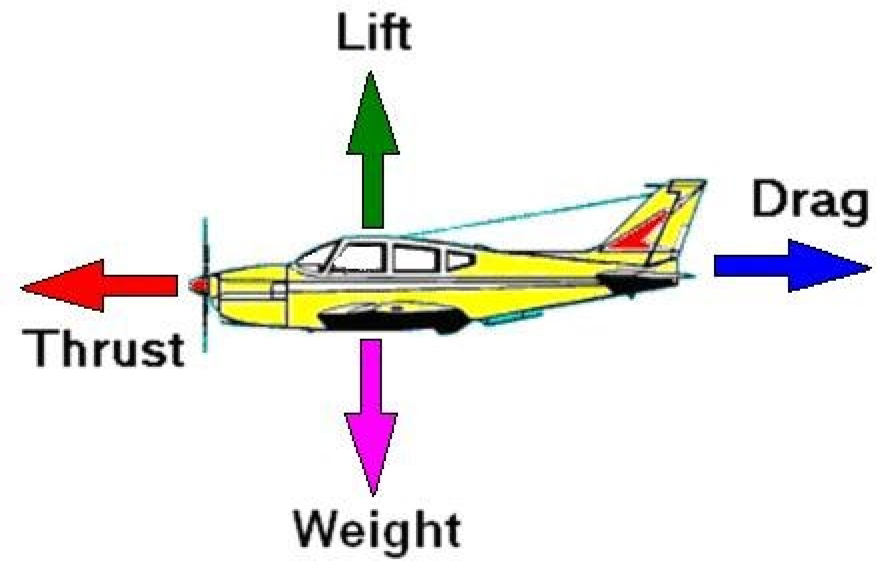
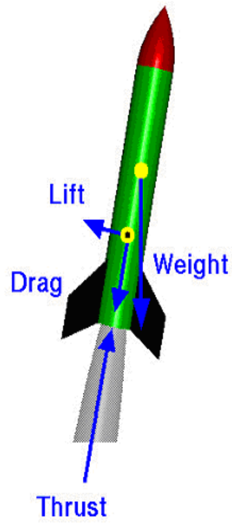
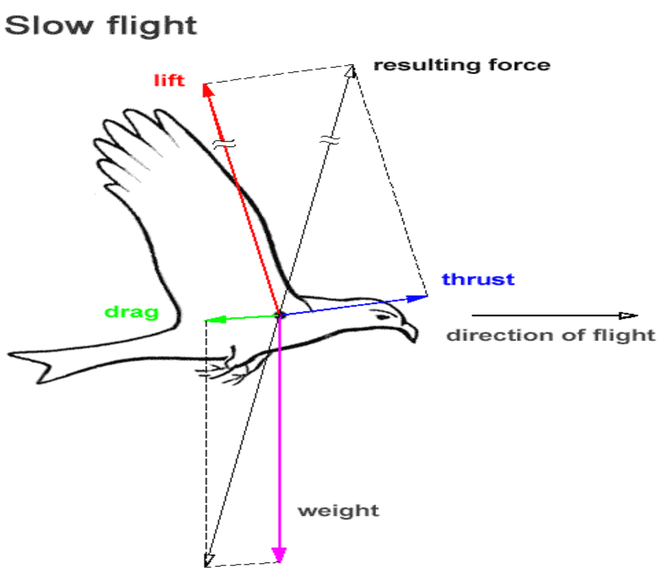




Chapter 9



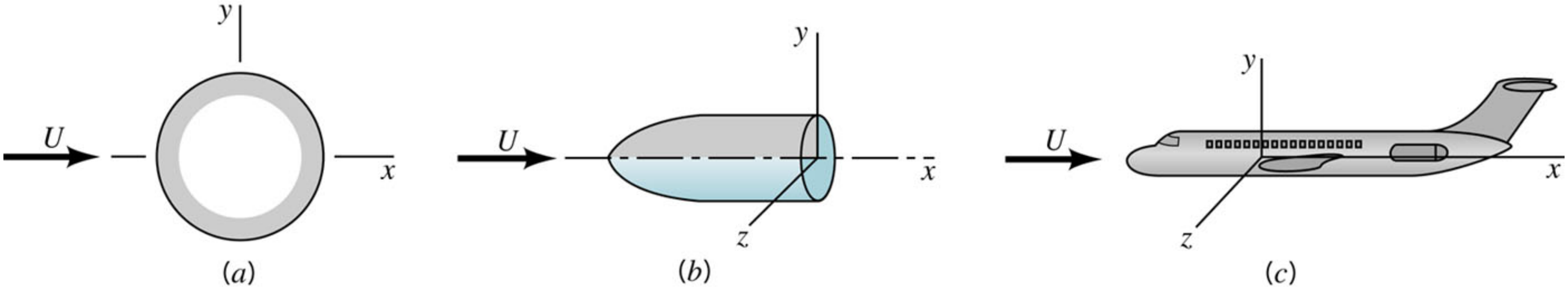
Flow Over Immersed Bodies

External Flow Characteristics

- Lift and Drag

Flow Over Immersed Bodies

- **General External Flow Characteristics**
  - **Two D Objectives: infinitely long of constant cross-section size and shape.**

