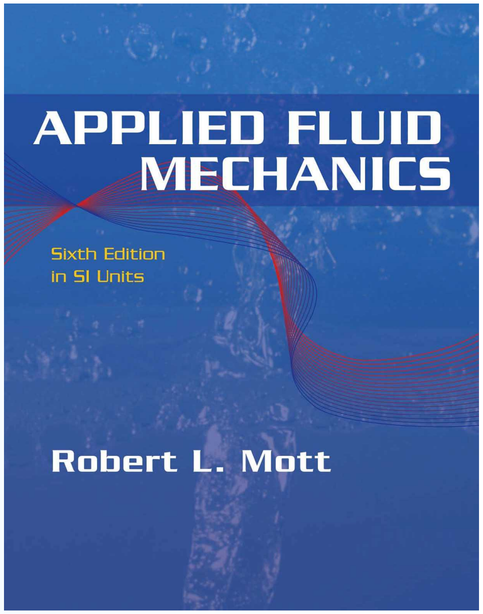
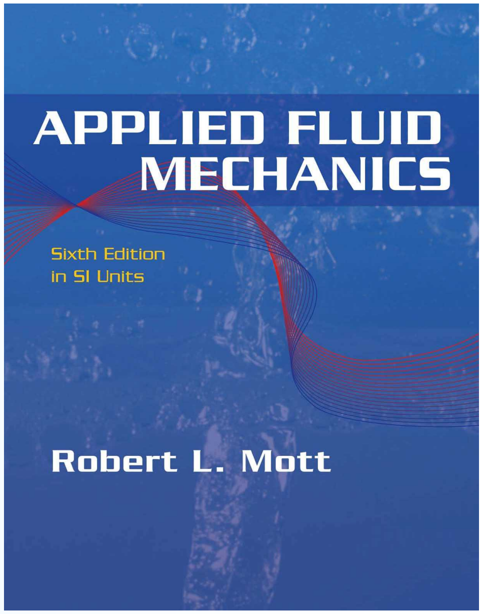
Applied Fluid Mechanics



1. The Nature of Fluid and the Study of Fluid Mechanics
2. Viscosity of Fluid
3. Pressure Measurement
4. Forces Due to Static Fluid
5. Buoyancy and Stability
6. Flow of Fluid and Bernoulli's Equation
7. General Energy Equation
8. Reynolds Number, Laminar Flow, Turbulent Flow and Energy Losses Due to Friction

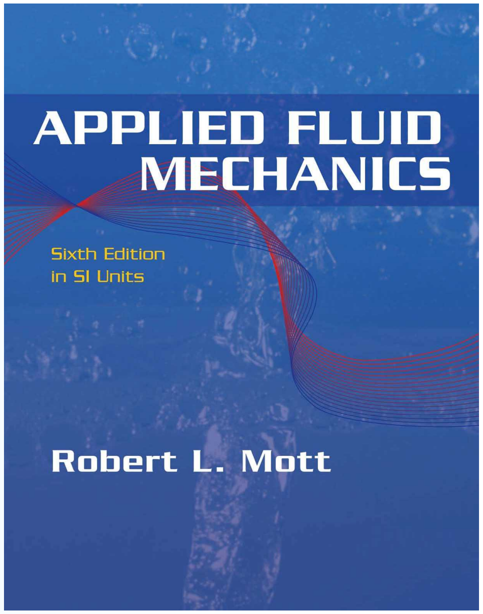
Applied Fluid Mechanics



9. Velocity Profiles for Circular Sections and Flow in Noncircular Sections
10. Minor Losses
11. Series Pipeline Systems
12. Parallel Pipeline Systems
13. Pump Selection and Application
14. Open-Channel Flow
15. Flow Measurement
16. Forces Due to Fluids in Motion

Applied Fluid Mechanics

17. Drag and Lift
18. Fans, Blowers, Compressors and the Flow of Gases
19. Flow of Air in Ducts



17. Drag and Lift

Chapter Objectives

- Define *drag*.
- Define *lift*.
- Write the expression for computing the drag force on a body moving relative to a fluid.
- Define the *drag coefficient*.
- Define the term *dynamic pressure*.
- Describe the stagnation point for a body moving relative to a fluid.
- Distinguish between *pressure drag* and *friction drag*.
- Discuss the importance of flow separation on pressure drag.
- Determine the value of the pressure drag coefficient for cylinders, spheres, and other shapes.
- Discuss the effect of Reynolds number and surface geometry on the drag coefficient.

17. Drag and Lift

Chapter Objectives

- Compute the magnitude of the pressure drag force on bodies moving relative to a fluid.
- Compute the magnitude of the friction drag force on smooth spheres.
- Discuss the importance of drag on the performance of ground vehicles.
- Discuss the effects of compressibility and cavitation on drag and the performance of bodies immersed in fluids.
- Define the lift coefficient for a body immersed in a fluid.
- Compute the lift force on a body moving relative to a fluid.
- Describe the effects of friction drag, pressure drag, and induced drag on airfoils.

17. Drag and Lift

Chapter Outline

1. Introductory Concepts
2. Drag Force Equation
3. Pressure Drag
4. Drag Coefficient
5. Friction Drag on Spheres in Laminar Flow
6. Vehicle Drag
7. Compressibility Effects and Cavitation
8. Lift and Drag on Airfoils

17. Drag and Lift

17.1 Introductory Concepts

- A moving body immersed in a fluid experiences forces caused by the action of the fluid.
- *Drag* is the force on a body caused by the fluid that resists motion in the direction of travel of the body.
- *Lift* is a force caused by the fluid in a direction perpendicular to the direction of travel of the body.
- The study of the performance of bodies in moving air streams is called *aerodynamics*.
- *Hydrodynamics* is the name given to the study of moving bodies immersed in liquids, particularly water.

17.2 Drag Force Equation

- Drag forces are usually expressed in the form

$$F_D = \text{drag} = C_D(\rho v^2/2)A \qquad (17\text{–}1)$$

- C_D is the *drag coefficient*. It is a dimensionless number that depends on the shape of the body and its orientation relative to the fluid stream.
- The combined term $\rho v^2/2$is called the *dynamic pressure*.

