P6.1 An engineer claims that flow of SAE 30W oil, at 20°C, through a 5-cm-diameter smooth pipe at 1 million N/h, is laminar. Do you agree? A million newtons is a lot, so this sounds like an awfully high flow rate.

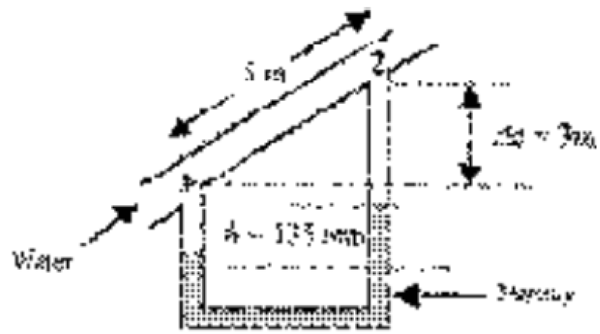
Solution: For SAE 30W oil at 20°C (Table A.3), take ρ = 891 kg/m^3 and μ = 0.29 kg/m-s. Convert the weight flow rate to volume flow rate in SI units:

$$Q = \frac{\dot{w}}{\rho g} = \frac{(1E6\,N/h)(1/3600\,h/s)}{(891kg/m^3)(9.81m/s^2)} = 0.0318\frac{m^3}{s} = \frac{\pi}{4}(0.05m)^2 V\,,\ solve\ V = 16.2\frac{m}{s}$$

$$Calculate\quad Re_D = \frac{\rho VD}{\mu} = \frac{(891kg/m^3)(16.2m/s)(0.05m)}{0.29\,kg/m-s} \approx \mathbf{2500}\quad (transitional)$$

This is not high, but **not laminar**. *Ans.* With careful inlet design, low disturbances, and a very smooth wall, it might still be laminar, but **No**, this is *transitional*, not definitely laminar.

P6.11 Water at 20°C flows upward at 4 m/s in a 6-cm-diameter pipe. The pipe length between points 1 and 2 is 5 m, and point 2 is 3 m higher. A mercury manometer, connected between 1 and 2, has a reading h = 135 mm, with p_1 higher. (a) What is the pressure change $(p_1 - p_2)$? (b) What is the head loss, in meters? (c) Is the manometer reading proportional to head loss? Explain. (d) What is the friction factor of the flow?



Solution: A sketch of this situation is shown at right. By moving through the manometer, we obtain the pressure change between points 1 and 2, which we compare with Eq. (6.9*b*):

$$p_1 + \gamma_w h - \gamma_m h - \gamma_w \Delta z = p_2,$$

$$or:\quad p_1 - p_2 = \left(133100 - 9790\ \frac{N}{m^3}\right)(0.135\ m) + \left(9790\ \frac{N}{m^3}\right)(3\ m)$$

$$= 16650 + 29370 = \mathbf{46{,}000\ Pa}\quad Ans.\ (a)$$

$$From\ Eq.\ (6.9b),\quad h_f = \frac{\Delta p}{\gamma_w} - \Delta z = \frac{46000\ Pa}{9790\ N/m^3} - 3\ m = 4.7 - 3.0 = \mathbf{1.7\ m}\quad Ans.\ (b)$$

$$The\ friction\ factor\ is\quad f = h_f \frac{d}{L}\frac{2g}{V^2} = (1.7\ m)\left(\frac{0.06\ m}{5\ m}\right)\frac{2(9.81\ m/s^2)}{(4\ m/s)^2} = \mathbf{0.025}\quad Ans.\ (d)$$

By comparing the manometer relation to the head-loss relation above, we find that:

$$h_f = \frac{(\gamma_m - \gamma_w)}{\gamma_w} h$$ ***and thus head loss* is *proportional to manometer reading.*** *Ans.* (c)

P6.31 A *laminar flow element* or LFE (Meriam Instrument Co.) measures low gas-flow rates with a bundle of capillary tubes packed inside a large outer tube. Consider oxygen at 20°C and

1 atm flowing at 84 ft^3/min in a 4-in-diameter pipe. (*a*) Is the flow approaching the element turbulent? (*b*) If there are 1000 capillary tubes, L = 4 in, select a tube diameter to keep Re_d below 1500 and also to keep the tube pressure drop no greater than 0.5 lbf/in^2. (*c*) Do the tubes selected in part (*b*) fit nicely within the approach pipe?

