major loss
minor loss

due to viscous effects in the straight pipes, termed the ***major loss*** and denoted $h_{L\,\text{major}}$, and the head loss in the various pipe components, termed the ***minor loss*** and denoted $h_{L\,\text{minor}}$. That is,

$$h_L = h_{L\,\text{major}} + h_{L\,\text{minor}}$$

The head loss designations of "major" and "minor" do not necessarily reflect the relative importance of each type of loss. For a pipe system that contains many components and a relatively short length of pipe, the minor loss may actually be larger than the major loss.

14.5.1 Major Losses

The major loss is associated with friction (viscous) effects as the fluid flows through the straight pipe and can be expressed in functional form as

$$h_{L\,\text{major}} = F(\text{V}, D, \ell, \varepsilon, \mu, \rho)$$

where V is the average velocity, ℓ is the pipe length, D the pipe diameter, and ε is a length characterizing the roughness of the pipe wall. Although the head loss or pressure drop for laminar pipe flow is found to be independent of the roughness of the pipe (e.g., the pipe roughness does not appear in Eq. 14.4), it is necessary to include this parameter when considering turbulent flow. The above relationship between the head loss and the other physical variables can be expressed as

$$h_{L\,\text{major}} = f\frac{\ell}{D}\frac{\text{V}^2}{2g} \tag{14.11}$$

friction factor

relative roughness

where f is termed the ***friction factor.*** Equation 14.11 is called the *Darcy-Weisbach equation.* The dimensionless friction factor, f, is a function of two other dimensionless terms—the Reynolds number based on the pipe diameter, $Re = \rho\text{V}D/\mu$, and the ***relative roughness,*** ε/D. That is, $f = f(Re, \varepsilon/D)$. As seen by Eq. 14.11, the head loss in a straight pipe is proportional to the friction factor, f, the length-to-diameter ratio, ℓ/D, and the velocity head, $\text{V}^2/2g$.

Moody chart

Figure 14.7 shows the experimentally determined functional dependence of f on Re and ε/D. This is called the ***Moody chart.*** Typical roughness values, ε, for various new, clean pipe surfaces are given in Table 14.1.

The following characteristics are observed from the data of Fig. 14.7. For laminar flow, the friction factor is independent of the relative roughness and is a function of the Reynolds number only:

$$f = 64/Re \qquad (\text{laminar}, Re < 2100) \tag{14.12}$$

wholly turbulent

For ***wholly turbulent flow,*** where the Reynolds number is relatively large, the friction factor is independent of the Reynolds number and is a function of the relative roughness only: $f = f(\varepsilon/D)$.

Table 14.1 Equivalent Roughness for New Pipes.

	Equivalent Roughness, ε	
Pipe	Feet	Millimeters
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Wood stave	0.0006–0.003	0.18–0.9
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.045
Drawn tubing	0.000005	0.0015
Plastic, glass	0.0 (smooth)	0.0 (smooth)

