# FLOW OVER BLUFF OBJECTS

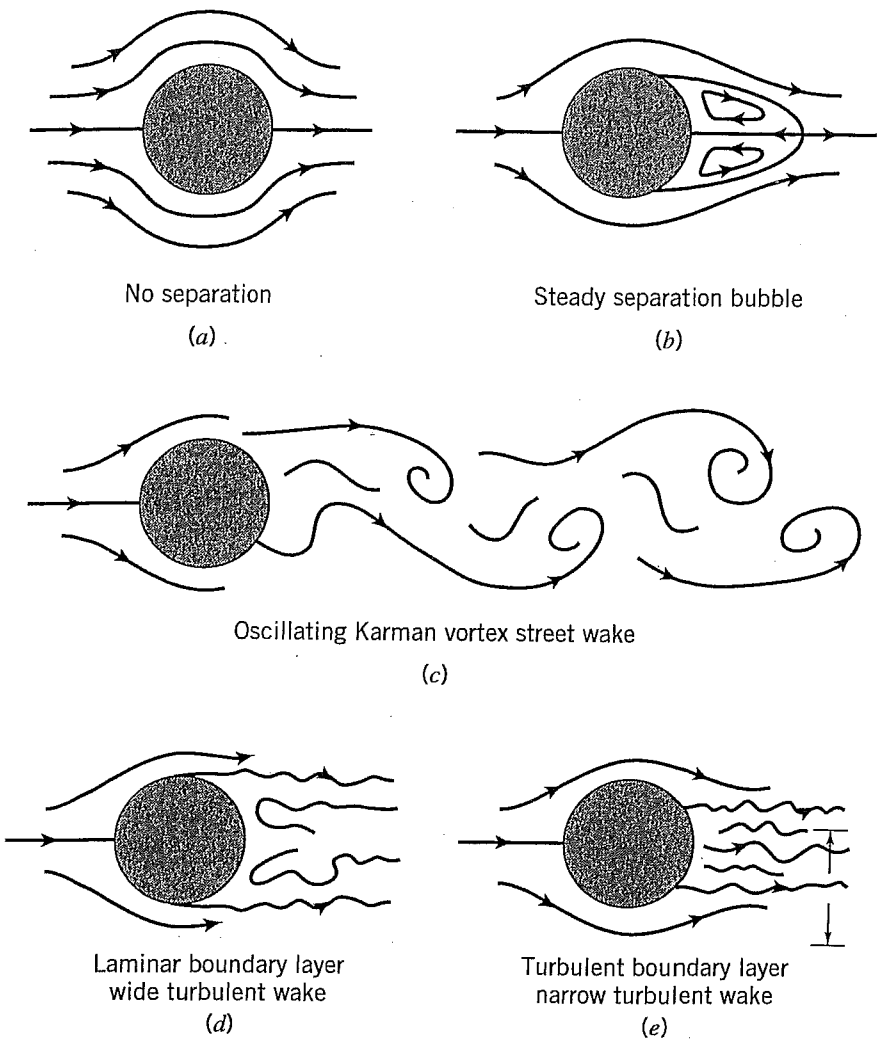



**FIGURE 10.13** Flow patterns for flow over a cylinder. (*a*) Reynolds number = 0.2; (*b*) 12; (*c*) 120; (*d*) 30,000; and (*e*) 500,000. Patterns correspond to the points marked on Figure 10.12. From Munson, Young, & Okiishi, *Fundamentals of Fluid Mechanics,* John Wiley & Sons, 1998.

