8.2

8.2 Rainwater runoff from a parking lot flows through a 3-ft-diameter pipe, completely filling it. Whether flow in a pipe is laminar or turbulent depends on the value of the Reynolds number. (See Video V8.2) Would you expect the flow to be laminar or turbulent? Support your answer with appropriate calculations.

$Re = \frac{\rho V D}{\mu} = \frac{VD}{\nu}$ If $Re > 4000$ the flow is turbulent. The corresponding velocity is

$$V = \frac{Re\,\nu}{D} = \frac{(4000)(1.21\times10^{-5}\ \frac{ft^2}{s})}{3\ ft} = 0.0161\ \frac{ft}{s}$$

Most likely the velocity will be greater than this, i.e., <u>turbulent flow.</u>

8.3

8.3 Blue and yellow streams of paint at 60 °F (each with a density of 1.6 $slugs/ft^3$ and a viscosity 1000 times greater than water) enter a pipe with an average velocity of 4 ft/s as shown in Fig. P8.3. Would you expect the paint to exit the pipe as green paint or separate streams of blue and yellow paint? Explain. Repeat the problem if the paint were "thinned" so that it is only 10 times more viscous than water. Assume the density remains the same.

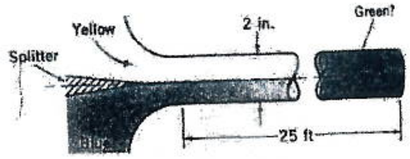


FIGURE P8.3

If the flow is laminar the paint would exit as separate blue and yellow streams.

$$Re = \frac{\rho V D}{\mu} = \frac{\rho V D}{1000\,\mu_{H_2O}} = \frac{1.6\,\frac{slugs}{ft^3}\left(4\,\frac{ft}{s}\right)\left(\frac{2}{12}\,ft\right)}{1000\left(2.34\times10^{-5}\,\frac{lb\cdot s}{ft^2}\right)} = 45.6 < 2100$$

Thus, laminar flow so blue and yellow streams.

If use $\mu = 10\,\mu_{H_2O}$ obtain

$Re = 4560 > 4000$ so have turbulent flow with natural mixing and green paint.

Note: Check to determine if the 25 ft length is greater than the entrance length, ℓ_e.

For laminar flow $\frac{\ell_e}{D} = 0.06\,Re$, or $\ell_e = 0.06(45.6)\left(\frac{2}{12}\,ft\right) = 0.456\,ft < 25\,ft$

For turbulent flow $\frac{\ell_e}{D} = 4.4\,Re^{1/6}$, or $\ell_e = 4.4(4560)^{1/6}\left(\frac{2}{12}\,ft\right) = 2.99\,ft < 25\,ft$

8.4

8.4 Air at 200 °F flows at standard atmospheric pressure in a pipe at a rate of 0.08 lb/s. Determine the minimum diameter allowed if the flow is to be laminar.

Maximum $Re = \frac{\rho V D}{\mu}$ for laminar flow is $Re = 2100$.
or with

$$V = \frac{Q}{A} = \frac{4Q}{\pi D^2}, \quad Re = \frac{\rho\left(\frac{4Q}{\pi D^2}\right)D}{\mu} = \frac{4\rho Q}{\pi \mu D} = 2100$$

Hence,

$$Q = \frac{2100 \pi \mu D}{4\rho} \qquad (1)$$

Given $\gamma Q = 0.08 \frac{lb}{s}$, where $\gamma = g\rho$ and $\rho = \frac{p}{RT}$

Thus,

$$\rho = \frac{(14.7 \times 144 \frac{lb}{ft^2})}{(1716 \frac{ft \cdot lb}{slug \cdot {}^\circ R})(460+200)^\circ R} = 0.00187 \frac{slugs}{ft^3}$$

so that

$$Q = \frac{0.08 \frac{lb}{s}}{(32.2 \frac{ft}{s^2})(0.00187 \frac{slugs}{ft^3})} = 1.33 \frac{ft^3}{s}$$

Hence, with $\mu = 4.49 \times 10^{-7} \frac{lb \cdot s}{ft^2}$ (see Table B.3), Eq. (1) gives

$$D = \frac{4\rho Q}{2100 \pi \mu} = \frac{4(0.00187 \frac{slugs}{ft^3})(1.33 \frac{ft^3}{s})}{2100 \pi (4.49 \times 10^{-7} \frac{lb \cdot s}{ft^2})} = \underline{\underline{3.36 \, ft}}$$

8.7

8.7 Carbon dioxide at 20 °C and a pressure of 550 kPa (abs) flows in a pipe at a rate of 0.04 N/s. Determine the maximum diameter allowed if the flow is to be turbulent.

For turbulent flow, $Re = \frac{\rho V D}{\mu} > 4000$, where $Q = VA = \frac{\pi}{4}D^2 V$

or $Re = \frac{4\rho Q D}{\pi \mu D^2} = \frac{4\rho Q}{\pi \mu D} = 4000$

Thus, $D = \frac{4\rho Q}{4000 \pi \mu}$, where $g\rho Q = 0.04 \frac{N}{s}$ and $\mu = 1.4 \times 10^{-5} \frac{N \cdot s}{m^2}$ (Table 1.8)

Hence,
$$D = \frac{4\left(0.04 \frac{N}{s}\right)\left(\frac{1}{9.81 \frac{m}{s^2}}\right)}{4000\pi\left(1.47 \times 10^{-5} \frac{N \cdot s}{m^2}\right)} = \underline{\underline{0.0883\ m}}$$

8.6

8.9

8.9 (See Fluids in the News article titled "Nanoscale flows," Section 8.1.1.) (a) Water flows in a tube that has a diameter of $D = 0.1$ m. Determine the Reynolds number if the average velocity is 10 diameters per second. (b) Repeat the calculations if the tube is a nanoscale tube with a diameter of $D = 100$ nm.

(a) $Re = \frac{VD}{\nu}$, where $D = 0.1 m$, $V = 10(0.1 m)/s = 1 \frac{m}{s}$, and $\nu = 1.12 \times 10^{-6} \frac{m^2}{s}$

Thus,

$$Re = \frac{(1 \frac{m}{s})(0.1 m)}{1.12 \times 10^{-6} \frac{m^2}{s}} = \underline{\underline{89,300}}$$

(b) $Re = \frac{VD}{\nu}$, where $D = 100\, nm \left(\frac{1 m}{10^9 nm}\right) = 10^{-7} m$, $V = 10(10^{-7} m)/s = 10^{-6} \frac{m}{s}$, and $\nu = 1.12 \times 10^{-6} \frac{m^2}{s}$

Thus,

$$Re = \frac{(10^{-6} \frac{m}{s})(10^{-7} m)}{1.12 \times 10^{-6} \frac{m^2}{s}} = \underline{\underline{8.93 \times 10^{-8}}}$$

8.11

8.11 The wall shear stress in a fully developed flow portion of a 12-in.-diameter pipe carrying water is 1.85 lb/ft². Determine the pressure gradient, $\partial p/\partial x$, where x is in the flow direction, if the pipe is (a) horizontal, (b) vertical with flow up, or (c) vertical with flow down.