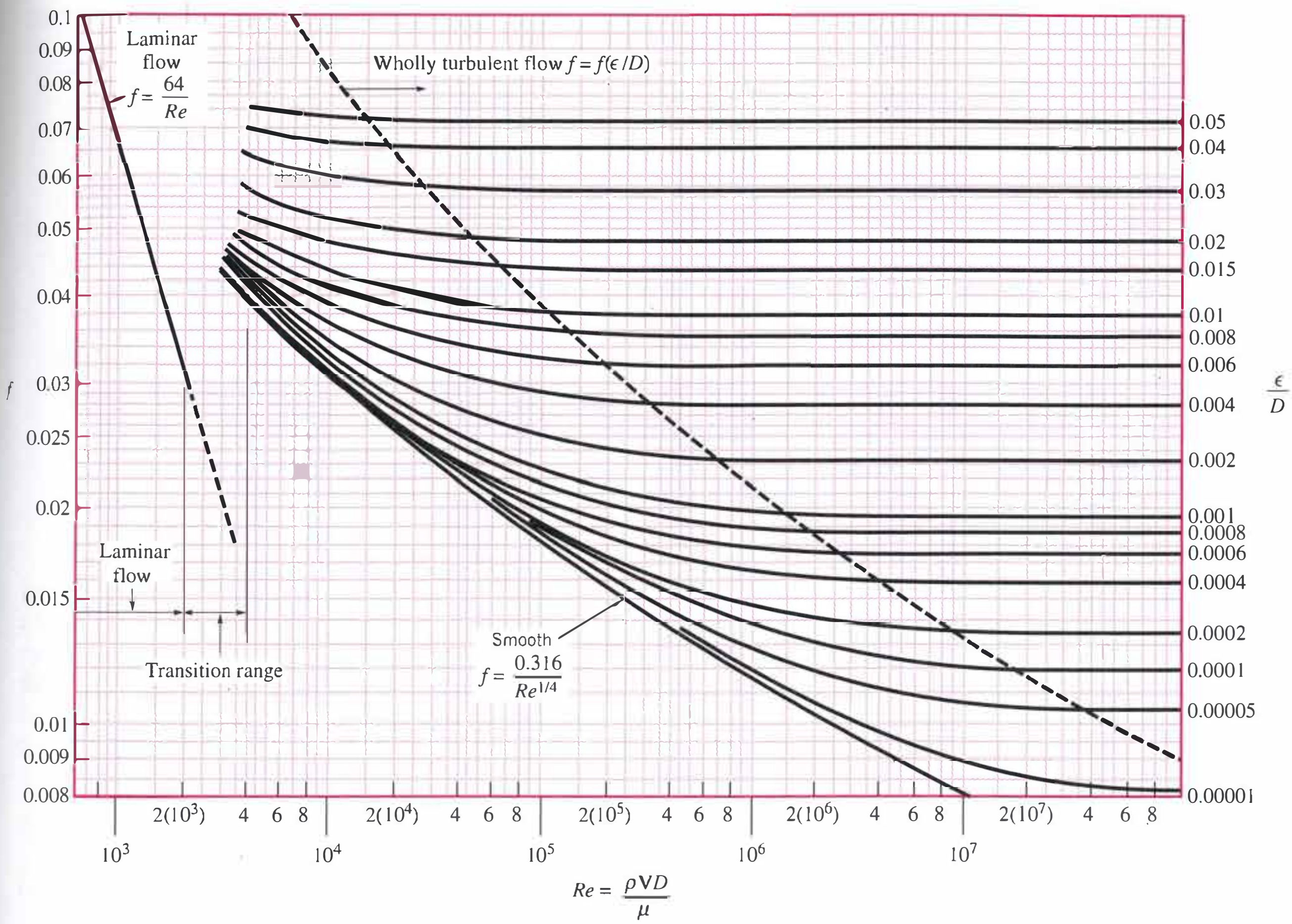


Figure 14.7 Friction factor as a function of Reynolds number and relative roughness for round pipes—the Moody chart

Inspection of Fig. 14.7 also indicates that between the laminar flow and wholly turbulent flow regimes the friction factor depends on both the Reynolds number and the relative roughness.

For the entire turbulent flow range, friction factors can be read from the Moody chart or evaluated using the ***Colebrook formula***

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad \text{(turbulent)} \qquad (14.13)$$

Colebrook formula

which is an empirical fit of the pipe flow data. For ***hydraulically smooth*** ($\varepsilon = 0$) pipes the friction factor is given by the ***Blasius formula***

hydraulically smooth

$$f = 0.316/Re^{1/4} \qquad \text{(turbulent, } \varepsilon = 0) \qquad (14.14)$$

Blasius formula

Example 14.1 Turbulent Pipe Flow—Friction Factors

Air under standard conditions flows through a horizontal section of 4.0-mm-diameter drawn tubing with an average velocity of V = 50 m/s. Determine the pressure drop in a 0.1-m length of the tube.

Solution

Known: Air at standard conditions flows through a horizontal section of drawn tubing with a specified velocity.
Find: Determine the pressure drop.

Assumptions:

1. The air is modeled as an incompressible fluid with a density of $\rho = 1.23\ \text{kg/m}^3$ and a viscosity of $\mu = 1.79 \times 10^{-5}\ \text{N}\cdot\text{s/m}^2$ (see Appendix FM-1).
2. The flow is fully developed and steady.
3. Minor losses are zero since we are considering only a straight portion of pipe.

Analysis: The mechanical energy equation, Eq. 12.15, for this flow can be written as

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L \tag{1}$$

where points (1) and (2) are located within the tube a distance 0.1 m apart.

Since the density and tube area are constant, the mass balance gives $V_1 = V_2$. Also, the tube is horizontal so $z_1 = z_2$. From Eq. 14.11, $h_L = f(\ell/D)(V^2/2g)$. Thus, with $\Delta p = p_1 - p_2$, Eq. 1 becomes

$$\Delta p = \gamma h_L = \rho g\, h_L = f\frac{\ell}{D}\frac{1}{2}\rho V^2 \tag{2}$$

Using known data, the Reynolds number is

$$Re = \frac{\rho V D}{\mu} = \frac{(1.23\ \text{kg/m}^3)(50\ \text{m/s})(0.004\ \text{m})}{1.79 \times 10^{-5}\ \text{N}\cdot\text{s/m}^2}\left|\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right| = 13{,}700$$

which indicates turbulent flow.

