Friction Drag
(flow over a flat plate parallel to the flow)

Laminar Boundary Layer:

$$C_D = \frac{1.328}{\sqrt{\mathrm{Re}_L}}$$

Turbulent Boundary Layer:

$$C_D = \frac{0.074}{\mathrm{Re}_L^{1/5}} \quad 5\cdot 10^5 < \mathrm{Re}_L < 10^7 \text{ or } C_D = \frac{0.455}{\left(\log(\mathrm{Re}_L)\right)^{2.58}} \quad \mathrm{Re}_L < 10^9$$

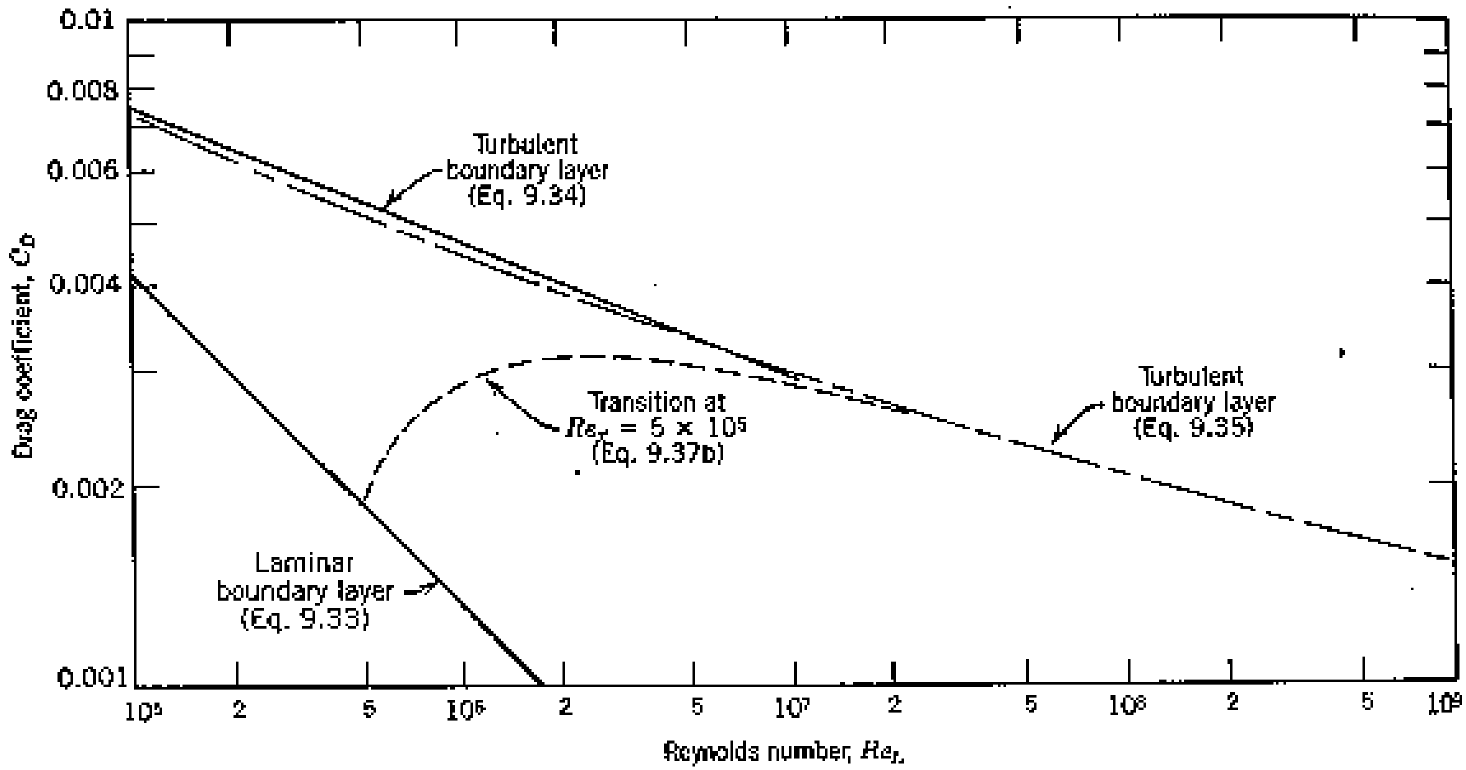
Laminar + Transition+Turbulent Boundary Layer:

$$C_D = \frac{0.074}{\mathrm{Re}_L^{1/5}} - \frac{1740}{\mathrm{Re}_L} \quad 5\cdot 10^5 < \mathrm{Re}_L < 10^7$$

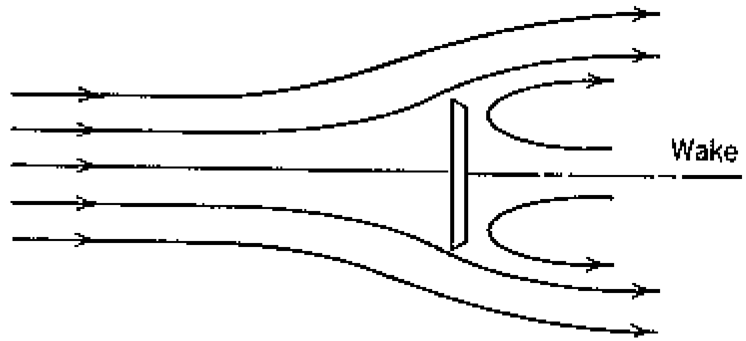
or

$$C_D = \frac{0.455}{\left(\log(\mathrm{Re}_L)\right)^{2.58}} - \frac{1610}{\mathrm{Re}_L} \quad 5\cdot 10^5 < \mathrm{Re}_L < 10^9$$

Drag Coefficient for Smooth Flat Plate Parallel to the Flow



Flow Over Flat Plate Normal to the Flow



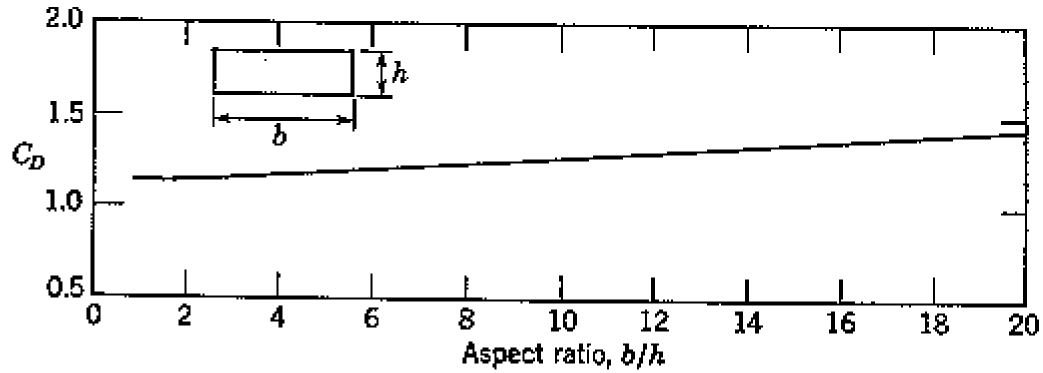
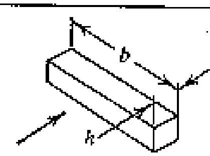
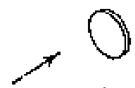
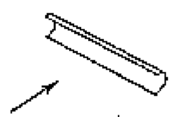
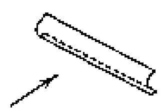


Fig. 9.10 Variation of drag coefficient with aspect ratio for a flat plate of finite width normal to the flow with $Re_h > 1000$ [14].

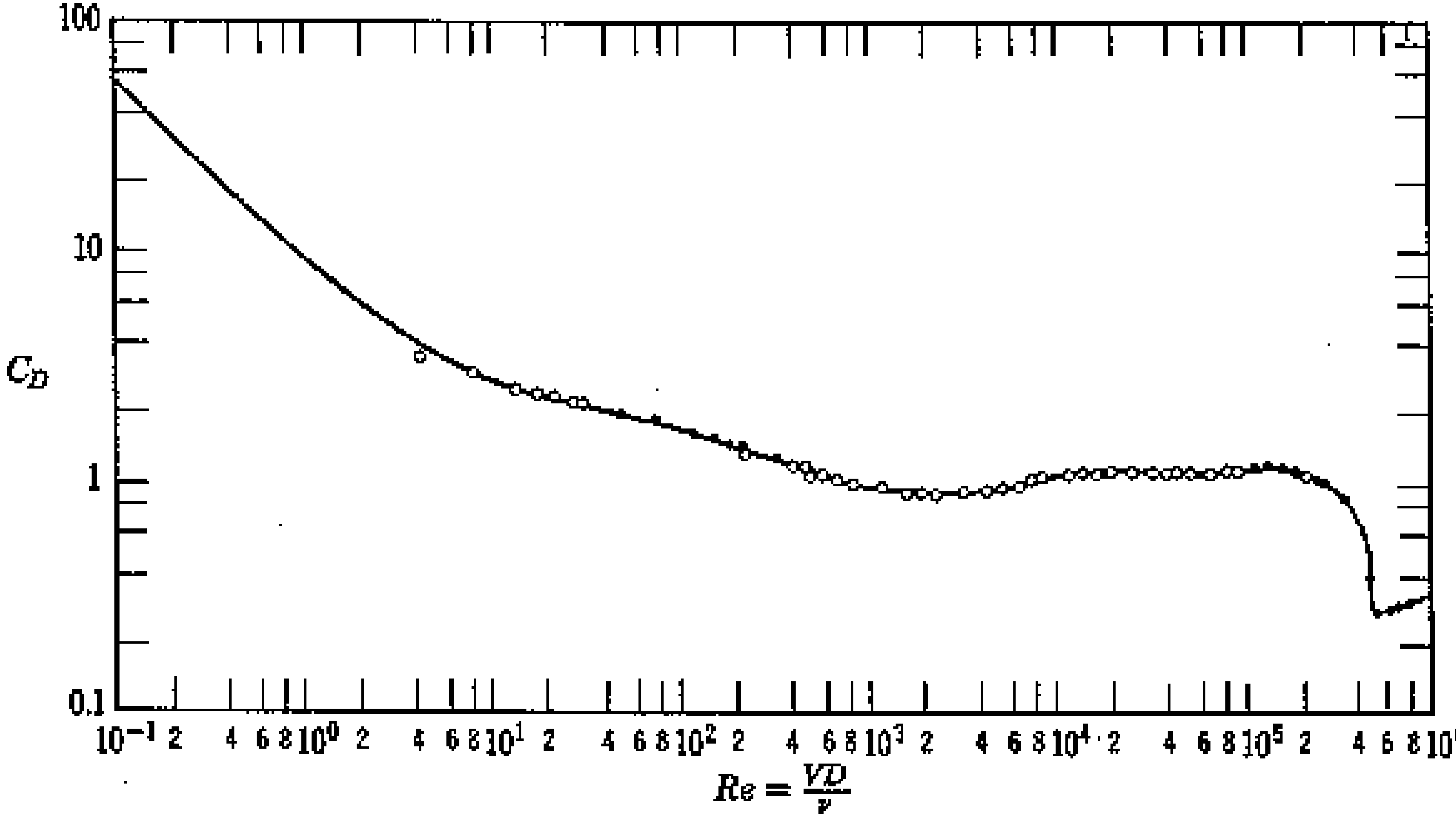
Drag Coefficients for Selected Objects

Table 9.3 Drag Coefficient Data for Selected Objects ($Re \gtrsim 10^3$)[a]

