to a higher pressure drop. The loss coefficient, K_{SC}, can be *approximated* by the equation:

$$K_{SC} = 0.42\left[1 - \left(\frac{D_2}{D_1}\right)^2\right] \tag{18.10}$$

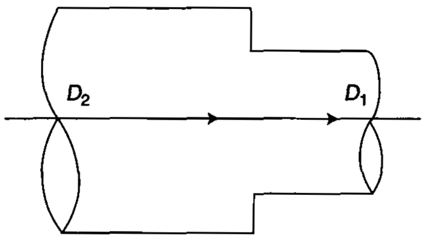

Figure 18.2 Sudden contraction.

Note that values of 0.50 rather than 0.42 have been reported in the literature; for this case,

$$K_{SC} = 0.50\left[1 - \left(\frac{D_2}{D_1}\right)^2\right] \tag{18.11}$$

Note that the loss coefficient, K_{SC}, is based on the velocity head of the smaller pipe at exit conditions.

The above information on the various minor losses is summarized in Table 18.3.

Another approach to describe these losses is through the equivalent length concept. L_{eq} is the length of straight pipe that produces the same head loss as the device in question. The term, L_{eq}, is related to the loss coefficient through Equation (18.12)

$$L_{eq} = K\frac{D}{4f} \tag{18.12}$$

This equation may be rewritten as

$$K = 4f\frac{L_{eq}}{D} \tag{18.13}$$

The L_{eq} in the above equation is not usually expressed as actual feet of straight pipe, but rather as a certain number of pipe diameters. Table 18.4 provides some of these values.[5]

Crane Co. provides information on the equivalent length of straight pipe that would have the same effect as the device. Their results, published by Bennett and Myers,[6] appear in the equivalent length chart in Fig. 18.3.

It should be noted that either the K or the L_{eq} approach assumes a "zero-length" fitting/device. The resistance of the fitting is therefore taken as the total resistance of the pipe/fitting system less the resistance of the length of straight pipe of the section of flow under study.

Using the above approach, the total friction can be expressed as

$$h_f = \left[4f\frac{L}{d} + \sum K_c + \sum K_e + \sum K_f\right]\frac{v^2}{2g_c} \tag{18.14}$$

The above equation may also be written in terms of equivalent lengths instead of the loss coefficients.

Table 18.3 Minor loss calculations

Configuration	Calculation of K
Entrance losses	Equation (18.9)
Exit losses	Equations (18.10) and (18.11)
Fittings: elbows, tees	Table 18.1
Valves: Fully open	Table 18.1
Partially open	Tables 18.1 and 18.2

Table 18.4 Friction loss of screwed fittings, valves, etc.

	Equivalent Lengths, Pipe Diameters
45° elbows	15
90° elbows, standard radius	32
90° elbows, medium radius	26
90° elbows, long sweep	20
90° square elbows	60
180° close return bends	75
180° medium-radius return bends	50
Tee (used as elbow, entering run)	60
Tee (used as elbow, entering branch)	90
Couplings	Negligible
Unions	Negligible
Gate valves, open	7
Globe valves, open	300
Angle valves, open	170
Water meters, disk	400
Water meters, piston	600
Water meters, impulse wheel	300

Illustrative Example 18.2 Calculate the equivalent length of pipe that would cause the same head loss for a gate and globe valve located in piping with a diameter of 3 inches.

Solution The equivalent length of piping that will cause the same head loss for a particular component can be determined by multiplying the L/D for that component by the diameter of pipe. Refer to Table 18.4.

The L/D for a fully open gate valve is 7. The L/D for a fully open globe valve is 300. Based on the definition of the equivalent length

$$L_{eq} = (L/D)D$$

Thus

$$L_{eq}(\text{gate}) = (7)(3) = 21\text{ in.}$$
$$L_{eq}(\text{globe}) = (300)(3) = 900\text{ in.}$$

Illustrative Example 18.3 Water is flowing at room temperature through 30 ft of 3/8 in. pipe at a velocity of 10 ft/s. The pipe contains a flanged globe valve. What is the pressure drop along the length of the pipe? Assume that the friction factor is given by the equations provided in Illustrative Example 14.3, i.e.,

$$f = 0.0015 + 0.125/(\text{Re})^{0.30}$$

Solution At room temperature,

$$\rho = 62.4\text{ lb/ft}^3$$
$$\mu = 6.72 \times 10^{-4}\text{ lb/ft}\cdot\text{s}$$

