CHAPTER 19

19.1 1 mi/hr = 0.4471 m/sec

$$V_\infty = \left(141\frac{\text{mi}}{\text{hr}}\right)\left(\frac{0.4471\ \text{m/sec}}{1\ \text{mi/hr}}\right) = 63.04 \text{ m/sec}$$

$$\text{Re}_c = \frac{\rho_\infty V_\infty c}{\mu_\infty} = \frac{(1.23)(63.04)(1.6)}{1.7894 \times 10^{-5}} = 6.93 \times 10^6$$

(a) $$C_f = \frac{1.328}{\sqrt{\text{Re}_c}} = \frac{1.328}{\sqrt{6.93 \times 10^6}} = 5.04 \times 10^{-4}$$

Noting that drag exists on both the bottom and top surfaces, we have

$$D_f = 2\, q_\infty\, S\, C_f = 2(½)(1.23)(63.04)^2(9.75)(1.6)(5.04 \times 10^{-4}) = \boxed{38.4 \text{ N}}$$

(b) $$C_f = \frac{0.074}{\text{Re}_c^{1/5}} = \frac{0.074}{(6.93\text{x}10^6)^{1/5}} = 3.17 \times 10^{-3}$$

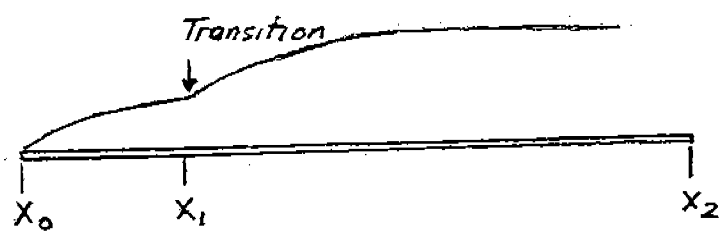
$$D_f = \frac{(C_f)_{\text{turb}}}{(C_f)_{\text{lam}}}(38.4) = \frac{3.17 \times 10^{-3}}{5.04 \times 10^{-4}}(38.4) = \boxed{241.5\text{N}}$$

Note that turbulent skin friction is 6.28 times larger than the laminar value.

19.2 (a) $$= \frac{5.0x}{\sqrt{\text{Re}_x}} = \frac{(5.0)(1.6)}{\sqrt{6.93 \times 10^6}} = 3.04 \times 10^{-3} \text{ m} = \boxed{0.304 \text{ cm}}$$

(b) $$= \frac{0.37x}{\text{Re}_x^{1/5}} = \frac{(0.37)(1.6)}{(6.93\text{x}10^6)^{1/5}} = 2.54 \times 10^{-2} \text{ m} = \boxed{2.54 \text{ cm}}$$

19.3



$q_\infty = \frac{1}{2}(1.23)(63.04)^2 = 2444 \text{ N/m}^2$

$$Re_c = 5 \times 10^5 \; \frac{\rho_\infty V_\infty (x_1 - x_o)}{\mu_\infty}$$

$$(x_1 - x_o) = \frac{5 \times 10^5 \mu_\infty}{\rho_\infty V_\infty} = \frac{(5\text{x}10^5)(1.7894 \times 10^{-5})}{(1.23)(63.04)} = 0.1154 \text{ m}$$

Laminar drag on $(x_1 - x_o)$:

$$C_f = \frac{1.328}{\sqrt{5 \times 10^5}} = 1.878 \times 10^{-3}$$

$$D_f = q_\infty \, S \, C_f = (2444)(0.1154)(9.75)(1.878 \times 10^{-3}) = 5.16 \text{ N}$$

Turbulent drag on $(x_1 - x_o)$:

$$C_f = \frac{0.074}{(5 \times 10^5)^{1/5}} = 5.36 \times 10^{-3}$$

$$D_f = \left(\frac{5.36 \times 10^{-3}}{1.878 \times 10^{-3}}\right) 5.16 = 14.73 \text{ N}$$