## VORTEX SHEDDING

$$\text{FREQUENCY} = f(V, D, \rho, \mu)$$

$$f\frac{D}{V} = F\left(\frac{\rho V D}{\mu}\right)$$

$$f\frac{D}{V} = \text{STROUHAL NUMBER}$$

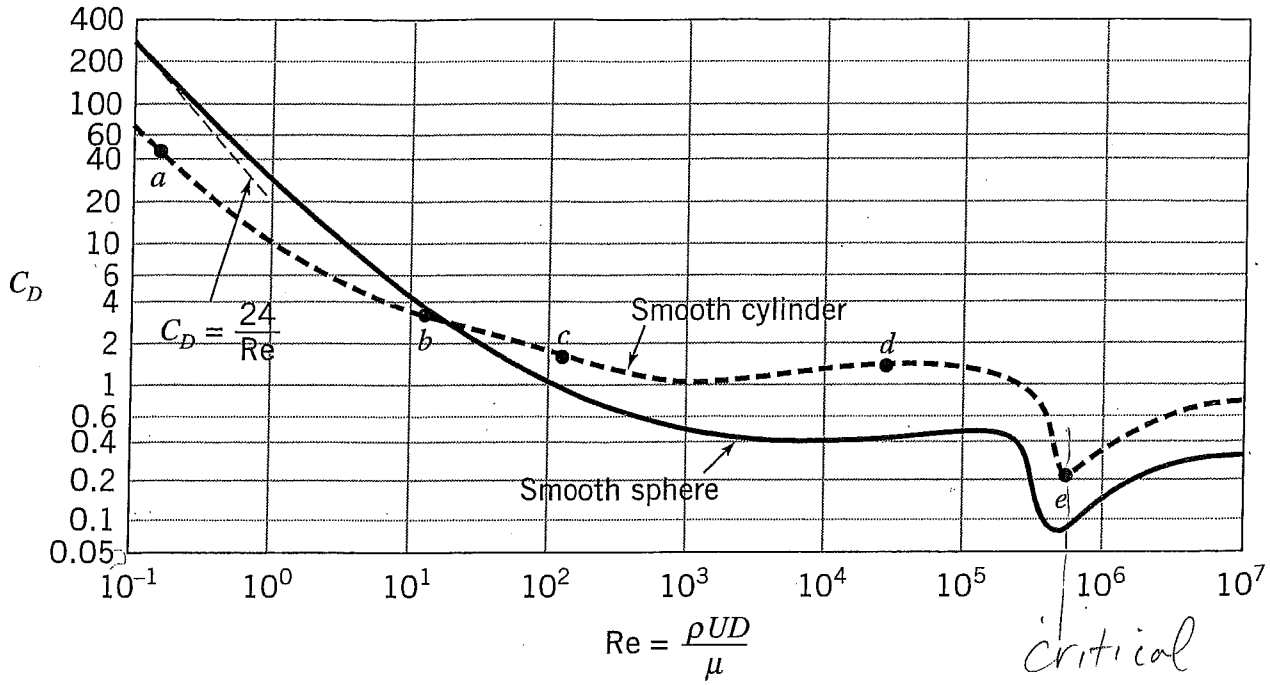



**FIGURE 10.12** Drag coefficient as a function of Reynolds number for smooth circular cylinders and smooth spheres. From Munson, Young, & Okiishi, *Fundamentals of Fluid Mechanics,* John Wiley & Sons, 1998.