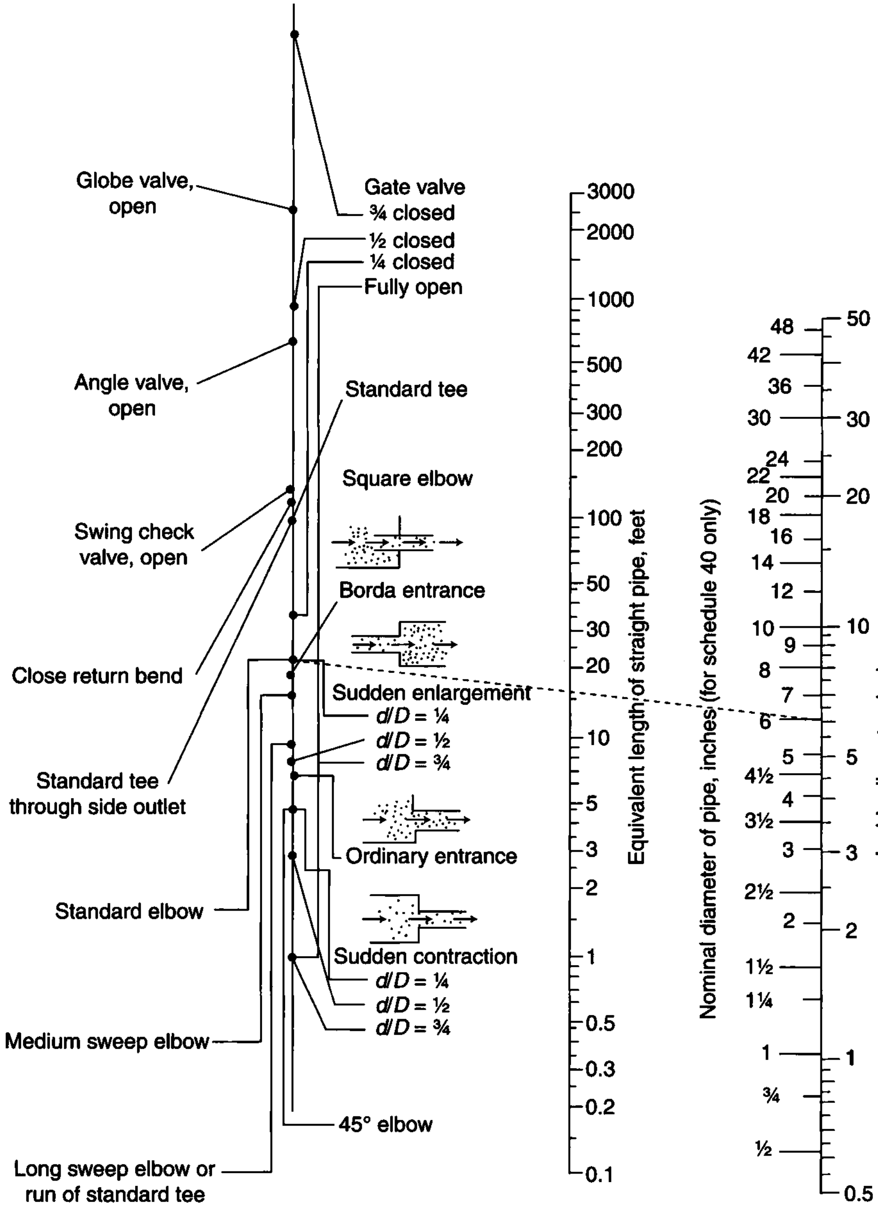

Figure 18.3 Equivalent lengths for friction losses (Crane Co.).