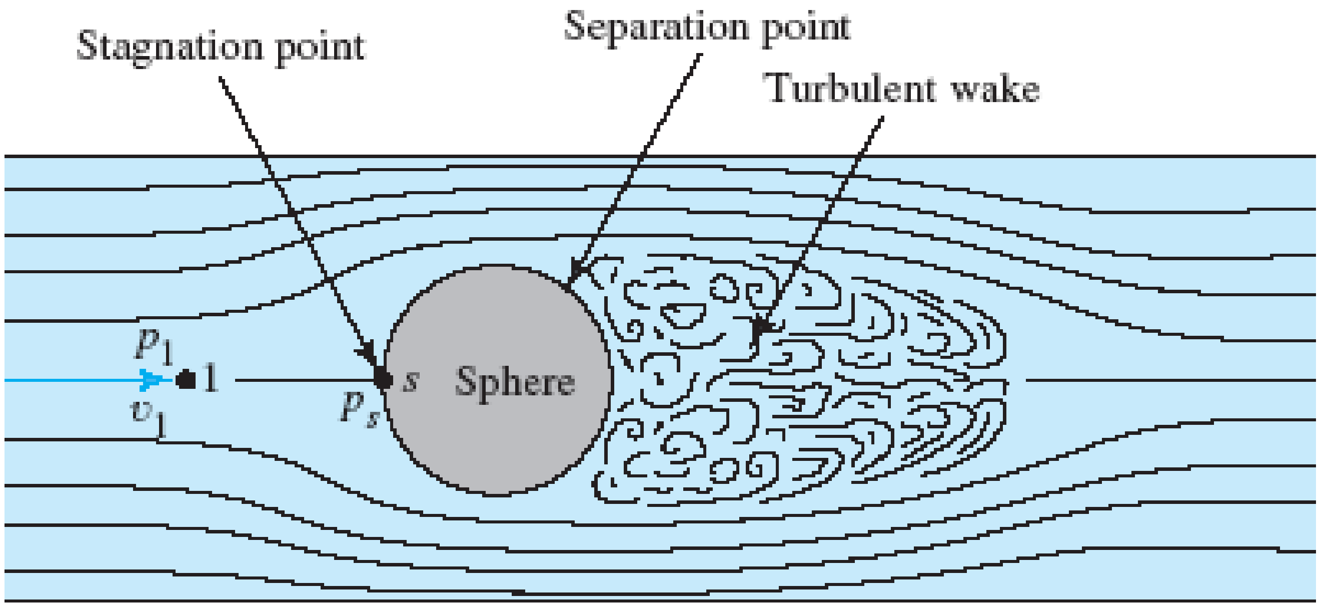
17.2 Drag Force Equation

- You can visualize the influence of the dynamic pressure on drag by referring to Fig. 17.1, which shows a sphere in a fluid stream.
- The relationship between the pressure and that in the undisturbed stream at point 1 can be found using Bernoulli's equation along a streamline:

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} = \frac{p_s}{\gamma} \qquad (17\text{–}2)$$

17. Drag and Lift

17.2 Drag Force Equation



17.2 Drag Force Equation

- Solving for p_s we get

$$p_s = p_1 + \gamma v_1^2/2g$$

- Because ρ = γg we have

$$p_s = p_1 + \rho v_1^2/2 \qquad (17\text{–}3)$$

- The stagnation pressure is greater than the static pressure in the free stream by the magnitude of the dynamic pressure.
- The kinetic energy of the moving stream is transformed into a kind of potential energy in the form of pressure.

17. Drag and Lift

17.2 Drag Force Equation

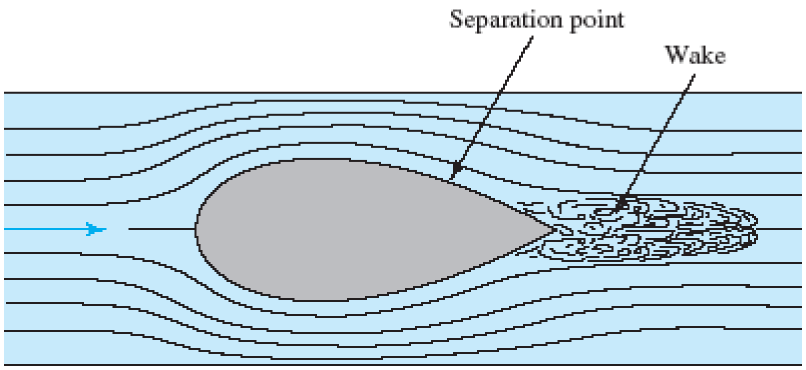
- The total drag on a body is due to two components.
- *Pressure drag* (also called *form drag*) is due to the disturbance of the flow stream as it passes the body, creating a turbulent wake.
- *Friction drag* is due to shearing stresses in the thin layer of fluid near the surface of the body called the *boundary layer*.

17.3 Pressure Drag

- As a fluid stream flows around a body, it tends to adhere to the surface for a portion of the length of the body.
- Then at a certain point, the thin boundary layer separates from the surface, causing a turbulent wake to be formed (see Fig. 17.1).
- The pressure in the wake is significantly lower than that at the stagnation point at the front of the body.
- A net force is thus created that acts in a direction opposite to that of the motion.
- This force is the pressure drag.

17.3 Pressure Drag

- The pressure drag force is calculated from Eq. (17–1) in which A *is taken to be the maximum cross-sectional area of the body perpendicular to the flow*.
- The coefficient C_D is the pressure drag coefficient.
- Figure 17.2 illustrates the change in the wake caused by the elongation and tapering of the tail of the body.



17.3.1 Properties of Air

- Drag on bodies moving in air is often the goal for drag analysis.
- To use Eq. (17–1) to calculate the drag forces, we need to know the density of the air.
- As with all gases, the properties of air change drastically with temperature.
- In addition, as altitude above sea level increases, the density decreases.

17.4 Drag Coefficient

- The magnitude of the drag coefficient for pressure drag depends on many factors, most notably the shape of the body, the Reynolds number of the flow, the surface roughness, and the influence of other bodies or surfaces in the vicinity.