From Prob. 19.1, the turbulent drag on $(x_2 - x_o)$ was 241.5 N. Hence,

Turbulent drag on $(x_2 - x_1) = 241.5 - 14.73 = 226.8$ N

Total skin friction drag = [Laminar drag on $(x_1 - x_o)$] + [Turbulent drag on $(x_2 - x_1)$]

$$= 5.16 + 226.8 = \boxed{232 \text{ N}}$$

19.4 At standard sea level: $\rho_\infty = 0.002377$ slug/ft

$$T_\infty = 519°R$$

$$a_\infty = \sqrt{\gamma RT} = \sqrt{(1.4)(1716)(519)} = 1117 \text{ ft/sec}$$

$$V_\infty = M_\infty \, a_\infty = 4\,(1117) = 4468 \text{ ft/sec}$$

$$\text{Re}_c = \frac{\rho_\infty V_\infty c}{\mu_\infty} = \frac{(.002377)(4468)(5/12)}{3.7373 \times 10^{-7}} = 1.18 \times 10^7$$

$$\text{Incompressible } C_f \equiv C_{f_o} = \frac{1.328}{\sqrt{\text{Re}_c}} = \frac{1.328}{\sqrt{1.18 \times 10^7}} = 3.866 \times 10^{-4}$$

From Fig. 18.8:

$C_f/C_{f_o} \approx 0.85$; $C_f = 3.286 \times 10^{-4}$

$D_f = q_\infty S C_f = (½)(.002377)(4468)^2(5/12)(3.286 \times 10^{-4})$

$D_f =$ **3.248 lb** on one side of the plate.

19.5 For incompressible flow:

$$C_{f_o} = \frac{0.074}{\text{Re}_c^{1/5}} = \frac{0.074}{(1.18 \times 10^7)^{1/5}} = 2.85 \times 10^{-3}$$

From Fig. 19.1: $C_f \approx 1.6 \times 10^{-3}$

(The effect of Mach number is to reduce C_f by about 44% in this case.)

From Prob. 19.4, the laminar value of D_f is 3.248 for a value of $C_f = 3.286 \times 10^{-4}$. Hence, the turbulent value is

$$D_f = \left(\frac{2.85 \times 10^{-3}}{3.286 \times 10^{-4}}\right)(3.248) = \boxed{28.2 \text{ lb}}$$

19.6 From Eq. (18.32):

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \quad (1)$$

From Eq. (18.41) with Pr = 1:

$$\rho u \frac{\partial h_o}{\partial x} + \rho v \frac{\partial h_o}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial h_o}{\partial y}\right) \quad (2)$$

Eqs. (1) and (2) are identical. Hence

$h_o = c_1 + c_2\, u$, where c_1 and c_2 are constants.

At the wall, $u = 0$ and $h_o = h_{o_w} = h_w$. Hence,

$$h_w = c_1 + 0, \text{ or } c_1 = h_w$$

At the boundary layer edge:

$$h_{o_e} = c_1 + c_2\, u_e = h_w + c_2\, u_e$$

$$c_2 = \frac{h_{o_e} - h_w}{u_e}$$

Thus:

$$h_o = c_1 + c_2\, u = h_w + \frac{h_{o_e} - h_w}{u_e}\, u$$

Since

$$h = c_p\, T, \text{ then}$$

$$\boxed{T_o = T_w + \left(T_{o_e} - T_w\right)\frac{u}{u_e}}$$

19.7 From Eq. (18.70),

$$\dot{q}_w = 0.763\, Pr^{-0.65}\, (\rho_e \mu_e) \sqrt{\frac{du_e}{dx}}\, (h_{aw} - h_w) \qquad (1)$$

where, from Eq. (18.82), the velocity gradient is given by

$$\frac{du_e}{dx} = \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}} \qquad (2)$$

The subscript e denotes properties at the outer edge of the stagnation point boundary layer, i.e., p_e and ρ_e are the inviscid stagnation point values of pressure and density. The speed of sound in the ambient atmosphere is

$$a_\infty = \sqrt{\gamma R T_\infty} = \sqrt{(1.4)(287)(246.1)} = 314.5 \text{ m/sec}$$

