11. Freeman, H. B. "Force Measurements on a 1/40-Scale Model of the U.S. Airship 'Akron.'" *NACA Rept.*, 432 (1932).

12. Rouse, H. *Elementary Mechanics of Fluids*. New York: John Wiley, 1946.

13. Clift, R., J. R. Grace, and M. E. Weber. *Bubbles, Drops and Particles*. San Diego, CA: Academic Press, 1978.

14. Clift, R., and W. H. Gauvin. "The Motion of Particles in Turbulent Gas Streams." *Proc. Chemeca '70*, vol. 1, pp. 14–28 (1970).

15. Hoerner, S. F. *Fluid Dynamic Drag*. Published by the author, 1958.

16. Morrison, R. B. (ed). *Design Data for Aeronautics and Astronautics*. New York: John Wiley, 1962.

17. Roberson, J. A., et al. "Turbulence Effects on Drag of Sharp-Edged Bodies." *J. Hydraulics Div., Am. Soc. Civil Eng.* (July 1972).

18. Scher, S. H., and L. J. Gale. "Wind Tunnel Investigation of the Opening Characteristics, Drag, and Stability of Several Hemispherical Parachutes." *NACA Tech. Note*, 1869 (1949).

19. Crowe, C. T., et al. "Drag Coefficient for Particles in Rarefied, Low Mach-Number Flows." In *Progress in Heat and Mass Transfer*, vol. 6, pp. 419–431. New York: Pergamon Press, 1972.

20. Barkla, H. M., et al. "The Magnus or Robins Effect on Rotating Spheres." *J. Fluid Mech.*, vol. 47, part 3 (1971).

21. Kuethe, A. M., and J. D. Schetzer. *Foundations of Aerodynamics*. New York: John Wiley, 1967.

22. Abbott, H., and A. E. Von Doenhoff. *Theory of Wing Sections*. New York: Dover, 1949.

23. Prandtl, L. "Applications of Modern Hydrodynamics to Aeronautics." *NACA Rept.*, 116 (1921).

24. Hucho, Wolf-Heinrich, ed. *Aerodynamics of Road Vehicles*. London: Butterworth, 1987.

25. Schenkel, Franz K. "The Origins of Drag and Lift Reductions on Automobiles with Front and Rear Spoilers." *SAE Paper*, no. 770389 (February 1977).

26. Sharke, P. "Smooth Body." *Mechanical Engineer*, vol. 121, pp. 74–77 (1999).

27. Smith, C. *Engineer to Win*. Osceola, WI: Motorbooks International, 1984.

28. Mehta, R. D. "Aerodynamics of Sports Balls." *Annual Review of Fluid Mechanics*, 17, p. 151 (March 1985).

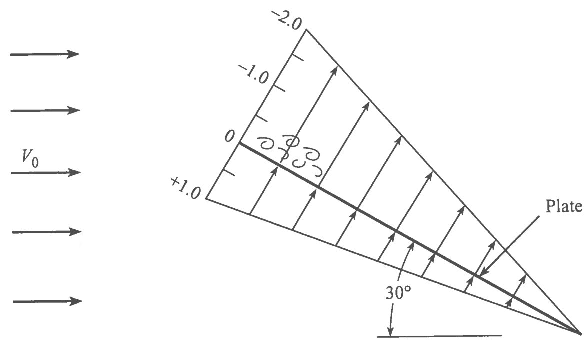
## PROBLEMS

WILEY PLUS Problem available in *WileyPLUS* at instructor's discretion.

WILEY GO Guided Online (GO) Problem, available in *WileyPLUS* at instructor's discretion.

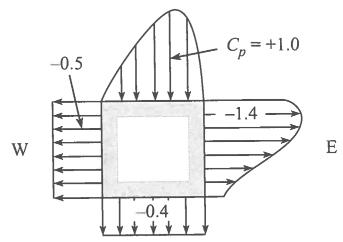
### Relating Pressure Distribution and $C_D$ (§11.1)

**11.1** WILEY PLUS A hypothetical pressure coefficient variation over a long (length normal to the page) plate is shown. What is the coefficient of drag for the plate in this orientation and with the given pressure distribution? Assume that the reference area is the surface area (one side) of the plate.



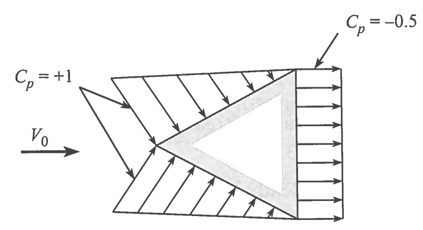

PROBLEM 11.1

**11.2** WILEY PLUS Flow is occurring past the square rod. The pressure coefficient values are as shown. From which direction do you think the flow is coming? (a) SW direction, (b) SE direction, (c) NW direction, or (d) NE direction.




PROBLEM 11.2

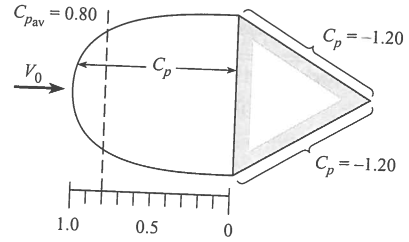
**11.3** The hypothetical pressure distribution on a rod of triangular (equilateral) cross section is shown, where flow is from left to right. That is, $C_p$ is maximum and equal to $+1.0$ at the leading edge and decreases linearly to zero at the trailing edges. The pressure coefficient on the downstream face is constant with a value of $-0.5$. Neglecting skin friction drag, find $C_D$ for the rod.




PROBLEM 11.3



**11.4** WILEY PLUS The pressure distribution on a rod having a triangular (equilateral) cross section is shown, where flow is from left to right. What is $C_D$ for the rod?




PROBLEM 11.4

**11.5** WILEY PLUS Fill in the blanks for the following two statements:

A. ______________ is associated with the viscous shear-stress distribution.

a. Form drag

b. Friction drag

B. ______________ is associated with the pressure distribution

a. Form drag

b. Friction drag.