For turbulent flow $f = f(Re, \varepsilon/D)$, where from Table 14.1, $\varepsilon = 0.0015$ mm so that $\varepsilon/D = 0.0015\ \text{mm}/4.0\ \text{mm} = 0.000375$. ❶ From the Moody chart (Fig. 14.7) with $Re = 1.37 \times 10^4$ and $\varepsilon/D = 0.000375$ we obtain $f = 0.028$. Thus, from Eq. 2

$$\Delta p = f\frac{\ell}{D}\frac{1}{2}\rho V^2 = (0.028)\frac{(0.1\ \text{m})}{(0.004\ \text{m})}\frac{1}{2}(1.23\ \text{kg/m}^3)(50\ \text{m/s})^2\left|\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right|\left|\frac{1\ \text{kPa}}{10^3\ \text{N/m}^2}\right|$$

or

$$\Delta p = 1.076\ \text{kPa} \triangleleft$$

❶ An alternate method to determine the friction factor for the turbulent flow would be to use the Colebrook formula, Eq. 14.13. Thus,

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) = -2.0\log\left(\frac{0.000375}{3.7} + \frac{2.51}{1.37 \times 10^4\sqrt{f}}\right)$$

or

$$\frac{1}{\sqrt{f}} = -2.0\log\left(1.01 \times 10^{-4} + \frac{1.83 \times 10^{-4}}{\sqrt{f}}\right)$$

A simple iterative solution of this equation gives $f = 0.0291$, which is in agreement (within the accuracy of reading the graph) with the Moody chart value of $f = 0.028$.

14.5.2 Minor Losses

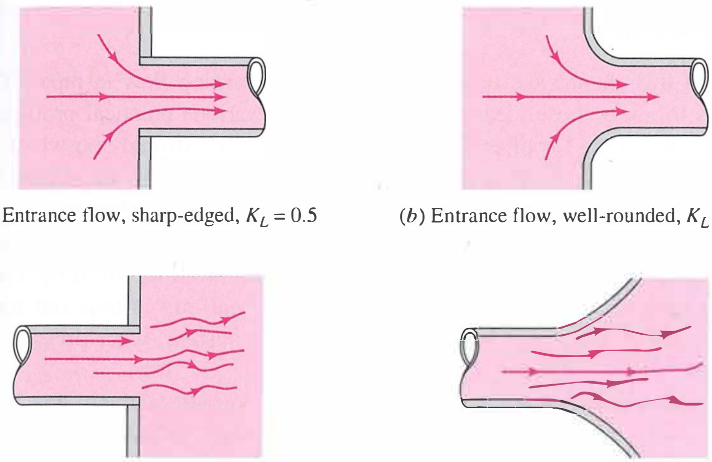
Losses due to the components of pipe systems (other than the straight pipe itself) are termed minor losses and are given in terms of the dimensionless ***loss coefficient,*** K_L, as

loss coefficient

$$h_{L\ \text{minor}} = K_L\frac{V^2}{2g} \tag{14.15}$$

Numerical values of the loss coefficients for various components (elbows, valves, entrances, etc.) are determined experimentally.

Many pipe systems contain various transition sections in which the pipe diameter changes from one size to another. Any change in flow area contributes losses that are not accounted for by the friction factor. The extreme cases involve flow into a pipe from a reservoir (an entrance) or out of a pipe into a reservoir (an exit). Some loss coefficients for entrance and exit flows are shown in Fig. 14.8.



(*a*) Entrance flow, sharp-edged, $K_L = 0.5$

(*b*) Entrance flow, well-rounded, $K_L = 0.04$

(*c*) Exit flow, sharp-edged, $K_L = 1.0$

(*d*) Exit flow, well-rounded, $K_L = 1.0$

Figure 14.8 Loss coefficient values for typical entrance and exit flows.

V14.4 Entrance/exit flows

Another important category of pipe system components is that of commercially available pipe fittings such as elbows, tees, reducers, valves, and filters. The values of K_L for such components depend strongly on the shape of the component and only very weakly on the Reynolds number for typical large *Re* flows. Thus, the loss coefficient for a 90° elbow depends on whether the pipe joints are threaded or flanged, but is, within the accuracy of the data, fairly independent of the pipe diameter, flow rate, or fluid properties—that is, independent of the Reynolds number. Typical values of K_L for such components are given in Table 14.2.

Table 14.2 Loss Coefficients for Pipe Components $\left(h_L = K_L \frac{V^2}{2g}\right)$

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
b. 180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
c. Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
d. Union, threaded	0.08
e. Valves	
Globe, fully open	10
Angle, fully open	2
Gate, fully open	0.15
Ball valve, fully open	0.05