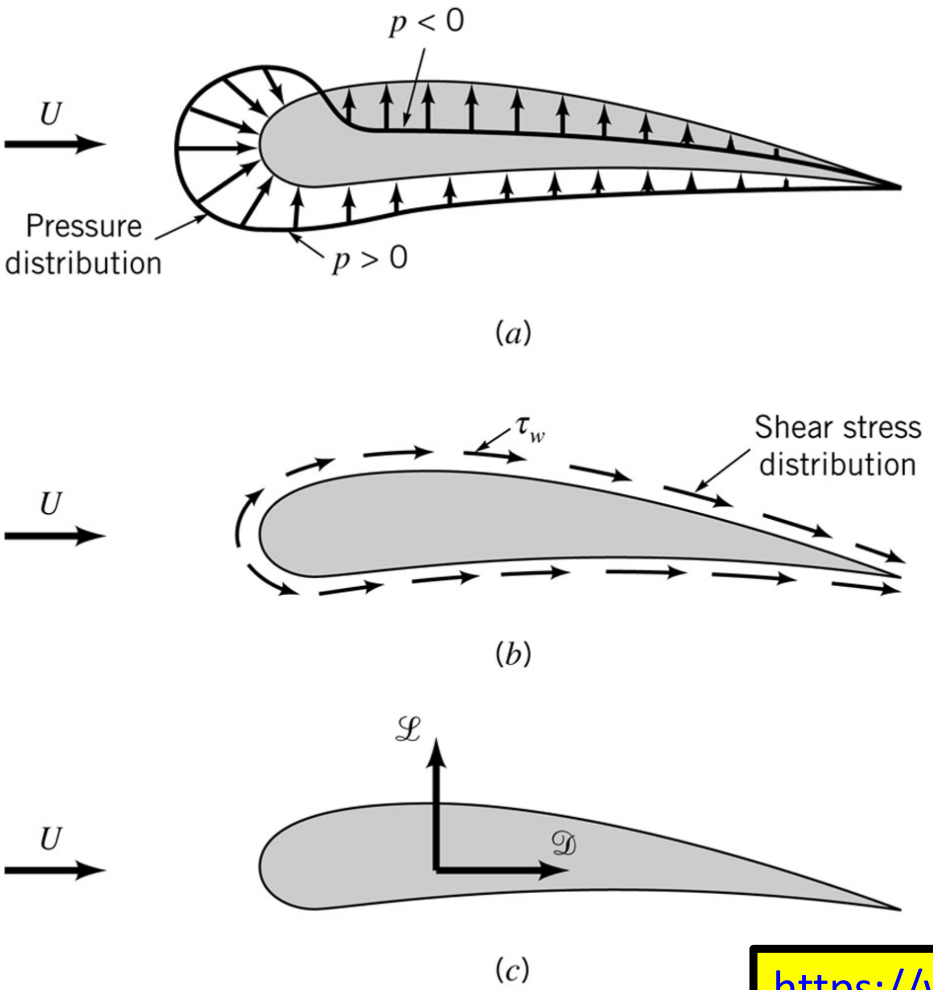


Flow Characteristics: (a) two-dimensional, (b) axisymmetric and (c) three-dimensional

The ease with which the flow can be described and analyzed often depend on the nature of the body in the flow as shown above. In practice however, there an be no truly 2D bodies as nothing extends into infinity.

Another class is streamlined (i.e., airfoils, racing cars) or blunt (i.e., parachutes, buildings).It is easier to force a streamlined body through a field than it is to force a blunt object through of same size.

Lift & Drag Concepts

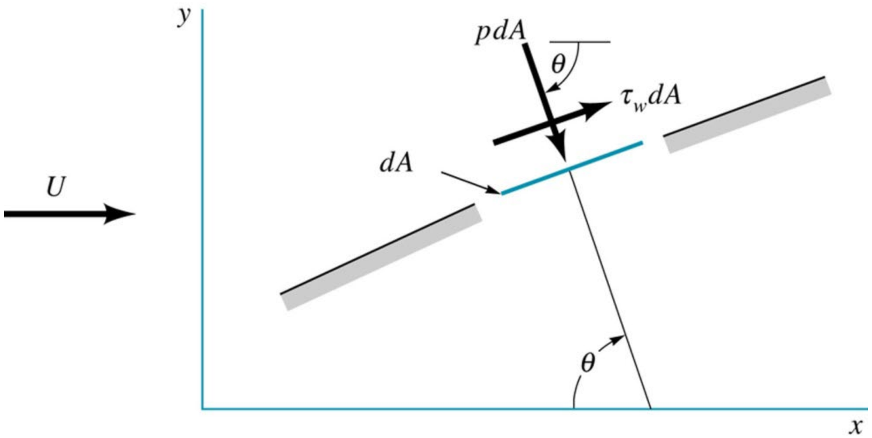


- **A body interacts with surrounding fluid through pressure and shear stresses**

https://www.youtube.com/watch?v=5ltjFEei3AI

Forces on a two-dimensional object: (a) pressure force, (b) viscous force and (c) resultant force (Lift & Drag)

Lift & Drag Concepts



- **Lift and Drag on a section of a body depend on the orientation of the surface**

Pressure and shear forces on a small element of the surface of a body

x and y components of the fluid force on the small area element dA are

$$dF_x = (pdA)\cos\theta + (\tau_w dA)\sin\theta; \qquad dF_y = -(pdA)\sin\theta + (\tau_w dA)\cos\theta$$

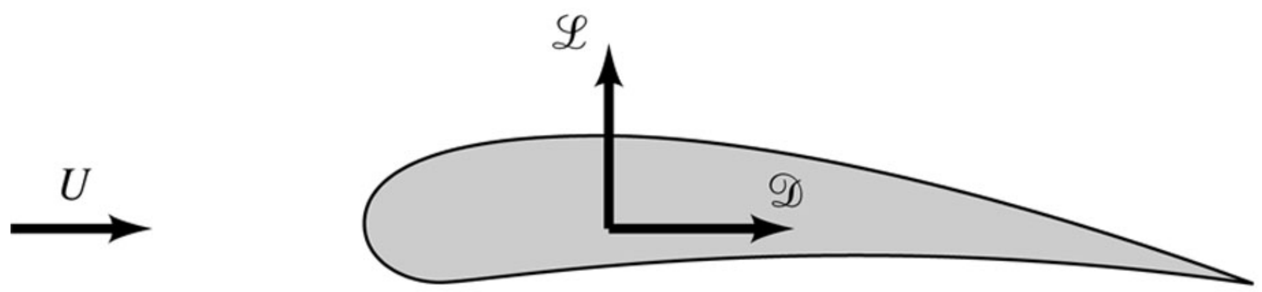
- **Lift and Drag Force**

$$Drag\ Force,\ F_D = \int dF_x = \int (pdA)\cos\theta + \int (\tau_w dA)\sin\theta;$$

$$Lift\ Force,\ F_L = \int dF_y = -\int (pdA)\sin\theta + \int (\tau_w dA)\cos\theta$$