The Reynolds number is

$$\begin{aligned}\text{Re} &= \frac{Dv\rho}{\mu}\\ &= \frac{(0.375/12)(10)(62.4)}{6.72\times10^{-4}}\\ &= 29{,}000\end{aligned}$$

For

$$f = 0.0015 + 0.125/(\text{Re})^{0.30}$$

$$\begin{aligned}f &= 0.0015 + 0.125/(29{,}000)^{0.30}\\ &= 0.0015 + 0.0057\\ &= 0.0072\end{aligned}$$

The pressure drop is calculated by some modest of manipulation of either Equation (13.15) or (14.3).

$$\begin{aligned}\Delta P &= \frac{2f\rho v^2 L}{Dg_c}\\ &= \frac{(2)(0.0072)(62.44)(10)^2(30)}{(0.375/12)(32.2)}\\ &= 2681\ \text{lb}_\text{f}/\text{ft}^2\\ &= 2681/62.4\\ &= 43.0\ \text{ft}\cdot\text{lb}_\text{f}/\text{lb}\\ &= 516\ \text{in. } H_2O\end{aligned}$$

Illustrative Example 18.4 Refer to Illustrative Example 18.3. Determine the frictional loss for the fitting.

Solution The frictional loss for the globe valve is calculated by employing Equation 18.4:

$$h_{f,\text{fitting}} = K_f\frac{v^2}{2g_c}$$

The loss coefficient K_f is obtained by linear extrapolation in Table 18.1.

$$K_f \cong 22$$

Substitution

$$h_f = \frac{(22)(10)^2}{(2)(32.2)}$$
$$= 34.16 \ \frac{\text{ft} \cdot \text{lb}_\text{f}}{\text{lb}}$$

Illustrative Example 18.5 Calculate the total pressure drop in $\text{lb}_\text{f}/\text{ft}^2$ (psf) for the 30 ft pipe system.

Solution The total pressure drop is given by the sum of the results of the two previous problems. Thus,

$$\Delta P_T = (\Delta P + h_f)\rho$$
$$= (34.16 + 43.0)\,62.4$$
$$= 4815\,\text{lb}_\text{f}/\text{ft}^2$$

Illustrative Example 18.6 Water flows from a large open tank (point 1) through a new cast iron pipe (10 in diameter and 5000 ft length). The discharge point (point 2) to the atmosphere is 260 ft below the tank level ($z_1 - z_2 = 260$ ft). The pipe entrance is sharp cornered (see Fig. 18.4). Water properties are $\rho = 62.4\,\text{lb/ft}^3$ and $\mu/\rho = 1.082 \times 10^{-5}\,\text{ft}^2/\text{s}$. Calculate the water volumetric flow rate in ft^3/s.

Solution Obtain the relative roughness of pipe from Table 14.1. For cast iron:

$$k = 0.00085\,\text{ft}$$
$$D = 10\,\text{in} = 0.833\,\text{ft}$$
$$k/D = 0.001$$

Since the flow rate is unknown, the Reynolds number cannot be immediately calculated. Assume a Fanning friction factor in the 0.004–0.005 range. Select the upper limit, that is,

$$f = 0.005$$

The entrance loss coefficient is estimated from Equations (18.10) and (18.11).

$$K = 0.45 \text{ (average value)}$$

Calculate the friction head loss in terms of the line velocity

$$h_f{}' = 4f\frac{L}{D}\frac{v_2{}^2}{2g} = (0.02)\frac{5000}{0.833}\frac{v_2{}^2}{2g} = 12\frac{v_2{}^2}{2g}$$

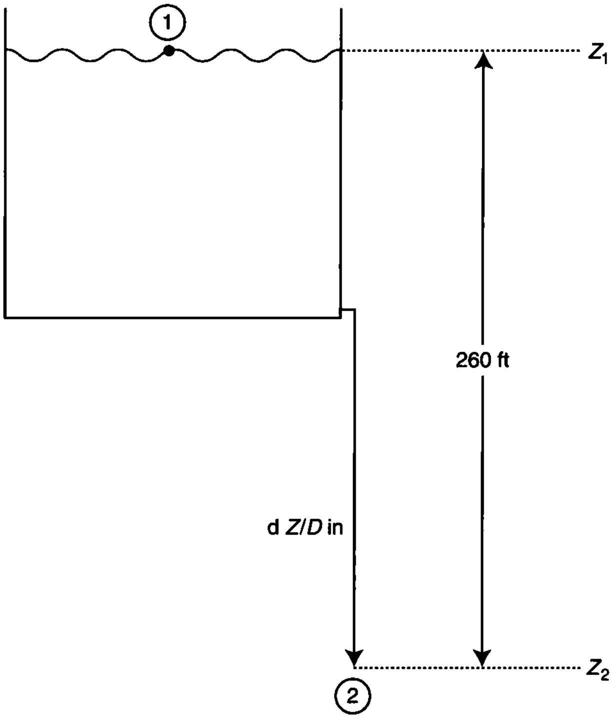

Figure 18.4 Flow system.