### Calculating Drag Force (§11.2)

**11.6** WILEY PLUS The coefficient of drag for a body (select all that apply):

a. is dimensionless

b. is usually determined by experiment

c. depends on thrust

d. depends on the body's shape

e. requires an updraft

**11.7** WILEY PLUS Apply the grid method to each situation that follows.

a. Use Eq. (11.5) on p. 409 in §11.2, to predict the drag force in newtons for an automobile that is traveling at $V = 100$ km/h on a summer day. Assume that the frontal area is 2 m$^2$, and the coefficient of drag is $C_D = 0.4$.

b. Apply Eq. (11.5) on p. 409 in §11.2, to predict the speed in km/h of a bicycle rider that is subject to a drag force of 22 N on a summer's day. Assume the frontal area of the rider is $A = 0.5$ m$^2$, and the coefficient of drag is $C_D = 0.3$.

**11.8** Using the first two sections in this chapter and using other resources, answer the questions that follow. Strive for depth, clarity, and accuracy. Also, strive for effective use of sketches, words, and equations.

a. What are the four most important factors that influence the drag force?

b. How are stress and drag related?

c. What is form drag? What is friction drag?

**11.9** Use information in §11.2 and 11.3 to find the coefficient of drag for each case described here.

a. A sphere is falling through water, Re = 10,000.

b. Air is blowing normal to a very long circular cylinder, and Re = 7000.

c. Wind is blowing normal to a billboard that is 6 m wide by 3 m high.

**11.10** Estimate the wind force on a billboard 4 m high and 12 m wide when a 100 km/h wind ($T = 15$°C) is blowing normal to it.

**11.11** If Stokes's law is considered valid below a Reynolds number of 0.5, what is the largest raindrop that will fall in accordance with Stokes's law?

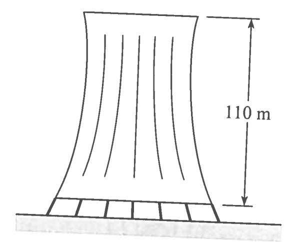
**11.12** Determine the drag of a 0.6 m × 1.2 m sheet of plywood held at a right angle to a stream of air (15°C, 1 atm) having a velocity of 56 km/h.

**11.13** WILEY PLUS Estimate the drag of a thin square plate (3 m by 4 m) when it is towed through water (10°C). Assume a towing speed of about 5 m/s.

a. The plate is oriented for minimum drag.

b. The plate is oriented for maximum drag.

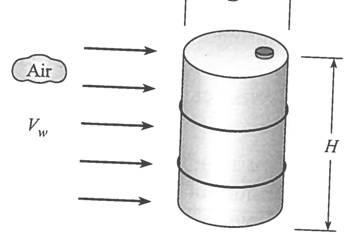
**11.14** A cooling tower, used for cooling recirculating water in a modern steam power plant, is 110 m high and 60 m average diameter. Estimate the drag on the cooling tower in a 240 km/h wind ($T = 15$°C).




PROBLEM 11.14

**11.15** Estimate the wind force that would act on *you* if you were standing on top of a tower in a 30 m/s wind on a day when the temperature was 20°C and the atmospheric pressure was 96 kPa.

**11.16** WILEY GO As shown, wind is blowing on a 210 L drum. Estimate the wind speed needed to tip the drum over. The mass of the drum is 22 kg, the diameter is 57 cm, and the height is 88 cm.




PROBLEM 11.16

11. Freeman, H. B. "Force Measurements on a 1/40-Scale Model of the U.S. Airship 'Akron.'" *NACA Rept.*, 432 (1932).

12. Rouse, H. *Elementary Mechanics of Fluids*. New York: John Wiley, 1946.

13. Clift, R., J. R. Grace, and M. E. Weber. *Bubbles, Drops and Particles*. San Diego, CA: Academic Press, 1978.

14. Clift, R., and W. H. Gauvin. "The Motion of Particles in Turbulent Gas Streams." *Proc. Chemeca '70*, vol. 1, pp. 14–28 (1970).

15. Hoerner, S. F. *Fluid Dynamic Drag*. Published by the author, 1958.

16. Morrison, R. B. (ed). *Design Data for Aeronautics and Astronautics*. New York: John Wiley, 1962.

17. Roberson, J. A., et al. "Turbulence Effects on Drag of Sharp-Edged Bodies." *J. Hydraulics Div., Am. Soc. Civil Eng.* (July 1972).

18. Scher, S. H., and L. J. Gale. "Wind Tunnel Investigation of the Opening Characteristics, Drag, and Stability of Several Hemispherical Parachutes." *NACA Tech. Note*, 1869 (1949).

19. Crowe, C. T., et al. "Drag Coefficient for Particles in Rarefied, Low Mach-Number Flows." In *Progress in Heat and Mass Transfer*, vol. 6, pp. 419–431. New York: Pergamon Press, 1972.

20. Barkla, H. M., et al. "The Magnus or Robins Effect on Rotating Spheres." *J. Fluid Mech.*, vol. 47, part 3 (1971).

21. Kuethe, A. M., and J. D. Schetzer. *Foundations of Aerodynamics*. New York: John Wiley, 1967.

22. Abbott, H., and A. E. Von Doenhoff. *Theory of Wing Sections*. New York: Dover, 1949.

23. Prandtl, L. "Applications of Modern Hydrodynamics to Aeronautics." *NACA Rept.*, 116 (1921).

24. Hucho, Wolf-Heinrich, ed. *Aerodynamics of Road Vehicles*. London: Butterworth, 1987.

25. Schenkel, Franz K. "The Origins of Drag and Lift Reductions on Automobiles with Front and Rear Spoilers." *SAE Paper*, no. 770389 (February 1977).