Lift & Drag Concepts

- **Calculation of Lift & Drag**



$$Lift\ Force,\ F_L = \int_{bottom} P dA - \int_{top} p dA$$

$$Drag\ Force,\ F_D = \int_{top} \tau_w dA + \int_{bottom} \tau_w dA$$

- **Lift and Drag Coefficients**

$$Lift\ Coefficent,\ C_L = \frac{F_L}{1/2 \rho V^2 A};\quad Drag\ Coefficient,\ C_D = \frac{F_D}{1/2 \rho V^2 A}$$

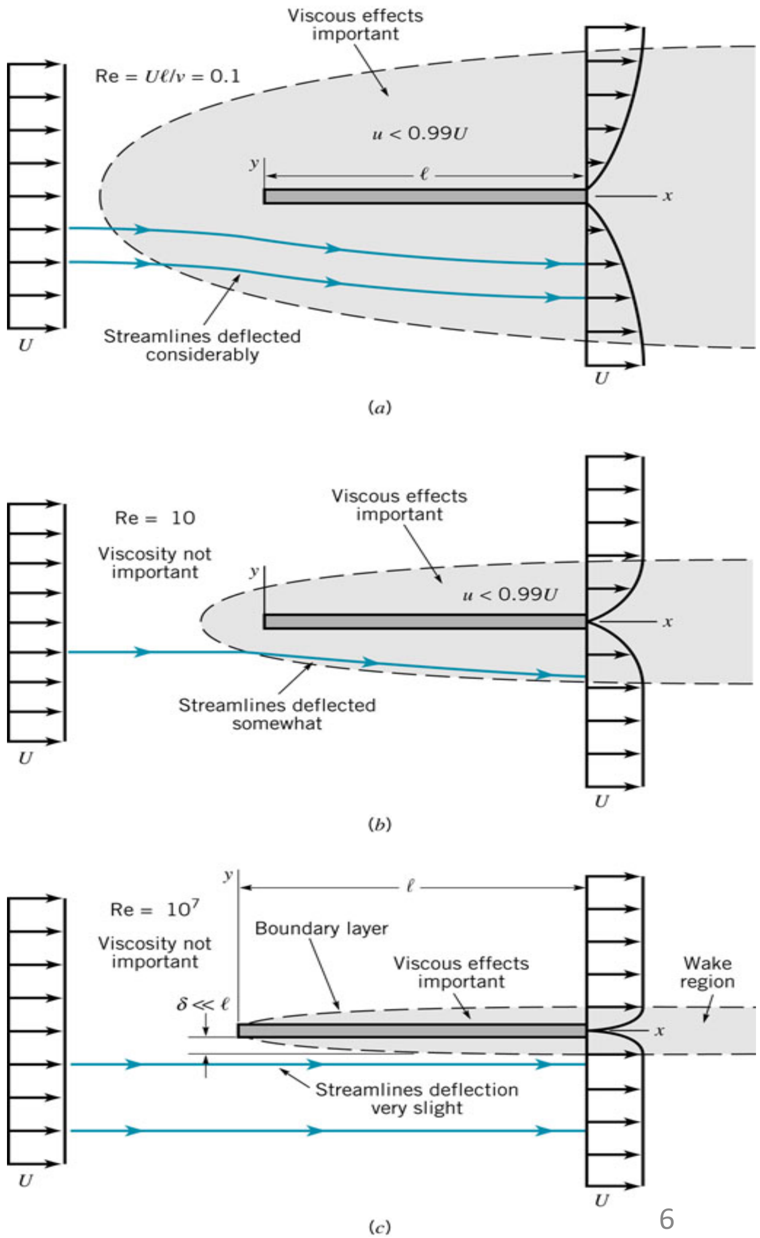
- **Lift Coefficient and Drag Coefficients are dimensionless forms of Lift and Drag**

Characteristics of Flow Past an Object

- **Characteristics of Flow Past an Object**

- **The characteristics of flow past an object is dependent on the value of the Reynolds Number**

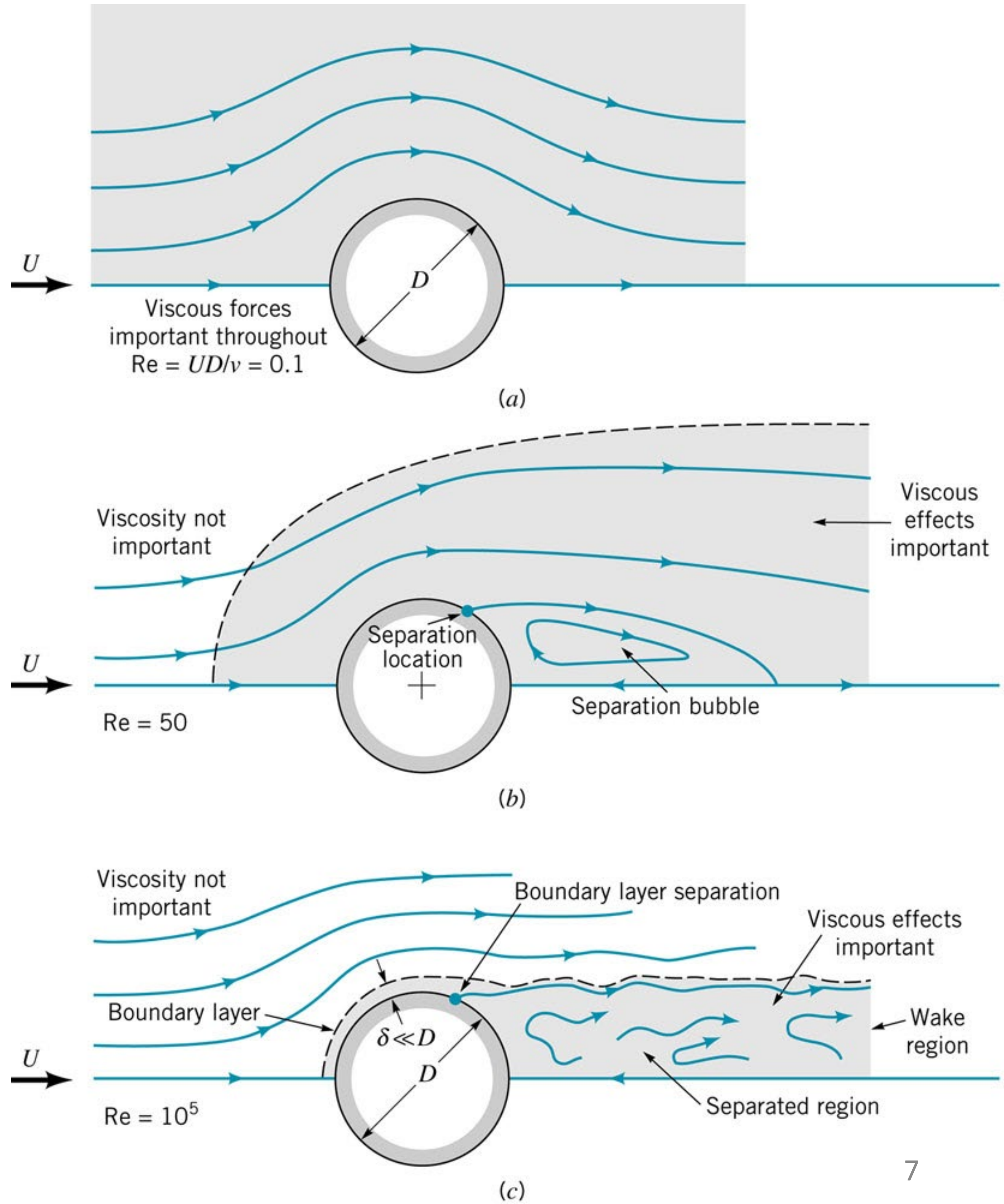
- **Figure: (a) low Reynolds number flow, (b) moderate Reynolds number flow and (c) large Reynolds number flow**