Solution: For oxygen at 20°C and 1 atm (Table A.4), take R = 260 $m^2/(s^2K)$, hence $\rho = p/RT$ = (101350Pa)/[260(293K)] = 1.33 kg/m^3 = 0.00258 slug/ft^3. Also read μ = 2.0E-5 kg/m-s = 4.18E-7 slug/ft-s. Convert Q = 84 ft^3/min = 1.4 ft^3/s. Then the entry pipe Reynolds number is

$$\mathrm{Re}_D = \frac{\rho V D}{\mu} = \frac{4\rho Q}{\pi \mu D} = \frac{4(0.00258\,slug/ft^3)(1.4\,ft^3/s)}{\pi(4.18E-7\,slug/ft-s)(4/12\,ft)} = \mathbf{33{,}000\ \ (turbulent)}\quad Ans.(a)$$

(*b*) To keep Re_d below 1500 and keep the (laminar) pressure drop no more than 72 psf (0.5 psi),

$$\mathrm{Re}_d = \frac{\rho V d}{\mu} \le 1500 \quad \text{and} \quad \Delta p = \frac{32\mu L V}{d^2} \le 72\frac{lbf}{ft^2}, \quad \text{where } V = \frac{Q/1000}{(\pi/4)d^2}$$

$$\mathrm{Re}_d = 1500 \quad \text{if} \quad d = 0.00734\,ft = \mathbf{0.088\,in}\ ; \quad \Delta p = 2.74\,lbf/ft^2 \quad Ans.(b)$$

Select values of d and iterate, or use Excel. The upper limit on Reynolds number gives

This is a satisfactory answer, since the pressure drop is no problem, quite small. One thousand of these tubes would have an area about one-half of the pipe area, so would fit nicely. *Ans.*(*c*)

Increasing the tube diameter would lower Re_d and have even smaller pressure drop. Example: d = 0.01 ft, Re_d = 1100, Δp = 0.8 psf. These 0.01-ft-diameter tubes would just barely fit into the larger pipe. One disadvantage, however, is that these tubes are *short*: the entrance length is *longer* than the tube length, and thus Δp will be larger than calculated by "fully-developed" formulas.

P6.59 The following data were obtained for flow of 20°C water at 20 m^3/hr through a badly corroded 5-cm-diameter pipe which slopes downward at an angle of 8°: p_1 = 420 kPa, z_1 = 12 m, p_2 = 250 kPa, z_2 = 3 m. Estimate (a) the roughness ratio of the pipe; and (b) the percent change in head loss if the pipe were smooth and the flow rate the same.

Solution: The pipe length is given indirectly as $L = \Delta z/\sin\theta$ = (9 m)/sin8° = 64.7 m. The steady flow energy equation then gives the head loss:

$$\frac{p_1}{\rho g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{V_2^2}{2g}+z_2+h_f,\quad or:\quad \frac{420000}{9790}+12=\frac{250000}{9790}+3+h_f,$$

$$\text{Solve}\quad h_f = 26.4\ m$$

Now relate the head loss to the Moody friction factor:

$$h_f = 26.4 = f\frac{L}{d}\frac{V^2}{2g} = f\frac{64.7}{0.05}\frac{(2.83)^2}{2(9.81)},\quad \text{Solve}\ f = 0.050,\ Re = 141000,\ \text{Read}\ \frac{\varepsilon}{d}\approx 0.0211$$

The estimated (and uncertain) pipe roughness is thus $\varepsilon = 0.0211d \approx$ **1.06 mm** *Ans.* (a)
(b) At the same Re_d = 141,000, f_{smooth} = 0.0168, or **66% less head loss.** *Ans.* (b)