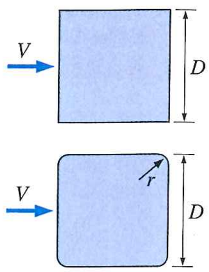
TABLE 10–1

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length in direction normal to the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

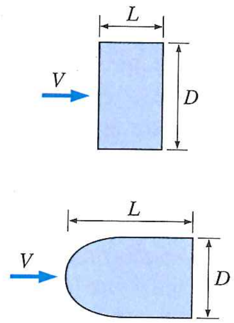
Square rod



Sharp corners: $C_D = 2.2$

Round corners ($r/D = 0.2$): $C_D = 1.2$

Rectangular rod



Sharp corners:

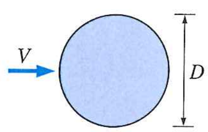
L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

* Corresponds to thin plate

Round front edge:

L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

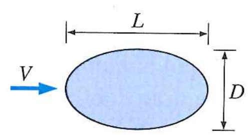
Circular rod (cylinder)



Laminar: $C_D = 1.2$

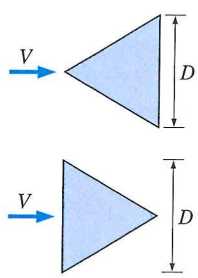
Turbulent: $C_D = 0.3$

Elliptical rod



L/D	C_D Laminar	C_D Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

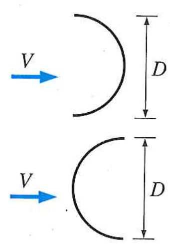
Equilateral triangular rod



$C_D = 1.5$

$C_D = 2.0$

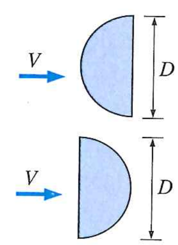
Semicircular shell



$C_D = 2.3$

$C_D = 1.2$

Semicircular rod



$C_D = 1.2$

$C_D = 1.7$

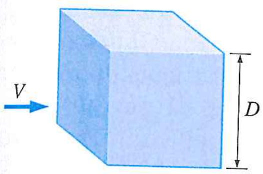
side faces the flow, but it increases threefold to 1.2 when the flat side faces the flow (Fig. 10–19).

For blunt bodies with sharp corners, such as flow over a rectangular block or a flat plate normal to flow, separation occurs at the edges of the front and back surfaces, with no significant change in the character of flow. Therefore, the drag coefficient of such bodies is nearly independent of the Reynolds number. Note that the drag coefficient of a long rectangular rod can be reduced almost by half from 2.2 to 1.2 by rounding the corners.

TABLE 10–2

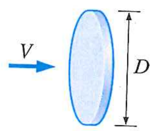
Representative drag coefficients C_D for various three-dimensional bodies for $Re > 10^4$ based on the frontal area (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Cube, $A = D^2$



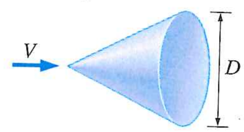
$C_D = 1.05$

Thin circular disk, $A = \pi D^2/4$



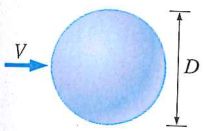
$C_D = 1.1$

Cone (for $\theta = 30°$), $A = \pi D^2/4$



$C_D = 0.5$

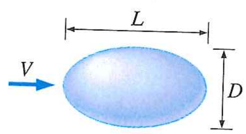
Sphere, $A = \pi D^2/4$



Laminar: $Re \lesssim 2 \times 10^5$ $C_D = 0.5$

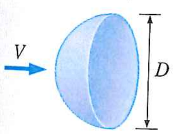
Turbulent: $Re \gtrsim 2 \times 10^6$ $C_D = 0.2$

Ellipsoid, $A = \pi D^2/4$

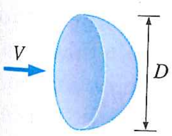


L/D	C_D Laminar $Re \lesssim 2 \times 10^5$	C_D Turbulent $Re \gtrsim 2 \times 10^6$
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

Hemisphere, $A = \pi D^2/4$

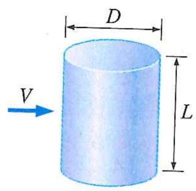


$C_D = 0.4$



$C_D = 1.2$

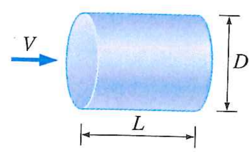
Short cylinder, vertical, $A = LD$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9
40	1.0
∞	1.2