Characteristics of Flow Past an Object

- **Characteristics of Flow Past an Object**

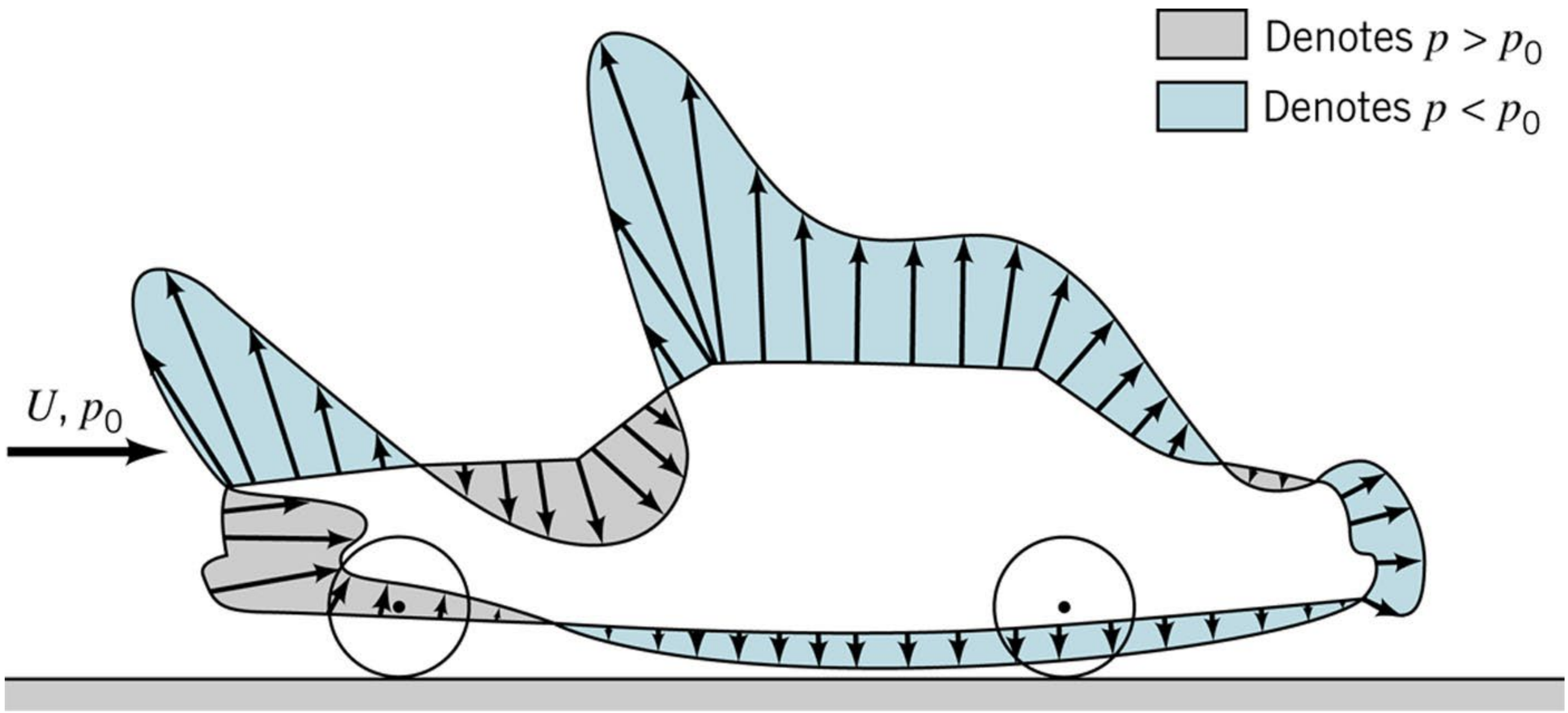
- **The characteristics of flow past an object is dependent on the value of the Reynolds Number**



- **Figure: (a) low Reynolds number flow, (b) moderate Reynolds number flow and (c) large Reynolds number flow**