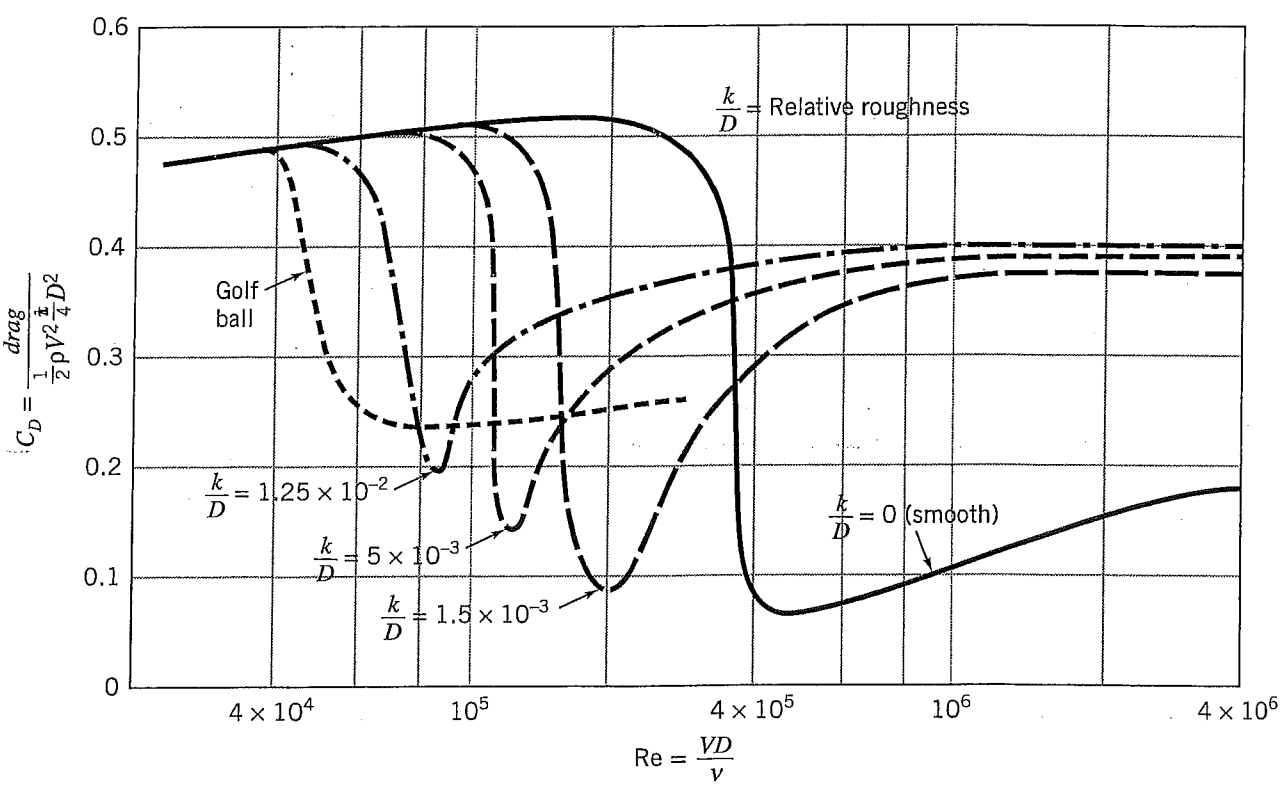



**FIGURE 10.16** Drag coefficient as a function of Reynolds number for spheres with different degrees of roughness. *k* is the equivalent roughness height, and *D* is the sphere diameter. From Munson, Young, & Okiishi, *Fundamentals of Fluid Mechanics,* John Wiley & Sons, 1998.

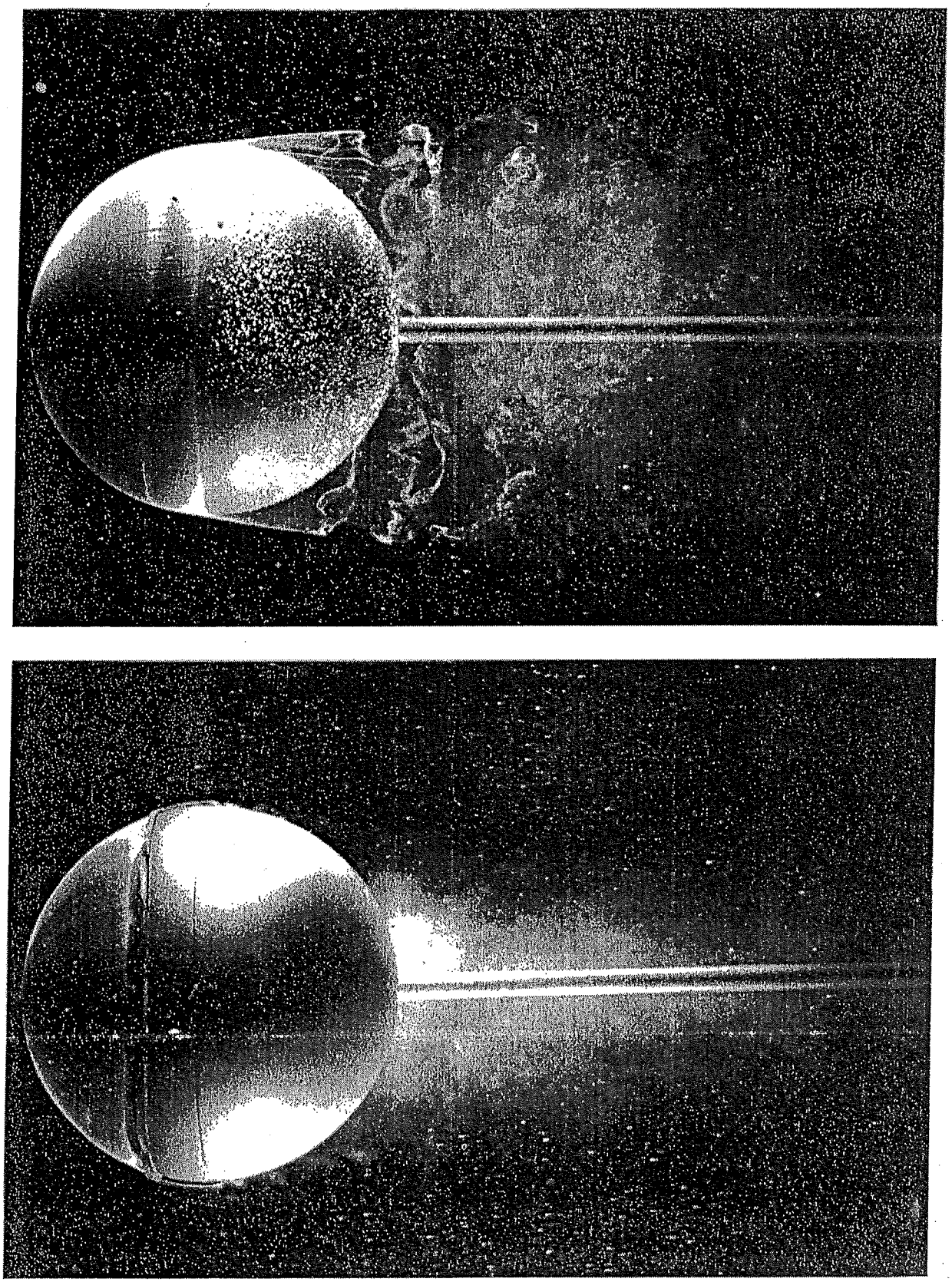


**FIGURE 10.15** Flow over a sphere. (*a*) Reynolds number = 15,000 (laminar separation). (*b*) Reynolds number = 30,000, with trip wire (turbulent separation). From Van Dyke, *Album of Fluid Motion,* Parabolic Press, 1982. Original photographs by Werlé, ONERA, 1980.