Apply Bernoulli's equation between points 1 and 2 to calculate v_2

$$P_1 = P_2 = 0\,\text{psig (both locations open to the atmosphere)}$$
$$v_1 = 0\ \text{(large tank)}$$
$$h_s = 0\ \text{(no shaft head)}$$

$$260 = \frac{v_2{}^2}{2g} + 12\frac{v_2{}^2}{2g} + 0.45\frac{v_2{}^2}{2g}$$
$$= 13.45\frac{v_2{}^2}{2g}$$

The positive root is:

$$v_2 = 11.75\,\text{ft/s}$$

Check on the flow condition

$$\text{Re} = \frac{Dv}{\mu/\rho} = \frac{(0.833)(11.75)}{(1.082 \times 10^{-5})}$$
$$= 904{,}600$$

Read f from Fig. 14.2 to check on the assumed f for $k/D = 0.001$.

$$f = 0.005;\ \text{agrees}$$

Finally, calculate the volumetric flow rate.

$$q = vS = 11.75\frac{\pi(0.833)^2}{4}$$
$$= 6.4\ \text{ft}^3/\text{s}$$

Illustrative Example 18.7 Two large water reservoirs (see Fig. 18.5) are connected by 2000 ft of 3-in. schedule 40 pipe. Water at 20°C is to be pumped from one to the other at a rate of 200 gallon per minute. Both tanks are open to the atmosphere and the level in both reservoirs are the same. The pipes are commercial steel. Calculate the friction loss neglecting minor losses due to entrance and exit effects and assuming fully developed flow.

Solution From Table A.5 in the Appendix, for 3 in. schedule 40 pipe:

$$D = 3.068\ \text{in.} = 0.0779\ \text{m}$$

Obtain the roughness of the pipe, k, from Table 14.1

$$k = 0.046\ \text{mm}$$
$$k/D = 0.046 \times 10^{-3}/0.0779$$
$$= 0.0006$$

The flow velocity of water is ($q = 200\ \text{gpm} = 0.0126\ \text{m}^3/\text{s}$)

$$v = \frac{q}{S} = \frac{q}{\pi D^2/4} = \frac{0.0126}{\pi(0.0779)^2/4}$$
$$= 2.64\ \text{m/s}$$

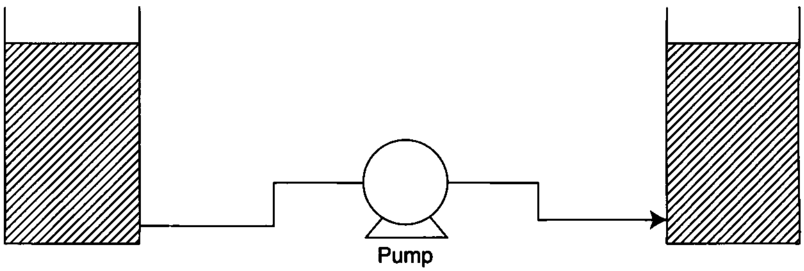

Figure 18.5 Water reservoir.

Check the flow regime

$$\text{Re} = \frac{vD}{\nu} = \frac{(2.64)(0.0779)}{10^{-6}} = 205{,}656$$

Therefore, the flow is turbulent.

From the Fanning chart, Fig. 14.2, at

$$\text{Re} = 205{,}656 \quad \text{and} \quad k/D = 0.0006$$

one obtains

$$f = 0.00345$$

Calculate the head loss

$$h_f' = 4f\frac{L}{D}\frac{v^2}{2g_c} = 4(0.00345)\frac{(2000)(0.3048)}{0.0779}\frac{2.64^2}{2} = 376.3\,\text{J/kg}$$

Apply Bernoulli's equation between stations 1 and 2. Note that $P_1 = P_2 = 1$ atm, $v_1 = v_2$ and $z_1 = z_2$.

$$\frac{\Delta P}{\rho} + \frac{\Delta v^2}{2g_c} + \Delta z\frac{g}{g_c} = h_s - h_f$$

The above equation reduces to

$$h_s = h_f$$

or

$$h_s' = h_f'$$

Therefore

$$h_s' = h_f' = 376.3\,\text{J/kg}$$

Illustrative Example 18.8 Refer to Illustrative Example 18.7. What are the ideal pumping requirements in kW and hp (i.e., calculate the fluid power)? What is the required pressure rise in the pump?