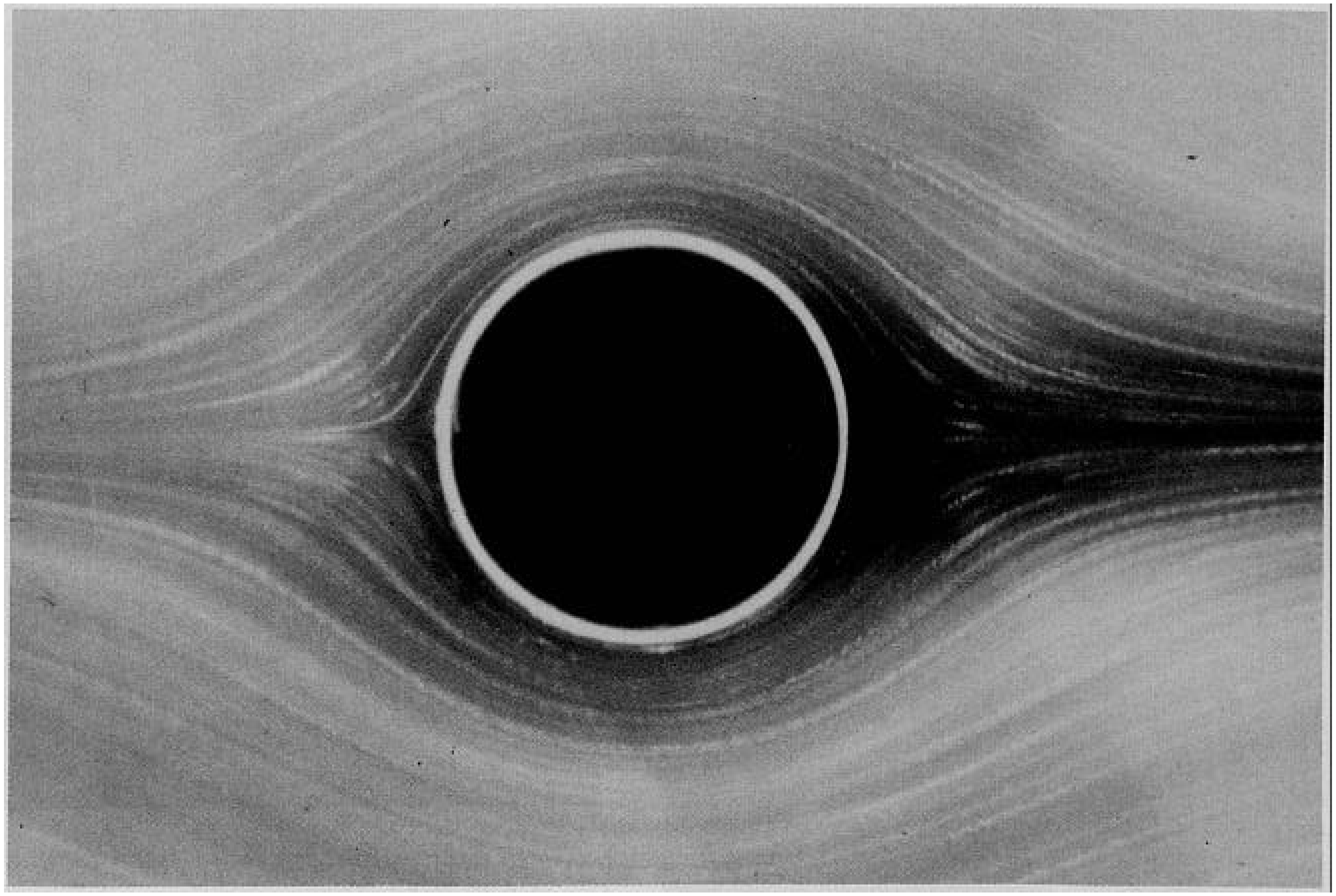
Object	Diagram		$C_D(Re \gtrsim 10^3)$
Square cylinder		$b/h = \infty$ $b/h = 1$	2.05 1.05
Disk			1.17
Ring			1.20[b]
Hemisphere (open end facing flow)			1.42
Hemisphere (open end facing downstream)			0.38
C-section (open side facing flow)			2.30
C-section (open side facing downstream)			1.20

[a] Data from [14].
[b] Based on ring area.

Pressure Distribution Around Smooth Circular Cylinder

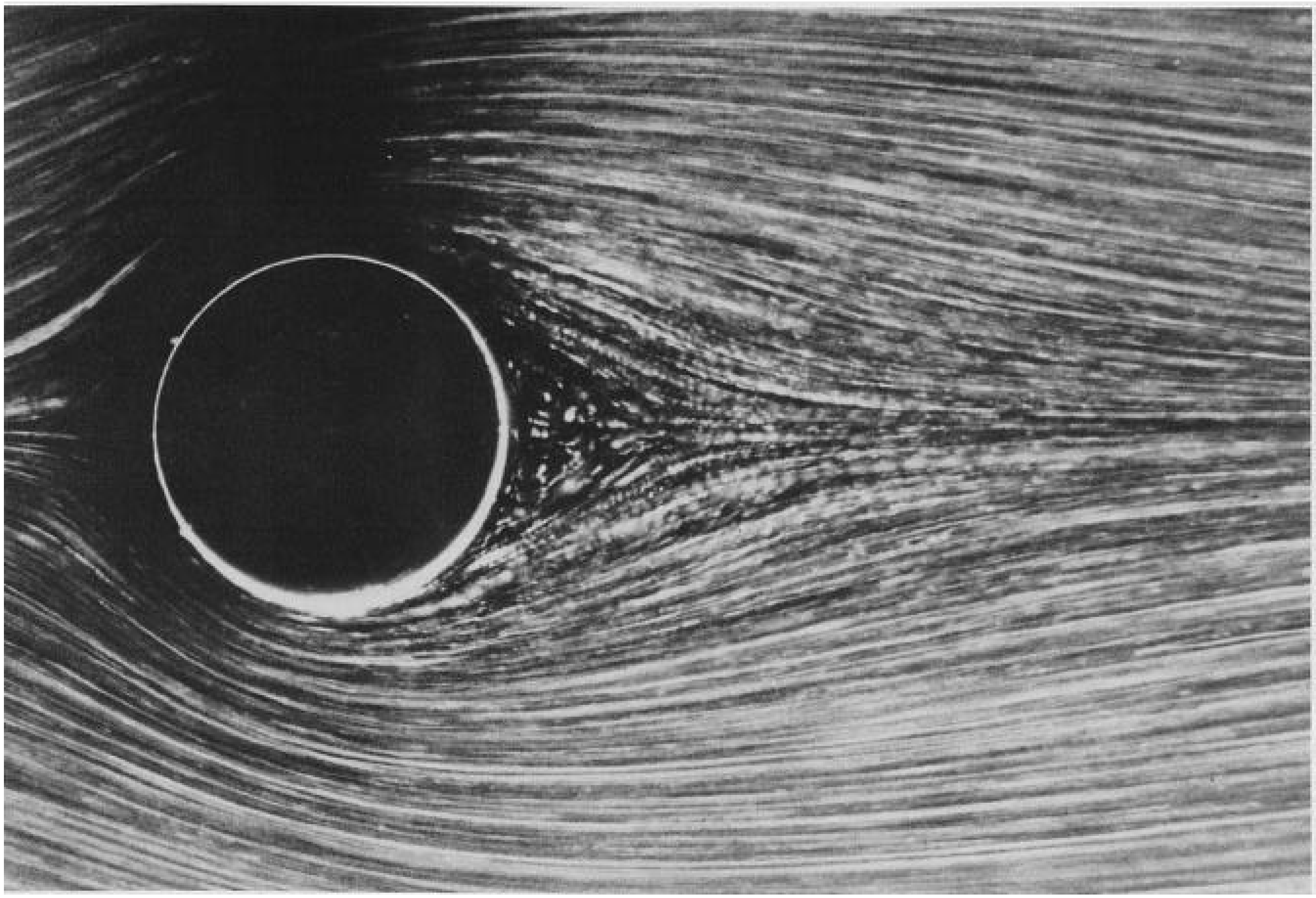


# Visualization of Flow Around Smooth Circular Cylinder
Re=0.16



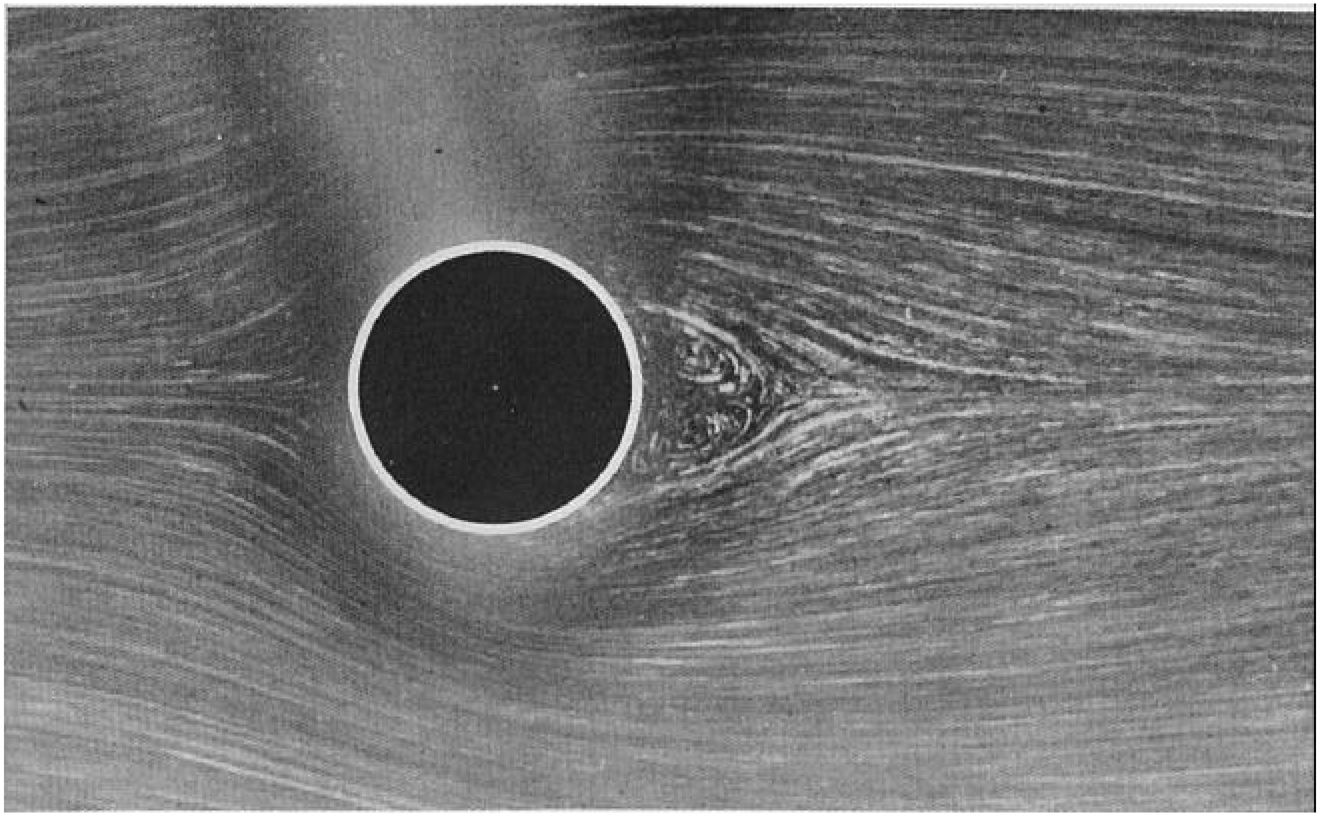
From Van Dyke (1982)