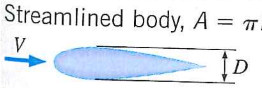
Values are for laminar flow ($Re \lesssim 2 \times 10^5$)

Short cylinder, horizontal, $A = \pi D^2/4$



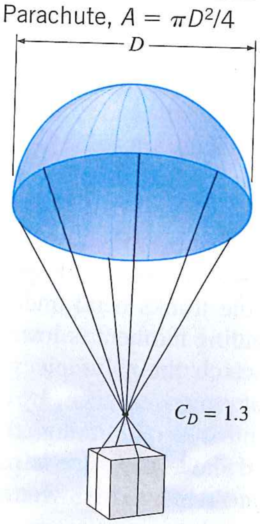
L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

Streamlined body, $A = \pi D^2/4$



$C_D = 0.04$

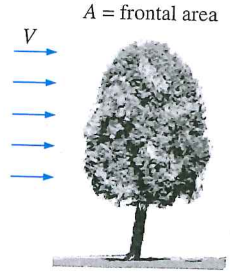
Parachute, $A = \pi D^2/4$



$C_D = 1.3$

Tree, A = frontal area

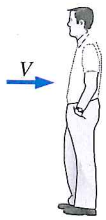
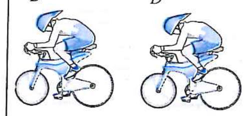
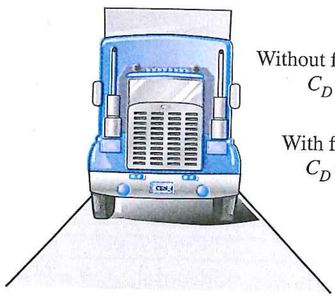
A = frontal area



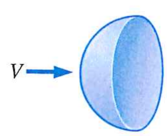
V, m/s	C_D
10	0.4–1.2
20	0.3–1.0
30	0.2–0.7

(*continues*)

TABLE 10–2 (Continued)

Person (average)	Bikes	
 Standing: C_DA = 9 ft^2 = 0.84 m^2 Sitting: C_DA = 6 ft^2 = 0.56 m^2	 Upright: $A = 5.5$ ft^2 = 0.51 m^2 $C_D = 1.1$  Racing: $A = 3.9$ ft^2 = 0.36 m^2 $C_D = 0.9$	$C_D = 0.5$ $C_D = 0.9$  Drafting: $A = 3.9$ ft^2 = 0.36 m^2 $C_D = 0.50$  With fairing: $A = 5.0$ ft^2 = 0.46 m^2 $C_D = 0.12$
Semitrailer, A = frontal area	Automotive, A = frontal area	High-rise buildings, A = frontal area
 Without fairing: $C_D = 0.96$ With fairing: $C_D = 0.76$	 Minivan: $C_D = 0.4$  Passenger car: $C_D = 0.3$	$C_D \approx 1.0$ to 1.4 

A hemisphere at two different orientations for Re > 10^4



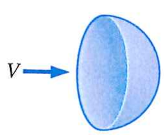


FIGURE 10–19
The drag coefficient of a body may change drastically by changing the body's orientation (and thus shape) relative to the direction of flow.

Biological Systems and Drag

The concept of drag also has important consequences for biological systems. For example, the bodies of *fish*, especially the ones that swim fast for long distances (such as dolphins), are highly streamlined to minimize drag (the drag coefficient of dolphins based on the wetted skin area is about 0.0035, comparable to the value for a flat plate in turbulent flow). So it is no surprise that we build submarines that mimic large fish. Tropical fish with fascinating beauty and elegance, on the other hand, swim short distances only. Obviously grace, not high speed and drag, was the primary consideration in their design. Birds teach us a lesson on drag reduction by extending their beak forward and folding their feet backward during flight (Fig. 10–20). Airplanes, which look somewhat like big birds, retract their wheels after takeoff in order to reduce drag and thus fuel consumption.

The flexible structure of plants enables them to reduce drag at high winds by changing their shapes. Large flat leaves, for example, curl into a low-drag conical shape at high wind speeds, while tree branches cluster to reduce drag. Flexible trunks bend under the influence of the wind to reduce drag, and the bending moment is lowered by reducing frontal area.

If you watch the Olympic games, you have probably observed many instances of conscious effort by the competitors to reduce drag. Some examples: During 100-m running, the runners hold their fingers together and straight and move their hands parallel to the direction of motion to reduce the drag on their hands. Swimmers with long hair cover their head with a tight and smooth cover to reduce head drag. They also wear well-fitting one-piece swimming suits. Horse and bicycle riders lean forward as much