26. Sharke, P. "Smooth Body." *Mechanical Engineer*, vol. 121, pp. 74–77 (1999).

27. Smith, C. *Engineer to Win*. Osceola, WI: Motorbooks International, 1984.

28. Mehta, R. D. "Aerodynamics of Sports Balls." *Annual Review of Fluid Mechanics*, 17, p. 151 (March 1985).

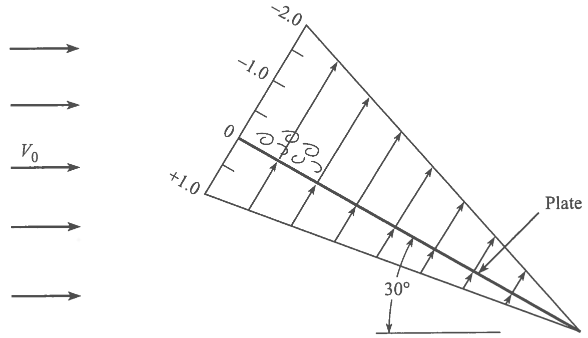
## PROBLEMS

WILEY PLUS Problem available in *WileyPLUS* at instructor's discretion.

WILEY GO Guided Online (GO) Problem, available in *WileyPLUS* at instructor's discretion.

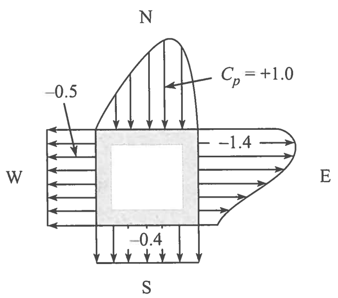
### Relating Pressure Distribution and $C_D$ (§11.1)

**11.1** WILEY PLUS A hypothetical pressure coefficient variation over a long (length normal to the page) plate is shown. What is the coefficient of drag for the plate in this orientation and with the given pressure distribution? Assume that the reference area is the surface area (one side) of the plate.



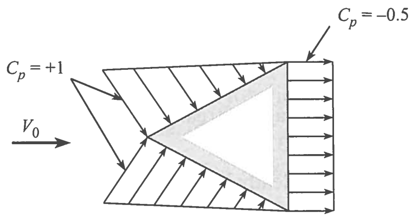

PROBLEM 11.1

**11.2** WILEY PLUS Flow is occurring past the square rod. The pressure coefficient values are as shown. From which direction do you think the flow is coming? (a) SW direction, (b) SE direction, (c) NW direction, or (d) NE direction.




PROBLEM 11.2

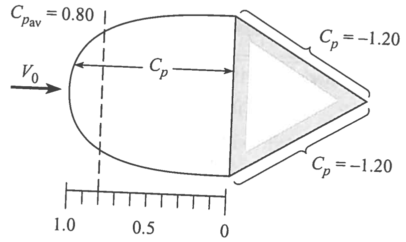
**11.3** The hypothetical pressure distribution on a rod of triangular (equilateral) cross section is shown, where flow is from left to right. That is, $C_p$ is maximum and equal to $+1.0$ at the leading edge and decreases linearly to zero at the trailing edges. The pressure coefficient on the downstream face is constant with a value of $-0.5$. Neglecting skin friction drag, find $C_D$ for the rod.




PROBLEM 11.3



**11.4** WILEY PLUS The pressure distribution on a rod having a triangular (equilateral) cross section is shown, where flow is from left to right. What is $C_D$ for the rod?




PROBLEM 11.4

**11.5** WILEY PLUS Fill in the blanks for the following two statements:

A. ____________ is associated with the viscous shear-stress distribution.

a. Form drag

b. Friction drag

B. ____________ is associated with the pressure distribution

a. Form drag

b. Friction drag.

### Calculating Drag Force (§11.2)

**11.6** WILEY PLUS The coefficient of drag for a body (select all that apply):

a. is dimensionless

b. is usually determined by experiment

c. depends on thrust

d. depends on the body's shape

e. requires an updraft

**11.7** WILEY PLUS Apply the grid method to each situation that follows.

a. Use Eq. (11.5) on p. 409 in §11.2, to predict the drag force in newtons for an automobile that is traveling at $V = 100$ km/h on a summer day. Assume that the frontal area is 2 m$^2$, and the coefficient of drag is $C_D = 0.4$.

b. Apply Eq. (11.5) on p. 409 in §11.2, to predict the speed in km/h of a bicycle rider that is subject to a drag force of 22 N on a summer's day. Assume the frontal area of the rider is $A = 0.5$ m$^2$, and the coefficient of drag is $C_D = 0.3$.

**11.8** Using the first two sections in this chapter and using other resources, answer the questions that follow. Strive for depth, clarity, and accuracy. Also, strive for effective use of sketches, words, and equations.

a. What are the four most important factors that influence the drag force?

b. How are stress and drag related?

c. What is form drag? What is friction drag?

**11.9** Use information in §11.2 and 11.3 to find the coefficient of drag for each case described here.

a. A sphere is falling through water, Re = 10,000.

b. Air is blowing normal to a very long circular cylinder, and Re = 7000.

c. Wind is blowing normal to a billboard that is 6 m wide by 3 m high.

**11.10** Estimate the wind force on a billboard 4 m high and 12 m wide when a 100 km/h wind ($T = 15$°C) is blowing normal to it.

**11.11** If Stokes's law is considered valid below a Reynolds number of 0.5, what is the largest raindrop that will fall in accordance with Stokes's law?

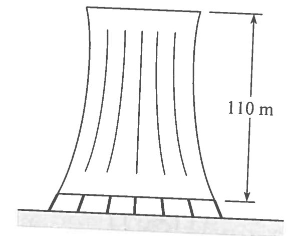
**11.12** Determine the drag of a 0.6 m × 1.2 m sheet of plywood held at a right angle to a stream of air (15°C, 1 atm) having a velocity of 56 km/h.

**11.13** WILEY PLUS Estimate the drag of a thin square plate (3 m by 4 m) when it is towed through water (10°C). Assume a towing speed of about 5 m/s.

a. The plate is oriented for minimum drag.

b. The plate is oriented for maximum drag.