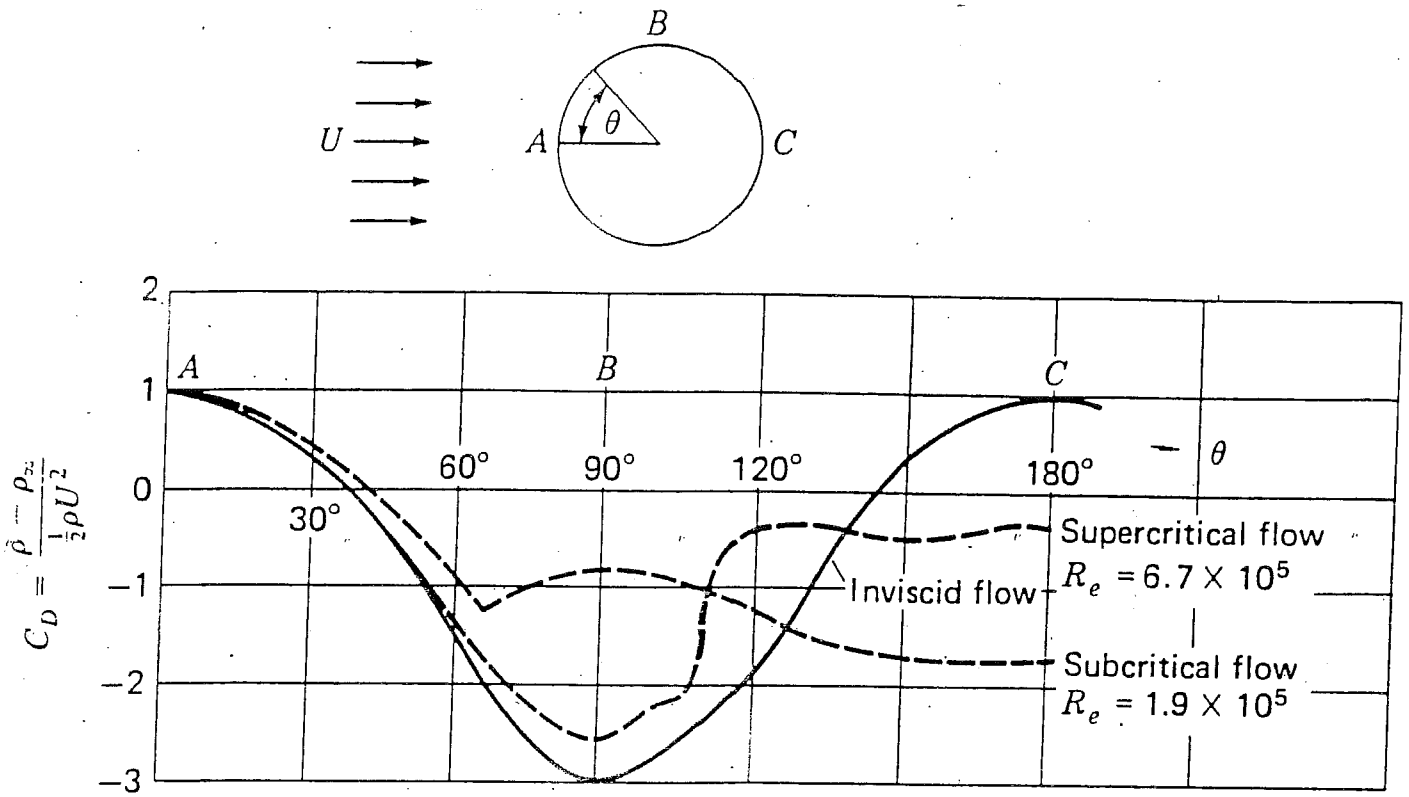
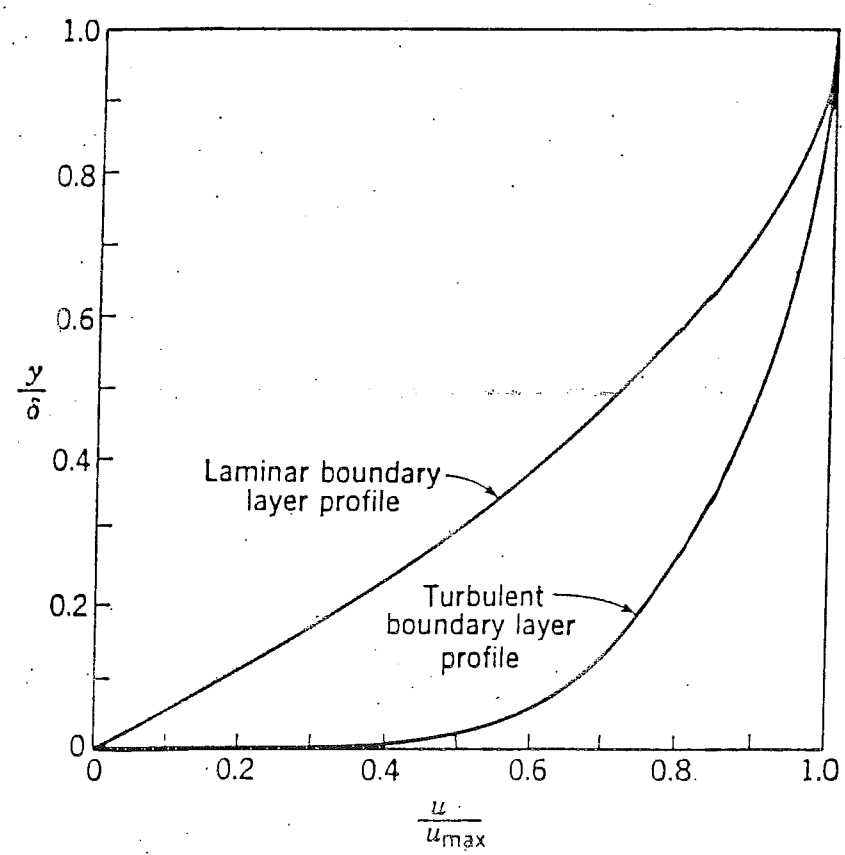