Solution Calculate the pressure rise across the pump.

$$\begin{aligned}\Delta P &= \rho g h_f' = (1000)(9.807)(38.39)\\ &= 376{,}500\,\text{Pa} = 54.61\,\text{psi}\end{aligned}$$

Finally, calculate the ideal pumping requirement (the fluid power).

$$\begin{aligned}\dot{W}_s &= q\Delta P = 0.0126(475{,}000)\\ &= 5985\,\text{kW} = 8.0\,\text{hp}\end{aligned}$$

18.5 FLUID FLOW EXPERIMENT: DATA AND CALCULATIONS

One of the experiments conducted in the Chemical Engineering Laboratory at Manhattan College was concerned with flow through pipes and fittings. Students performed the experiment and later submitted a report. In addition to theory, experimental procedure, discussion of results, and so on, the report contained sample calculations. The following is an (edited) example of those calculations that cover a wide range of flow through pipes and fittings principles and applications.

A photograph of the flow through pipes and fittings experimental setup is provided in Fig. 18.7. A line diagram of the system follows in Figure 18.8. (The system was designed by one of the authors approximately 40 years ago.) Water enters the system at different flow rates and flows along the outer or inner loop and exits the system. As the water flows through the system, the pressure drops along the various pipe lengths and fittings are read from two mercury manometers. One manometer is solely dedicated to read the pressure drop across the orifice meter. Pressure taps are located at the start and end of each section of pipe, fitting and valve to assist in taking the pressure drop across the appropriate section.

Referring to Fig. 18.7, the outer loop consists of a/an:

1. length of 3/8 inch diameter brass pipe,
2. straight portion of tee,
3. gate valve,

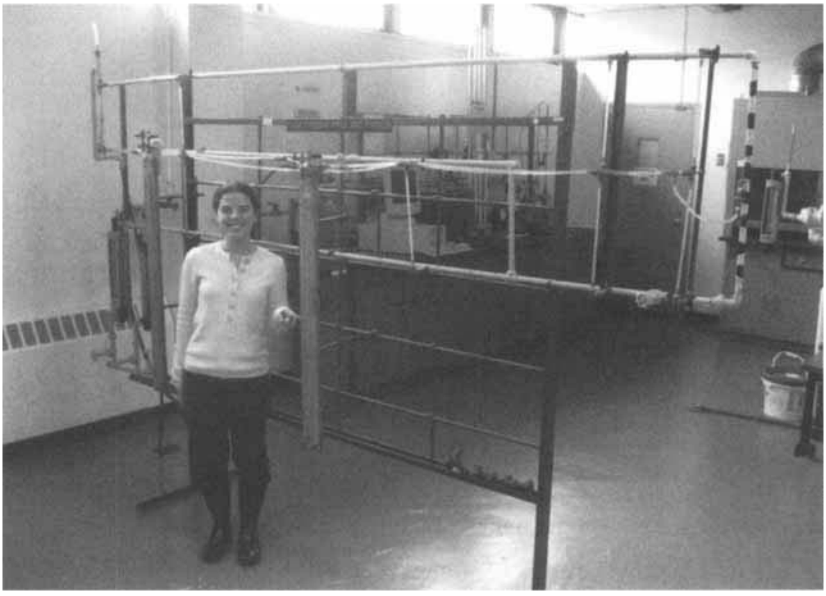

Figure 18.7 Flow through pipes and fittings.