In general, $\frac{\Delta p - \gamma \ell \sin\theta}{\ell} = \frac{2\tau}{r}$

Thus, with $\tau = \tau_w$ at $r = \frac{D}{2}$ and $\frac{\partial p}{\partial x} = -\frac{\Delta p}{\ell}$ this becomes

$$\frac{\partial p}{\partial x} = -\frac{4\tau_w}{D} - \gamma \sin\theta$$

a) For a horizontal pipe $\theta = 0$

$$\frac{\partial p}{\partial x} = -\frac{4\tau_w}{D} = -\frac{4\left(1.85\,\frac{lb}{ft^2}\right)}{1\,ft} = \underline{\underline{-7.40\,\frac{lb}{ft^3}}}$$

b) For vertical flow up $\theta = 90°$

$$\frac{\partial p}{\partial x} = -\frac{4\tau_w}{D} - \gamma = -\frac{4\left(1.85\,\frac{lb}{ft^2}\right)}{1\,ft} - 62.4\,\frac{lb}{ft^3} = \underline{\underline{-69.8\,\frac{lb}{ft^3}}}$$

and

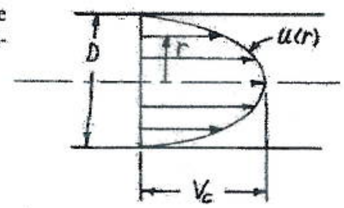
c) For vertical flow down $\theta = -90°$

$$\frac{\partial p}{\partial x} = -\frac{4\tau_w}{D} + \gamma = -\frac{4\left(1.85\,\frac{lb}{ft^2}\right)}{1\,ft} + 62.4\,\frac{lb}{ft^3} = \underline{\underline{55.0\,\frac{lb}{ft^3}}}$$

8.17

8.16

8.16 For laminar flow in a round pipe of diameter D, at what distance from the centerline is the actual velocity equal to the average velocity?



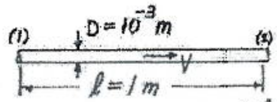
For laminar flow

$$u = V_c\left[1-\left(\frac{2r}{D}\right)^2\right]$$

Thus, if $u = \frac{V_c}{2} = V_c\left[1-\left(\frac{2r}{D}\right)^2\right]$, $r = \frac{D}{2\sqrt{2}} = \underline{\underline{0.354D}}$

8.17

8.17 Water at 20 °C flows through a horizontal 1-mm-diameter tube to which are attached two pressure taps a distance 1 m apart. **(a)** What is the maximum pressure drop allowed if the flow is to be laminar? **(b)** Assume the manufacturing tolerance on the tube diameter is $D = 1.0 \pm 0.1$ mm. Given this uncertainty in the tube diameter, what is the maximum pressure drop allowed if it must be assured that the flow is laminar?



From Table B.2 $\nu = 1.00 \times 10^{-6}\, \frac{m^2}{s}$
$\mu = 1.00 \times 10^{-3}\, \frac{N \cdot s}{m^2}$

a) Maximum Δp corresponds to maximum V, or

$$Re = \frac{VD}{\nu} = 2100$$

Thus, $V = \frac{2100\,\nu}{D} = \frac{2100\,(1 \times 10^{-6}\, \frac{m^2}{s})}{10^{-3}\, m} = 2.10\, \frac{m}{s}$

For laminar flow

$$V = \frac{\Delta p\, D^2}{32\, \mu\, \ell}\ , \text{ or } \Delta p = \frac{32\, \mu\, \ell\, V}{D^2} = \frac{32\,(1 \times 10^{-3}\, \frac{N \cdot s}{m^2})(1\, m)(2.10\, \frac{m}{s})}{(10^{-3}\, m)^2}$$

Thus,

$$\Delta p = \underline{\underline{6.72 \times 10^4\, \frac{N}{m^2}}}$$

b) Since $V = \frac{2100\,\nu}{D}$ and $\Delta p = \frac{32\,\mu\,\ell\,V}{D^2}$ it follows that

$$\Delta p = \frac{32\,\mu\,\ell\,(2100\,\nu)}{D^3}$$

Thus, the larger the diameter, the smaller the Δp allowed to maintain laminar flow.

Thus, consider $D = 1.1\, mm = 1.1 \times 10^{-3}\, m$, or

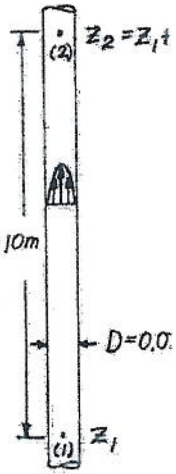
$$\Delta p = \frac{32\,(1 \times 10^{-3}\, \frac{N \cdot s}{m^2})(1\, m)(2100)(1 \times 10^{-6}\, \frac{m^2}{s})}{(1.1 \times 10^{-3}\, m)^3} = \underline{\underline{5.05 \times 10^4\, \frac{N}{m^2}}}$$

8.18

8.18 Glycerin at 20 °C flows upward in a vertical 75-mm-diameter pipe with a centerline velocity of 1.0 m/s. Determine the head loss and pressure drop in a 10-m length of the pipe.