Pressure Distribution over a Car

- **Characteristics of Flow Past an Object**



- **Figure:** **Pressure distribution over a mid-size car.**

Reduction of Drag and Increase Fuel Economy

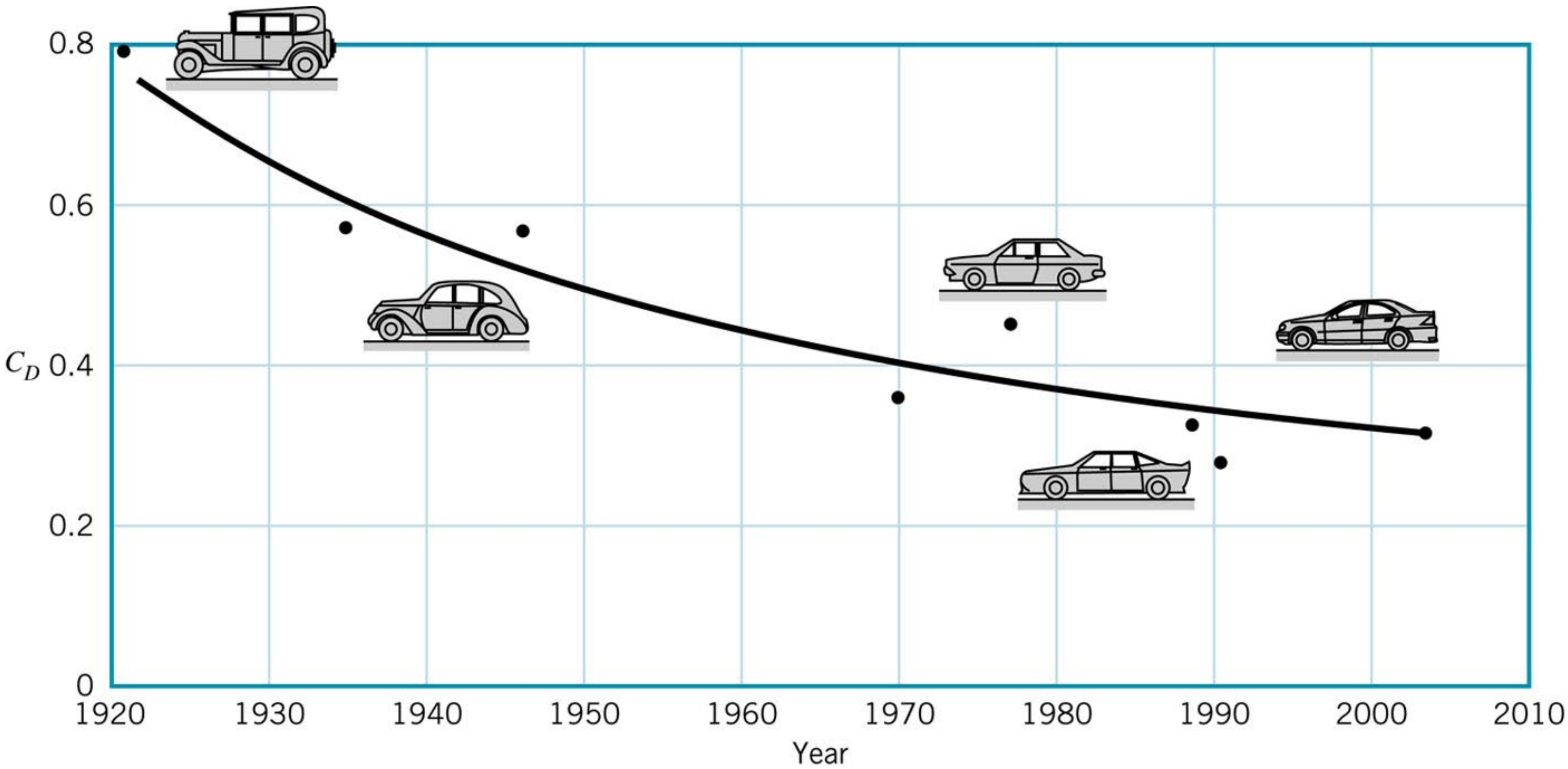
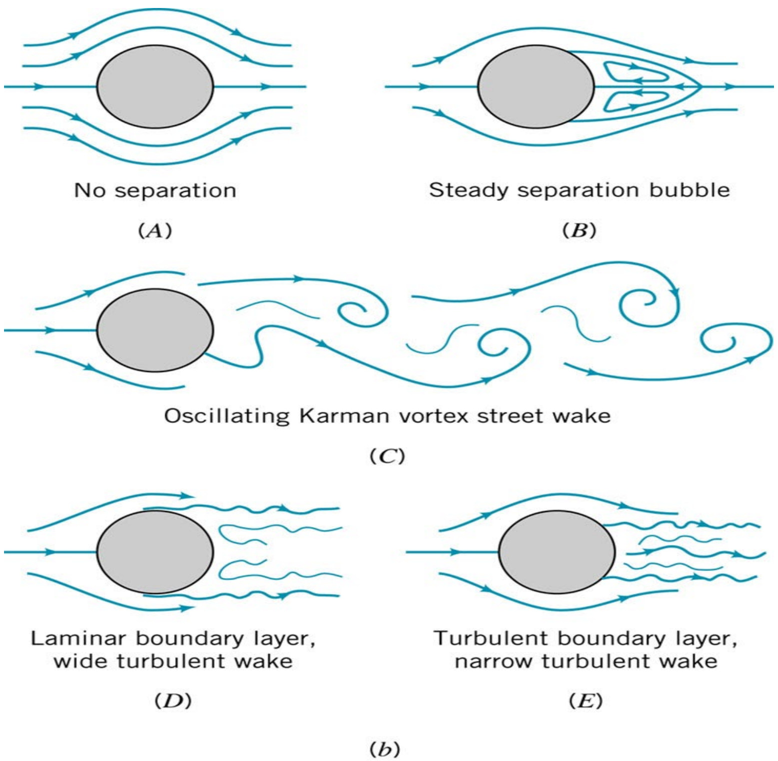


Figure: **The historical trend of streamlining automobiles to reduce their aerodynamic drag and increase their miles per gallon.**

VORTEX SHEDDING

Flow visualization, Separation and Wake formation

- **Flow over a circular cylinder and an Airfoil**



(a)