(a) For $V_\infty = 1500$ m/sec, we have

$$M_\infty = \frac{V_\infty}{a_\infty} = \frac{1500}{314.5} = 4.77$$

From Appendix B (nearest entry),

$$\frac{p_{o,2}}{p_\infty} = 29.52$$

and from Appendix A (nearest entry),

$$\frac{T_o}{T_\infty} = 5.512$$

Hence,

$$p_{o,2} \equiv p_e = (29.52)(583.59) = 1.723 \text{ x } 10^4 \text{ N/m}^2$$

$$T_o \equiv T_e = (5.512)(246.1) = 1357 \text{ K}$$

$$\rho_e \equiv \frac{p_e}{RT_e} = \frac{1.723 \text{ x } 10^4}{(287)(1357)} = 0.044 \text{ kg/m}^3$$

From Southerland's law, Eq. (15.3), using the standard sea level value of $\mu_o = 1.7894 \text{ x } 10^{-5}$ kg/(m)(sec) at $T_o = 288\text{K}$, we have

$$\frac{\mu_e}{\mu_o} = \left(\frac{T_e}{T_o}\right)^{3/2} \frac{T_o + 110}{T_e + 110} = \left(\frac{1357}{288}\right)^{3/2} \left(\frac{288 + 110}{1357 + 110}\right) = 2.77$$

$$\mu_e = (2.77)(1.789 \text{ x } 10^{-5}) = 4.957 \text{ x } 10^{-5} \text{ kg/(m)(sec)}$$

From Eq. (2) above

$$\frac{du_e}{dx} = \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}} = \frac{1}{(0.0254)}\sqrt{\frac{2(1.723 \text{ x } 10^4 - 583.59)}{0.044}} = 3.42 \text{ x } 10^4\text{/sec}$$

Assuming a recovery factor $r = 1$, then $h_{aw} = h_o$.

$$h_{aw} = h_o = h_\infty + \frac{V_\infty^{\ 2}}{2} = c_p\, T_\infty + \frac{V_\infty^{\ 2}}{2} = (1008)(246.1) + \frac{(1500)^2}{2}$$

$$= 2.48 \text{ x } 10^5 + 11.25 \text{ x } 10^5 = 13.73 \text{ x } 10^5 \text{ joule/kg}$$

$$h_{aw} = c_p\, T_w = (1008)(400) = 4.032 \text{ x } 10^5 \text{ joule/kg}$$

The "rho-mu" product is

$$\rho_e\mu_e = (1.044)(4.957 \times 10^{-5}) = 2.18 \times 10^{-6} \frac{(kg)^2}{m^4 \sec}$$

From Eq. (1) above

$$\dot{q}_w = 0.763 \, Pr^{-0.65} (\rho_e\mu_e) \sqrt{\frac{du_e}{dx}} \, (h_{aw} - h_w)$$

$$= 0.763 \, (0.72)^{-0.65} \, (2.18 \times 10^{-6})(3.42 \times 10^4)^{1/2} \, (13.73 - 4.032) \times 10^5$$

$$= 369.3 \frac{\text{joules}}{\sec(m^2)} = \boxed{369.3 \frac{\text{watt}}{m^2}}$$

(b) For $V_\infty = 4500$ m/sec, we have

$$M_\infty = \frac{V_\infty}{a_\infty} = \frac{4500}{314.5} = 14.31$$

From Appendix B (interpolated)

$$\frac{p_{o,2}}{p_\infty} = 264.0$$

From Appendix A (interpolated)

$$\frac{T_o}{T_\infty} = 41.94$$

Thus:

$$p_e = (264)(583.59) = 1.54 \times 10^5 \text{ N/m}^2$$

$$T_e = 41.94 \, (246.1) = 10{,}321 \text{ K}$$

$$\rho_e = \frac{p_e}{RT_e} = \frac{1.54 \times 10^5}{(187)(10{,}321)} = 0.052 \text{ kg/m}^3$$

$$\frac{\mu_e}{\mu_o} = \left(\frac{T_e}{T_o}\right)^{3/2} \frac{T_o + 110}{T_e + 110} = \left(\frac{10321}{288}\right)^{3/2} \left(\frac{288 + 110}{10321 + 110}\right) = 8.186$$