$\rho = 1260\ \frac{kg}{m^3}$

$\mu = 1.50\ \frac{N\cdot s}{m^2}$



For laminar flow in a pipe,

$V =$ average velocity $= \frac{1}{2} V_{max} = \frac{1}{2}(1\frac{m}{s}) = 0.5\frac{m}{s}$

Thus,

$$Re = \frac{\rho V D}{\mu} = \frac{(1260\frac{kg}{m^3})(0.5\frac{m}{s})(0.075\,m)}{1.50\ \frac{N\cdot s}{m^2}} = 31.5 < 2100$$

The flow is laminar so that

$$V = \frac{(\Delta p - \gamma \ell \sin\theta) D^2}{32\mu\ell}, \text{ where } \theta = 90^\circ$$

Thus,

$$\Delta p = \frac{32\mu\ell V}{D^2} + \gamma\ell = \frac{32\,(1.50\frac{N\cdot s}{m^2})(10m)(0.5\frac{m}{s})}{(0.075\,m)^2} + (9.81\frac{m}{s^2})(1260\frac{kg}{m^3})(10m$$

$$= 1.66\times 10^5\ \frac{N}{m^2}, \text{ or } \underline{\underline{\Delta p = 166\ kPa}}$$

Also,

$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + h_L$, or with $V_1 = V_2$, $z_2 - z_1 = \ell$, and

$p_1 = p_2 + \Delta p$ this gives

$$h_L = \frac{\Delta p}{\gamma} - \ell = \frac{1.66\times 10^5\ \frac{N}{m^2}}{(9.81\frac{m}{s^2})(1260\frac{kg}{m^3})} - 10m = \underline{\underline{3.43\,m}}$$

8.35

8.35 Water flows in a constant diameter pipe with the following conditions measured: At section (a) $p_a = 32.4$ psi and $z_a = 56.8$ ft; at section (b) $p_b = 29.7$ psi and $z_b = 68.2$ ft. Is the flow from (a) to (b) or from (b) to (a)? Explain.

Assume the flow is uphill. Thus, $\frac{p_a}{\gamma} + \frac{V_a^2}{2g} + z_a = \frac{p_b}{\gamma} + \frac{V_b^2}{2g} + z_b + h_L$

or with $V_a = V_b$,

$$h_L = \frac{p_a}{\gamma} + z_a - \frac{p_b}{\gamma} - z_b = \frac{(32.4\,psi - 29.7\,psi)(144\,\frac{in^2}{ft^2})}{62.4\,\frac{lb}{ft^3}} + 56.8\,ft - 68.2\,ft$$

or

$h_L = -5.17$ ft < 0, which is impossible. Thus, the flow is downhill, from (b) to (a)

8.39

8.39 Water flows through a horizontal plastic pipe with a diameter of 0.2 m at a velocity of 10 cm/s. Determine the pressure drop per meter of pipe using the Moody chart.

The pressure drop in the pipe can be found from

$$\Delta P = f \frac{l}{D} \frac{\rho V^2}{2}$$

The friction factor is determined from the Moody chart.

$$Re = \frac{\rho V D}{\mu} = \frac{(999)(0.1)(0.2)}{1.12 \times 10^{-3}} = 1.8 \times 10^4$$

For plastic pipe, $\varepsilon = 0.0\,mm$

$\varepsilon/D = 0.0/0.2 = 0.0$

From the Moody Chart

$f = 0.026$

So ΔP per meter ($l = 1m$)

$$\Delta P = (0.026)\left(\frac{1}{0.2}\right)\left[\frac{999(0.1)^2}{2}\right]$$

$\underline{\Delta P = 0.649}$ Pa per meter

8.32

8.40

8.40 For Problem 8.39 calculate the power lost to the friction per meter of pipe.

$\Delta P = 0.649\,\text{Pa}$ per meter of pipe, $V = 0.1\,m/s$, $D = 0.2\,m$

Based on equations in Ch.5, power can be found from

$\mathcal{P} = (\Delta P)\,Q$

$Q = VA = (0.1)\left(\frac{\pi}{4}(0.2)^2\right) = 3.14 \times 10^{-3}\ m^3/s$

$\mathcal{P} = (0.649)\,(3.14 \times 10^{-3}) = 2.04 \times 10^{-3}\ N \cdot m/s = \underline{\underline{2.04 \times 10^{-3}\ W}}$

8.41

8.41 Oil ($SG = 0.9$), with a kinematic viscosity of 0.007 ft^2/s, flows in a 3-in.-diameter pipe at 0.01 ft^3/s. Determine the head loss per unit length of this flow.

$h_L = f \frac{\ell}{D} \frac{V^2}{2g}$ where $\ell = 1$ ft for "per unit length of pipe".

Determine friction factor based on Re & ε/D

$Q = 0.01 \; ft^3/s = VA$

$V = \frac{0.01}{\frac{\pi}{4}\left(\frac{3}{12}\right)^2} = 0.20 \; ft/s$

$Re = \frac{VD}{\nu} = \frac{0.20(3/12)}{0.007} = 7.14$

Since Re is below 2100, the flow is laminar

The friction factor can be determined from

$f = 64/Re = 64/7.14 = 8.96$

$h_L = (8.96)\frac{1}{(3/12)}\frac{(0.2)^2}{2(32.2)} = \underline{\underline{0.022 \text{ ft}}}$ per ft of pipe

8.42

8.42 Water flows through a 6-in.-diameter horizontal pipe at a rate of 2.0 cfs and a pressure drop of 4.2 psi per 100 ft of pipe. Determine the friction factor.

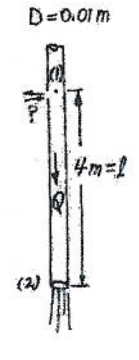
For a horizontal pipe $\Delta p = f \frac{\ell}{D} \frac{1}{2} \rho V^2$,

where $V = \frac{Q}{A} = \frac{2.0 \frac{ft^3}{s}}{\frac{\pi}{4}\left(\frac{6}{12} ft\right)^2} = 10.2 \frac{ft}{s}$

Thus,

$$f = \frac{2 D \Delta p}{\rho \ell V^2} = \frac{2\left(\frac{6}{12} ft\right)\left(4.2 \times 144 \frac{lb}{ft^2}\right)}{\left(1.94 \frac{slugs}{ft^3}\right)(100\ ft)\left(10.2 \frac{ft}{s}\right)^2} = \underline{\underline{0.0300}}$$

8.43 Water flows downward through a vertical 10-mm-diameter galvanized iron pipe with an average velocity of 5.0 m/s and exits as a free jet. There is a small hole in the pipe 4 m above the outlet. Will water leak out of the pipe through this hole, or will air enter into the pipe through the hole? Repeat the problem if the average velocity is 0.5 m/s.



$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+f\frac{\ell}{D}\frac{V^2}{2g}$, where $p_2=0$, $z_2=0$,

$z_1=4m$, $V_1=V_2=V$. Thus,

$\frac{p_1}{\gamma}=f\frac{\ell}{D}\frac{V^2}{2g}-z_1$, or $p_1=f\frac{\ell}{D}\frac{1}{2}\rho V^2-\gamma\ell$ With ε from Table 8.1, (1)

$\frac{\varepsilon}{D}=\frac{0.15\ mm}{10\ mm}=0.015$ so that with $Re=\frac{VD}{\nu}=\frac{(5\frac{m}{s})(0.01m)}{1.12\times10^{-6}\frac{m^2}{s}}=4.46\times10^4$

we obtain $f=0.045$ (see Fig. 8.20).