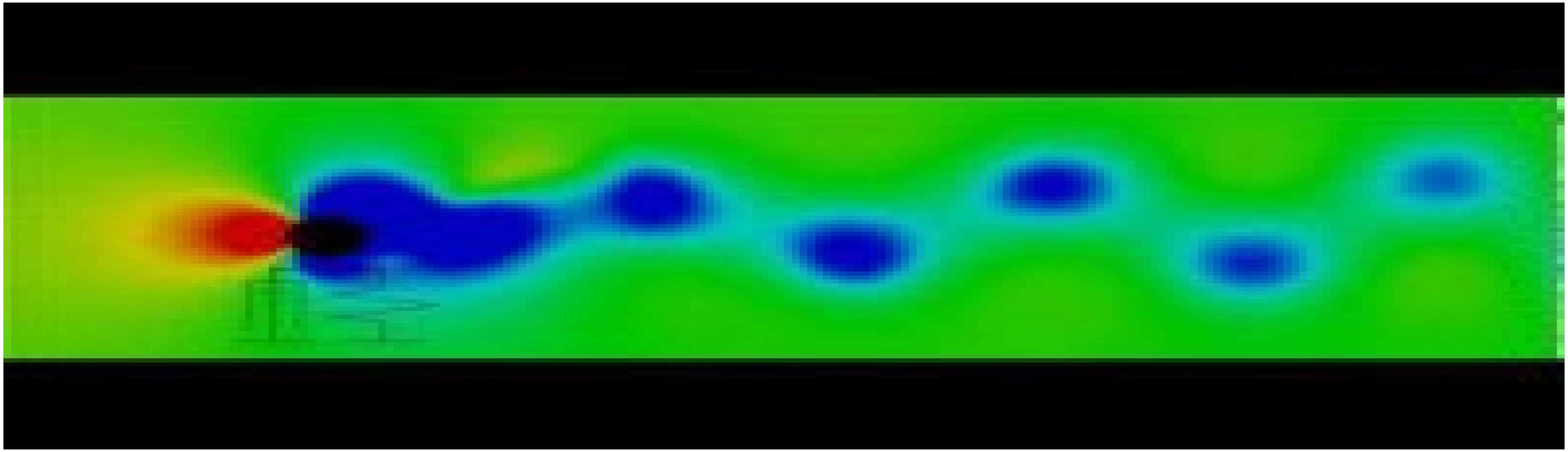
[Video Clip: (Aeroelastic Flutter)]

(b)

- **Figure: (a) flow over a circular cylinder and (b) flow past an airfoil**

Video Clip: https://www.youtube.com/watch?v=hrX11VtXXsU
Video Clip: https://www.youtube.com/watch?v=ttHn19QSGE4
Video Clip: https://www.youtube.com/watch?v=HwHQF0159X8