**FIGURE 13.26**
Pressure distributions around a cylinder for subcritical, supercritical, and completely inviscid flows.




TURBULENT BOUNDARY LAYER:

HIGHER SHEAR STRESS – BUT SEPARATES LATER.

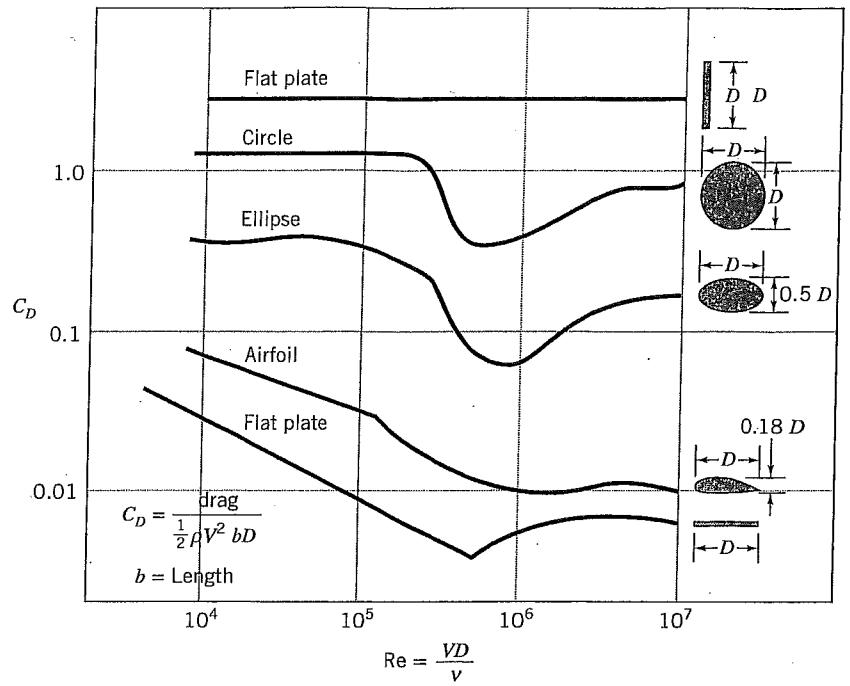
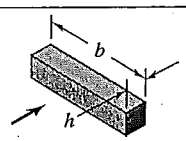
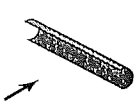
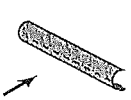



**FIGURE 10.14** Drag coefficients of bluff and streamlined bodies. From Munson, Young, & Okiishi, *Fundamentals of Fluid Mechanics,* John Wiley & Sons, 1998.