Visualization of Flow Around Smooth Circular Cylinder
Re=9.6



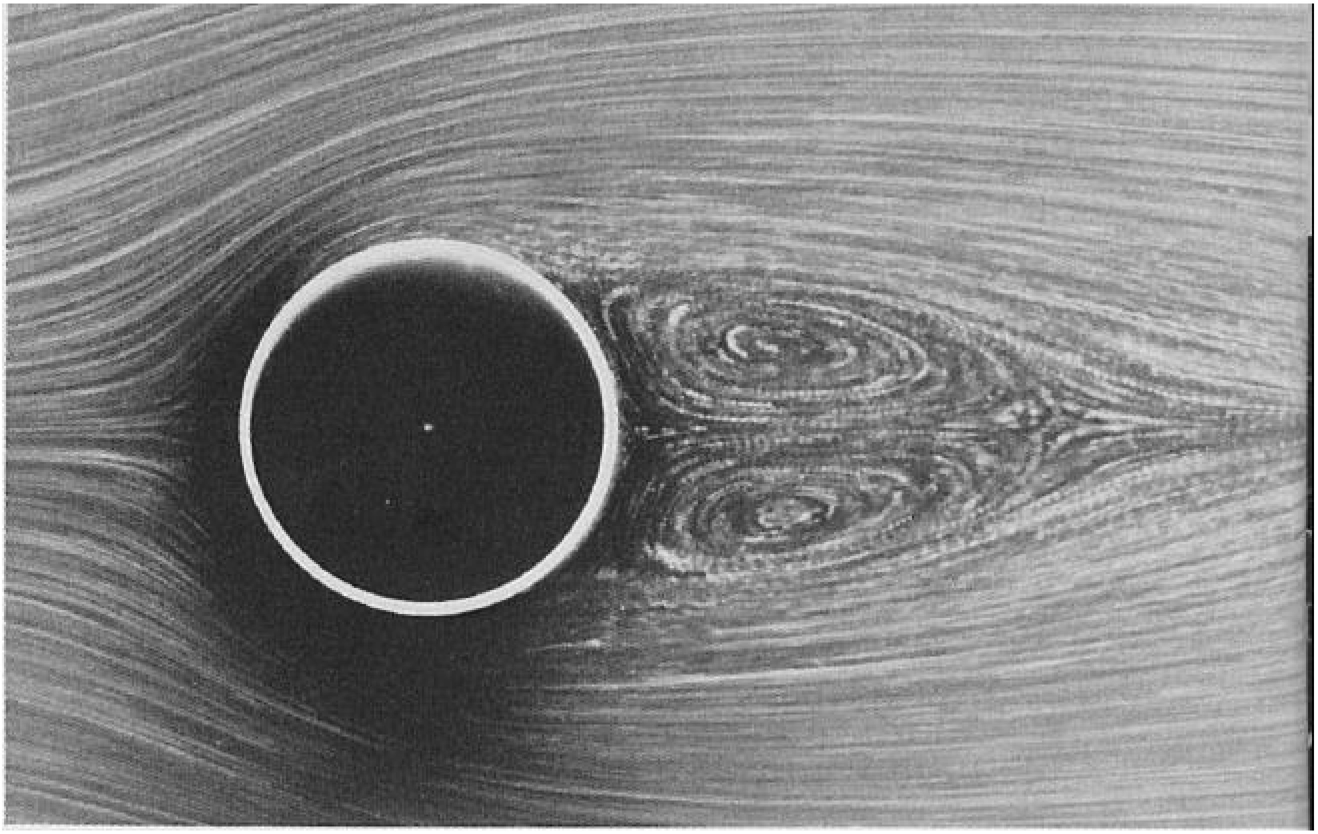
From Van Dyke (1982)

# Visualization of Flow Around Smooth Circular Cylinder
Re=13.1



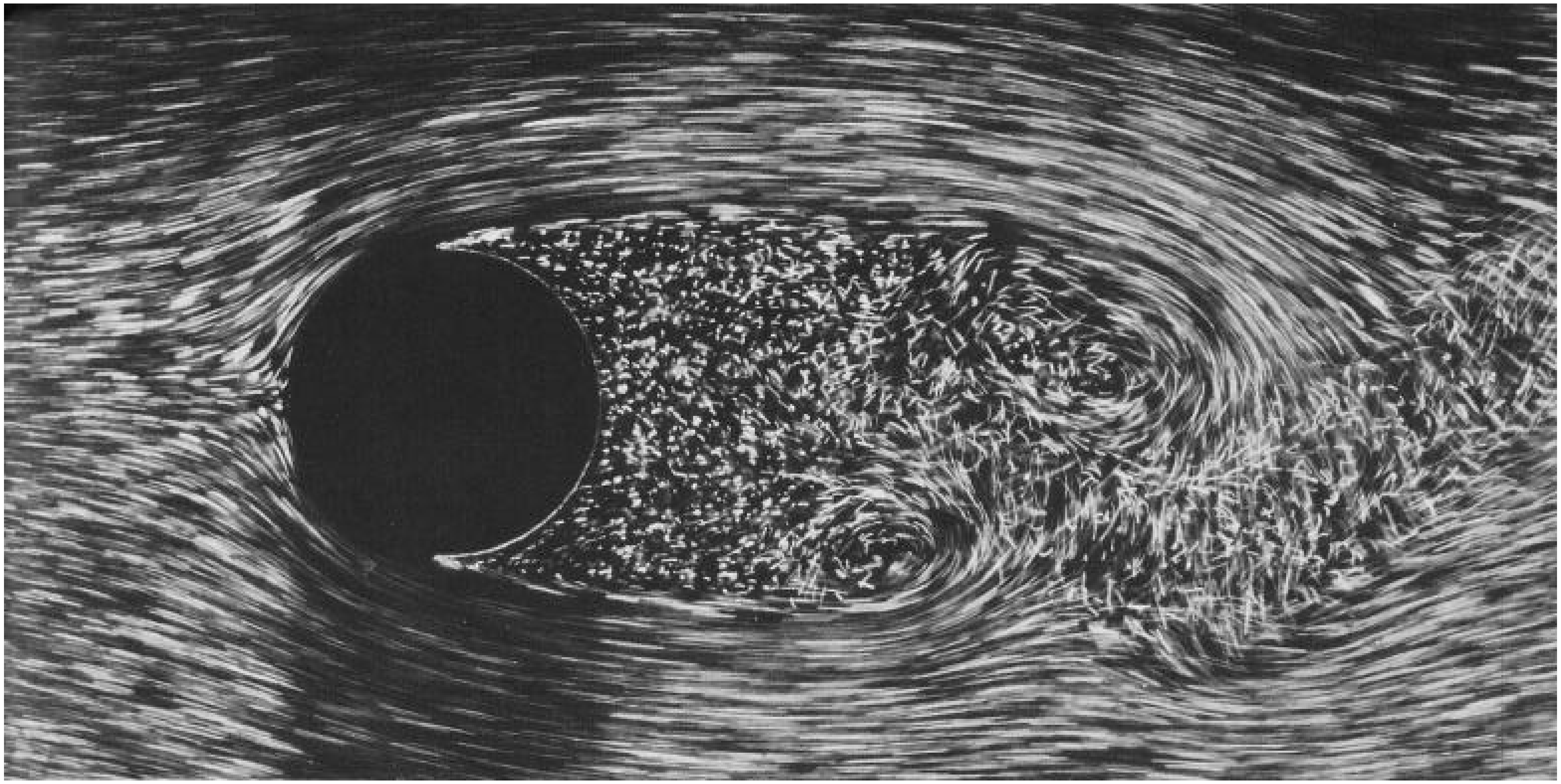
From Van Dyke (1982)

Visualization of Flow Around Smooth Circular Cylinder
Re=26



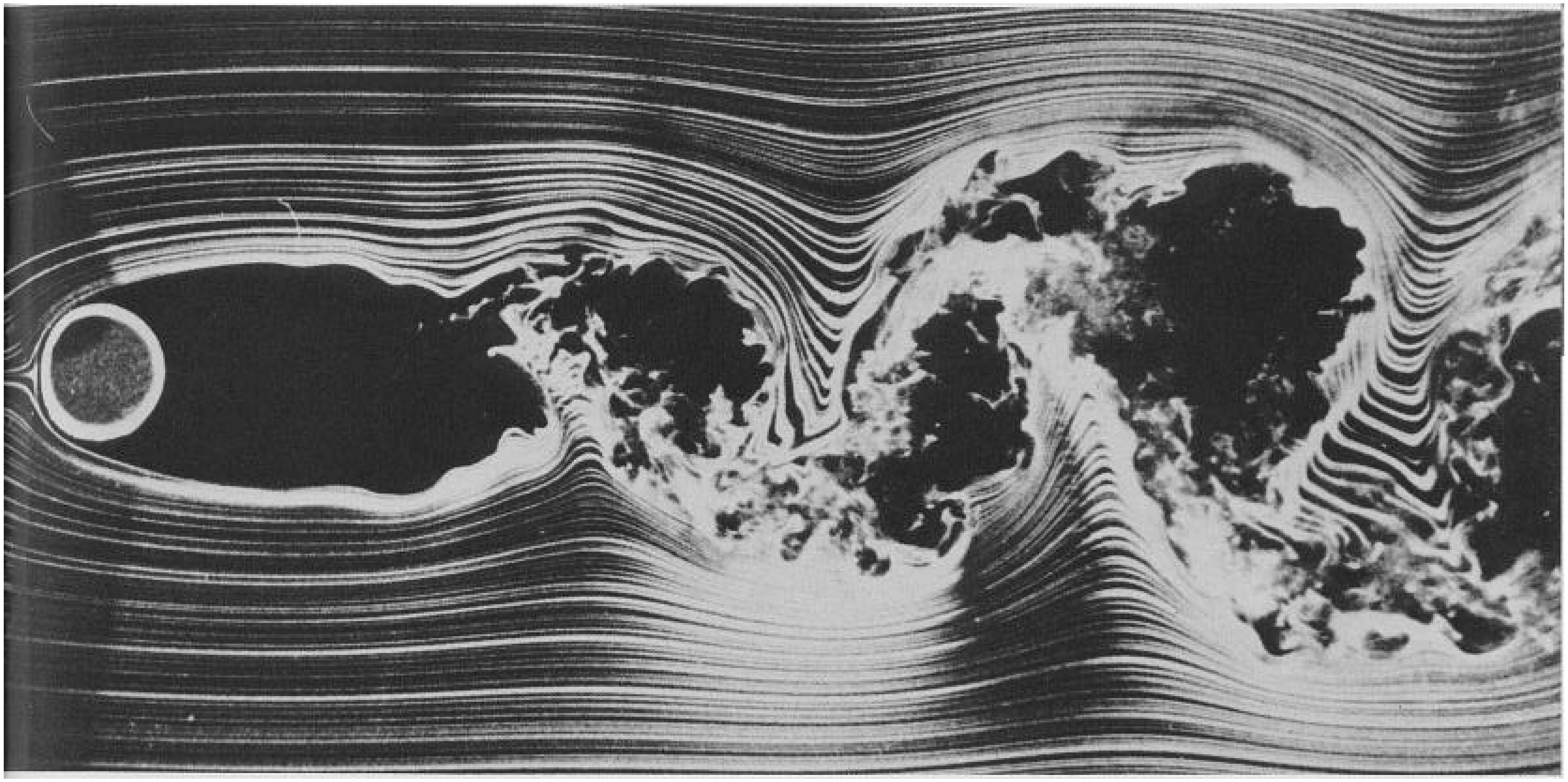
From Van Dyke (1982)

Visualization of Flow Around Smooth Circular Cylinder
Re=2,000



From Van Dyke (1982)

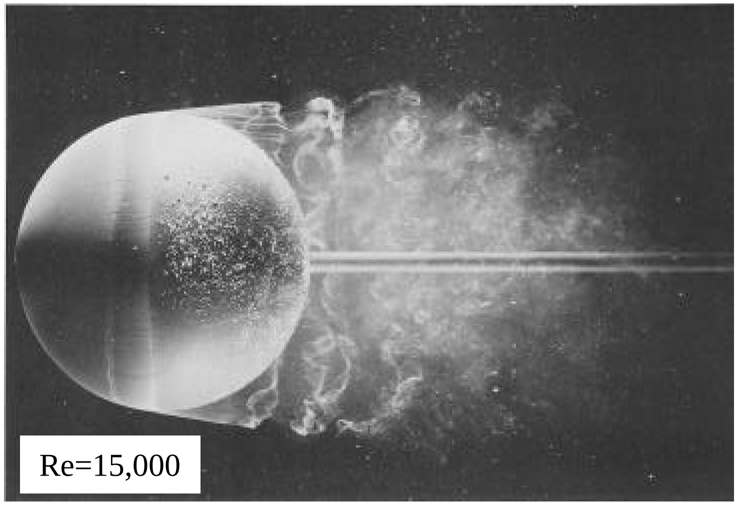
Visualization of Flow Around Smooth Circular Cylinder
Re=10,000