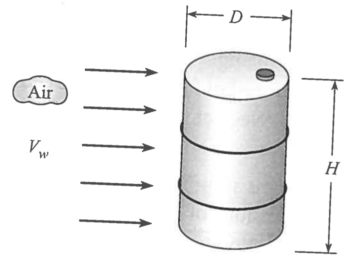
**11.14** A cooling tower, used for cooling recirculating water in a modern steam power plant, is 110 m high and 60 m average diameter. Estimate the drag on the cooling tower in a 240 km/h wind ($T = 15$°C).




PROBLEM 11.14

**11.15** Estimate the wind force that would act on *you* if you were standing on top of a tower in a 30 m/s wind on a day when the temperature was 20°C and the atmospheric pressure was 96 kPa.

**11.16** WILEY GO As shown, wind is blowing on a 210 L drum. Estimate the wind speed needed to tip the drum over. The mass of the drum is 22 kg, the diameter is 57 cm, and the height is 88 cm.




PROBLEM 11.16

**11.17** What drag is produced when a disk 0.75 m in diameter is submerged in water at 10°C and towed behind a boat at a speed of 4 m/s? Assume orientation of the disk so that maximum drag is produced.

**11.18** A circular billboard having a diameter of 7 m is mounted so as to be freely exposed to the wind. Estimate the total force exerted on the structure by a wind that has a direction normal to the structure and a speed of 50 m/s. Assume $T = 10°C$ and $p = 101$ kPa absolute.

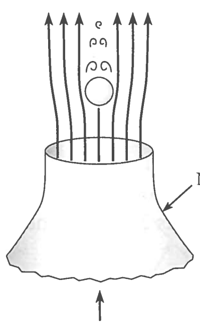
**11.19** Consider a large rock situated at the bottom of a river and acted on by a strong current. Estimate a typical speed of the current that will cause the rock to move downstream along the bottom of the river. List and justify all your major assumptions.

**11.20** Compute the overturning moment exerted by a 35 m/s wind on a smokestack that has a diameter of 2.5 m and a height of 75 m. Assume that the air temperature is 20°C and that $p_a$ is 99 kPa absolute.

**11.21** What is the moment at the bottom of a flagpole 20 m high and 8 cm in diameter in a 37.5 m/s wind? The atmospheric pressure is 100 kPa, and the temperature is 20°C.

**11.22** A cylindrical anchor (vertical axis) made of concrete ($\gamma = 15$ kN/m$^3$) is reeled in at a rate of 1.0 m/s by a man in a boat. If the anchor is 30 cm in diameter and 30 cm long, what tension must be applied to the rope to pull it up at this rate? Neglect the weight of the rope.

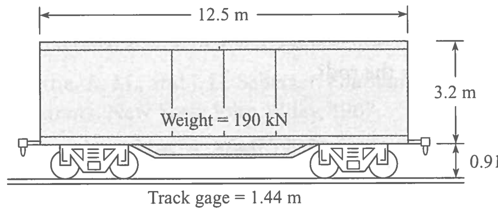
**11.23** A Ping-Pong ball of mass 2.6 g and diameter 38 mm is supported by an air jet. The air is at a temperature of 18°C and a pressure of 91.4 kPa. What is the minimum speed of the air jet?



PROBLEM 11.23

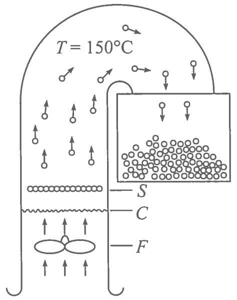
**11.24** Estimate the moment at ground level on a signpost supporting a sign measuring 3 m by 2 m if the wind is normal to the surface and has a speed of 35 m/s and the center of the sign is 4 m above the ground. Neglect the wind load on the post itself. Assume $T = 10°C$ and $p = 1$ atm.

**11.25** Windstorms sometimes blow empty boxcars off their tracks. The dimensions of one type of boxcar are shown. What minimum wind velocity normal to the side of the car would be required to blow the car over?



PROBLEM 11.25

**11.26** A semiautomatic popcorn popper is shown. After the unpopped corn is placed in screen $S$, the fan $F$ blows air past the heating coils $C$ and then past the popcorn. When the corn pops, its projected area increases; thus it is blown up and into a container. Unpopped corn has a mass of about 0.15 g per kernel and an average diameter of approximately 6 mm. When the corn pops, its average diameter is about 18 mm. Within what range of airspeeds in the chamber will the device operate properly?



PROBLEM 11.26

**11.27** Hoerner (15) presents data that show that fluttering flags of moderate-weight fabric have a drag coefficient (based on the flag area) of about 0.14. Thus the total drag is about 14 times the skin friction drag alone. Design a flagpole that is 30 m high and is to fly a flag 2 m high. Make your own assumptions regarding other required data.

## Power, Energy, and Rolling Resistance (§11.2)

**11.28** How much power is required to move a spherical-shaped submarine of diameter 1.5 m through seawater at a speed of 18.5 km/h? Assume the submarine is fully submerged.

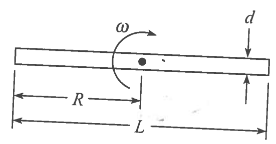
**11.29** A blimp flies at 9 m/s at an altitude where the specific weight of the air is 11 N/m$^3$ and the kinematic viscosity is $1.2 \times 10^{-5}$ m/s. The blimp has a length-to-diameter ratio of 5 and has a drag coefficient corresponding to the streamlined body in Fig. 11.9 (on p. 413 in §11.3). The diameter of the blimp is 24 m. What is the power required to propel the blimp at this speed?

**11.30** Estimate the energy in joules and kcal (food calories) that a runner supplies to overcome aerodynamic drag during a 10 km race. The runner runs a 4:30 pace (i.e., each kilometer takes 4 minutes and 30 seconds). The product of frontal area and coefficient of drag is $C_DA = 0.74$ m$^2$. (One "food calorie" is equivalent to 4186 J.) Assume an air density of 1.22 kg/m$^3$.