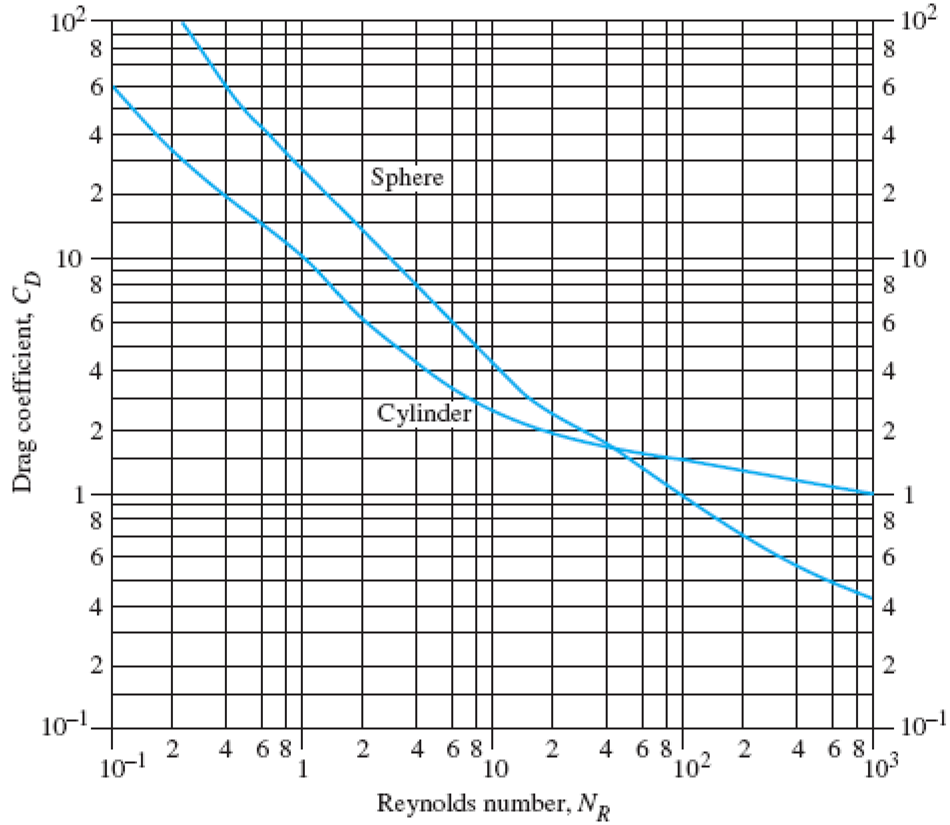
17.4.1 Drag Coefficient for Spheres and Cylinders

- Data plotted in Fig. 17.3 give the value of the drag coefficient versus Reynolds number for *smooth* spheres and cylinders.
- For spheres and cylinders, the Reynolds number is computed from the familiar-*looking* relation

$$N_R = \frac{\rho v D}{\mu} = \frac{vD}{\nu} \qquad (17\text{–}4)$$

17. Drag and Lift

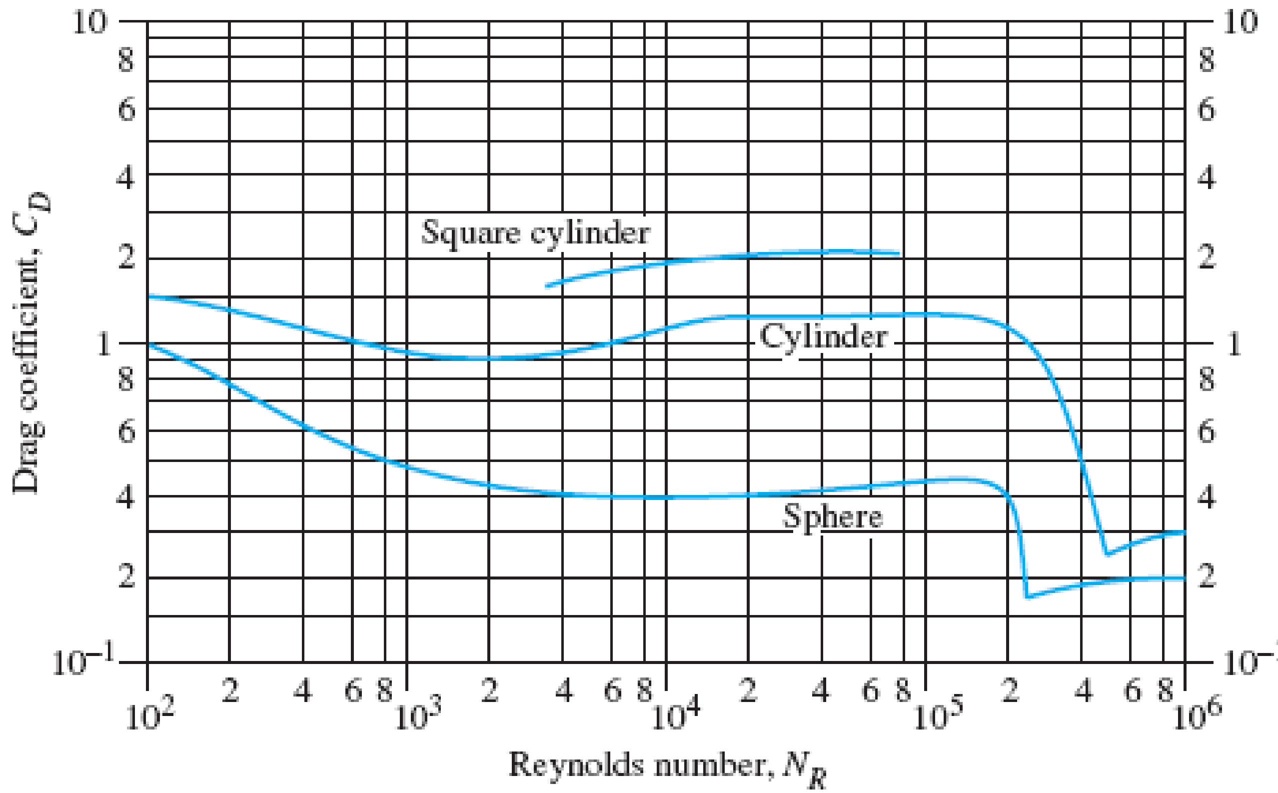
17.4.1 Drag Coefficient for Spheres and Cylinders