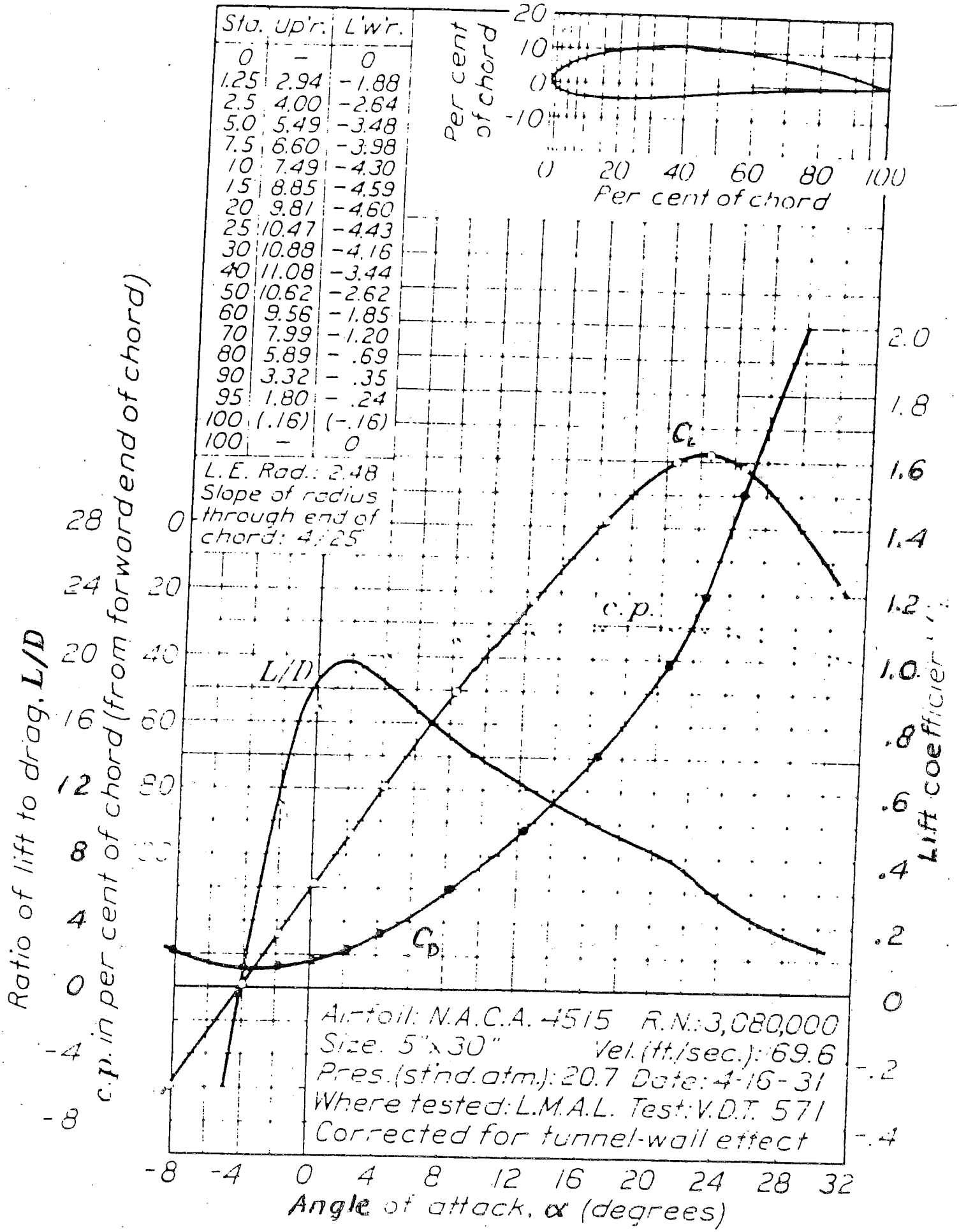
**TABLE 10.2 Drag Coefficient Data for Sharp-Edged Bodies**[a]

| Object | Diagrams | | $C_D$ ($Re \gtrsim 10^{-1}$) |
|---|---|---|---|
| Square cylinder |  | $b/h = \infty$<br>$b/h = 1$ | 2.05<br>1.05 |
| Disk | | | 1.17 |
| Ring | | | 1.20[b] |
| Hemisphere (open end facing flow) | | | 1.42 |
| Hemisphere (open end facing downstream) | | | 0.38 |
| *C*-section (open side facing flow) |  | | 2.30 |
| C-section (open side facing downstream) |  | | 1.20 |

From Fox & McDonald, *Introduction to Fluid Mechanics,* 4th edition, John Wiley & Sons, 1992.

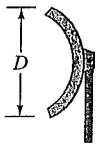
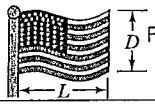
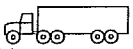
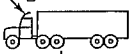
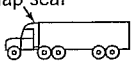
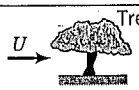
[a] Original data from Hoerner, Fluid-Dynamic Drag, 2nd edition, Midland Park, NJ, published by the author.

[b] Based on area of ring.