Thus, from Eq. (1)

$p_1=0.045\left(\frac{4m}{0.01m}\right)\frac{1}{2}(999\frac{kg}{m^3})(5\frac{m}{s})^2-9800\frac{N}{m^3}(4m)=1.86\times10^5\frac{N}{m^2}$

Since $p_1>0$, water will leak out of the pipe when $V=5\frac{m}{s}$

If $V=0.5\frac{m}{s}$, then $Re=4.46\times10^3$ and $f=0.052$

Thus, from Eq. (1)

$p_1=0.052\left(\frac{4m}{0.01m}\right)\frac{1}{2}(999\frac{kg}{m^3})(0.5\frac{m}{s})^2-9800\frac{N}{m^3}(4m)=-3.66\times10^4\frac{N}{m^2}$

Since $p_1<0$, air will enter the pipe when $V=0.5\frac{m}{s}$

Note: The above conclusion is valid regardless of the length, ℓ.

8.46

8.46 Water flows at a rate of 10 gallons per minute in a new horizontal 0.75-in.-diameter galvanized iron pipe. Determine the pressure gradient, $\Delta p/\ell$, along the pipe.

$$Q = 10\,\frac{gal}{min}\left(\frac{1\,min}{60\,s}\right)\left(\frac{231\,in.^3}{1\,gal}\right)\left(\frac{1\,gal}{1728\,in.^3}\right) = 0.0223\,\frac{ft^3}{s}$$

Thus,

$$V = \frac{Q}{A} = \frac{0.0223\,\frac{ft^3}{s}}{\frac{\pi}{4}\left(\frac{0.75}{12}\,ft\right)^2} = 7.27\,\frac{ft}{s}$$

Now, for a horizontal pipe

$\Delta p = f\,\frac{\ell}{D}\,\frac{1}{2}\rho V^2$ where since

$$Re = \frac{VD}{\nu} = \frac{7.27\,\frac{ft}{s}\left(\frac{0.75}{12}\,ft\right)}{1.21\times10^{-5}\,\frac{ft^2}{s}} = 3.76\times10^4$$

and

$$\frac{\varepsilon}{D} = \frac{0.0005\,ft}{\left(\frac{0.75}{12}\,ft\right)} = 0.008$$

it follows from Fig. 8.20 that $f = 0.037$

Thus,

$$\frac{\Delta p}{\ell} = \frac{0.037\,(1.94\,slugs/ft^3)\,(7.27\,ft/s)^2}{\left(\frac{0.75}{12}\,ft\right)(2)} = 30.4\,\frac{lb}{ft^3}\left(\frac{1\,ft^2}{144\,in.^2}\right)$$

$$= \underline{\underline{0.211\,psi/ft}}$$

8.53

8.53 A fluid flows in a smooth pipe with a Reynolds number of 6000. By what percent would the head loss be reduced if the flow could be maintained as laminar flow rather than the expected turbulent flow?

For either laminar or turbulent flow

$h_L = f \frac{\ell}{D} \frac{V^2}{2g}$. Thus, with the same $V, \ell, D,$ and g

$$\frac{h_{L\,lam}}{h_{L\,turb}} = \frac{f_{lam}}{f_{turb}}$$

If the flow is laminar $f_{lam} = \frac{64}{Re} = \frac{64}{6000} = 0.0107$

If the flow is turbulent with $Re = 6000$ and $\frac{\varepsilon}{D} = 0$, then from the Moody chart (Fig. 8.20) $f_{turb} = 0.035$

Thus,

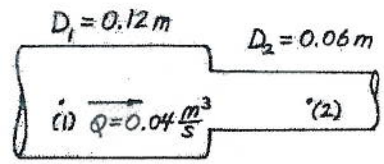
$$\frac{h_{L\,lam}}{h_{L\,turb}} = \frac{0.0107}{0.035} = 0.486$$

The headloss would be reduced by

$(h_{L\,turb} - h_{L\,lam})/h_{L\,turb} = 1 - 0.486 = 0.514$, or $\underline{\underline{51.4\%}}$

8.58

8.58 Water flows at a rate of 0.040 m³/s in a 0.12-m-diameter pipe that contains a sudden contraction to a 0.06-m-diameter pipe. Determine the pressure drop across the contraction section. How much of this pressure difference is due to losses and how much is due to kinetic energy changes?



$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + K_L\frac{V_2^2}{2g}\,,\quad \text{where } z_1 = z_2$$

and

$$V_1 = \frac{Q}{A_1} = \frac{0.04\,\frac{m^3}{s}}{\frac{\pi}{4}(0.12m)^2} = 3.54\,\frac{m}{s}\,,\quad V_2 = \frac{Q}{A_2} = \frac{0.04\,\frac{m^3}{s}}{\frac{\pi}{4}(0.06m)^2} = 14.1\,\frac{m}{s}$$

Thus, with $\frac{A_2}{A_1} = \left(\frac{D_2}{D_1}\right)^2 = \left(\frac{0.06m}{0.12m}\right)^2 = 0.25$ we obtain from Fig. 8.30

$K_L = 0.40$

Hence, from Eq.(1)

$$p_1 - p_2 = \frac{1}{2}\rho\left[K_L V_2^2 + V_2^2 - V_1^2\right] = \frac{1}{2}(999\,\frac{kg}{m^3})\left[0.40\,(14.1\,\frac{m}{s})^2 + (14.1\,\frac{m}{s})^2 - (3.54\right.$$

or

$$p_1 - p_2 = 39.7\times10^3\,\frac{N}{m^2} + 93.0\times10^3\,\frac{N}{m^2} = \underline{133\ kPa}$$

This represents a $\underline{39.7\ kPa}$ drop from losses and a $\underline{93.0\ kPa}$ drop due to an increase in kinetic energy.

8.69

8.69 Air at standard temperature and pressure flows at a rate of 7.0 cfs through a horizontal, galvanized iron duct that has a rectangular cross-sectional shape of 12 in. by 6 in. Estimate the pressure drop per 200 ft of duct.