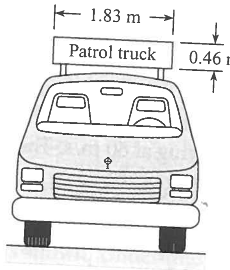
**11.31** A cylindrical rod of diameter $d$ and length $L$ is rotated in still air about its midpoint in a horizontal plane. Assume the drag force at each section of the rod can be calculated assuming a two-dimensional flow with an oncoming velocity equal to the relative velocity component normal to the rod. Assume $C_D$ is constant along the rod.

a. Derive an expression for the average power needed to rotate the rod.
b. Calculate the power for $\omega = 50$ rad/s, $d = 2$ cm, $L = 1.5$ m, $\rho = 1.2$ kg/m$^3$, and $C_D = 1.2$.



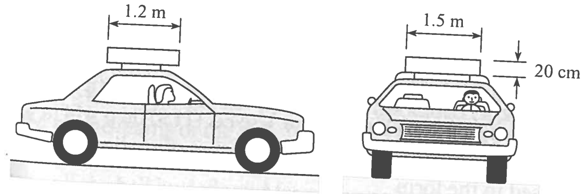
PROBLEM 11.31

**11.32** Estimate the additional power (in kW) required for the truck when it is carrying the rectangular sign at a speed of 30 m/s over that required when it is traveling at the same speed but is not carrying the sign.



PROBLEM 11.32

**11.33** Estimate the added power (in kW) required for the car when the cartop carrier is used and the car is driven at 100 km/h in a 25 km/h headwind over that required when the carrier is not used in the same conditions.



PROBLEM 11.33

**11.34** The resistance to motion of an automobile consists of rolling resistance and aerodynamic drag. The weight of an automobile is 13,350 N, and it has a frontal area of 1.86 m$^2$. The drag coefficient is 0.30, and the coefficient of rolling friction is 0.02. Determine the percentage savings in gas mileage that one achieves when one drives at 90 km/h instead of 105 km/h on a level road. Assume an air temperature of 15°C.

**11.35** A car coasts down a very long hill. The weight of the car is 8900 N, and the slope of the grade is 6%. The rolling friction coefficient is 0.01. The frontal area of the car is 1.67 m$^2$, and the drag coefficient is 0.29. The density of the air is 1.03 kg/m$^3$. Find the maximum coasting speed of the car in km/h.

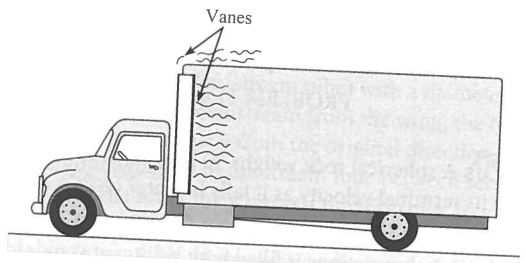
**11.36** An automobile with a mass of 1000 kg is driven up a hill where the slope is 3° (5.2% grade). The automobile is moving at 30 m/s. The coefficient of rolling friction is 0.02, the drag coefficient is 0.4, and the cross-sectional area is 4 m$^2$. Find the power (in kW) needed for this condition. The air density is 1.2 kg/m$^3$.

**11.37** A bicyclist is coasting down a hill with a slope of 4° into a headwind (measured with respect to the ground) of 7 m/s. The mass of the cyclist and bicycle is 80 kg, and the coefficient of rolling friction is 0.02. The drag coefficient is 0.5, and the projected area is 0.5 m$^2$. The air density is 1.2 kg/m$^3$. Find the speed of the bicycle in meters per second.

**11.38** A bicyclist is capable of delivering 275 W of power to the wheels. How fast can the bicyclist travel in a 3 m/s headwind if his or her projected area is 0.5 m$^2$, the drag coefficient is 0.3, and the air density is 1.2 kg/m$^3$? Assume the rolling resistance is negligible.

**11.39** Assume that the kilowatt power of the engine in the original 1932 Fiat Balillo (see Table 11.2 on p. 433 of §11.10) was 30 brake kW and that the maximum speed at sea level was 100 km/h. Also assume that the projected area of the automobile is 2.8 m$^2$. Assume that the automobile is now fitted with a modern 164 brake kW motor with a weight equal to the weight of the original motor; thus the rolling resistance is unchanged. What is the maximum speed of the "souped-up" Balillo at sea level?

**11.40** One way to reduce the drag of a blunt object is to install vanes to suppress the amount of separation. Such a procedure was used on model trucks in a wind-tunnel study by Kirsch and Bettes. For tests on a van-type truck, they noted that without vanes the $C_D$ was 0.78. However, when vanes were installed around the top and side leading edges of the truck body (see the figure), a 25% reduction in $C_D$ was achieved. For a truck with a projected area of 8.36 m$^2$, what reduction in drag force will be effected by installation of the vanes when the truck travels at 100 km/h? Assume standard atmospheric pressure and a temperature of 20°C.



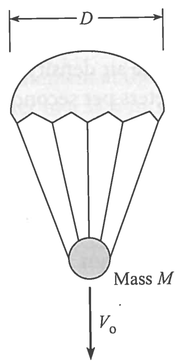
PROBLEM 11.40

**11.41** For the truck of Prob. 11.40, assume that the total resistance is given by $R = F_D + C$, where $F_D$ is the air drag and $C$ is the resistance due to bearing friction. If $C$ is constant at 350 N for the given truck, what fuel-savings percentage will be effected by the installation of the vanes when the truck travels at 100 km/h?

## Terminal Velocity (§11.4)

**11.42** Suppose you are designing an object to fall through seawater with a terminal velocity of exactly 1 m/s. What variables will have the most influence on the terminal velocity? List these variables and justify your decisions.