(a) C_D vs. N_R for lower values of N_R

17. Drag and Lift

17.4.1 Drag Coefficient for Spheres and Cylinders

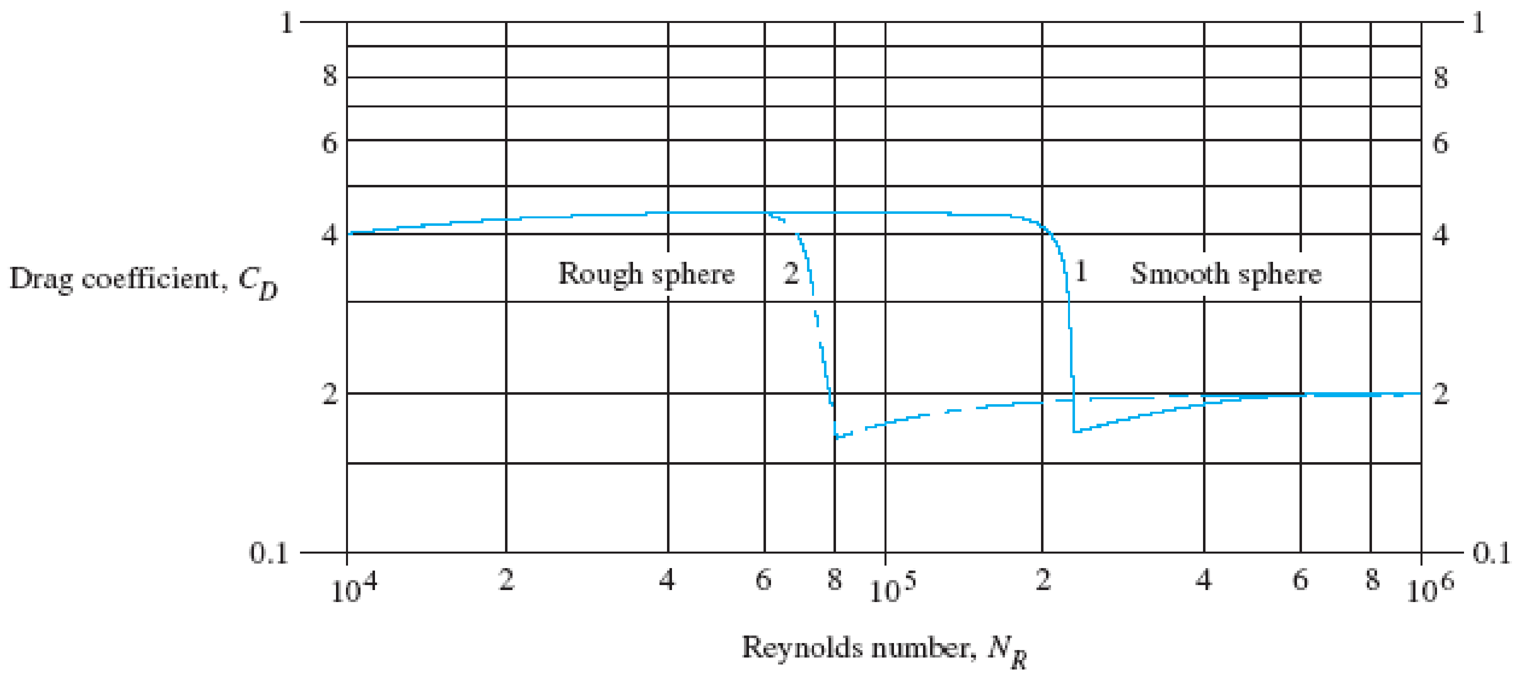


(b) C_D vs. N_R for higher values of N_R

17.4.1 Drag Coefficient for Spheres and Cylinders

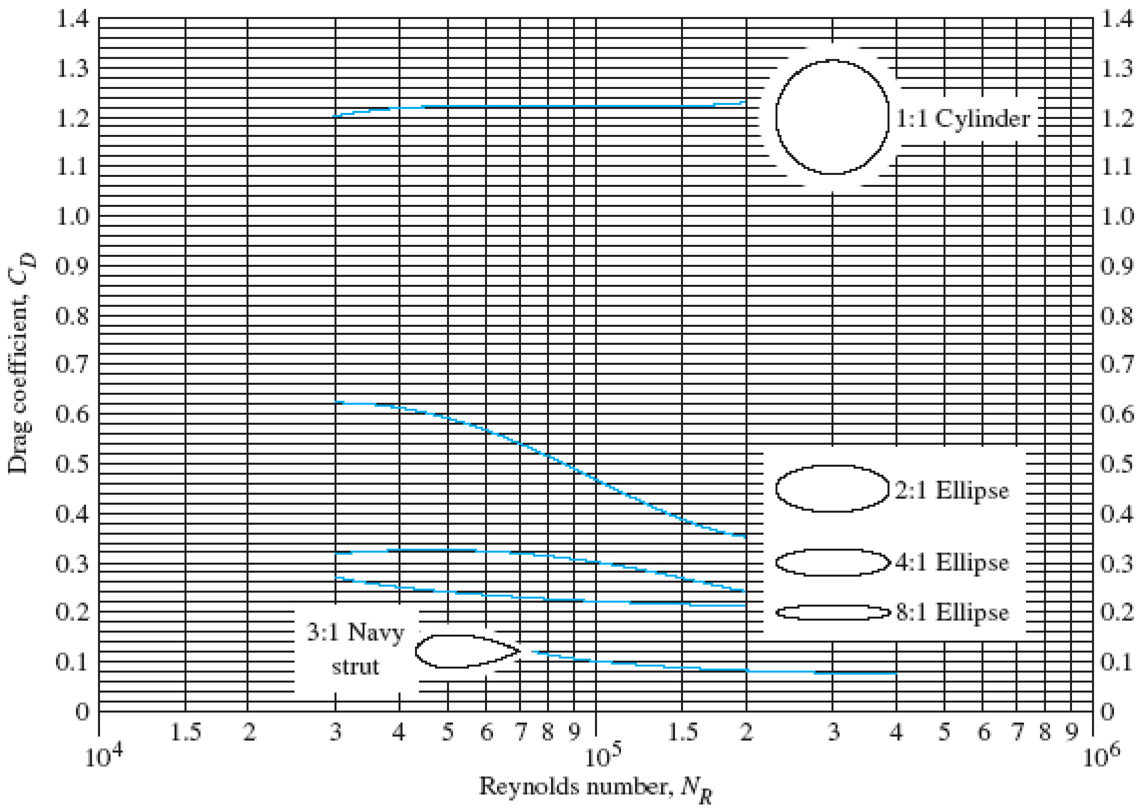
- Either roughening the surface or increasing the turbulence in the flow stream can decrease the value of the Reynolds number at which the transition from a laminar to a turbulent boundary layer occurs, as illustrated in Fig. 17.4.
- This graph is meant to show typical curve shapes only and should not be used for numerical values.