For a horizontal duct $\Delta p = \gamma h_L = f \frac{\ell}{D_h} \frac{1}{2} \rho V^2$, where $V = \frac{Q}{A}$

or $V = \dfrac{7 \frac{ft^3}{s}}{(12\,in.)(6\,in.)\left(\frac{1\,ft^2}{144\,in.^2}\right)} = 14.0 \frac{ft}{s}$ and $Re_h = \frac{V D_h}{\nu}$

with $D_h = \frac{4A}{P} = \dfrac{4(0.5\,ft^2)}{(2+1)ft} = 0.667\,ft$

Thus, $Re_h = \dfrac{(14.0 \frac{ft}{s})(0.667\,ft)}{1.57 \times 10^{-4} \frac{ft^2}{s}} = 5.95 \times 10^4$

Also, for galvanized iron $\varepsilon = 0.0005\,ft$, or $\frac{\varepsilon}{D_h} = \dfrac{0.0005\,ft}{0.667\,ft} = 0.000750$

From Fig. 8.20 we obtain $f = 0.0227$

Thus, from Eq. (1) with $\ell = 200\,ft$,

$$\Delta p = (0.0227)\frac{200\,ft}{0.667\,ft}\,\frac{1}{2}(2.38 \times 10^{-3} \frac{slug}{ft^3})(14.0 \frac{ft}{s})^2 = 1.59 \frac{lb}{ft^2} = \underline{\underline{0.0110\ psi}}$$

8.70

8.70 Air flows through a rectangular galvanized iron duct of size 0.30 m by 0.15 m at a rate of 0.068 m³/s. Determine the head loss in 12 m of this duct.

$h_L = f\frac{\ell}{D_h}\frac{V^2}{2g}$, where $D_h = \frac{4A}{P} = \frac{4(0.3m)(0.15m)}{2[0.3m+0.15m]} = 0.2\ m$

and

$V = \frac{Q}{A} = \frac{0.068\frac{m^3}{s}}{(0.3m)(0.15m)} = 1.51\frac{m}{s}$ Also, $Re_h = \frac{VD_h}{\nu} = \frac{(1.51\frac{m}{s})(0.2m)}{1.46\times10^{-5}\frac{m^2}{s}} = 20{,}700$

and from Table 8.1,

$\frac{\varepsilon}{D_h} = \frac{0.15\times10^{-3}m}{0.2\ m} = 7.5\times10^{-4}$ Hence, from Fig. 8.20 $f = 0.027$

so that

$h_L = (0.027)\left(\frac{12\ m}{0.2\ m}\right)\frac{(1.51\frac{m}{s})^2}{2(9.81\frac{m}{s^2})} = \underline{\underline{0.188m}}$

8.71

8.71 Air at standard conditions flows through a horizontal 1 ft by 1.5 ft rectangular wooden duct at a rate of 5000 ft³/min. Determine the head loss, pressure drop, and power supplied by the fan to overcome the flow resistance in 500 ft of the duct.

$h_L = f\frac{\ell}{D_h}\frac{V^2}{2g}$, where $V = \frac{Q}{A} = \frac{(5000\frac{ft^3}{min})(\frac{1\ min}{60\ s})}{(1\ ft)(1.5\ ft)} = 55.6\ \frac{ft}{s}$

and $D_h = \frac{4A}{P} = \frac{4(1\ ft)(1.5\ ft)}{2[1\ ft+1.5\ ft]} = 1.2\ ft$

Also, $Re_h = \frac{VD_h}{\nu} = \frac{(55.6\frac{ft}{s})(1.2\ ft)}{1.57\times10^{-4}\frac{ft^2}{s}} = 4.25\times10^5$ and from Table 8.1

$\varepsilon \approx 0.0006\ ft$ to $0.003\ ft$. Use an "average" $\varepsilon = 0.0018\ ft$ so that

$\frac{\varepsilon}{D_h} = \frac{0.0018\ ft}{1.2\ ft} = 0.0015$ Thus, from Fig. 8.20 $f = 0.022$, or

$h_L = (0.022)\left(\frac{500\ ft}{1.2\ ft}\right)\frac{(55.6\frac{ft}{s})^2}{2(32.2\frac{ft}{s^2})} = \underline{\underline{440\ ft}}$

For this horizontal pipe $\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$, where $z_1 = z_2$ and $V_1 = V_2$.

Thus, $p_1 - p_2 = \gamma h_L = (7.65\times10^{-2}\frac{lb}{ft^3})(440\ ft) = 33.7\frac{lb}{ft^2} = \underline{\underline{0.234 psi}}$

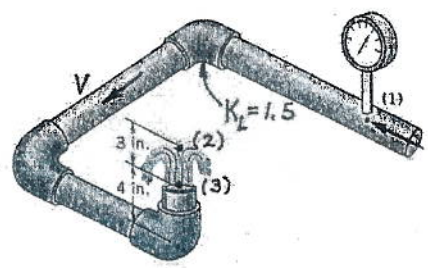
$\mathcal{P} = \gamma Q h_L = Q(p_1 - p_2) = (5000\frac{ft^3}{min})(\frac{1\ min}{60\ s})(33.7\frac{lb}{ft^2}) = (2810\ \frac{ft\cdot lb}{s})\left[\frac{1\ hp}{(550\ \frac{ft\cdot lb}{s})}\right]$

or

$\mathcal{P} = \underline{\underline{5.11\ hp}}$

8.78

8.78 As shown in Video V8.13 and Fig. P8.78 water "bubbles up" 3 in. above the exit of the vertical pipe attached to three horizontal pipe segments. The total length of the 0.75-in.-diameter galvanized iron pipe between point (1) and the exit is 21 in. Determine the pressure needed at point (1) to produce this flow.



■ FIGURE P8.78

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

where $z_1 = 0$, $p_2 = 0$, $V_2 = 0$ Thus,

(1) $\frac{p_1}{\gamma} = z_2 + h_L - \frac{V_1^2}{2g}$ where $V_1 = V_3 = V$

With no head loss from (3) to (2) and $p_2 = p_3 = V_2 = 0$ we obtain

$$\frac{V_3^2}{2g} + z_3 = z_2, \text{ or } V_3 = \sqrt{2g(z_2 - z_3)} = \sqrt{2\left(32.2\frac{ft}{s^2}\right)\left(\frac{3}{12}ft\right)} = 4.01$$

Thus,

$$Re = \frac{VD}{\nu} = \frac{V_3 D}{\nu} = \frac{4.01\frac{ft}{s}\left(\frac{0.75}{12}ft\right)}{1.21 \times 10^{-5}\frac{ft^2}{s}} = 2.07 \times 10^4$$

and

$$\frac{\varepsilon}{D} = \frac{0.0005\,ft}{\left(\frac{0.75}{12}\right)ft} = 0.008 \quad \text{(see Table 8.1), so that (see Fig. 8.20)}$$