**11.43** WILEY PLUS As shown, a 35-cm-diameter emergency medicine parachute supporting a mass of 20 g is falling through air (20°C). Assume a coefficient of drag of $C_D = 2.2$, and estimate the terminal velocity $V_0$. Use a projected area of $(\pi D^2)/4$.

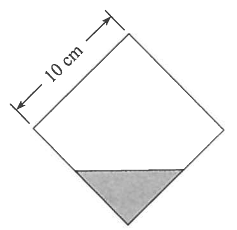



PROBLEM 11.43

**11.44** Consider a small air bubble (approximately 4 mm diameter) rising in a very tall column of liquid. Will the bubble accelerate or decelerate as it moves upward in the liquid? Will the drag of the bubble be largely skin friction or form drag? Explain.

**11.45** WILEY GO Determine the terminal velocity in water ($T = 10°C$) of a 8-cm ball that weighs 15 N in air.

**11.46** WILEY PLUS This cube is weighted so that it will fall with one edge down as shown. The cube weighs 22.2 N in air. What will be its terminal velocity in water?




PROBLEM 11.46

**11.47** WILEY PLUS A spherical rock weighs 30 N in air and 5 N in water. Estimate its terminal velocity as it falls in water (20°C).

**11.48** A spherical balloon 2 m in diameter that is used for meteorological observations is filled with helium at standard conditions. The empty weight of the balloon is 3 N. What velocity of ascent will it attain under standard atmospheric conditions?

**11.49** A sphere 2 cm in diameter rises in oil at a velocity of 1.5 cm/s. What is the specific weight of the sphere if the oil density is 900 kg/m³ and the dynamic viscosity is 0.096 N · s/m²?

**11.50** WILEY PLUS Estimate the terminal velocity of a 1.5-mm plastic sphere in oil. The oil has a specific gravity of 0.95 and a kinematic viscosity of $10^{-4}$ m²/s. The plastic has a specific gravity of 1.07. The volume of a sphere is given by $\pi D^3/6$.

**11.51** WILEY GO A 534 N skydiver is free-falling at an altitude of 1980 m. Estimate the terminal velocity in mph for minimum and maximum drag conditions. At maximum drag conditions, the product of frontal area and coefficient of drag is $C_D A = 0.743$ m². At minimum drag conditions, $C_D A = 0.0929$ m². Assume the pressure and temperature at sea level are 101 kPa abs and 15°C. To calculate air properties, use the lapse rate for the U.S. standard atmosphere (see Chapter 3).

PROBLEM 11.51

**11.52** What is the terminal velocity of a 0.5-cm hailstone in air that has an atmospheric pressure of 96 kPa absolute and a temperature of 0°C? Assume that the hailstone has a specific weight of 6 kN/m³.

**11.53** WILEY PLUS A drag chute is used to decelerate an airplane after touchdown. The chute has a diameter of 3.6 m and is deployed when the aircraft is moving at 60 m/s. The mass of the aircraft is 9000 kg, and the density of the air is 1.2 kg/m³. Find the initial deceleration of the aircraft due to the chute.

**11.54** A paratrooper and parachute weigh 900 N. What rate of descent will they have if the parachute is 7 m in diameter and the air has a density of 1.20 kg/m³?

**11.55** If a balloon weighs 0.10 N (empty) and is inflated with helium to a diameter of 60 cm, what will be its terminal velocity in air (standard atmospheric conditions)? The helium is at standard conditions.

**11.56** A 2-cm plastic ball with a specific gravity of 1.2 is released from rest in water at 20°C. Find the time and distance needed to achieve 99% of the terminal velocity. Write out the equation of motion by equating the mass times acceleration to the buoyant force, weight, and drag force and solve by developing a computer program or using available software. Use Eq. (11.9) on p. 414 in §11.3, for the drag coefficient. [*Hint:* The equation of motion can be expressed in the form

$$\frac{dv}{dt} = -\left(\frac{C_D \mathrm{Re}}{24}\right)\frac{18\mu}{\rho_b d^2}v + \frac{\rho_b - \rho_w}{\rho_b}g$$

where $\rho_b$ is the density of the ball and $\rho_w$ is the density of the water. This form avoids the problem of the drag coefficient approaching infinity when the velocity approaches zero because $C_D \mathrm{Re}/24$ approaches unity as the Reynolds number approaches zero. An "if-statement" is needed to avoid a singularity in Eq. (11.9) when the Reynolds number is zero.]



## Theory of Lift (§11.8)

**11.57** From the following list, select one topic that is interesting to you. Then, use references such as the Internet to research your topic and prepare one page of written documentation that you could use to present your topic to your peers.

a. Explain how an airplane works.
b. Describe the aerodynamics of a flying bird.
c. Explain how a propeller produces thrust.
d. Explain how a kite flies.

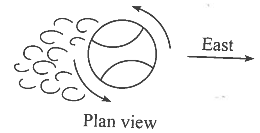
**11.58** Apply the grid method to each situation that follows.

a. Use Eq. (11.17), on p. 424 in §11.8, to predict the lift force in newtons for a spinning baseball. Use a coefficient of lift of $C_L = 1.2$. The speed of the baseball is 145 km/h. Calculate area using $A = \pi r^2$, where the radius of a baseball is $r = 37$ mm. Assume a hot summer day.
b. Use Eq. (11.17), on p. 424 in §11.8, to predict the size of wing in mm² needed for a model aircraft that has a mass of 570 g. Wing size is specified by giving the wing area ($A$) as viewed by an observer looking down on the wing. Assume the airplane is traveling at 130 km/h on a hot summer day. Use a coefficient of lift of $C_L = 1.2$. Assume straight and level flight so lift force balances weight.

**11.59** Using §11.8 and other resources, answer the following questions. Strive for depth, clarity, and accuracy. Also, use effective sketches, words, and equations.

a. What is circulation? Why is it important?
b. What is lift force?
c. What variables influence the magnitude of the lift force?