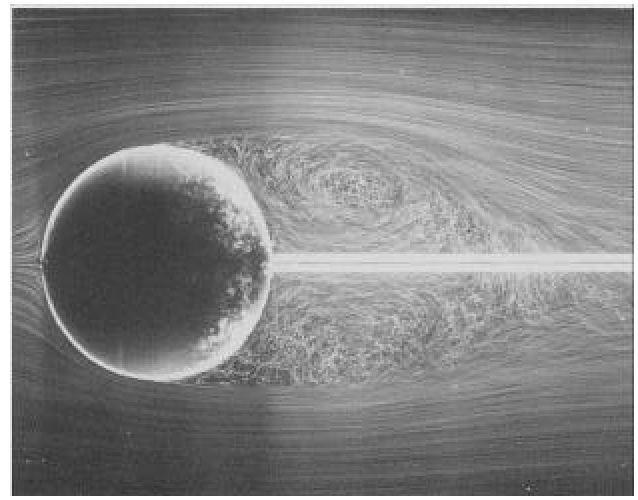
From Van Dyke (1982)

Visualization of Flow Around Smooth Circular Cylinder Re=10,000

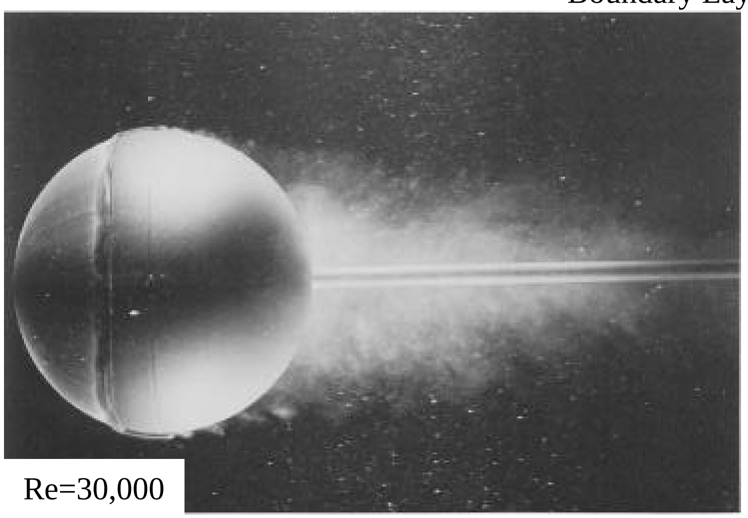
Boundary Layer is Laminar



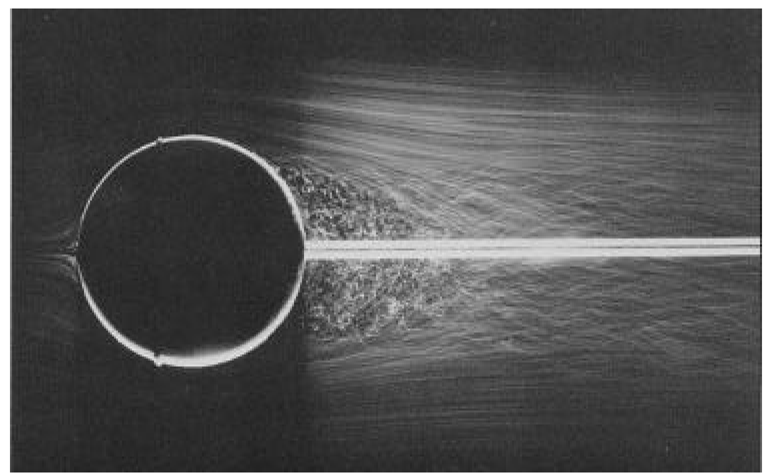
Re=15,000



Boundary Layer is made Turbulent through tripping

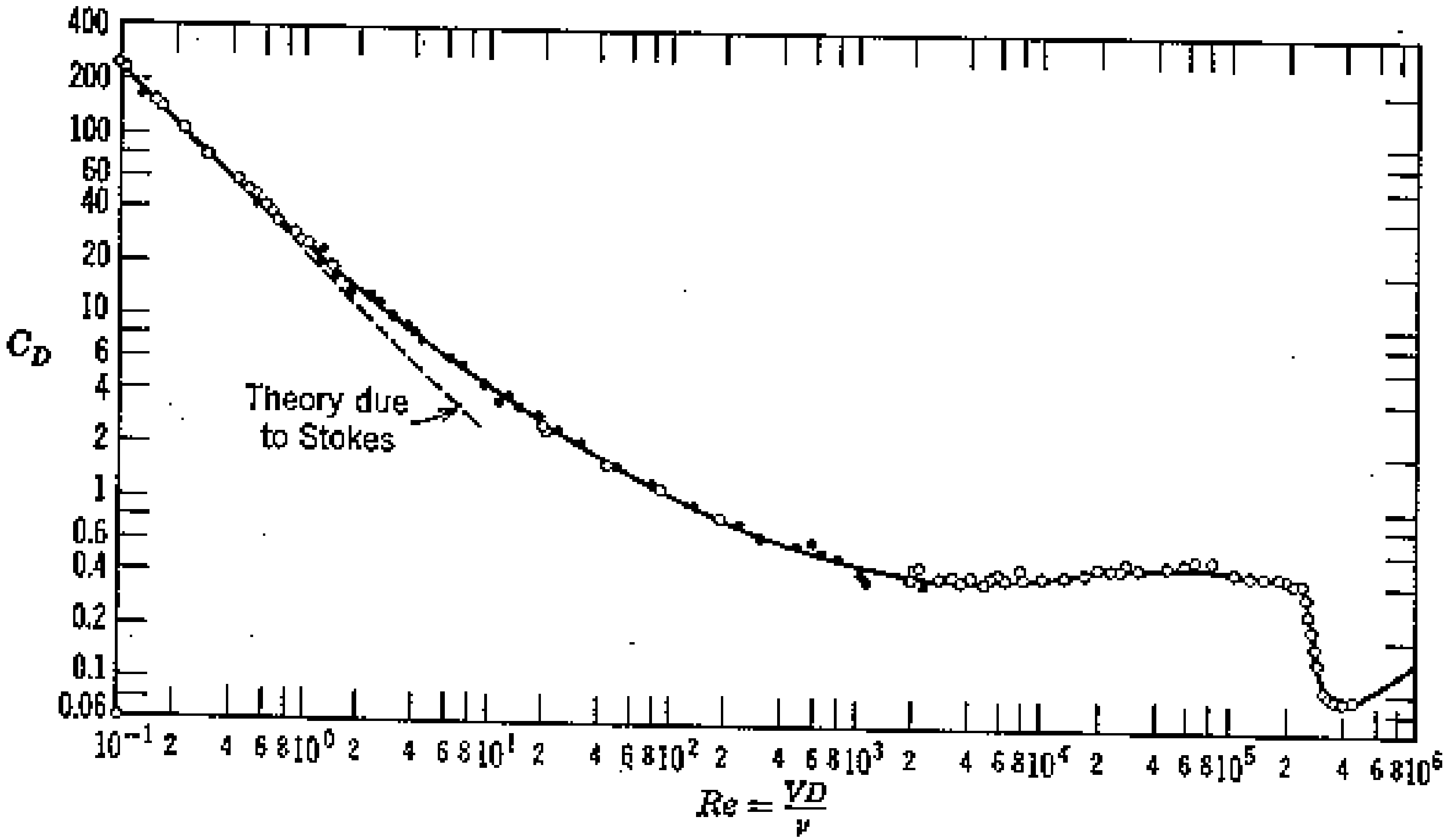


Re=30,000

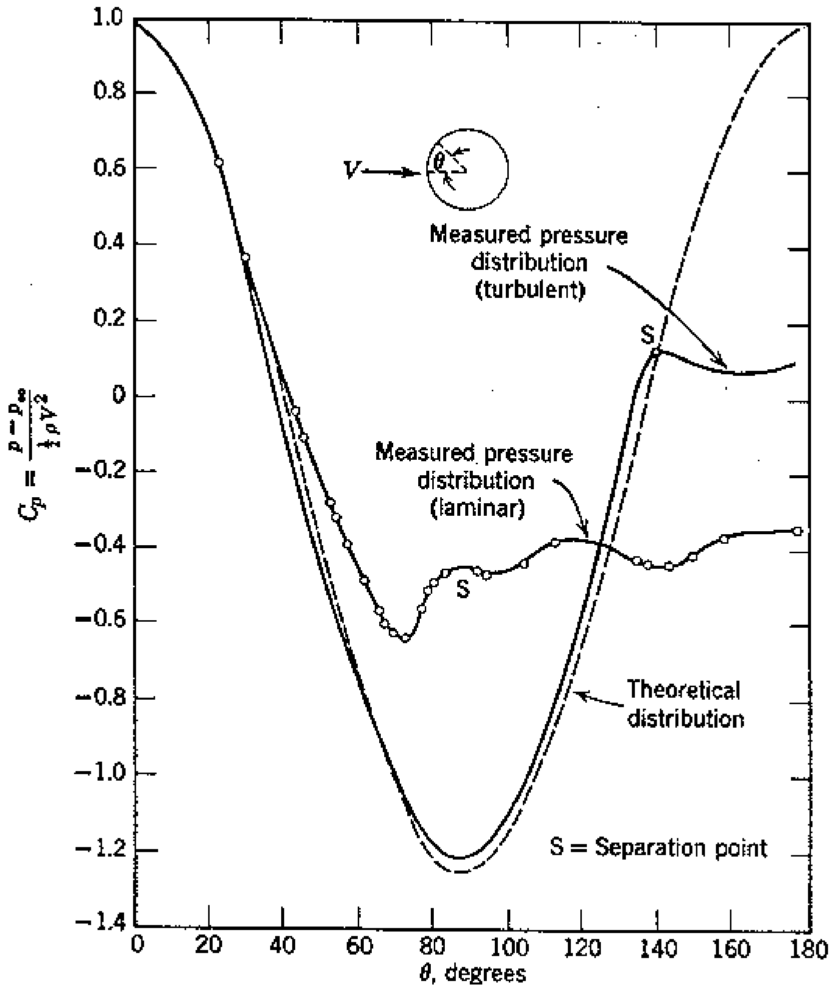


From Van Dyke (1982)

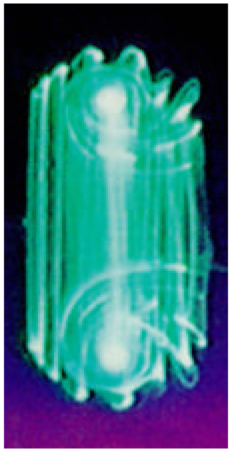
Drag Coefficients for a Smooth Sphere



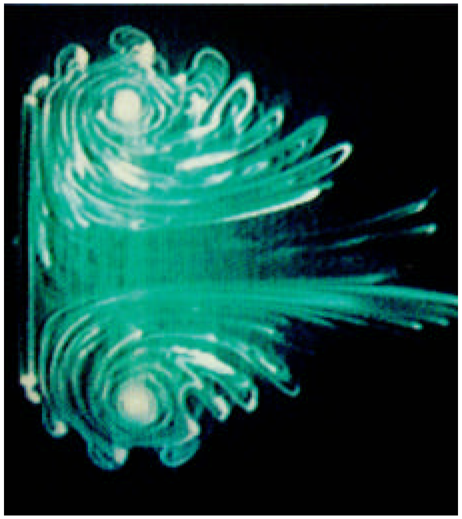
Pressure Distribution Around Smooth Sphere



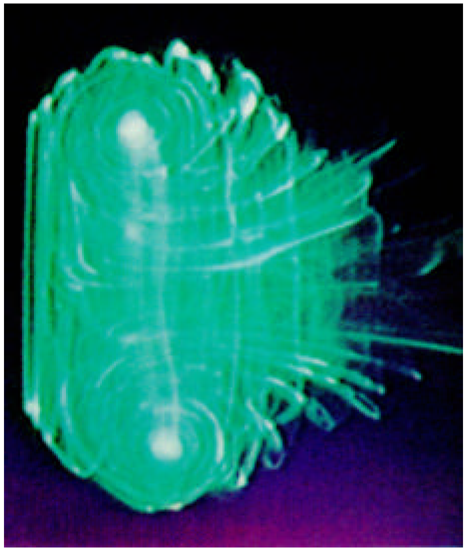
Visualization of Flow Structure Behind a Moving Disk
Re=6,200-4,200



