9.19

9.19 Because of the velocity deficit, $U - u$, in the boundary layer, the streamlines for flow past a flat plate are not exactly parallel to the plate. This deviation can be determined by use of the displacement thickness, δ^*. For air blowing past the flat plate shown in Fig. P9.19, plot the streamline A–B that passes through the edge of the boundary layer ($y = \delta_B$ at $x = \ell$) at point B. That is, plot $y = y(x)$ for streamline A–B. Assume laminar boundary layer flow.

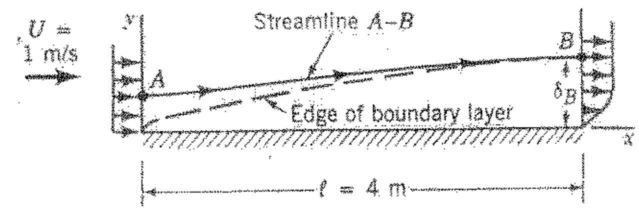
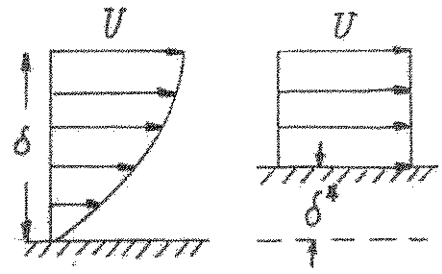


FIGURE P9.19

Since $Re_\ell = \frac{U\ell}{\nu} = \frac{(1\frac{m}{s})(4m)}{1.46\times10^{-5}\frac{m^2}{s}} = 2.74\times10^5 < 5\times10^5$, the boundary layer flow remains laminar along the entire plate. Hence,

$$\delta = 5\sqrt{\frac{\nu x}{U}} \quad \text{or} \quad \delta_B = 5\left[\frac{(1.46\times10^{-5}\frac{m^2}{s})(4m)}{1\frac{m}{s}}\right]^{1/2} = 0.0382\ m$$

The flowrate carried by the actual boundary layer is by definition equal to that carried by a uniform velocity with the plate displaced by an amount δ^*. Since there is no flow through the plate or streamline A-B,



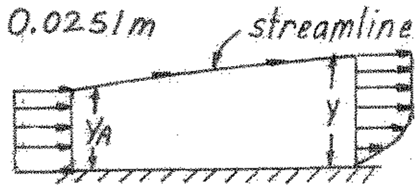
$$Q_A = Q_B\text{, or } U y_A = (\delta_B - \delta_B^*)U \qquad (1)$$

where $\delta^* = 1.721\sqrt{\frac{\nu x}{U}}$

or $\delta_B^* = 1.721\left[\frac{(1.46\times10^{-5}\frac{m^2}{s})(4m)}{1\frac{m}{s}}\right]^{1/2} = 0.01315\ m$

Thus,

$$y_A = \delta_B - \delta_B^* = 0.0382\,m - 0.01315\,m = 0.0251\,m$$



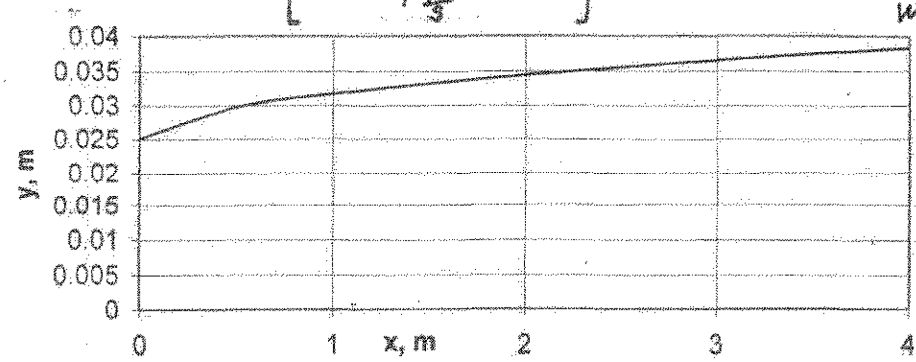
Hence, for any x-location

$Q_A = Q$ or $U y_A = U(y - \delta^*)$

or $y = y_A + \delta^* = y_A + 1.721\sqrt{\frac{\nu x}{U}}$

$$= 0.0251\,m + 1.721\left[\frac{(1.46\times10^{-5}\frac{m^2}{s})x\,m}{1\frac{m}{s}}\right]^{1/2} = \underline{\underline{0.0251 + 6.58\times10^{-3}\sqrt{x}\ m,}}$$

where $x \sim m$



9.24

9.39

9.39 The aerodynamic drag on a car depends on the "shape" of the car. For example, the car shown in Fig. P9.39 has a drag coefficient of 0.36 with the windows and roof closed. With the windows and roof open, the drag coefficient increases to 0.45. With the windows and roof open, at what speed is the amount of power needed to overcome aerodynamic drag the same as it is at 65 mph with the windows and roof closed? Assume the frontal area remains the same. Recall that power is force times velocity.