$f = 0.039$

Also, $h_L = f\frac{\ell}{D}\frac{V^2}{2g} + \sum K_L \frac{V^2}{2g}$ where $\sum K_L = 3(1.5) = 4.5$

Hence, Eq. (1) becomes

$$\frac{p_1}{\gamma} = z_2 + \left[f\frac{\ell}{D} + \sum K_L\right]\frac{V^2}{2g} - \frac{V_1^2}{2g} \quad \text{where } V_1 = V$$

or

$$\frac{p_1}{\gamma} = \frac{7}{12}ft + \left[0.039\,\frac{21\,in.}{0.75\,in.} + 4.5 - 1\right]\frac{\left(4.01\frac{ft}{s}\right)^2}{2\left(32.2\frac{ft}{s^2}\right)} = (0.583 + 1.147)$$

$= 1.73\ ft$

Thus,

$$p_1 = \left(62.4\frac{lb}{ft^3}\right)(1.73\,ft) = 108\frac{lb}{ft^2} = \underline{\underline{0.750\ psi}}$$

8.79

8.79 Water at 10 °C is pumped from a lake as shown in Fig. P8.79. If the flowrate is 0.011 m^3/s, what is the maximum length inlet pipe, ℓ, that can be used without cavitation occurring?

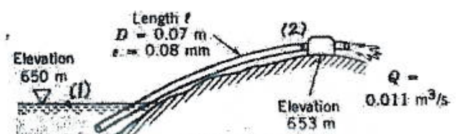


FIGURE P8.79

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+\left(f\frac{\ell}{D}+\Sigma K_L\right)\frac{V^2}{2g}, \text{ where } p_1=101\ kPa,\ z_1=650m \quad (1)$$

$V_1=0$, $V_2=V$, $z_2=653\,m$, and from Table B.2 $p_2=p_v=1.228\ kPa$

Also, $V=\frac{Q}{A}=\frac{0.011\frac{m^3}{s}}{\frac{\pi}{4}(0.07m)^2}=2.86\frac{m}{s}$ so that

$Re=\frac{VD}{\nu}=\frac{(2.86\frac{m}{s})(0.07m)}{1.307\times10^{-6}\frac{m^2}{s}}=1.53\times10^5$. With this Re and from Table 8.1 with

$\frac{\varepsilon}{D}=\frac{0.08\,mm}{70\,mm}=0.00114$ we obtain $f=0.0216$ (see Fig. 8.20)

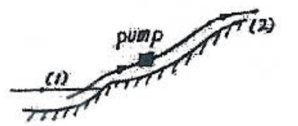
Hence, with $\Sigma K_L=0.8$ for the entrance, Eq.(1) becomes

$$\frac{(101-1.228)\times10^3\frac{N}{m^2}}{9.80\times10^3\frac{N}{m^3}}+650\,m=653\,m+\left(1+(0.0216)\left(\frac{\ell}{0.07m}\right)+0.8\right)\frac{(2.86\frac{m}{s})^2}{2(9.81\frac{m}{s^2})}$$

or $\ell = \underline{\underline{50.0\ m}}$

8.80

8.80 At a ski resort water at 40 °F is pumped through a 3-in.-diameter, 2000-ft-long steel pipe from a pond at an elevation of 4286 ft to a snow-making machine at an elevation of 4623 ft at a rate of 0.26 ft³/s. If it is necessary to maintain a pressure of 180 psi at the snow-making machine, determine the horsepower added to the water by the pump. Neglect minor losses.



$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1+h_p=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+f\frac{\ell}{D}\frac{V^2}{2g}$, where $p_2=180\,\frac{lb}{in.^2}$, $p_1=0$, $V_1=0$ (1)

and $V=V_2=\frac{Q}{\frac{\pi}{4}D^2}=\frac{0.26\frac{ft^3}{s}}{\frac{\pi}{4}(\frac{3}{12}ft)^2}=5.30\frac{ft}{s}$. From Table 8.1, $\frac{\varepsilon}{D}=\frac{0.00015\,ft}{(3/12\,ft)}=6\times10^{-4}$

Also, $Re=\frac{VD}{\nu}=\frac{(5.30\frac{ft}{s})(\frac{3}{12}ft)}{1.664\times10^{-5}\frac{ft^2}{s}}=7.96\times10^4$ so that $f=0.0212$ (see Fig. 8.20)

Thus, from Eq. (1)

$h_p=\frac{p_2}{\gamma}+z_2-z_1+(1+f\frac{\ell}{D})\frac{V^2}{2g}$

or

$h_p=\frac{(180\frac{lb}{in.^2})(144\frac{in.^2}{ft^2})}{62.4\frac{lb}{ft^3}}+4623\,ft-4286\,ft+\left(1+(0.0212)\left(\frac{2000\,ft}{\frac{3}{12}ft}\right)\right)\frac{(5.30\frac{ft}{s})^2}{2(32.2\frac{ft}{s^2})}$

Hence, $h_p=827\,ft$ so that

$\mathcal{P}=\gamma Q h_p=(62.4\frac{lb}{ft^3})(0.26\frac{ft^3}{s})(827\,ft)=(13{,}420\frac{ft\cdot lb}{s})\left(\frac{1\,hp}{550\frac{ft\cdot lb}{s}}\right)=\underline{\underline{24.4\,hp}}$

8.94

8.94 The pump shown in Fig. P8.94 adds 25 kW to the water and causes a flowrate of 0.04 m^3/s. Determine the flowrate expected if the pump is removed from the system. Assume $f = 0.016$ for either case and neglect minor losses.

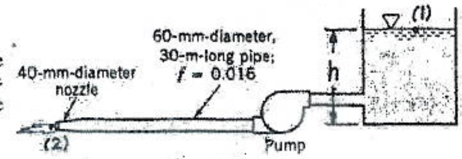


FIGURE P8.94

$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1+h_p=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+f\frac{\ell}{D}\frac{V^2}{2g}$, where $p_1=p_2=0$, $z_1=h$, $z_2=0$,

$V_1=0$, $V_2=\frac{Q}{A_2}=\frac{0.04\,\frac{m^3}{s}}{\frac{\pi}{4}(0.04m)^2}=31.8\,\frac{m}{s}$, $V=\frac{Q}{A}=\frac{0.04\,\frac{m^3}{s}}{\frac{\pi}{4}(0.06m)^2}=14.15\,\frac{m}{s}$