**11.60** WILEY PLUS The baseball is thrown from west to east with a spin about its vertical axis as shown. Under these conditions it will "break" toward the (a) north, (b) south, or (c) neither.

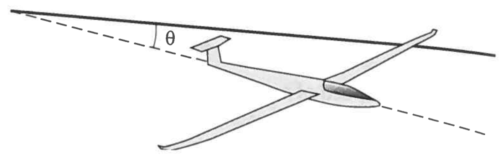



PROBLEM 11.60

**11.61** Analyses of pitched baseballs indicate that $C_L$ of a rotating baseball is approximately three times that shown in Fig. 11.18 (on p. 425 in §11.8). This greater $C_L$ is due to the added circulation caused by the seams of the ball. What is the lift of a ball pitched at a speed of 137 km/h and with a spin rate of 35 rps? Also, how much will the ball be deflected from its original path by the time it gets to the plate as a result of the lift force? *Note:* The mound-to-plate distance is 18 m, the weight of the baseball is 150 g, and the circumference is 22.5 cm. Assume standard atmospheric conditions, and assume that the axis of rotation is vertical.

## Lift and Drag on Airfoils (§11.9)

**11.62** As shown, a glider traveling at a constant velocity will move along a straight glide path that has an angle θ with respect to the horizontal. The angle θ, also called the glide ratio, is given by $\theta = (C_D/C_L)$. Use basic principles to prove the preceding statement.




PROBLEM 11.62

**11.63** WILEY PLUS A sphere of diameter 100 mm, rotating at a rate of 286 rpm, is situated in a stream of water (15°C) that has a velocity of 1.5 m/s. Determine the lift force (in newtons) on the rotating sphere.

**11.64** An airplane wing having the characteristics shown in Fig. 11.24 (on p. 429 in §11.9) is to be designed to lift 8000 N when the airplane is cruising at 60 m/s with an angle of attack of 3°. If the chord length is to be 1 m, what span of wing is required? Assume $\rho = 1.24$ kg/m³.

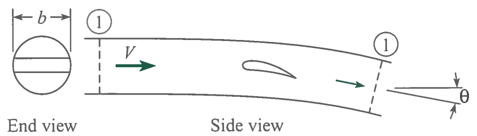
**11.65** A boat of the hydrofoil type has a lifting vane with an aspect ratio of 4 that has the characteristics shown in Fig. 11.24 (on p. 429 in §11.9). If the angle of attack is 4° and the weight of the boat is 9535 kg, what foil dimensions are needed to support the boat at a velocity of 18 m/s?

**11.66** One wing (wing A) is identical (same cross section) to another wing (wing B) except that wing B is twice as long as wing A. Then for a given wind speed past both wings and with the same angle of attack, one would expect the total lift of wing B to be (a) the same as that of wing A, (b) less than that of wing A, (c) double that of wing A, or (d) more than double that of wing A.

**11.67** What happens to the value of the induced drag coefficient for an aircraft that increases speed in level flight? (a) it increases, (b) it decreases, (c) it does not change.

**11.68** WILEY PLUS The total drag coefficient for an airplane wing is $C_D = C_{D0} + C_L^2/\pi\Lambda$, where $C_{D0}$ is the form drag coefficient, $C_L$ is the lift coefficient and $\Lambda$ is the aspect ratio of the wing. The power is given by $P = F_D V = 1/2\, C_D \rho V^3 S$. For level flight the lift is equal to the weight, so $W/S = 1/2\rho C_L V^2$, where $W/S$ is called the "wing loading." Find an expression for $V$ for which the power is a minimum in terms of $V_{\mathrm{MinPower}} = f(\rho, \Lambda, W/S, C_{D0})$, and find the $V$ for minimum power when $\rho = 1$ kg/m³, $\Lambda = 10$, $W/S = 600$ N/m², and $C_D = 0.02$.

**11.69** The airstream affected by the wing of an airplane can be considered to be a cylinder (stream tube) with a diameter equal to the wingspan, $b$. Far downstream from the wing, the tube is deflected through an angle θ from the original direction. Apply the momentum equation to the stream tube between sections 1 and 2 and find the lift of the wing as a function of $b$, $\rho$, $V$, and θ. Relating the lift to the lift coefficient, find θ as a function of $b$, $C_L$, and wing area, $S$. Using the relation for induced drag, $F_{Di} = F_L\theta/2$, show that $C_{Di} = C_L^2/\pi\Lambda$, where $\Lambda$ is the wing aspect ratio.

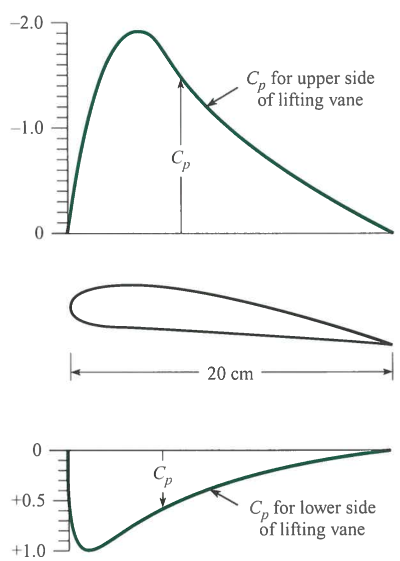



PROBLEM 11.69

**11.70** The landing speed of an airplane is 8 m/s faster than its stalling speed. The lift coefficient at landing speed is 1.2, and the maximum lift coefficient (stall condition) is 1.4. Calculate both the landing speed and the stalling speed.

**11.71** An airplane has a rectangular-planform wing that has an elliptical spanwise lift distribution. The airplane has a mass of 1000 kg, a wing area of 16 $m^2$, and a wingspan of 10 m, and it is flying at 50 m/s at 3000 m altitude in a standard atmosphere. If the form drag coefficient is 0.01, calculate the total drag on the wing and the power ($P = F_D V$) necessary to overcome the drag.