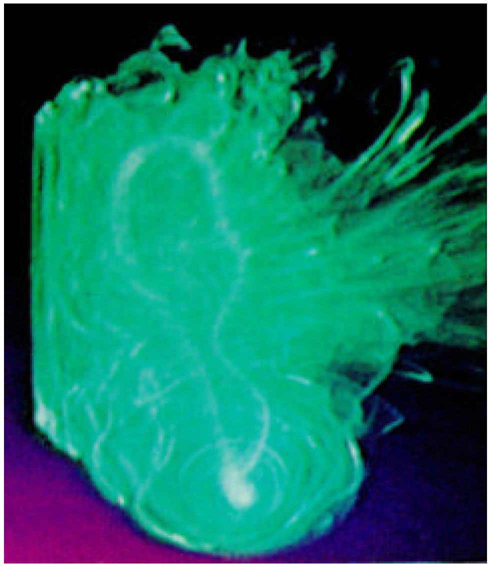
t_1



t_2



t_3



t_4

Disk motion is from right to left

From Higuchi and Belligand (Physics of Fluids, 1992)

Effect of Streamlining on Drag Coefficient

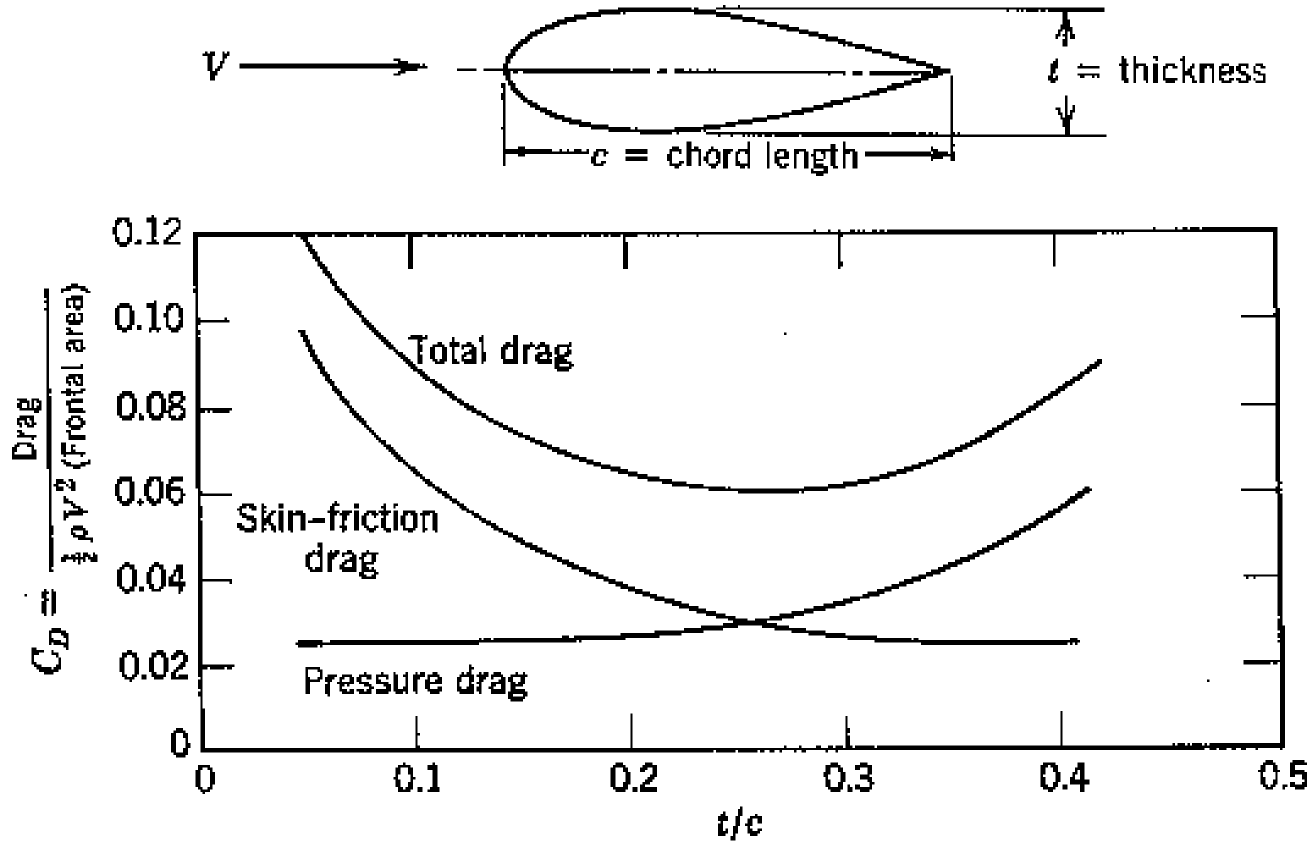
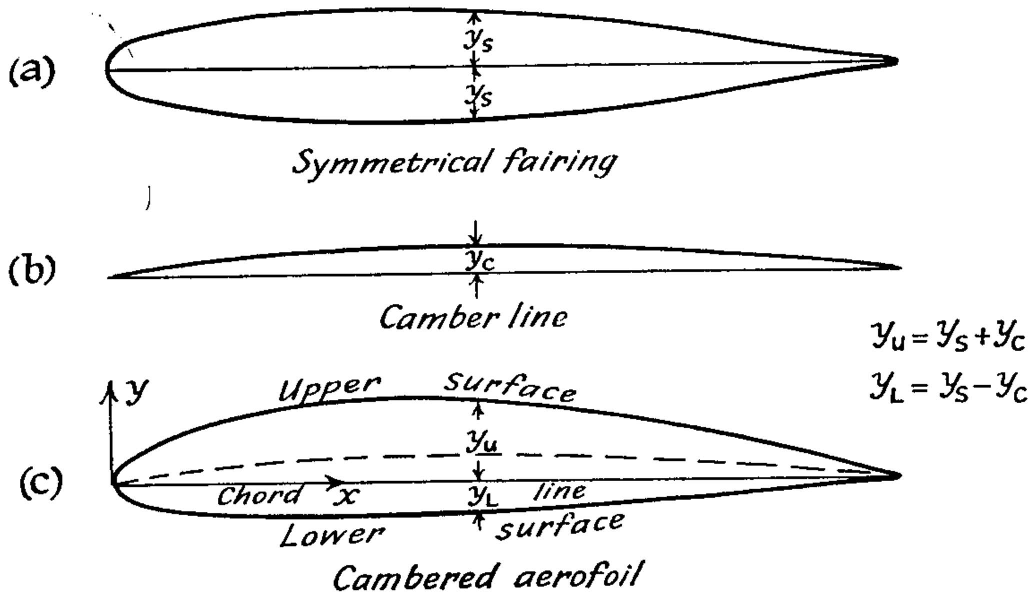
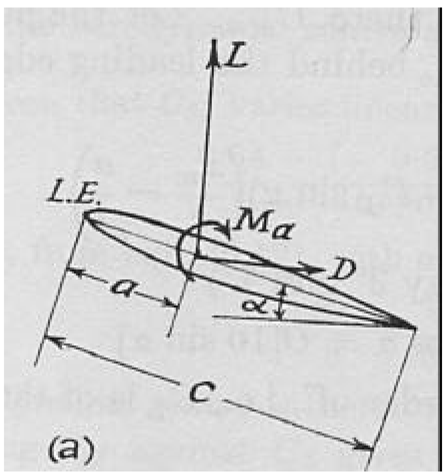


Fig. 9.14 Drag coefficient on a streamlined strut as a function of thickness ratio, showing contributions of skin friction and pressure to total drag [18].

Airfoils: Geometrical Aspects





α: Angle of Attack

Airfoils: Terminology

Lift Coefficient:

$$C_L = \frac{\left|\vec{L}\right|}{\frac{1}{2}\, r U^2 A_p}$$

$$A_p = \text{planform area of the wing (maximum projected area)}$$

Example of Airfoil Section Shape Designations

Conventional: 23015

2 30 15

- 15 — Section Thickness % (15 %)
- 30 — Maximum Camber Location (1/2 x 30=15% chord)
- 2 — Design Lift Coefficient (3/2 x 2/10=0.3)

Laminar Flow: 66_2-215

6 6 $_2$ - 2 15

- 15 — Section Thickness % (15 %)
- 2 — Design Lift Coefficient (2/10=0.2)
- $_2$ — Maximum Lift Coef. for Favorable Pressure Gradient (2/10=0.2)
- 6 (second) — Location of Minimum Pressure (x/c=6/10=0.6)
- 6 (first) — Series Designation (Laminar Flow)

Pressure Distribution Around Airfoils

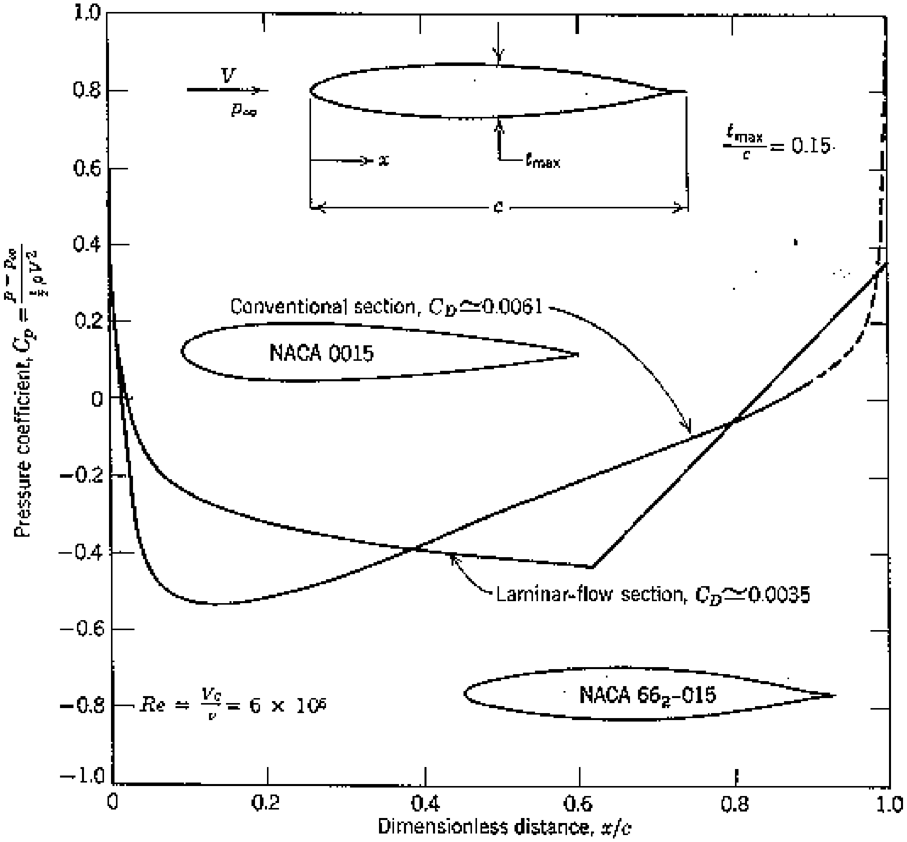
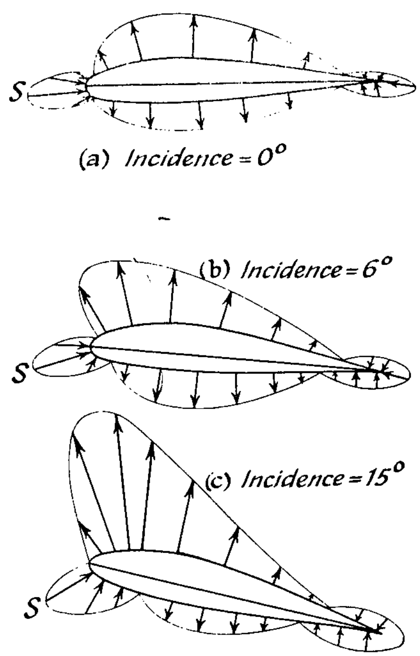


Fig. 9.15 Theoretical pressure distributions at zero angle of attack for two symmetric airfoil sections of 15 percent thickness ratio. (Data from [19].)