Sta. Up'r. L'w'r.
0 – 0
1.25 2.94 -1.88
2.5 4.00 -2.64
5.0 5.49 -3.48
7.5 6.60 -3.98
10 7.49 -4.30
15 8.85 -4.59
20 9.81 -4.60
25 10.47 -4.43
30 10.88 -4.16
40 11.08 -3.44
50 10.62 -2.62
60 9.56 -1.85
70 7.99 -1.20
80 5.89 -.69
90 3.32 -.35
95 1.80 -.24
100 (.16) (-.16)
100 – 0
L.E. Rad.: 2.48
Slope of radius through end of chord: 4.25
Per cent of chord
Per cent of chord
L/D
c.p.
$C_L$
$C_D$
Ratio of lift to drag, L/D
c.p. in per cent of chord (from forward end of chord)
Lift coefficient
Angle of attack, α (degrees)
Airfoil: N.A.C.A. 4515 R.N.: 3,080,000
Size: 5" x 30" Vel. (ft./sec.): 69.6
Pres. (stnd. atm.): 20.7 Date: 4-16-31
Where tested: L.M.A.L. Test: V.D.T. 571
Corrected for tunnel-wall effect

240

**TABLE 10.3 Drag Coefficient Data for Selected Objects**

| Shape | Reference area | Drag coefficient $C_D$ |
|---|---|---|
| Parachute | Frontal area $A = \frac{\pi}{4}D^2$ | 1.4 |
|  Porous parabolic dish | Frontal area $A = \frac{\pi}{4}D^2$ | Porosity 0 / 0.2 / 0.5<br>→ 1.42 / 1.20 / 0.82<br>← 0.95 / 0.90 / 0.80<br>Porosity = open area/total area |
| Average person | Standing<br>Sitting<br>Crouching | $C_DA = 9$ ft$^2$<br>$C_DA = 6$ ft$^2$<br>$C_DA = 2.5$ ft$^2$ |
|  Fluttering flag | $A = lD$ | $lD$ / $C_D$<br>1 / 0.07<br>2 / 0.12<br>3 / 0.15 |
| Empire State Building | Frontal area | 1.4 |
| Six-car passenger train | Frontal area | 1.8 |
| Bikes | | |
| Upright commuter | $A = 5.5$ ft$^2$ | 1.1 |
| Racing | $A = 3.9$ ft$^2$ | 0.88 |
| Drafting | $A = 3.9$ ft$^2$ | 0.50 |
| Streamlined | $A = 5.0$ ft$^2$ | 0.12 |
| Tractor-trailor trucks | | |
|  Standard | Frontal area | 0.96 |
| Fairing  With fairing | Frontal area | 0.76 |
| Gap seal  With fairing and gap seal | Frontal area | 0.70 |
|  Tree | Frontal area | $U = 10$ m/s: 0.43<br>$U = 20$ m/s: 0.26<br>$U = 30$ m/s: 0.20 |
| Dolphin | Wetted area | 0.0036 at Re = $6 \times 10^6$<br>(flat plate has $C_{Df} = 0.0031$) |
| Large birds | Frontal area | 0.40 |

SOURCE: From Munson, Young & Okiishi, *Fundamentals of Fluid Mechanics*, John Wiley & Sons, 1998.

# AUTOMOBILE AERODYNAMICS

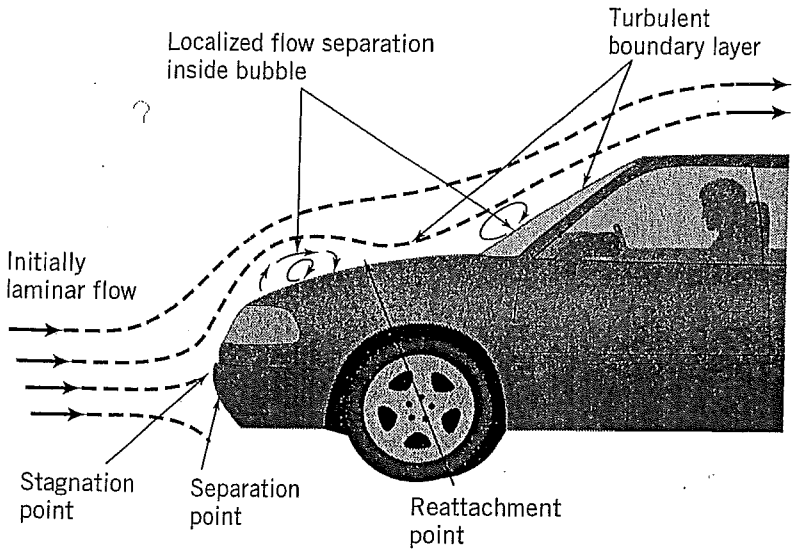
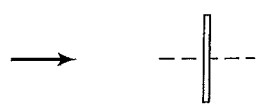
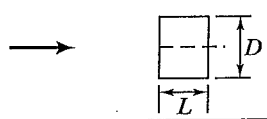
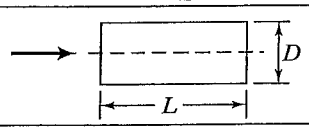
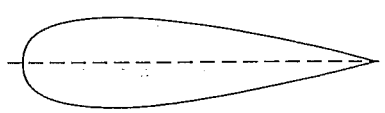
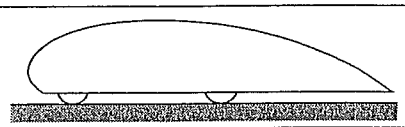
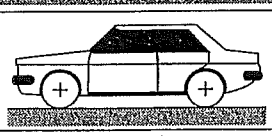
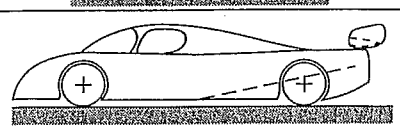