CLOSED LOOP CONTROL--Flow Induced Vibrations

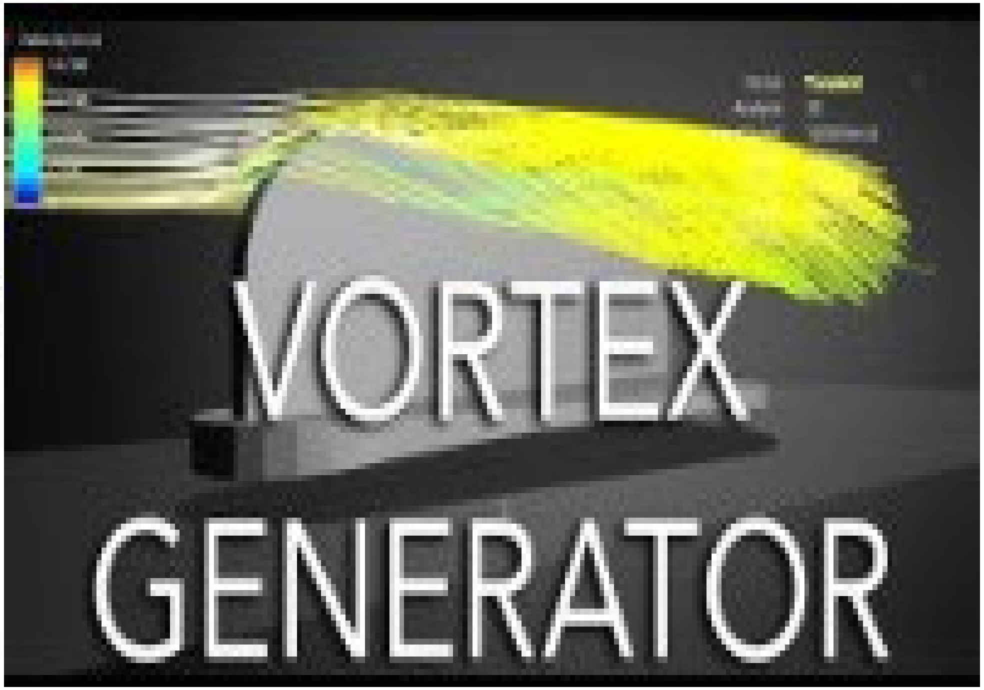


https://www.youtube.com/watch?v=cIBXAcZltTQ

Air Pressure Relationships

https://youtu.be/JivvuSYic5A

Vortex Generators



https://www.youtube.com/watch?v=eP-YUDe9HF0

Drag Coefficients for Different Geometries

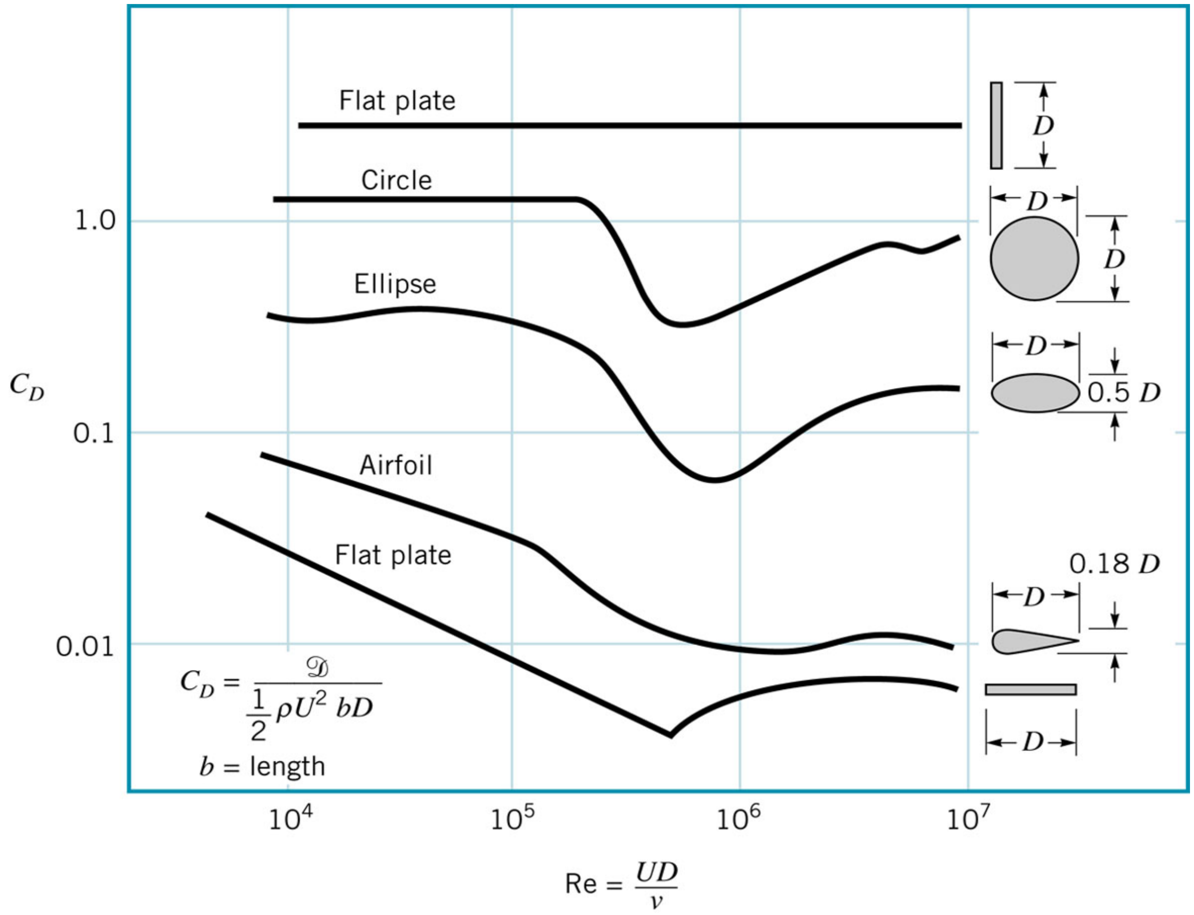


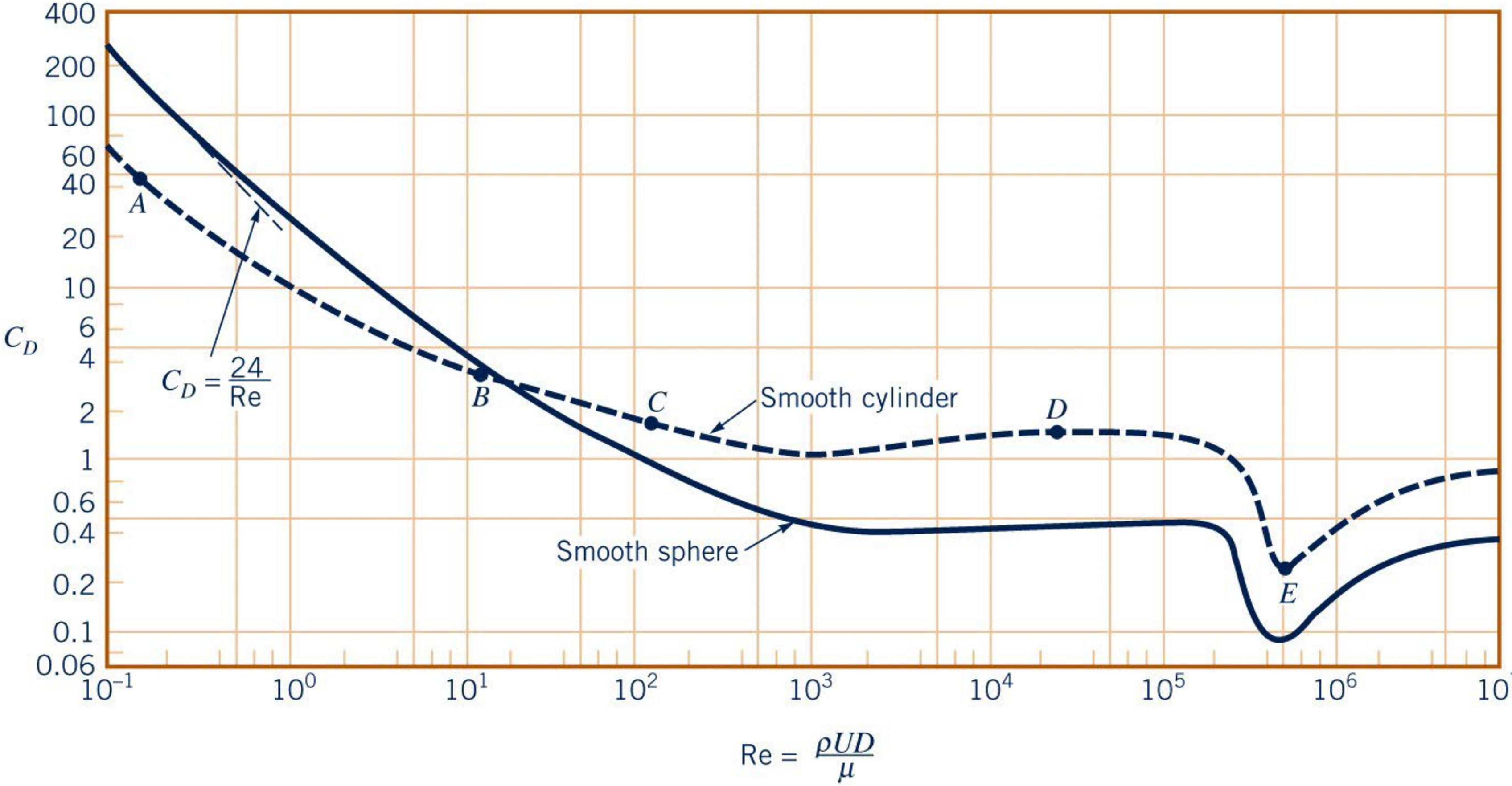
Figure: Variation of Drag for different geometries

$$Lift\ Coefficent,\ C_L = \frac{F_L}{1/2\rho V^2 A};$$

$$Drag\ Coefficient,\ C_D = \frac{F_D}{1/2\rho V^2 A}$$

$$Power[W] = FORCE[N] \bullet Velocity[m/s]$$

Smooth Cylinder and Sphere



(*a*)