Length of arrows ∝ C_p

S denotes C_p at stagnation where C_{ps} = unity

Direction of arrows indicates +ve or −ve C_p

Airfoil Lift and Drag Coefficients

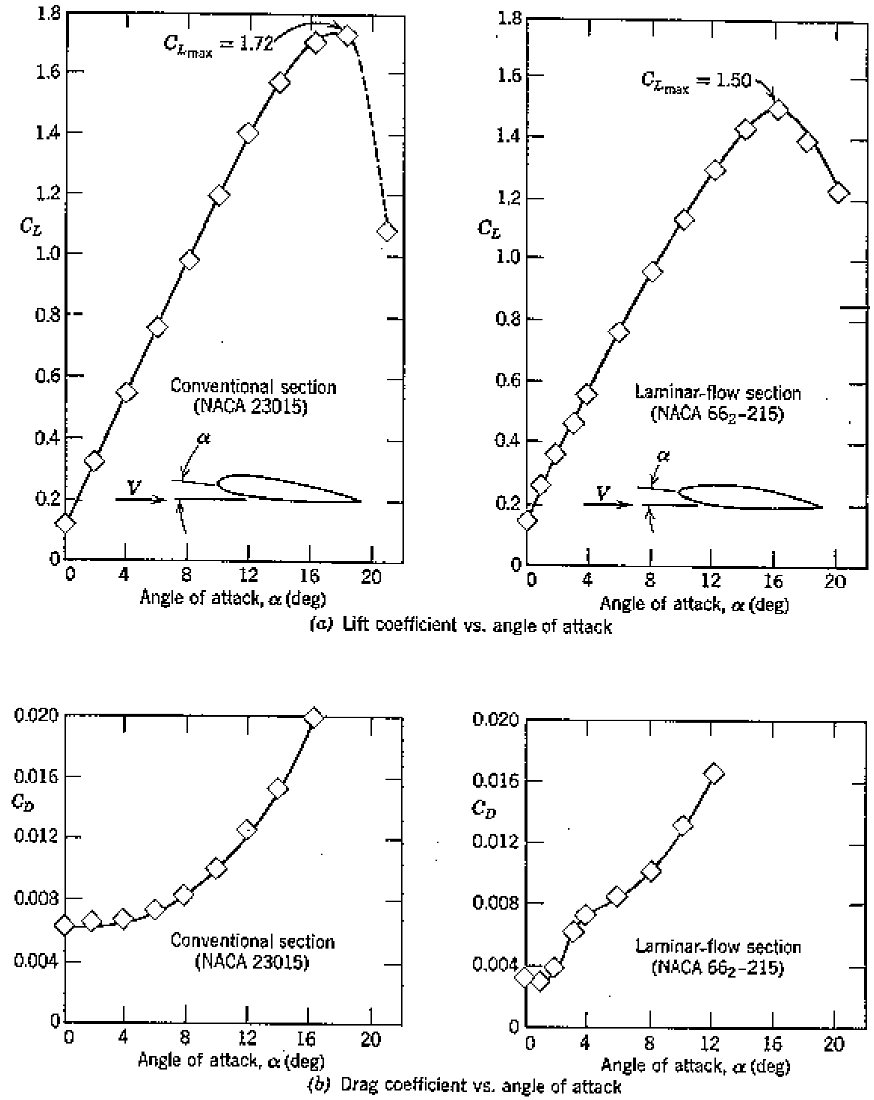
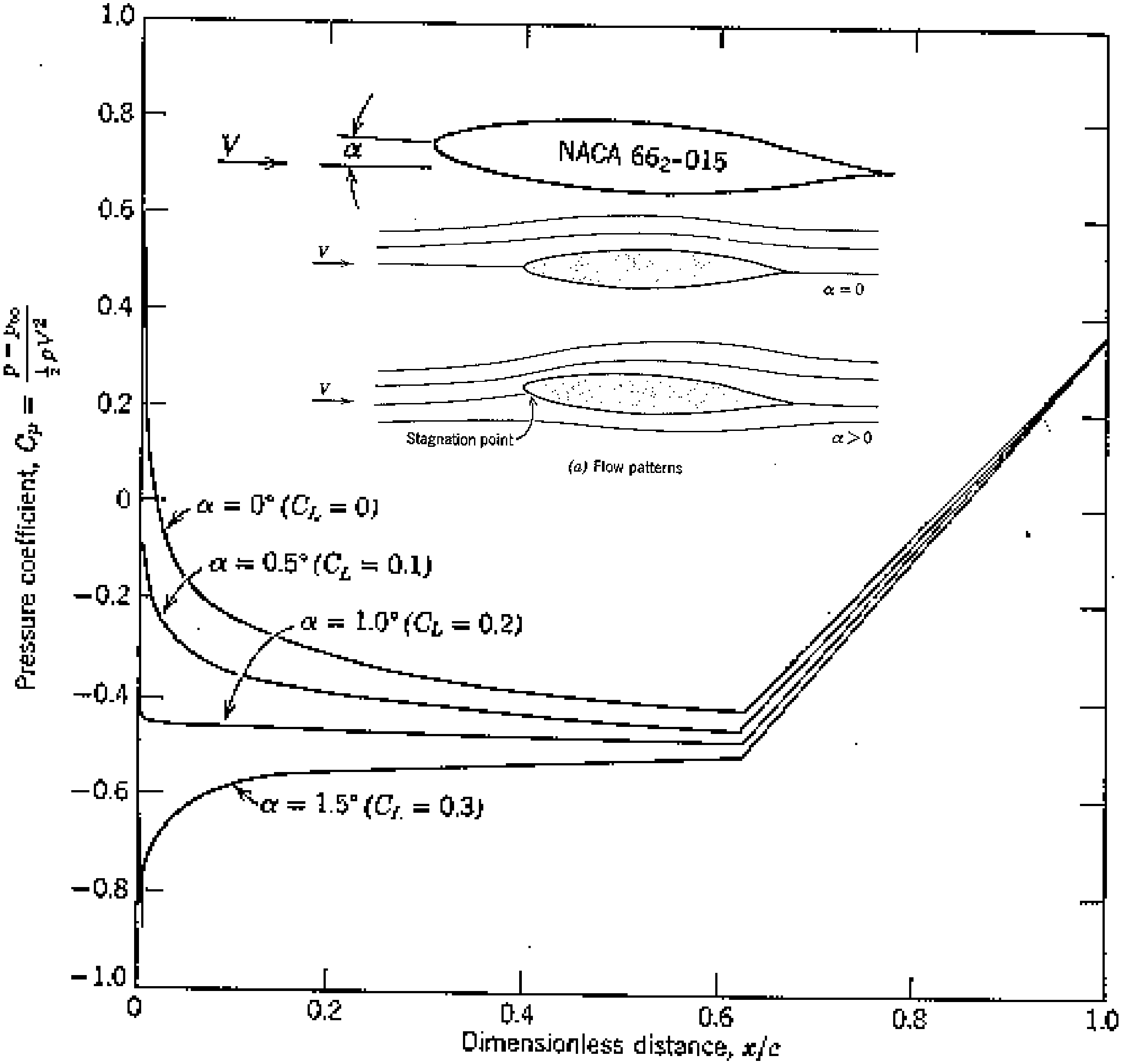


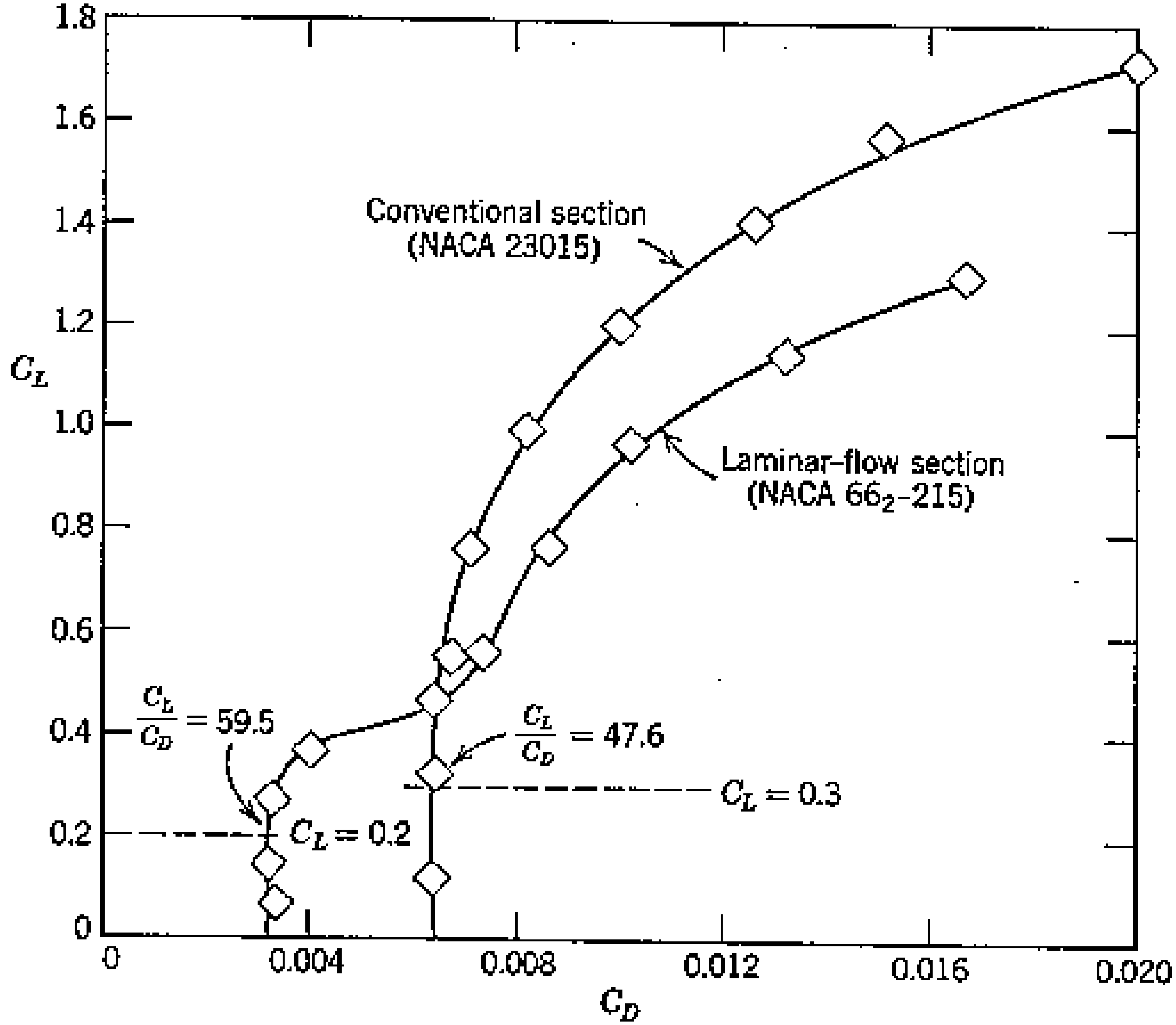
Fig. 9.17 Lift and drag coefficients versus angle of attack for two airfoil sections of 15 percent thickness ratio. (Data from [19].)