**FIGURE 10.7** Sketch of the flow over the front of a car, showing points of separation and reattachment. From *Race Car Aerodynamics,* J. Katz, Robert Bentley Publishers, 1995, with permission.

**TABLE 10.4 Typical Lift and Drag Coefficients**

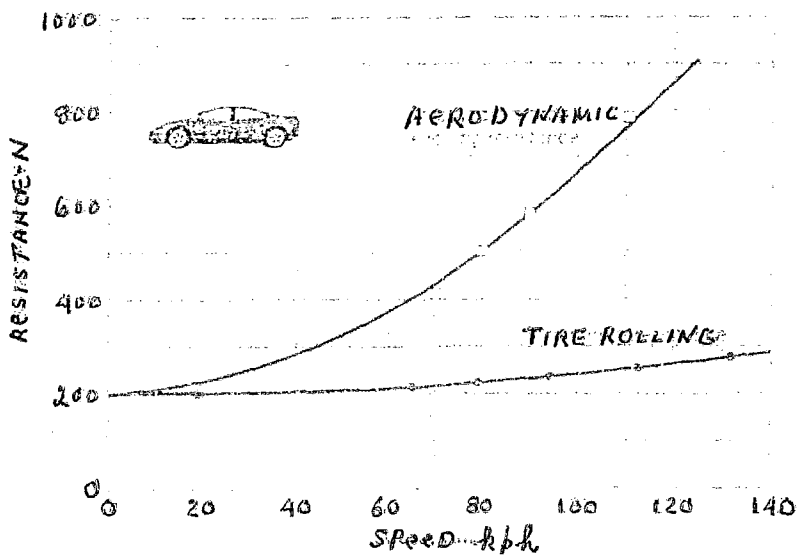
| | | | $C_L$ | $C_D$ |
|---|---|---|---|---|
| 1 | Circular plate |  | 0 | 1.17 |
| 2 | Circular cylinder $L/D < 1$ |   | 0 | 1.15 |
| 3 | Circular cylinder $L/D > 2$ |   | 0 | 0.82 |
| 4 | Low drag body of revolution |  | 0 | 0.04 |
| 5 | Low drag vehicle near the ground |  | 0.18 | 0.15 |
| 6 | Generic automobile |  | 0.32 | 0.43 |
| 7 | Prototype race car |  | −3.00 | 0.75 |

SOURCE: From *Race Car Aerodynamics,* J. Katz, Robert Bentley Publishers, 1995, with permission.

## Fuel utilization for resistance

Car traveling at 100 kph = 27.8 m/s. Assume $C_D = 0.4$

$$F_D = C_D \frac{1}{2}\rho V^2 A = 0.4\frac{1}{2}1.2(27.8^2)(2.1x1.2) = 467N$$




$F_{total} = 670N$

$F_{rolling} = 230N$

$F_D = 440N$

Power = $P = F_{total}V = 670(27.8) = 18{,}600Nm/s$

Enthalpy of combustion

for a hydrocarbon fuel $\approx 11{,}100\frac{cal}{gram} = 4.64x10^7\frac{Nm}{kg}$

Fuel mass rate for resistance

$$\frac{18600Nm/s}{4.64x10^7 Nm/kg} = 4.01x10^{-4}\frac{kg}{s}x\frac{3600s}{hr} = 1.44\frac{kg}{hr}$$

$$\rho = 680\frac{kg}{m^3}\frac{m^3}{1000l} = .680\frac{kg}{l}$$

Fuel volume rate for resistance $= \frac{1.44kg/hr}{.680kg/l} = 2.12\frac{l}{hr}$

Total fuel consumption = $25mi/gal = 10.6km/l$

$$\frac{100km/hr}{10.6km/l} = 9.43\frac{l}{hr}$$

Resistance = 22.3%

# SOURCES OF DRAG

FRICTION

PRESSURE

WAVE DRAG

- LIQUID SURFACE
- COMPRESSIBLE

DRAG DUE TO LIFT

(THREE DIMENSIONAL FLOW LOSSES ON WINGS)