17.4.1 Drag Coefficient for Spheres and Cylinders



17.4.2 Drag Coefficient for Other Shapes

- Fig 17.5 shows the drag coefficients for elliptical cylinders and struts.

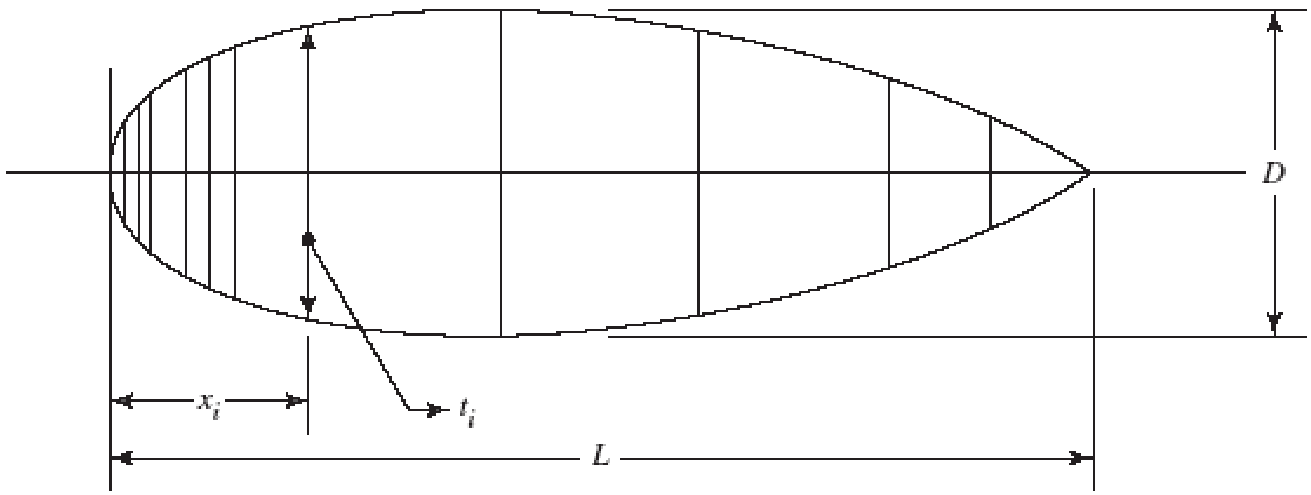


17.4.2 Drag Coefficient for Other Shapes

- Even more reduction in drag coefficient can be made with the familiar “teardrop” shape, also shown in Fig. 17.5.
- This is a standard shape called a *Navy strut,* which has values for C_D in the range of 0.07–0.11.
- Figure 17.6 shows the strut geometry.
- The computation of the Reynolds number for the shapes shown in Table 17.1 uses the *length of the body parallel to the flow* as the characteristic dimension for the body.

17. Drag and Lift

17.4.2 Drag Coefficient for Other Shapes



x/L	0.00	.0125	.025	.040	.075	.100	.125	.200
t/D	0.00	.260	.371	.525	.630	.720	.785	.911

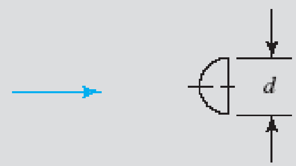
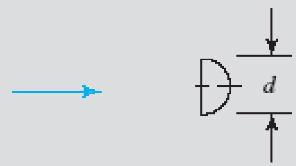
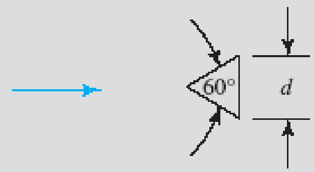
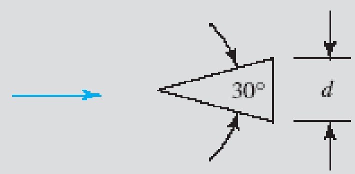
x/L	.400	.600	.800	.900	1.00
t/D	.995	.861	.562	.338	0.00

17. Drag and Lift

17.4.2 Drag Coefficient for Other Shapes

Shape of body	Orientation		C_D
Square cylinder	Flow		1.60
Semitubular cylinders			1.12
			2.30
Triangular cylinders	30°		1.05
	30°		1.85
			1.39
	60°		2.20
			1.60
	90°		2.15
			1.75
	120°		2.05
Rectangular plate	Flow	a/b	
		1	1.16
		4	1.17
		8	1.23
		12.5	1.34
		25	1.57
		50	1.76
		∞	2.00
Tandem disks L = spacing d = diameter		L/d	
		1	0.93
		1.5	0.78
		2	1.04
		3	1.52
One circular disk			1.11
Cylinder L = length d = diameter		L/d	
		1	0.91
		2	0.85
		4	0.87
		7	0.99

17.4.2 Drag Coefficient for Other Shapes

Shape of body	Orientation	C_D
Hemispherical cup, open back		0.41
Hemispherical cup, open front		1.35
Cone, closed base		0.51
		0.34

Note: Reynolds numbers are typically from 10^4 to 10^5 and are based on the length of the body parallel to the flow direction, except for the semitubular cylinders, for which the characteristic length is the diameter.

Source: Data adapted from Avallone, Eugene A., and Theodore Baumeister III, eds. 1987. *Marks' Standard Handbook for Mechanical Engineers*, 9th ed. New York: McGraw-Hill, Table 4; and Lindsey, W. F. 1938. *Drag of Cylinders of Simple Shapes* (Report No. 619). National Advisory Committee for Aeronautics.