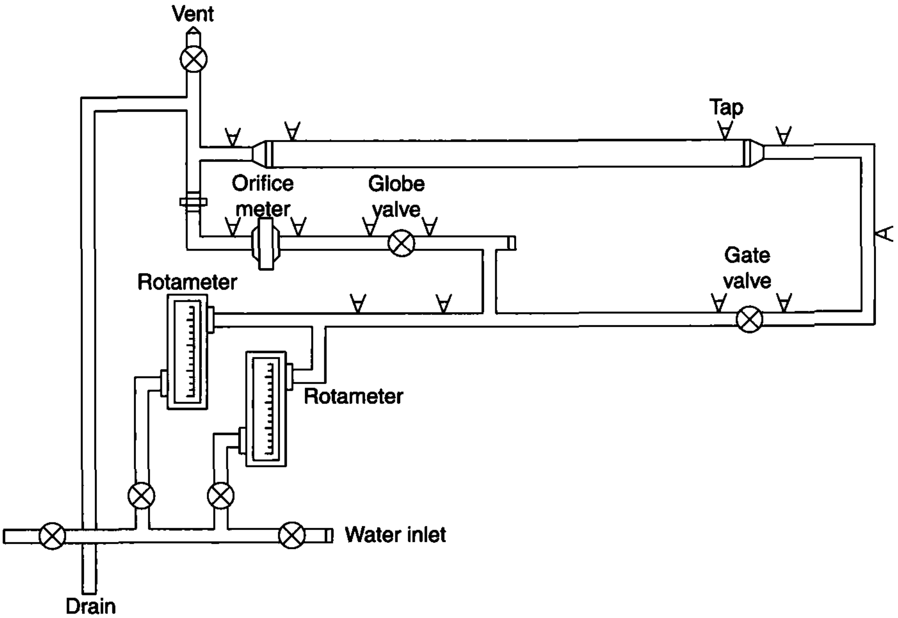

Figure 18.8 Flow through pipes and fittings.

4. 90° elbow plus junction,
5. 90° elbow only,
6. expansion from 3/8 to 1/2 inch diameter pipe,
7. length of 1/2 inch diameter brass pipe, and
8. contraction from 1/2 to 3/8 inch diameter pipe

The inner pipe consists of a/an:

1. length of 3/8 inch diameter brass pipe,
2. pair of right angle elbow portion of tees,
3. globe valve,
4. length of 3/8 inch diameter brass pipe, and
5. orifice meter

The following sample calculations represent some of the calculations that were performed in the analysis of this experiment. The sample calculations are for both outer and inner loops for 80% of the maximum flow rate in the 6 gpm rotameter.

Therefore,

$$q = (0.8)(6\,\text{gpm}) = 4.8\,\text{gpm}$$

$$= 0.01069\ \text{ft}^3/\text{s}$$

The cross-section area of the outer pipe is

$$S = \frac{\pi D^2}{4}$$
$$= \frac{\pi(0.0413^2)\,\text{ft}^2}{4}$$
$$= 0.00134\,\text{ft}^2$$

The velocity is therefore,

$$v = \frac{0.01069\,\text{ft}^3/\text{s}}{0.00134\,\text{ft}^2} = 7.98\,\text{ft/s}$$

The Reynolds number for this flow rate is

$$\text{Re} = \frac{Dv\rho}{\mu}$$
$$= \frac{(62.4)(7.98\,\text{ft/s})(0.0413\,\text{ft})}{7.29 \times 10^{-4}}$$
$$= 28{,}210$$

This Re number indicates that the flow rate is turbulent.

Calculate the pressure drop across the length of 3/8 inch diameter pipe. The equation used to calculate the pressure drop is:

$$\Delta P = P_1 - P_2 = \left(\frac{g}{g_c}\right)(R_m)(\rho_{Hg} - \rho_{H_2O})$$

where ρ_{Hg} = density of mercury, 999.2 kg/m^3
ρ_{H_2O} = density of water, 13,600 kg/m^3
R_m = vertical distance between two meniscuses, (7.0 cm) 0.070 m

Substituting

$$\Delta P = \frac{(9.8)(0.070)(13{,}600 - 999)(14.7)(144)}{1.01325 \times 10^5}$$
$$= 180.59\,\text{lb}_f/\text{ft}^2$$

After obtaining the pressure drop for the length of 3/8 inch diameter pipe between pressure taps 1 and 2 (3.979 ft), the pressure drop per unit length is determined as follows:

$$\Delta P_{L\frac{3}{8}} = \frac{\Delta P}{L} = \frac{180.59}{3.979}$$
$$= 45.38\,\text{lb}_f/\text{ft}^3$$