Windows and roof closed: $C_D = 0.35$ | Windows open; roof open: $C_D = 0.45$

■ FIGURE P9.39

$$\text{Power} = \mathcal{P} = F \cdot V$$

The force is the drag force. Let $(\ )_c$ and $(\ )_o$ denote closed and open.

$$\mathcal{D} = C_D \tfrac{1}{2}\rho U^2 A$$

We want to find U_o when $\mathcal{P}_o = \mathcal{P}_c$

$$\mathcal{P}_o = U_o \mathcal{D}_o = \tfrac{1}{2}\rho U_o^3 A_o C_{D_o} = \mathcal{P}_c = U_c \mathcal{D}_c = \tfrac{1}{2}\rho U_c^3 A_c C_{D_c}$$

The frontal areas are the same, so $A_o = A_c$

$$U_o^3 C_{D_o} = U_c^3 C_{D_c}$$

$$U_o = U_c \left(\frac{C_{Dc}}{C_{Do}}\right)^{1/3} = (65\,\text{mph})\left(\frac{0.36}{0.45}\right)^{1/3}$$

$$\underline{\underline{U_o = 60.3\ \text{mph}}}$$

9.84

9.84 A 2-in.-diameter sphere weighing 0.14 lb is suspended by the jet of air shown in Fig. P9.84 and Video V3.2. The drag coefficient for the sphere is 0.5. Determine the reading on the pressure gage if friction and gravity effects can be neglected for the flow between the pressure gage and the nozzle exit.

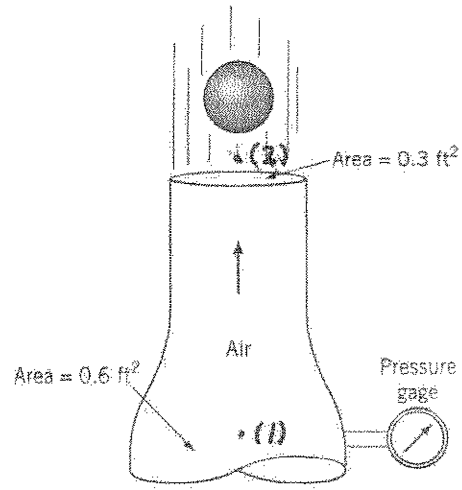
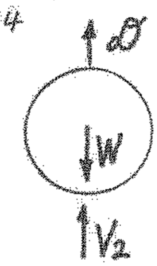


FIGURE P9.84



For equilibrium, $\mathscr{D} = W$ or

$C_D \frac{1}{2}\rho V_2^2 A = W$, where $A = \frac{\pi}{4}D^2$

Thus,

$$V_2 = \left[\frac{2W}{C_D \rho \pi D^2/4}\right]^{1/2}$$

$$= \left[\frac{8\,(0.14\,lb)}{0.5(0.00238\,\frac{slugs}{ft^3})\pi(\frac{2}{12}\,ft)^2}\right]^{1/2} = 104\,\frac{ft}{s}$$

Also,

$V_1 A_1 = V_2 A_2$ or $V_1 = V_2 \frac{A_2}{A_1} = (104\,\frac{ft}{s})\frac{0.3\,ft^2}{0.6\,ft^2} = 52.0\,\frac{ft}{s}$

and

$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2$ where $p_2 = 0$

Thus,

$$p_1 = \frac{1}{2}\rho[V_2^2 - V_1^2] = \frac{1}{2}(0.00238\,\frac{slugs}{ft^3})[(104\,\frac{ft}{s})^2 - (52.0\,\frac{ft}{s})^2]$$

$$= \underline{\underline{9.65\,\frac{lb}{ft^2}}}$$

9.105

9.105 As shown in Video V9.25 and Fig. P9.105 a spoiler is used on race cars to produce a negative lift, thereby giving a better tractive force. The lift coefficient for the airfoil shown is $C_L = 1.1$, and the coefficient of friction between the wheels and the pavement is 0.6. At a speed of 200 mph, by how much would use of the spoiler increase the maximum tractive force that could be generated between the wheels and ground? Assume the air speed past the spoiler equals the car speed and that the airfoil acts directly over the drive wheels.