Thus,

$$h+h_p=\frac{(31.8\,\frac{m}{s})^2}{2(9.81\,\frac{m}{s^2})}+0.016\left(\frac{30\,m}{0.06\,m}\right)\frac{(14.15\,\frac{m}{s})^2}{2(9.81\,\frac{m}{s^2})}=133.2\,m$$

but,

$$h_p=\frac{P}{\gamma Q}=\frac{25\times10^3\,\frac{N\cdot m}{s}}{(9.80\times10^3\,\frac{N}{m^3})(0.04\,\frac{m^3}{s})}=63.8\,m$$

Hence,

$h=133.2m-63.8\,m=69.5m$

Without the pump $h_p=0$ and $z_1=\frac{V_2^2}{2g}+f\frac{\ell}{D}\frac{V^2}{2g}$ where $h=69.5m=z_1$

and

$V_2=\frac{AV}{A_2}=\left(\frac{D}{D_2}\right)^2V$ or $V_2=\left(\frac{60mm}{40mm}\right)^2V=2.25V$

Thus,

$$69.5\,m=\frac{(2.25V)^2+0.016\left(\frac{30\,m}{0.06\,m}\right)V^2}{2(9.81\,\frac{m}{s^2})}\quad\text{or } V=10.22\,\frac{m}{s}$$

so that

$$Q=AV=\frac{\pi}{4}(0.06m)^2(10.22\,\frac{m}{s})=\underline{\underline{0.0289\,\frac{m^3}{s}}}$$

8.100

8.100 A flowrate of 3.5 ft^3/s is to be maintained in a horizontal aluminum pipe ($\varepsilon = 5 \times 10^{-6}$ ft). The inlet and outlet pressures are 65 psi and 30 psi, respectively, and the pipe length is 500 ft. Determine the diameter of the pipe.

$$\frac{p_1}{\gamma}+z_1+\frac{V_1^2}{2g}=\frac{p_2}{\gamma}+z_2+\frac{V_2^2}{2g}+f\frac{\ell}{D}\frac{V^2}{2g} \; ; \; z_1=z_2 \; , \; V_1=V_2=V$$

where

$$V=\frac{Q}{A}=\frac{3.5}{\frac{\pi}{4}D^2}=\frac{4.46}{D^2} \quad \text{where } D\sim ft, \; V\sim ft/s$$

Thus,

$$\frac{p_1-p_2}{\gamma}=f\frac{\ell}{D}\frac{V^2}{2g} \quad \text{or} \quad \frac{(65-30)\frac{lb}{in^2}\left(144\frac{in^2}{ft^2}\right)}{62.4\frac{lb}{ft^3}}=f\,\frac{500}{D}\,\frac{\left(\frac{4.46}{D^2}\right)^2}{2(32.2)}$$

which simplifies to

$$D=1.138\,f^{1/5} \qquad (1)$$

Also, from Table 8.1, $\frac{\varepsilon}{D}=\frac{5\times10^{-6}}{D}$ (2)

and

$$Re=\frac{\rho VD}{\mu}=\frac{1.94\left(\frac{4.46}{D^2}\right)D}{2.34\times10^{-5}} \quad \text{or} \quad Re=\frac{3.70\times10^5}{D} \qquad (3)$$

Trial and error solution: 4 unknowns (D, $\frac{\varepsilon}{D}$, Re, f); 4 equations ((1), (2), (3), and Moody chart (Fig. 8.20))

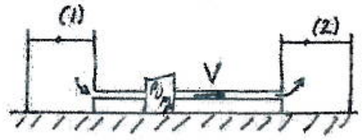
Assume $f=0.02$ so from Eq. (1) $D=0.520$ ft. Thus, from Eqs. (2) and (3) $Re=7.11\times10^5$ and $\frac{\varepsilon}{D}=9.6\times10^{-6}$, so from Fig. 8.20, $f=0.0128\neq0.02$

Assume $f=0.0128$ which gives $D=0.476$ ft, $Re=7.77\times10^5$, and $\frac{\varepsilon}{D}=1.1\times10^{-5}$. Thus, from Fig. 8.20, $f=0.0128$ which agrees with the assumed value.

Thus, $D=\underline{\underline{0.476\text{ ft}}}$

8.101

8.101 Water is pumped between two large open reservoirs through 1.5 km of smooth pipe. The water surfaces in the two reservoirs are at the same elevation. When the pump adds 20 kW to the water the flowrate is 1 m^3/s. If minor losses are negligible, determine the pipe diameter.



$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} + h_s - h_L = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g}, \text{ where } p_1 = p_2 = 0,\ V_1 = V_2 = 0,\ z_1 = z_2$$

Thus,

(1) $h_s = h_L$ where $h_s = \frac{\dot{W}_s}{\gamma Q} = \frac{20\times10^3\,N\cdot m/s}{(9.80\times10^3\frac{N}{m^3})(1\frac{m^3}{s})} = 2.04\,m$

and

$h_L = f\frac{\ell}{D}\frac{V^2}{2g}$ with $V = \frac{Q}{A} = \frac{1\,m^3/s}{\frac{\pi}{4}D^2} = \frac{1.273}{D^2}$ m/s with $D \sim m$

Hence,

(2) $h_L = f\,\frac{1.5\times10^3 m}{D}\,\frac{(1.23/D^2)^2 m^2/s^2}{2(9.81\,m/s^2)} = 123.9\,f/D^5$ m

From Eqs (1) and (2), $2.04 = 123.9\,f/D^5$ or $f = 0.0165\,D^5$

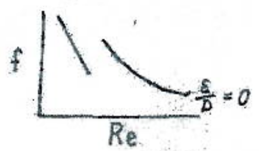
(3) $D = 2.27\,f^{1/5}$

Also,

$Re = \frac{\rho V D}{\mu} = \frac{999\frac{kg}{m^3}(1.273/D^2)m\,D\,m}{1.12\times10^{-3}\frac{N\cdot s}{m^2}}$ or

(4) $Re = 1.14\times10^6/D$

Finally, with $\varepsilon/D = 0$ the Moody chart (Fig. 8.20) is the final equation.

(5) 

Trial and error solution of Eqs. (3), (4), and (5) for f, Re, and D:
Assume $f = 0.02$ so Eq (3) gives $D = 2.27\,(0.02)^{1/5} = 1.04\,m$ and Eq (4) gives $Re = 1.14\times10^6/1.04 = 1.10\times10^6$. Thus, from Eq (5), $f = 0.0115$ which is not equal to the assumed $f = 0.02$. Try again with $f = 0.0115$ which gives $D = 0.931\,m$, $Re = 1.22\times10^4$, and $f = 0.0113 \neq 0.0115$. One final try with $f = 0.0113$ gives $D = 0.927\,m$, $Re = 1.23\times10^4$, and $f = 0.0113$ as assumed. Thus, $\underline{\underline{D = 0.927\,m}}$.