Effect of Angle of Attack on Flow Pattern and Theoretical Pressure Distribution for an Airfoil

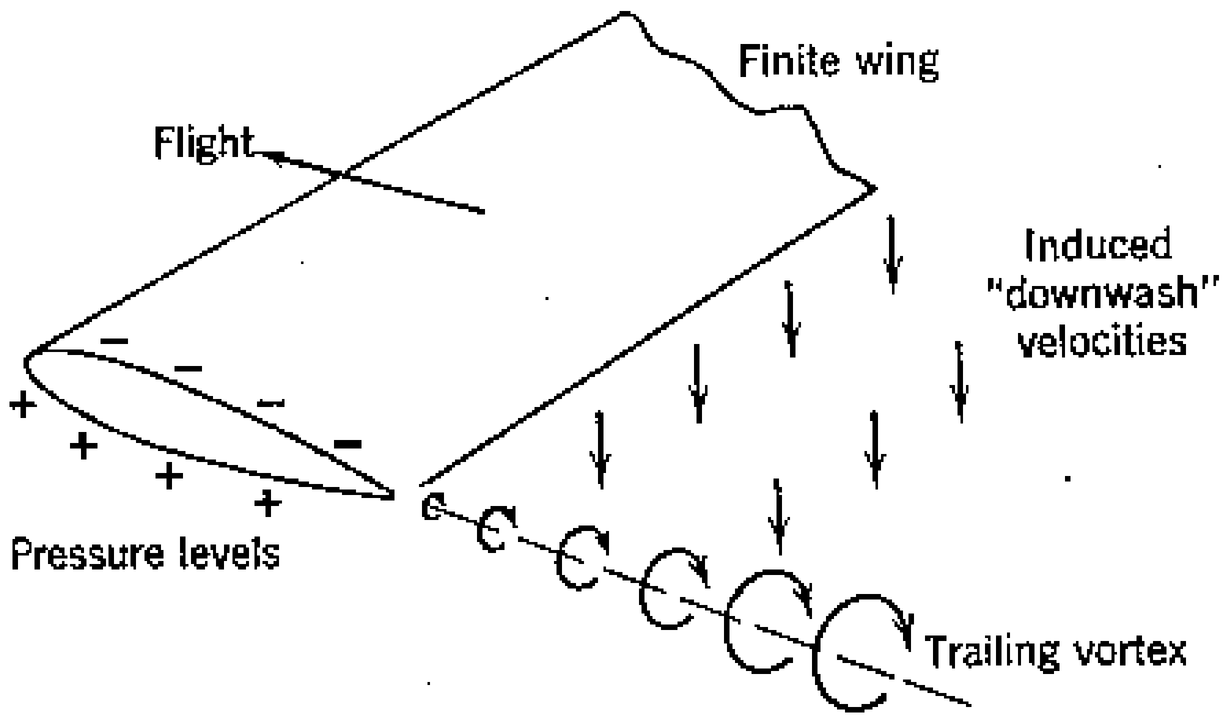


(b) Pressure distribution on upper surface

Airfoil-Lift and Drag Polars



Trailing Vortices of a Finite Wing



Trailing Vortices in the Wake of an Aircraft

Cessna Citation VI
Wing Span 16.3 m
Wing Area $29 m^2$
V=170 knots (313 km/hr)
$Re=1.1 \times 10^7$ based on mean aerodynamic chord of 2.1 m)

From Higuchi (Physics of Fluids, 1993)
Photograph by P. Bowen of Cessna Aircraft Co.

Finite Wingspan Effects

Aspect Ratio: $$\mathrm{ar} = \frac{b^2}{A} = \frac{(\mathrm{wingspan})^2}{\mathrm{Planform\ Area}}$$

Approximate Lift Coefficient Dependence on Angle of Attack: $$C_L \approx \mathrm{Const} \cdot \alpha$$

Effective Increase of Angle of Attack Due to Finite Wingspan: $$\Delta\alpha \approx \frac{C_L}{\pi \cdot \mathrm{ar}}$$

Induced Drag Due to Finite Wingspan: $$C_{D,i} = \Delta C_D \approx C_L \cdot \Delta\alpha$$

$$C_D \approx C_{D,\infty} + C_{D,i} = C_{D,\infty} + \frac{C_L^2}{\pi \cdot \mathrm{ar}}$$

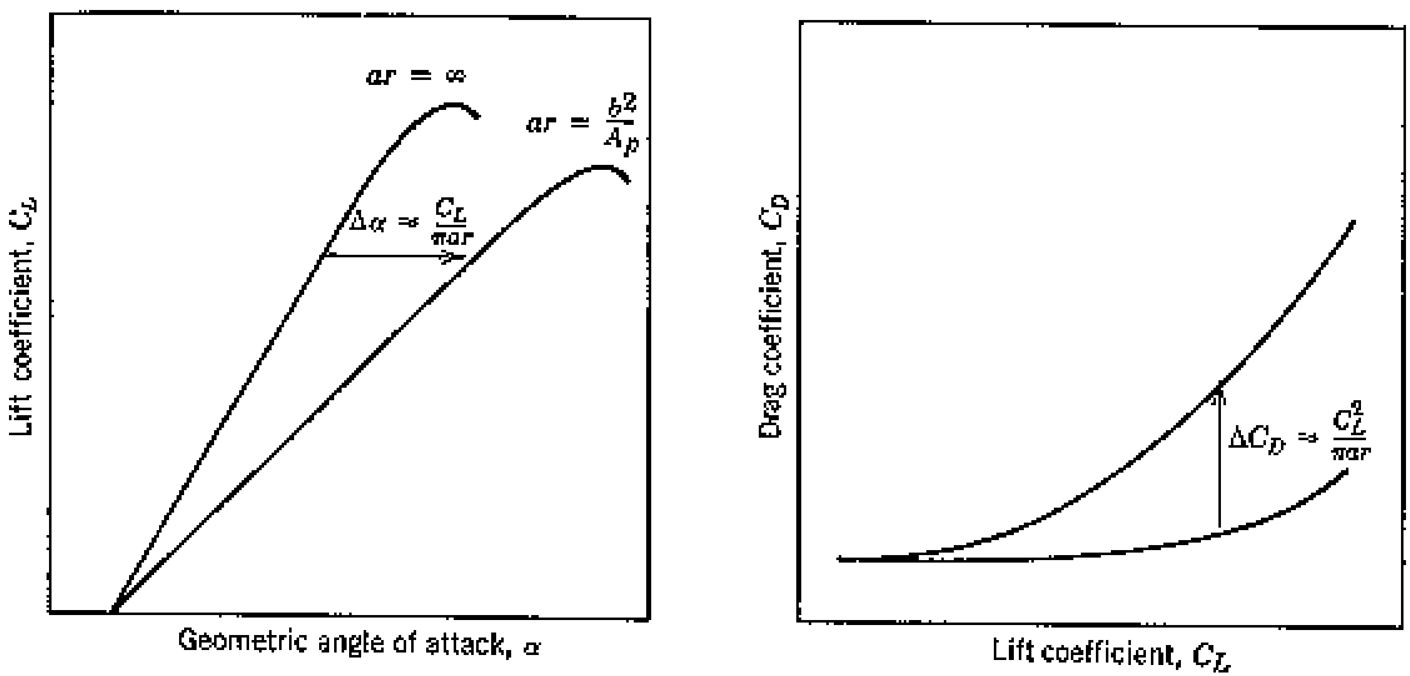
is the Total Drag for Finite Wingspan

Drag Polar Approximation for Complete Aircraft:

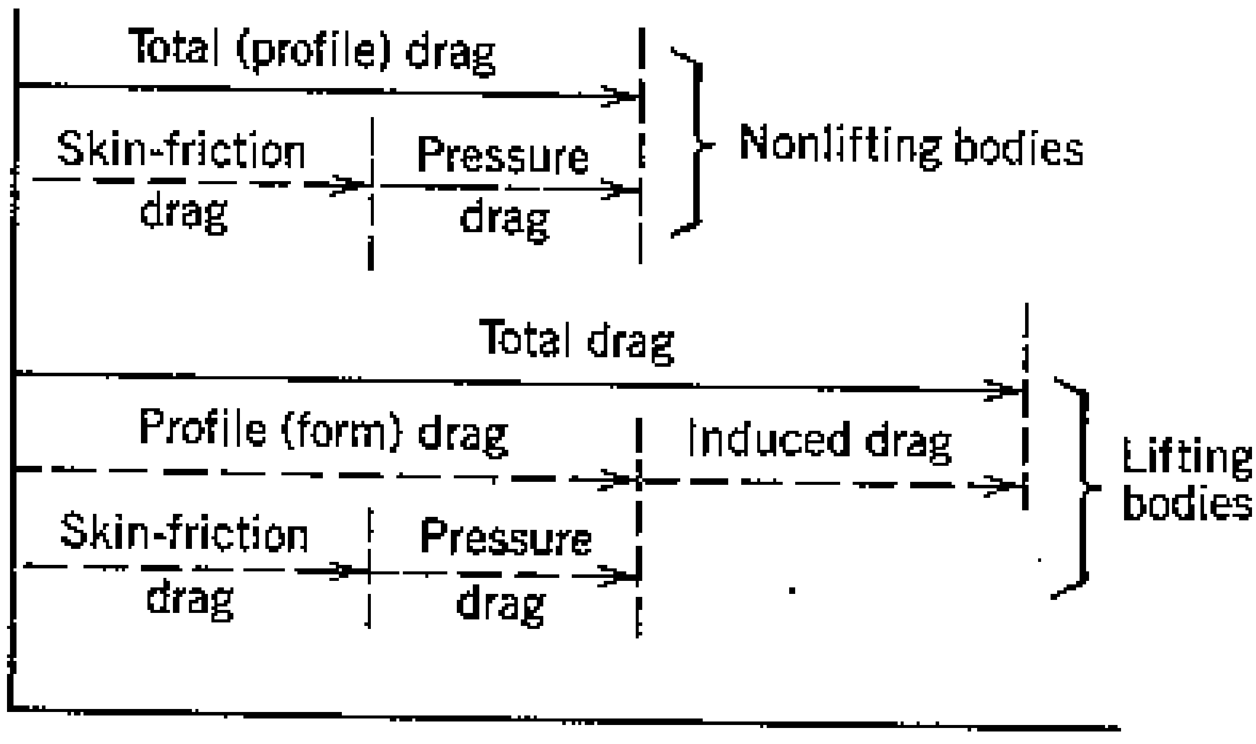
$$C_D \approx C_{D,0} + C_{D,i} = C_{D,0} + \frac{C_L^2}{\pi \cdot \mathrm{ar}}$$

$C_{D,0}$ is the drag coefficient at Zero Lift

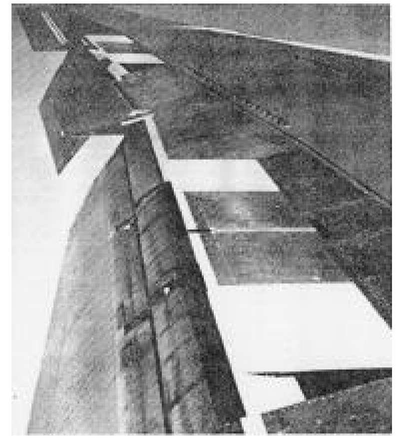
Lift and Drag Coefficients for a Finite-Aspect-Ratio Wing



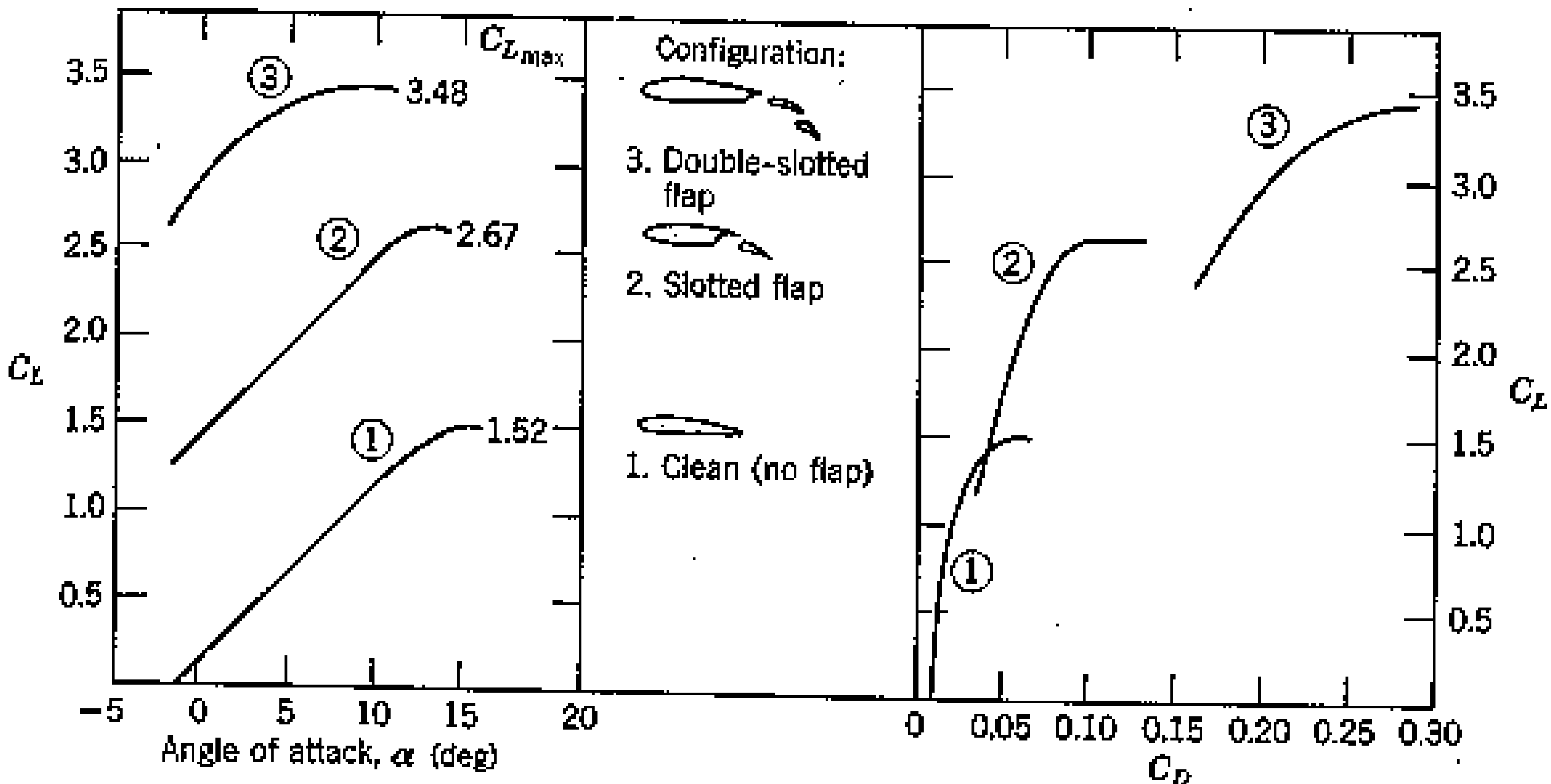
Drag Breakdown on Non-Lifting and Lifting Bodies