17.4.2 Drag Coefficient for Other Shapes

- The formula then becomes

$$N_R = \frac{\rho v L}{\mu} = \frac{v L}{\nu} \tag{17–5}$$

Example 17.1

Compute the drag force on a 1.8-m square bar with a cross section of 0.1 m x 0.1 m when the bar is moving at 1.2 m/s through water at 5°C. The long axis of the bar and a flat face are placed perpendicular to the flow.

We can use Eq. (17–1) to compute the drag force:

$$F_D = C_D(\rho v^2/2)A$$

Figure 17.3 shows that the drag coefficient depends on the Reynolds number found from Eq. (17-5):

$$N_R = \frac{vL}{\nu}$$

Example 17.1

Then

$$N_R = \frac{(1.2 \text{ m/s})(0.1 \text{ m})}{1.52 \times 10^{-6} \text{ m}^2/s} = 7.9 \times 10^4$$

Then, the drag coefficient C_D = 2.05. The maximum area perpendicular to the flow, *A*, can now be computed. *A* can also be described as the projected area seen if you look directly at the bar. In this case, then, the bar is a rectangle 0.1 m high and 1.8 m long. That is,

$$A = (0.1 \text{ m})(1.8 \text{ m}) = 0.18 \text{ m}^2$$

Example 17.1

We can now compute the drag force:

$$F_D = (2.05)(\tfrac{1}{2})(1000\ \text{kg/m}^3)(1.2\ \text{m/s})^2(0.18\ \text{m}^2) = 265.7\ \text{N}$$

17. Drag and Lift

17.5 Friction Drag on Spheres in Laminar Flow

- A special method of analysis is used for computing friction drag for spheres moving at low velocities in a viscous fluid, which results in very low Reynolds numbers.
- An important application of this phenomenon is the *falling-ball viscometer*.
- The general form of the drag force equation is

$$F_D = C_D\left(\frac{\rho v^2}{2}\right)A$$

17.5 Friction Drag on Spheres in Laminar Flow

- After reduction

$$C_D = \frac{24}{N_R} = \frac{24\mu}{vD\rho}$$

- Then, the drag force becomes

$$F_D = \frac{24\mu}{vD\rho}\left(\frac{\rho v^2}{2}\right)A = \frac{12\mu v A}{D} \qquad (17\text{–}6)$$

- When computing friction drag, we use the surface area of the object.

$$F_D = \frac{12\mu v A}{D} = \frac{12\mu v(\pi D^2)}{D} = 12\,\pi\mu v D \qquad (17\text{–}7)$$

17.5 Friction Drag on Spheres in Laminar Flow

- To correlate drag in the low-Reynolds-number range with that already presented in Section 17.5 dealing with pressure drag, we must redefine the area to be the maximum cross-sectional area of the sphere,

$$F_D = \frac{12\mu v A}{D}\left(\frac{12\mu v}{D}\right)\left(\frac{\pi D^2}{4}\right) = 3\pi\mu v D \qquad (17\text{–}8)$$

- This form for the drag on a sphere in a viscous fluid is commonly called *Stokes's law*.

17.6 Vehicle Drag

- Decreasing drag is a major goal in designing most kinds of vehicles because a significant amount of energy is required to overcome drag as vehicles move through fluids.
- Many factors affect the overall drag coefficient for vehicles, such as the following:

1. The shape of the forward end, or *nose*, of the vehicle
2. The smoothness of the surfaces of the body
3. Such appendages as mirrors, door handles, antennas, and so forth

17.6.1 Automobiles

- The basic principles of drag reduction for automobiles include providing rounded, smooth contours for the forward part; elimination or streamlining of appendages; blending of changes in contour (such as at the hood/windshield interface); and rounding of rear corners.

17. Drag and Lift

Example 17.2

A prototype automobile has an overall drag coefficient of 0.35. Compute the total drag as it moves at 25 m/s through still air at 25°C. The maximum projected frontal area is 2.50 m^2.

We will use the drag force equation:

$$F_D = C_D\left(\frac{\rho v^2}{2}\right)A$$

From Appendix E,

$$F_D = 0.35\left[\frac{(1.204)(25)^2}{2}\right](2.50) = 329\ \text{kg}\cdot\text{m/s}^2 = 329\ \text{N}$$

17.6.2 Power Required to Overcome Drag

- *Power* is defined as the rate of doing work. When a force is continuously exerted on an object while the object is moving at a constant velocity, power equals force times velocity.
- Then, the power required to overcome drag is

$$P_D = F_D v$$

Example 17.3

Assume that a tugboat has a displacement of 636 tonne (1 tonne=9.81 kN) and is moving through water at 11 m/s. Compute the total ship resistance and the total effective power required to drive the boat.

From Table 17.2, we find the specific resistance ratio to be 0.006. Then, the total ship resistance is

$$\Delta = 636 \times 9.81 \text{ kN} = 6.239 \text{ MN}$$

$$R_{ts} = (0.006)(\Delta) = (0.006)(6.239 \times 10^6 \text{ kg}) = 37.434 \text{ kN}$$

