Solution: Use Prandtl's correlation for the left hand side of Eq. (7.32) in the text:

$$\tau_w \approx 0.0225\rho U^2(\nu/U\delta)^{1/4} = \rho U^2\frac{d\theta}{dx} \approx \rho U^2\frac{d}{dx}\left(\frac{7}{72}\delta\right), \quad \text{cancel } \rho U^2 \text{ and rearrange:}$$

$$\delta^{1/4}d\delta = 0.2314(\nu/U)^{1/4}dx, \quad \text{Integrate:} \quad \frac{4}{5}\delta^{5/4} = 0.2314(\nu/U)^{1/4}x$$

Take the (5/4)th root of both sides and rearrange for the final thickness result:

$$\delta \approx 0.37(\nu/U)^{1/5}x^{4/5}, \quad \text{or:} \quad \frac{\delta}{x} \approx \frac{0.37}{Re_x^{1/5}} \quad \textit{Ans. (a)}$$

$$\text{Substitute } \delta(x) \text{ into } \tau_w\text{:} \quad C_f \approx \frac{2(0.0225)}{(0.37)^{1/4}}\left(\frac{\nu}{Ux}\right)^{1/5}, \quad \text{or} \quad C_f \approx \frac{0.0577}{Re_x^{1/5}} \quad \textit{Ans. (b)}$$

$$\text{Finally,} \quad C_D = \int_0^1 C_f d\left(\frac{x}{L}\right) = \frac{5}{4}C_f(\text{at } x = L) \approx \frac{0.072}{Re_L^{1/5}} \quad \textit{Ans. (c)}$$

7.34 A thin equilateral-triangle plate is immersed parallel to a 12 m/s stream of water 20°C, as in Fig. P7.34. Assuming $Re_{tr} = 5 \times 10^5$, estimate the drag of this plate.

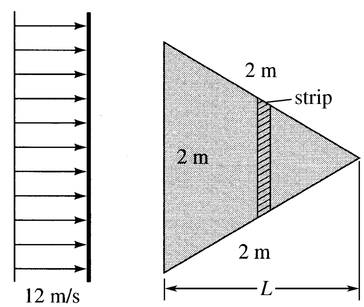

Fig. P7.34

Solution: Use a strip *dx* long and $(L - x)$ wide parallel to the leading edge of the plate, as shown in the figure. Let the side length of the triangle be *a*:

$$\text{Strip } dA = 2(L - x)\tan 30°\,dx, \quad \text{where } L = a\sin 60° \text{ and } a = 2 \text{ m} = \text{side length.}$$

$$\textit{Laminar part:} \quad dF_{lam} = \tau_w dA = 0.332\left(\frac{\rho\mu}{x}\right)^{1/2}U^{3/2}2(L-x)\tan 30°\,dx(2\ sides)$$

$$\textit{Integrate from 0 to } x_{crit}\text{:} \quad F_{lam} = 1.328(\rho\mu)^{1/2}U^{3/2}\tan 30°\left(2Lx_{crit}^{1/2} - \frac{2}{3}x_{crit}^{3/2}\right)$$

$$\textit{Turbulent part:} \quad dF_{turb} = \tau_w dA = 0.027\left(\frac{\rho U^2}{2}\right)\left(\frac{\nu}{Ux}\right)^{1/7}2(L-x)\tan 30°\,dx(2\ sides)$$

Integrate from x_{crit} to L:

$$F_{turb} = 0.054\rho\nu^{1/7}U^{13/7}\tan 30°\left[\frac{7}{6}\left(L^{13/7} - Lx_{crit}^{6/7}\right) - \frac{7}{13}\left(L^{13/7} - x_{crit}^{13/7}\right)\right]$$

The total force is, of course, $F_{lam} + F_{turb}$. For the numerical values given, L = 1.732 m. For water at 20°C, take $\rho = 998\ kg/m^3$ and $\mu = 0.001\ kg/m\cdot s$. Evaluate x_{crit} and F:

$$Re_{crit} = 5E5 = \frac{\rho U x}{\mu} = \frac{998(12)x_{crit}}{0.001}, \quad \text{or:} \quad x_{crit} = \mathbf{0.042\ m}$$

$$F_{lam} = 1.328[998(0.001)]^{1/2}(12)^{3/2}\tan 30°\left[2(1.732)(0.042)^{1/2} - \frac{2}{3}(0.042)^{3/2}\right] = 22\ N$$

$$F_{turb} = 0.054(998)\left(\frac{0.001}{998}\right)^{1/7}(12)^{13/7}\tan 30°\left[\frac{7}{6}\{(1.732)^{13/7} - 1.732(0.042)^{6/7}\}\right.$$

$$\left. - \frac{7}{13}\{(1.732)^{13/7} - (0.042)^{13/7}\}\right] = 703\ N; \quad \therefore\ F_{total} = 22 + 703 = \mathbf{725\ N} \quad \textit{Ans.}$$

7.35 Repeat Problem 7.26 for *turbulent* flow. Explain your results.

Solution: The turbulent formula $C_D = 0.031/Re_L^{1/7}$ means that $C_D \propto L^{-1/7}$. Thus:

$$\text{(a)} \quad F_a = \frac{const}{(2L_1)^{1/7}}(4A_1) = \mathbf{3.62F_1} \quad \textit{Ans.}\ \text{(a)}$$

$$\text{(b)} \quad F_b = \frac{const}{(4L_1)^{1/7}}(4A_1) = \mathbf{3.28F_1} \quad \textit{Ans.}\ \text{(b)}$$

The trailing areas have *slightly* less shear stress, hence we are *nearly* quadrupling drag.

7.36 A ship is 125 m long and has a wetted area of 3500 m^2. Its propellers can deliver a maximum power of 1.1 MW to seawater at 20°C. If all drag is due to friction, estimate the maximum ship speed, in kn.

Solution: For seawater at 20°C, take $\rho = 1025\ kg/m^3$ and $\mu = 0.00107\ kg/m\cdot s$. Evaluate

$$Re_L = \frac{\rho UL}{\mu} = \frac{1025V(125)}{0.00107} \ \text{(surely turbulent)}, \quad C_D = \frac{0.031}{Re_L^{1/7}} = \frac{0.00217}{V^{1/7}}$$

$$\text{Power} = FV = \left[\frac{0.0217}{V^{1/7}}\left(\frac{1025}{2}\right)V^2(3500)\right]V = 1.1E6\ \text{watts}, \quad \text{or} \quad V^{20/7} \approx 282.0$$

Solve for V = 7.2 m/s ≈ **14 knots**. *Ans.*