Use of Flaps for Landing Speed Reduction
Use of Spoilers as Lift Destroyers



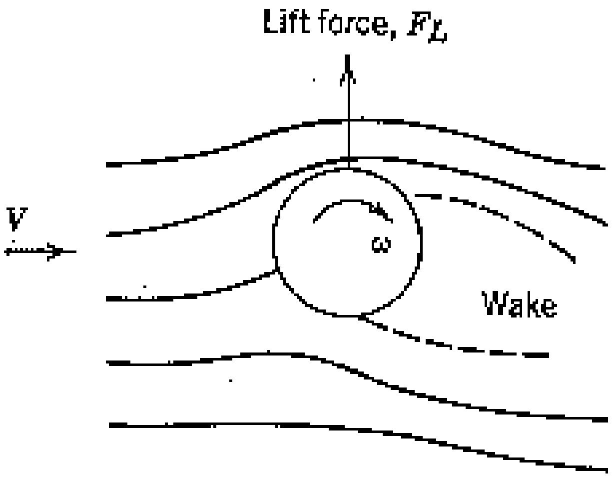
Effects of Flaps



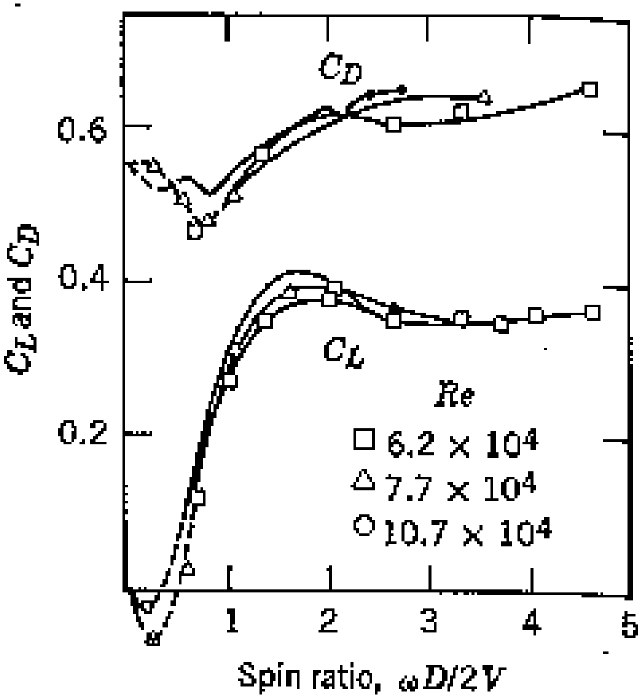
(a) Lift coefficient versus angle of attack

(b) Lift-drag polar

Drag and Lift on Smooth Spinning Sphere



(a) Flow pattern



(b) Lift coefficient

Sailing With a Rotating Cylinder Sail

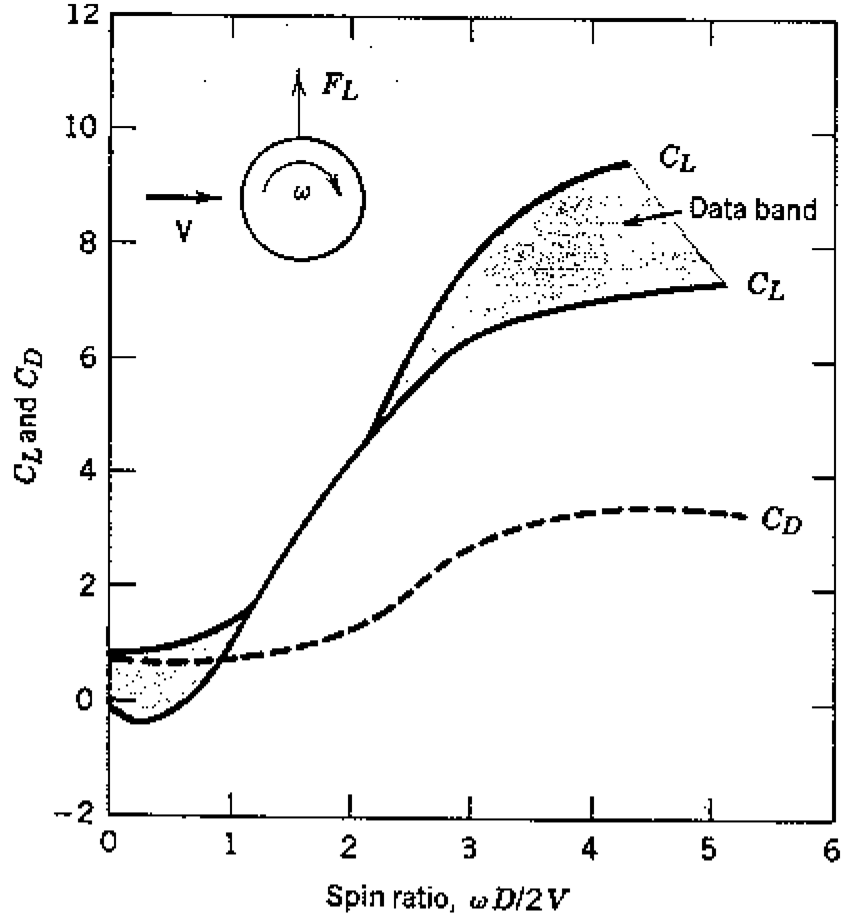
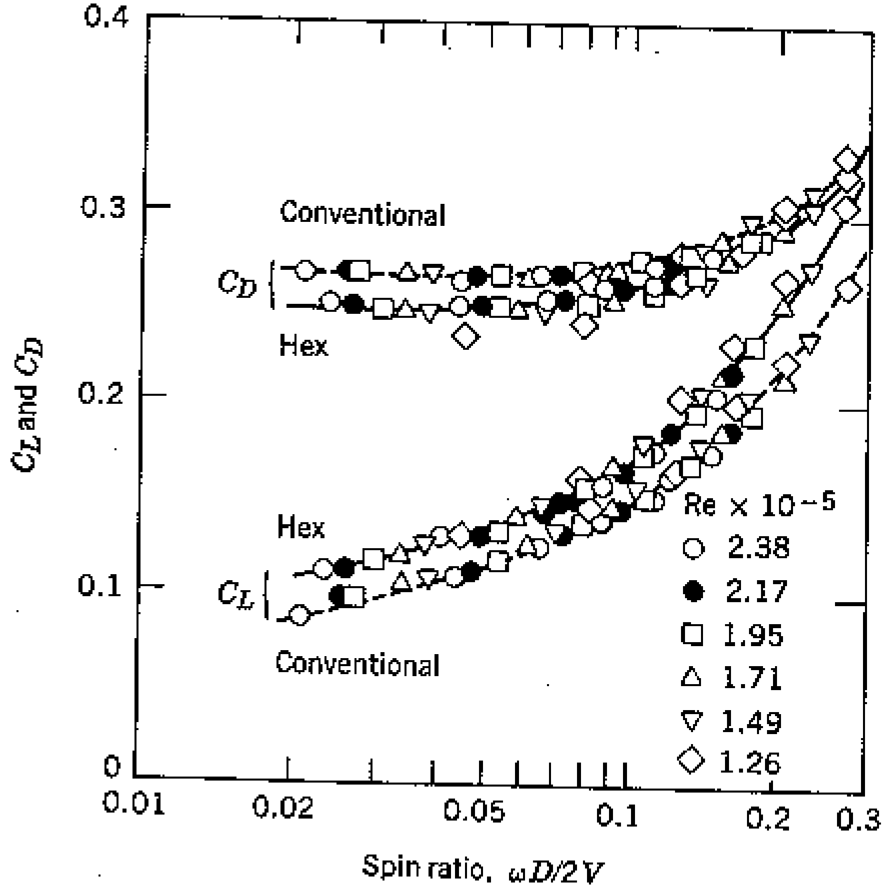


Fig. 9.29 Lift and drag of a rotating cylinder as a function of relative rotational speed: Magnus force. (Data from [32].)

Lift and Drag Coefficients of Golf Balls



Pressure Distribution on an Automobile

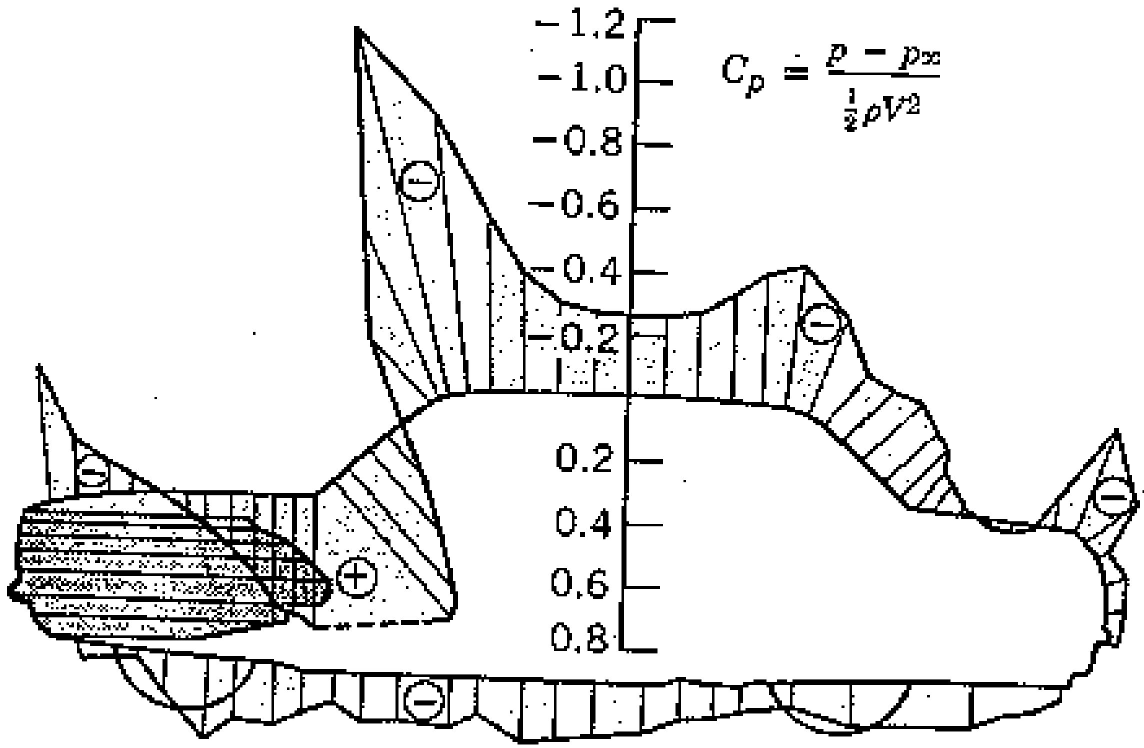


Fig. 9.25 Pressure distribution along the centerline of an automobile [28].