The Fanning friction factor is given

$$f = \frac{D \Delta P g_c}{2 L \rho v^2}$$

where ΔP = pressure drop calculated above, 180.59 lb_f/ft^2
D = diameter of the pipe, 0.0413 ft
g_c = Newton's law constant 32.2 $ft \cdot lb/lb_f \cdot s^2$
L = length of pipe, 3.979 ft
ρ = density of water, 62.4 lb/ft^3
v = average velocity of the fluid in the pipe, 7.98 ft/s

Substituting,

$$f = \frac{(0.0413)(180.59)(32.2)}{(2)(3.979)(62.4)(7.98)}$$
$$= 0.0076$$

This is in reasonable agreement with the Fanning friction plot.

Calculation of friction losses are determined from the Bernoulli equation:

$$\frac{P_2 - P_1}{\rho} + \frac{g}{g_c}(z_2 - z_1) + \frac{\alpha_2 v_2{}^2 - \alpha_1 v_1{}^2}{2 g_c} = h_f$$

where $P_1 - P_2$ = pressure drop at points 1 and 2, lb/ft^2
ρ = fluid density, lb/ft^3
g = acceleration due to gravity, ft/s^2
g_c = Newton's conversion constant, $ft \cdot lb/lb_f \cdot s^2$
z_1, z_2 = vertical distances at points 1 and 2, ft
α = kinetic energy correction factor
v_1, v_2 = velocities at points 1 and 2, ft/s
h_f = friction generated per pound mass of fluid, $ft \cdot lb_f/lb$

The Bernoulli equation above simplifies to the equation below for the length of 3/8 inch diameter brass pipe since there is no height difference along the pipe, and the velocity of the water along the pipe is assumed to be constant. Also assume $\alpha_1 = \alpha_2 = 1.05$ for turbulent flow.

$$h_f = \frac{P_2 - P_1}{\rho}$$

$$h_f = \frac{180.59}{62.4}$$
$$= 2.894 \, ft \cdot lb_f/lb$$

To calculate the frictional losses due to the straight portion of tee, the total frictional loss between taps 2 and 3 was found and the frictional losses due to the length of the pipe between the two taps subtracted from it

$$h_{ft} = \frac{P_2 - P_1}{\rho} - \frac{\left(\Delta P_{L\frac{3}{8}}\right)(L)}{\rho} = \left(\frac{110.94}{62.4}\right) - \frac{(45.38)(2.02)}{62.4}$$

$$h_{ft} = 0.308\ \text{ft} \cdot \text{lb}_f/\text{lb}$$

The frictional losses due to the gate valve are calculated in a manner similar to the frictional loss from the straight portion of tee.

$$h_{fg} = \frac{P_2 - P_1}{\rho} - \frac{(\Delta P_L)L}{\rho} = \left(\frac{108.36}{62.4}\right) - \frac{(45.38)(0.66)}{62.4}$$

$$h_{fg} = 1.26\ \text{ft} \cdot \text{lb}_f/\text{lb}$$

The frictional losses due to the two 90° elbows plus junction (union) were determined as above. The velocity is again assumed to be constant as the water moves up the elevation

$$h_f = \frac{P_2 - P_1}{\rho} - \frac{\left(\Delta P_{L\frac{3}{8}}\right)(L)}{\rho} - \frac{g(z_2 - z_1)}{g_c}$$

$$= \left(\frac{394.75}{62.4}\right) - \frac{(45.38)(2.35)}{62.4} - \frac{(32.2)(2.001)}{32.2}$$

$$h_f = 2.62\ \text{ft} \cdot \text{lb}_f/\text{lb}$$

The frictional losses due to the elbow alone are also determined as above. The velocity is again assumed to be constant as the water moves up the elevation

$$h_f = \frac{P_2 - P_1}{\rho} - \frac{(\Delta P_L)L}{\rho} - \frac{g(z_2 - z_1)}{g_c}$$

$$= \left(\frac{608.89}{62.4}\right) - \frac{(45.38)(1.283)}{62.4} - \frac{(32.2)(1.083)}{32.2}$$

$$h_f = 7.74\ \text{ft} \cdot \text{lb}_f/\text{lb}$$

The frictional losses due to the union are determined by subtracting the losses due to the two elbows and the length of the pipe between taps 4 and 6 from the total frictional loss determined in above. Thus,

$$h_f = (2.62 - 7.74)$$

$$= -5.12\ \text{ft} \cdot \text{lb}_f/\text{lb}$$

The frictional loss cannot be negative since this would imply energy is generated by the system due to the flow of the fluid. This result is attributed to experimental error.