Example 17.3

The power required is

$$P_E = R_{ts}v = (37.434 \text{ kN})(11 \text{ m/s}) = 411.8 \text{ kNm/s}$$

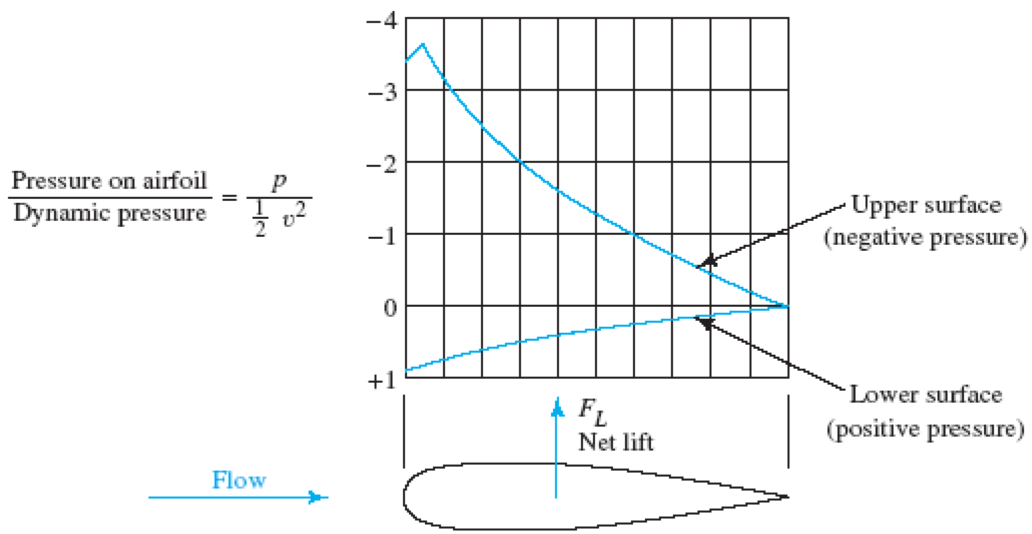
$$P_E = 412 \text{ kW}$$

17.7 Compressiblility Effects and Cavitation

- When the fluid is a liquid such as water, we do not need to consider compressibility because liquids are very slightly compressible.
- However, we must consider another phenomenon called *cavitation*.
- As the liquid flows past a body, the static pressure decreases. If the pressure becomes sufficiently low, the liquid vaporizes, forming bubbles.
- Because the region of low pressure is generally small, the bubbles burst when they leave that region.
- When the collapsing of the vapor bubbles occurs near a surface of the body, rapid erosion or pitting results.

17.8 Lift and Drag on Airfoils

- We define lift as a force acting on a body in a direction perpendicular to that of the flow of fluid.
- The manner in which an airfoil produces lift when placed in a moving air stream (or when moving in still air) is illustrated in Fig. 17.7.



17.8 Lift and Drag on Airfoils

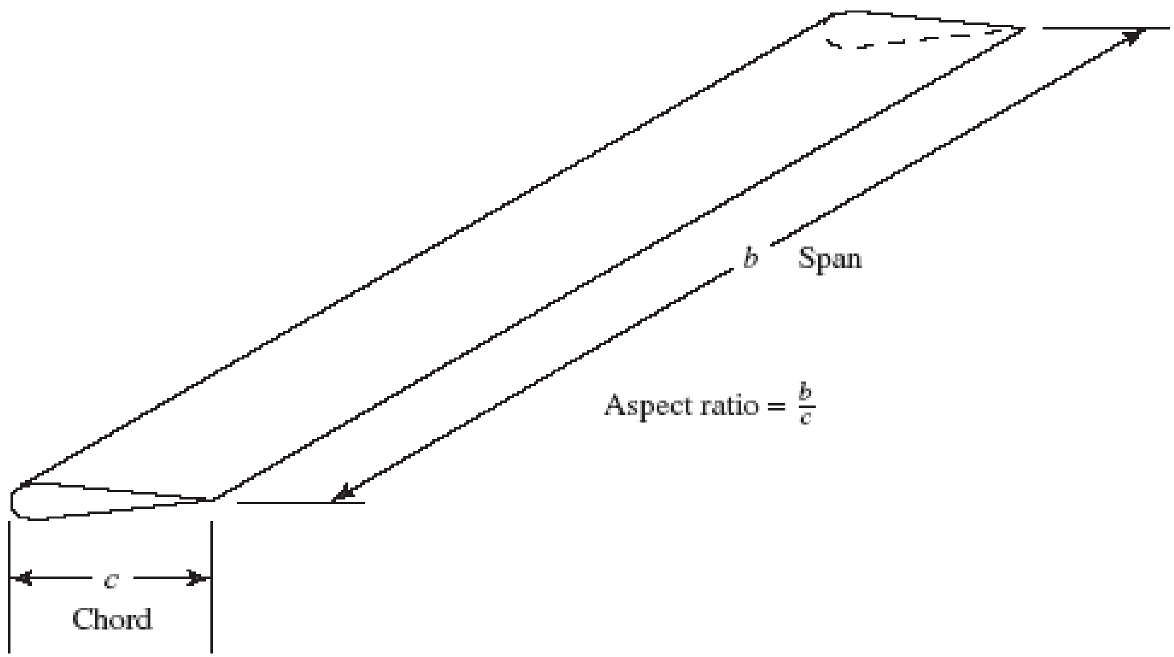
- The net result is an upward force called *lift*, the equation is as follow:

$$F_L = C_L(\rho v^2/2)A \qquad (17\text{–}10)$$

- The velocity v is the velocity of the free stream of fluid relative to the airfoil.
- To achieve uniformity in the comparison of one shape with another, we usually define the area *A* as the product of the span of the wing and the length of the airfoil section called the *chord*.