~~An alternate method is to use the Colebrook formula (Eq (8.35)) rather than the Moody chart (Eq (5)). Thus, with $\varepsilon/D = 0$,~~

~~(con't)~~

8.102

8.102 Determine the diameter of a steel pipe that is to carry 2,000 gal/min of gasoline with a pressure drop of 5 psi per 100 ft of horizontal pipe.

$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + f\frac{\ell}{D}\frac{V^2}{2g}$, where $z_1 = z_2$ and $V_1 = V_2$

Thus,

$p_1 - p_2 = f\frac{\ell}{D}\frac{1}{2}\rho V^2$ with $p_1 - p_2 = 5\frac{\text{lb}}{\text{in}^2}\left(144\frac{\text{in}^2}{\text{ft}^2}\right)$, $\ell = 100\text{ ft}$, (1)

$\rho = 1.32\frac{\text{slugs}}{\text{ft}^3}$, $\mu = 6.5\times10^{-6}\frac{\text{lb}\cdot\text{s}}{\text{ft}^2}$, and

$V = \frac{Q}{A} = \frac{\left(2000\frac{\text{gal}}{\text{min}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)\left(231\frac{\text{in}^3}{\text{gal}}\right)\left(\frac{\text{ft}^3}{1728\text{ in}^3}\right)}{\frac{\pi}{4}D^2}$, or $V = \frac{5.67}{D^2}\ \frac{\text{ft}}{\text{s}}$ with $D \sim \text{ft}$

Hence, Eq. (1) gives:

$5(144)\frac{\text{lb}}{\text{ft}^2} = f\left(\frac{100\text{ ft}}{D\text{ ft}}\right)\frac{1}{2}\left(1.32\frac{\text{slugs}}{\text{ft}^3}\right)\left(\frac{5.67}{D^2}\frac{\text{ft}}{\text{s}}\right)^2$

or

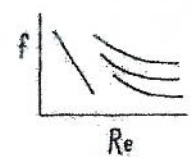
$D = 1.24 f^{1/5}$ (2)

Also, $Re = \frac{\rho V D}{\mu} = \frac{\left(1.32\frac{\text{slugs}}{\text{ft}^3}\right)\left(\frac{5.67}{D^2}\frac{\text{ft}}{\text{s}}\right)D\text{ ft}}{6.5\times10^{-6}\frac{\text{lb}\cdot\text{s}}{\text{ft}^2}}$, or $Re = \frac{1.15\times10^6}{D}$ (3)

and

$\frac{\varepsilon}{D} = \frac{0.00015}{D}$, where $D \sim \text{ft}$ (4)

Finally, the fourth equation is the Moody chart (or the Colebrook equation) (5)



Note: 4 equations ((2), (3), (4), and (5)) and 4 unknowns (f, $\frac{\varepsilon}{D}$, D, Re)

Trial and error solution:

Guess $f = 0.02 \xrightarrow{(2)} D = 0.567\text{ ft}$; $\xrightarrow{(3)} Re = 2.03\times10^6$, $\xrightarrow{(4)} \frac{\varepsilon}{D} = 0.000265$; $\xrightarrow{(5)} f = 0.0148 \neq 0.02$

Thus, the guessed value is not correct.

Guess $f = 0.0148 \xrightarrow{(2)} D = 0.534\text{ ft}$; $\xrightarrow{(3)} Re = 2.15\times10^6$, $\xrightarrow{(4)} \frac{\varepsilon}{D} = 0.000281$; $\xrightarrow{(5)} f = 0.0150 \approx 0.0148$

Thus, $D = 1.24(0.0150)^{1/5} = \underline{\underline{0.535\text{ ft}}}$

~~By using the Colebrook equation, Eq. 8.35, rather than the Moody chart, Eq. (5), we have~~

$\cancel{\frac{1}{\sqrt{f}} = -2.0\log\left[\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right]}$ ~~which, using Eqs. (2), (3), and (4) is,~~

$\cancel{\frac{1}{(D/1.24)^{5/2}} = -2.0\log\left[\frac{0.00015}{3.7D} + \frac{2.51D}{1.15\times10^6(D/1.24)^{5/2}}\right]}$

~~Using a computer root-finding program to solve Eq. (6) gives $D = 0.536\text{ ft}$ which is consistent with the above trial and error solution.~~

8.104

8.104 Water flows downward through a vertical smooth pipe. When the flowrate is 0.5 ft^3/s there is no change in pressure along the pipe. Determine the diameter of the pipe.

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + f\frac{\ell}{D}\frac{V^2}{2g}$$

where $p_1 = p_2$, $V_1 = V_2 = V$, and $z_1 - z_2 = \ell$

Thus,

$$\ell = f\frac{\ell}{D}\frac{V^2}{2g}, \text{ or } 1 = \frac{f}{D}\frac{V^2}{2g} \qquad (1)$$

Also,

$V = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}D^2}$ so that Eq. (1) becomes $1 = \frac{f}{D}\frac{\left(\frac{4Q}{\pi D^2}\right)^2}{2g}$

or

$$D^5 = \frac{8}{\pi^2} f \frac{Q^2}{g} = \frac{8}{\pi^2} f \frac{(0.5)^2}{32.2} \quad \text{or} \quad D = 0.363\, f^{1/5} \qquad (2)$$

Also,

$$Re = \frac{\rho V D}{\mu} = \frac{1.94\left(\frac{4Q}{\pi D^2}\right)D}{\mu} = \frac{1.94\left(\frac{4(0.5)}{\pi}\right)}{2.34\times10^{-5}\, D} \quad \text{or} \quad Re = \frac{5.28\times10^4}{D} \qquad (3)$$

From Fig. 8.20 with $\frac{\varepsilon}{D} = 0$ we have $f = f(Re, \frac{\varepsilon}{D} = 0)$

Trial and error solution: 3 unknowns (D, Re, f) and 3 equations ((2), (3), and Fig. 8.20)

Assume $f = 0.02$ so from Eq. (2), $D = 0.166$ ft and from Eq. (3), $Re = 3.18\times10^5$. Thus, from Fig. 8.20, $f = 0.014 \neq 0.02$

Assume $f = 0.014$ so that $D = 0.155$ ft and $Re = 3.42\times10^4$ Thus, from Fig. 8.20, $f = 0.14$ which checks with the assumed value.

Thus, $D = \underline{\underline{0.155 \text{ ft}}}$