The frictional loss in the length of 1/2 inch diameter brass pipe is determined the same way as the loss in the length of 3/8 inch diameter brass pipe:

$$h_f = \frac{P_2 - P_1}{\rho}$$

$$h_f = \frac{92.87}{62.4}$$

$$= 1.488\ \mathrm{ft \cdot lb_f/lb}$$

After obtaining the pressure drop for the length of 1/2 inch diameter pipe between pressure taps 7 and 8, the pressure drop per unit length (6.33 ft) in this section is determined as follows:

$$\Delta P_{L\frac{1}{2}} = \frac{\Delta P}{L} = \frac{92.87}{6.33}$$

$$= 14.67\ \mathrm{lb_f/ft^3}$$

The frictional losses due to expansion and contraction are calculated by including the change in velocity, which is factored into the calculation. For the expansion,

$$h_f = \frac{P_2 - P_1}{\rho} - \frac{(\Delta P_{L1})(L_1) + (\Delta P_{L2})(L_2)}{\rho} - \frac{\alpha_2 v_2^2 - \alpha_1 v_1^2}{2g_c}$$

$$= \left(\frac{5.16}{62.4}\right) - \frac{(45.38)(0.2625\ \mathrm{ft}) + (14.67)(0.4921)}{62.4} - \frac{(1.05)(5.00^2 - 7.98^2)}{(2)(32.2)}$$

$$h_f = 0.41\ \mathrm{ft \cdot lb_f/lb}$$

The frictional losses due to the contraction from 1/2 to 3/8 inch pipe are similarly calculated. The only difference is v_2 and v_1 that are the velocities in the 3/8 inch and 1/2 inch pipe, respectively.

$$h_f = \frac{P_2 - P_1}{\rho} - \frac{(\Delta P_{L1})(L_1) + (\Delta P_{L2})(L_2)}{\rho} - \frac{\alpha_2 v_2^2 - \alpha_1 v_1^2}{2g_c}$$

$$= \left(\frac{110.94}{62.4}\right) - \frac{(45.38)(1.00) + (14.67)(1.01)}{62.4} - \frac{(1.05)(7.98^2 - 5.00^2)\ \mathrm{ft/s}}{(2)(32.2)}$$

$$h_f = 0.18\ \mathrm{ft \cdot lb_f/lb}$$

The globe valve calculation is performed the same way as the determination of the frictional losses across the gate valve in the outer loop. Only the result will be provided here

$$h_{fg} = \frac{P_2 - P_1}{\rho} - \frac{(\Delta P_L)(L)}{\rho}$$
$$= 6.30\,\text{ft} \cdot \text{lb}_\text{f}/\text{lb}$$

Sample calculations for the determination of the frictional loss coefficient, K, for the straight through tee, orifice meter, and expansion from 3/8 inch to 1/2 inch diameter pipe are shown below. The determination of the frictional loss coefficient for all the other fittings is similar to the one for the straight through tee. Therefore, those calculations are not shown here. The frictional losses due to the straight through tee in the system are given by the equation below:

$$h_{f,\,\text{fitting}} = K_f \frac{v_1^{\,2}}{2g_c}$$

where v_1 = average velocity in pipe leading to fitting, ft/s
K_f = frictional loss coefficient for fitting

Re-arranging the equation above gives

$$\log_{10}(h_{f,\,\text{fitting}}) = 2\,\log_{10} V_1 + \log_{10}(K_f) - \log_{10}(2g_c)$$

The equation above is similar to the equation of a straight line

$$y = mx + b$$

Therefore,

$$b = \log_{10}(K_f) - \log_{10}(2g_c)$$

The value of b is obtained from the equation of a trend line in the graph of log h_f versus log v for the straight through tee fitting. From the graph (not shown here)

$$b = -2.2148$$

so that

$$K_f = 10^{-2.2148+\log_{10}(2*32.2)}$$
$$= 0.39$$

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