(c) $Re = 132000,\quad f_{smooth} = 0.0170,$ hence the reduction in f is

$$\left(1 - \frac{0.0170}{0.0314}\right) = \mathbf{46\%} \quad \textit{Ans. (c)}$$

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**6.51** The viscous sublayer (Fig. 6.10) is normally less than 1 percent of the pipe diameter and therefore very difficult to probe with a finite-sized instrument. In an effort to generate a thick sublayer for probing, Pennsylvania State University in 1964 built a pipe with a flow of glycerin. Assume a smooth 12-in-diameter pipe with $V$ = 60 ft/s and glycerin at 20°C. Compute the sublayer thickness in inches and the pumping horsepower required at 75 percent efficiency if $L$ = 40 ft.

**Solution:** For glycerin at 20°C, take $\rho = 2.44\ \text{slug/ft}^3$ and $\mu = 0.0311$ slug/ft·s. Then

$$\text{Re} = \frac{\rho V d}{\mu} = \frac{2.44(60)(1\ \text{ft})}{0.0311} = 4710\ \ \text{(barely turbulent!)} \quad \text{Smooth: } f_{Moody} \approx 0.0380$$

$$\text{Then} \quad u^* = V(f/8)^{1/2} = 60\left(\frac{0.0380}{8}\right)^{1/2} \approx 4.13\ \frac{\text{ft}}{\text{s}}$$

The sublayer thickness is defined by $y^+ \approx 5.0 = \rho y u^*/\mu$. Thus

$$y_{sublayer} \approx \frac{5\mu}{\rho u^*} = \frac{5(0.0311)}{(2.44)(4.13)} = 0.0154\ \text{ft} \approx \mathbf{0.185\ inches} \quad \textit{Ans.}$$

With $f$ known, the head loss and the power required can be computed:

$$h_f = f\frac{L}{d}\frac{V^2}{2g} = (0.0380)\left(\frac{40}{1}\right)\frac{(60)^2}{2(32.2)} \approx 85\ \text{ft}$$

$$P = \frac{\rho g Q h_f}{\eta} = \frac{1}{0.75}(2.44)(32.2)\left[\frac{\pi}{4}(1)^2(60)\right](85) = 419000 \div 550 \approx \mathbf{760\ hp} \quad \textit{Ans.}$$

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**6.52** The pipe flow in Fig. P6.52 is driven by pressurized air in the tank. What gage pressure $p_1$ is needed to provide a 20°C water flow rate $Q = 60\ \text{m}^3/\text{h}$?

**Solution:** For water at 20°C, take $\rho$ = 998 kg/m$^3$ and $\mu$ = 0.001 kg/m·s. Get V, Re, f:

$$V = \frac{60/3600}{(\pi/4)(0.05)^2} = 8.49\ \frac{\text{m}}{\text{s}};$$

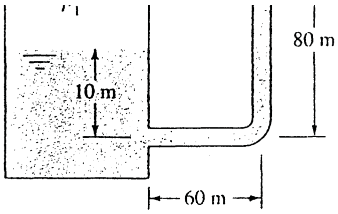


**Fig. P6.52**

$$Re = \frac{998(8.49)(0.05)}{0.001} \approx 424000; \quad f_{smooth} \approx \mathbf{0.0136}$$

Write the energy equation between points (1) (the tank) and (2) (the open jet):

$$\frac{p_1}{\rho g} + \frac{0^2}{2g} + 10 = \frac{0}{\rho g} + \frac{V_{pipe}^2}{2g} + 80 + h_f, \quad \text{where } h_f = f\frac{L}{d}\frac{V^2}{2g} \text{ and } V_{pipe} = 8.49 \frac{m}{s}$$

$$\text{Solve} \quad p_1 = (998)(9.81)\left[80 - 10 + \frac{(8.49)^2}{2(9.81)}\left\{1 + 0.0136\left(\frac{170}{0.05}\right)\right\}\right]$$

$$\approx \mathbf{2.38E6\ Pa} \quad \textit{Ans.}$$

[This is a *gage* pressure (relative to the pressure surrounding the open jet.)]

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**6.53** In Fig. P6.52 suppose $p_1$ = 700 kPa and the fluid specific gravity is 0.68. If the flow rate is 27 $m^3$/h, estimate the viscosity of the fluid. What fluid in Table A-5 is the likely suspect?

**Solution:** Evaluate $\rho = 0.68(998) = 679\ kg/m^3$. Evaluate $V = Q/A = (27/3600)/[\pi(0.025)^2] = 3.82$ m/s. The energy analysis of the previous problem now has *f* as the unknown:

$$\frac{p_1}{\rho g} = \frac{700000}{679(9.81)} = \Delta z + \frac{V^2}{2g} + f\frac{L}{d}\frac{V^2}{2g} = 70 + \frac{(3.82)^2}{2(9.81)}\left[1 + f\frac{170}{0.05}\right], \quad \text{solve } f = 0.0136$$

$$\text{Smooth pipe: } f = 0.0136,\ Re_d = 416000 = \frac{679(3.82)(0.05)}{\mu},$$

$$\text{Solve} \quad \mu = \mathbf{0.00031\ \frac{kg}{m \cdot s}} \quad \textit{Ans.}$$

The density and viscosity are close to the likely suspect, **gasoline**. *Ans.*

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**6.54*** A swimming pool W by Y by *h* deep is to be emptied by gravity through the long pipe shown in Fig. P6.54. Assuming an average pipe friction factor $f_{av}$ and neglecting minor losses, derive a formula for the time to empty the tank from an initial level $h_o$.