**11.72** The figure shows the relative pressure distribution for a Göttingen 387-FB lifting vane (19) when the angle of attack is 8°. If such a vane with a 20-cm chord were used as a hydrofoil at a depth of 70 cm, at what speed in 10°C freshwater would cavitation begin? Also, estimate the lift per unit of length of foil at this speed.




PROBLEM 11.72

**11.73** Consider the distribution of $C_p$ as given for the wing section in Prob. 11.72. For this distribution of $C_p$, the lift coefficient $C_L$ will fall within which range of values:
(a) $0 < C_L < 1.0$; (b) $1.01 < C_L < 2.0$; (c) $2.01 < C_L < 3.0$; or (d) $3.0 < C_L$?

**11.74** The total drag coefficient for a wing with an elliptical lift distribution is $C_D = C_{D_0} + C_L^2/\pi\Lambda$, where $\Lambda$ is the aspect ratio. Derive an expression for $C_L$ that corresponds to minimum $C_D/C_L$ (maximum $C_L/C_D$) and the corresponding $C_L/C_D$.

**11.75** WILEY PLUS A glider at 800 m altitude has a mass of 180 kg and a wing area of 20 $m^2$. The glide angle is 1.7°, and the air density is 1.2 $kg/m^3$. If the lift coefficient of the glider is 0.83, how many minutes will it take to reach sea level on a calm day?

**11.76** The wing loading on an airplane is defined as the aircraft weight divided by the wing area. An airplane with a wing loading of 2000 $N/m^2$ has the aerodynamic characteristics given by Fig. 11.25 (on p. 431 in §11.9). Under cruise conditions the lift coefficient is 0.3. If the wing area is 10 $m^2$, find the drag force.

**11.77** An ultralight airplane has a wing with an aspect ratio of 5 and with lift and drag coefficients corresponding to Fig. 11.24 (on p. 429 in §11.9). The planform area of the wing is 18.6 $m^2$. The weight of the airplane and pilot is 1800 N. The airplane flies at 15 m/s in air with a density of 1.03 $kg/m^3$. Find the angle of attack and the drag force on the wing.

**11.78** Your objective is to design a human-powered aircraft using the characteristics of the wing in Fig. 11.24 (on p. 429 in §11.9). The pilot weighs 600 N and is capable of outputting 373 W of continuous power. The aircraft without the wing has a weight of 180 N, and the wing can be designed with a weight of 5.7 $N/m^2$ of wing area. The drag consists of the drag of the structure plus the drag of the wing. The drag coefficient of the structure, $C_{D0}$ is 0.05, so that the total drag on the craft will be

$$F_D = (C_{D_0} + C_D)\frac{1}{2}\rho V_0^2 S$$

where $C_D$ is the drag coefficient from Fig. 11.24 (on p. 429 in §11.9). The power required is equal to $F_D V_0$. The air density is 1.23 $kg/m^3$. Assess whether the airfoil is adequate, and if it is, find the optimum design (wing area and aspect ratio).

# COMPRESSIBLE FLOW 12

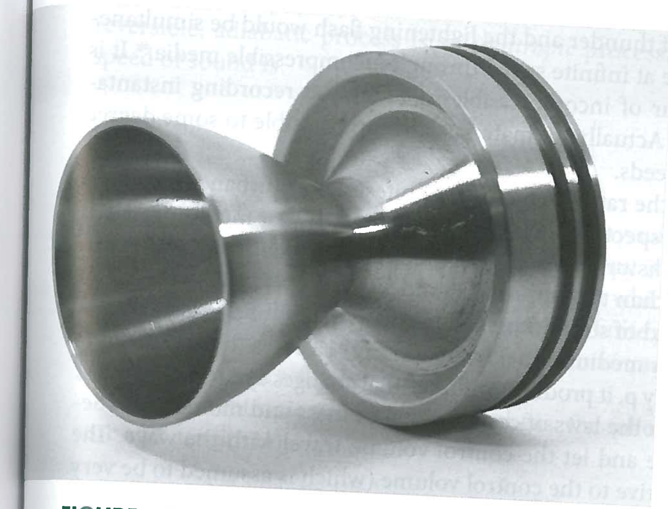


**FIGURE 12.1**
The de Laval nozzle is used to accelerate a gas to supersonic speeds. This nozzle is used in turbines, rocket engines, and supersonic jet engines.

This particular nozzle was designed by Andrew Donelick under the guidance of Dr. John Crepeau, Professor of Mechanical Engineering at the University of Idaho. The nozzle was built by Russ Porter, also at the University of Idaho. (Photo by Donald Elger.)

## Chapter Road Map

The compressibility effects in gas flows become significant when the Mach number exceeds 0.3. The performance of high-speed aircraft, the flow in rocket nozzles, and the reentry mechanics of spacecraft require inclusion of compressible flow effects. This chapter introduces topics in compressible flow.

## Learning Objectives

STUDENTS WILL BE ABLE TO

- Describe the propagation of a sound wave. (§12.1)
- Explain the significance of the Mach number. (§12.1)
- Calculate the speed of sound and Mach number. (§12.1)
- Describe how pressure and temperature vary for flow along a streamline in compressible flow. (§12.2)
- Describe a normal shock wave. (§12.3)
- Calculate property change across a normal shock wave. (§12.3)
- In a de Laval nozzle, describe how flow properties vary. Also, calculate the mass flow rate and Mach number. (§12.4).

## 12.1 Wave Propagation in Compressible Fluids

Wave propagation in a fluid is the mechanism through which the presence of boundaries is communicated to the flowing fluid. In a liquid the propagation speed of the pressure wave is much higher than the flow velocities, so the flow has adequate time to adjust to a change in boundary shape. Gas flows, on the other hand, can achieve speeds that are comparable to and even exceed the speed at which pressure disturbances are propagated. In this situation, with compressible fluids, the propagation speed is an important parameter and must be incorporated into the flow analysis. In this section it will be shown how the speed of an