17.8 Lift and Drag on Airfoils

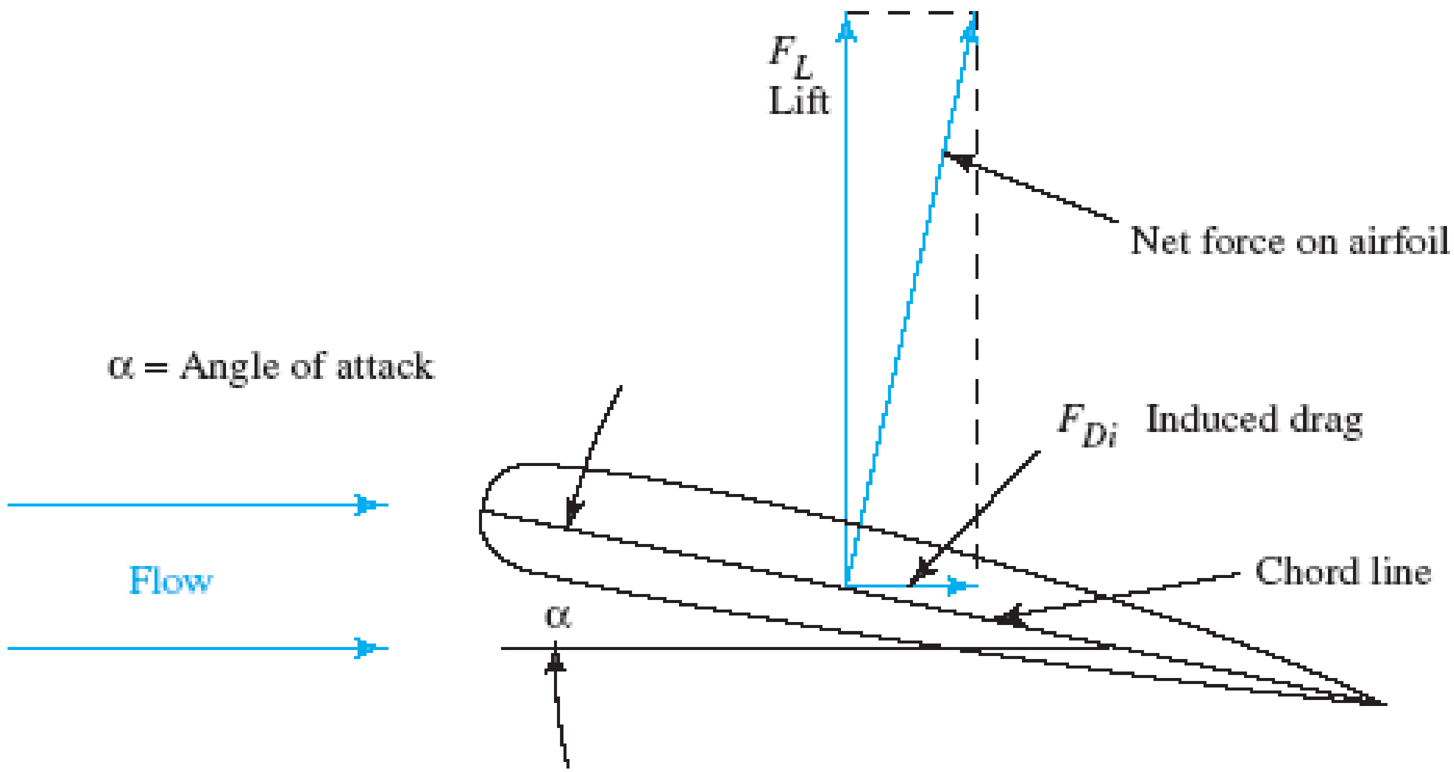
- In Fig. 17.8, the span is *b* and the chord length is *c*.



17.8 Lift and Drag on Airfoils

- Figure 17.9 shows that the angle of attack is the angle between the chord line of the airfoil and the direction of the fluid velocity.
- *Aspect ratio* is the name given to the ratio of the span b of the wing to the chord length c.
- It is important because the characteristics of the flow at the wing tips are different from those toward the center of the span.

17.8 Lift and Drag on Airfoils



17.8 Lift and Drag on Airfoils

- The total drag on an airfoil has three components.
- The third component is called *induced drag*, which is a function of the lift produced by the airfoil.
- The induced drag as a function of a drag coefficient gives

$$F_{Di} = C_{Di}(\rho v^2/2)A \qquad (17\text{–}11)$$

- It can be shown that

$$C_{Di} = \frac{C_L^2}{\pi(b/c)} \qquad (17\text{–}12)$$

17.8 Lift and Drag on Airfoils

- The total drag is then

$$F_D = F_{Df} + F_{Dp} + F_{Di} \qquad (17\text{–}13)$$

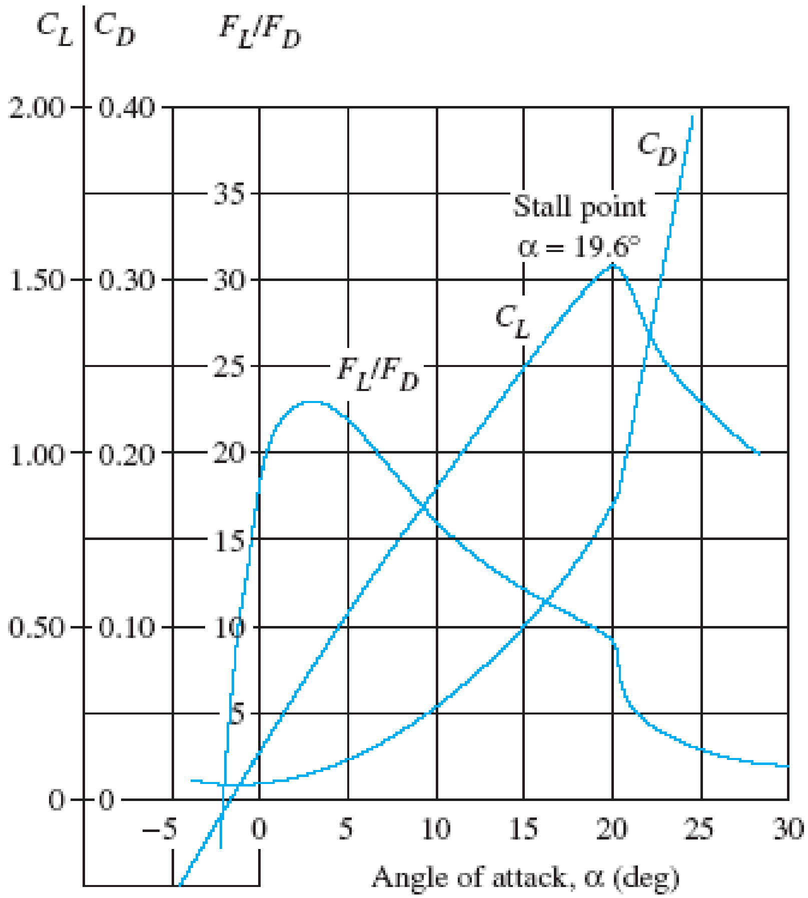
- We determine a single drag coefficient for the airfoil, from which the total drag can be calculated using the relation

$$F_D = C_D(\rho v^2/2)A \qquad (17\text{–}14)$$

- Fig 17.10 shows the airfoil performance curves.

17. Drag and Lift

17.8 Lift and Drag on Airfoils



17. Drag and Lift

17.8 Lift and Drag on Airfoils

- In both Fig. 17.10 and Fig. 17.11 it can be seen that the lift coefficient increases with increasing angle of attack up to a point where it abruptly begins to decrease.
- This point of maximum lift is called the *stall point*; at this angle of attack, the boundary layer of the air stream separates from the upper side of the airfoil.

17.8 Lift and Drag on Airfoils