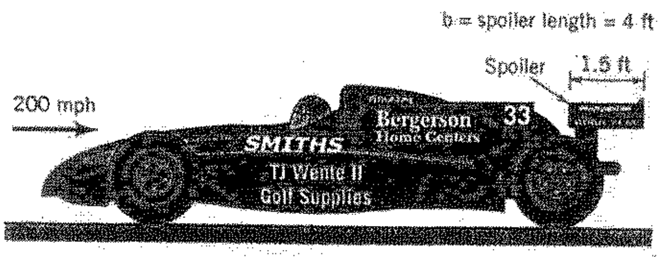
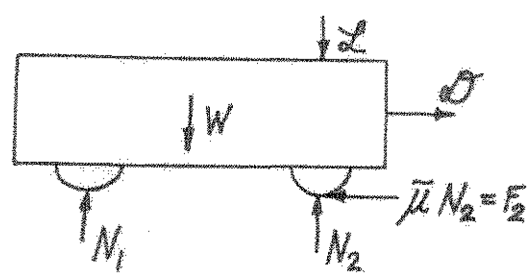


FIGURE P9.105



Tractive force $= F_2 = \tilde{\mu} N_2$

where $\tilde{\mu}$ = coefficient of friction = 0.6

Thus,

$\Delta F_2 = \tilde{\mu}\, \Delta N_2 = \tilde{\mu}\, \mathcal{L}$, where ΔF_2 is the increase in tractive force due to the (downward) lift.

Hence, with $U = 200\ mph = 293\ ft/s$,

$$\mathcal{L} = \frac{1}{2}\rho U^2 C_L A = \frac{1}{2}\left(0.00238\ \frac{slugs}{ft^3}\right)\left(293\ \frac{ft}{s}\right)^2 (1.1)(1.5\ ft)(4\ ft) = 674\ lb,$$

and

$$\Delta F_2 = 0.6\,(674\ lb) = \underline{\underline{405\ lb}}$$

*9.109

9.109 Air blows over the flat-bottomed, two-dimensional object shown in Fig. P9.109. The shape of the object, $y = y(x)$, and the fluid speed along the surface, $u = u(x)$, are given in the table. Determine the lift coefficient for this object.

x (% c)	y (% c)	u/U
0	0	0
2.5	3.72	0.971
5.0	5.30	1.232
7.5	6.48	1.273
10	7.43	1.271
20	9.92	1.276
30	11.14	1.295
40	11.49	1.307
50	10.45	1.308
60	9.11	1.195
70	6.46	1.065
80	3.62	0.945
90	1.26	0.856
100	0	0.807

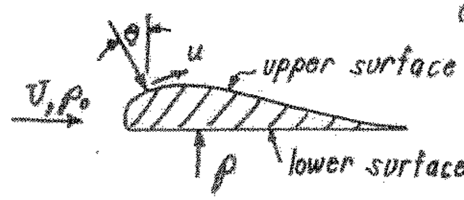
If viscous effects are negligible, then

$$\mathcal{L} = \int_{lower} p\cos\theta dA - \int_{upper} p\cos\theta dA \qquad (1)$$

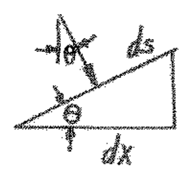
where from the Bernoulli equation

$$p + \tfrac{1}{2}\rho u^2 = p_0 + \tfrac{1}{2}\rho U^2 \qquad (2)$$

The effect of atmospheric pressure, p_0, drops out when the integration over the entire surface is performed.



With $\theta = 0$ on the lower surface and with $\cos\theta\, dA = \cos\theta\,(\ell ds) = \ell\, dx$, where ℓ = wing span, Eqs.(1) and (2) give



$$\mathcal{L} = \int_{lower}\left[p_0 + \tfrac{1}{2}\rho(U^2 - u^2)\right]\ell\, dx - \int_{upper}\left[p_0 + \tfrac{1}{2}\rho(U^2 - u^2)\right]\ell\, dx$$

or, since $u = U$ on the lower surface

$$\mathcal{L} = -\tfrac{1}{2}\rho\ell\int_{x=0}^{x=c}(U^2 - u^2)\,dx = \tfrac{1}{2}\rho U^2\ell c\int_{x'=0}^{x'=1}\left[\left(\frac{u}{U}\right)^2 - 1\right]dx' \text{ , where } x' = \frac{x}{c} \qquad (3)$$

Thus, since

$$C_L = \frac{\mathcal{L}}{\frac{1}{2}\rho U^2 A} = \frac{\mathcal{L}}{\frac{1}{2}\rho U^2 \ell c}$$ it follows from Eq.(3) that

$$C_L = \int_{x'=0}^{x'=1}\left[\left(\frac{u}{U}\right)^2 - 1\right]dx'$$

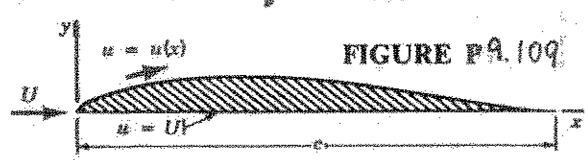


FIGURE P9.109

By using a standard numerical integration routine with the data given we obtain

$C_L = \underline{\underline{0.327}}$

x'	$\left(\frac{u}{U}\right)^2 - 1$
0	−1.00
0.025	−0.0572
0.050	0.518
0.075	0.621
0.100	0.615
0.200	0.628
0.300	0.677
0.400	0.708
0.500	0.711
0.600	0.428
0.700	0.134
0.800	−0.107
0.900	−0.267
1.000	−0.349

9.80