Figure 9.21a

Drag Coefficients for Different Geometries

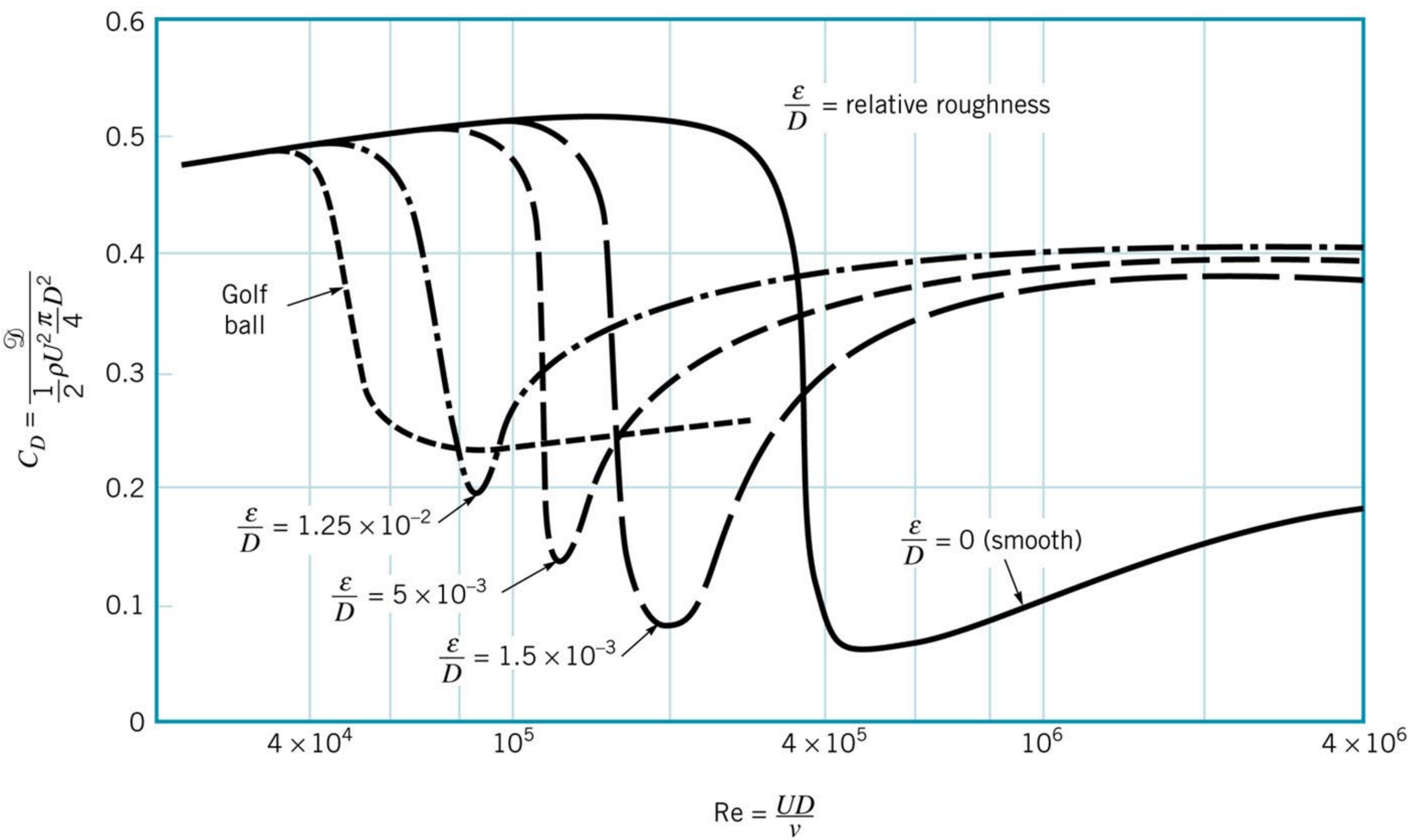


Figure: The effect of surface roughness on the Drag coefficient.

VORTEX SHEDDING and MOTH FLIGHT

https://youtu.be/0vLZVluPnOs

Example of Lift & Drag calculation

Problem # 9.38: The drag co-efficient of a newly designed hybrid car is predicted to be 0.21. The cross-sectional area of the car is 30ft^2. Determine the aerodynamic drag on the car when it is driven through still air at 55mph.

Solution: The aerodynamic drag can be determined by

$$Drag\left(F_D\right)=C_D\frac{1}{2}\rho V^2 A;\quad \text{V=55mph}\times\frac{\text{5280ft}}{\text{1mile}}\times\frac{\text{1h}}{\text{3600s}}=80.7\ ft/s$$

$$=\ (0.21)\left(\frac{1}{2}\right)\left(0.00238\,slugs/ft^3\right)\left(80.7\ ft/s\right)^2\left(30\,ft^2\right)$$

$$=48.8lb$$

Example of Lift & Drag calculation

Problem: **A Ping Pong ball is moving at 10m/s in air and is spinning at 100 rev/s in the clockwise direction which generates lift and drag co-efficient of 0.26 and 0.64 respectively (based upon projected area). The diameter of the ball is 3 cm. Calculate the lift and drag force. Assume the density of air is 1.2kg/m^3.**

Solution: The lift force is

$$F_L = C_L \frac{1}{2}\rho V^2 A$$

$$= (0.26)\left(\frac{1}{2}\right)\left(1.2\,kg/m^3\right)\left(10\,m/s\right)^2\left(\frac{\pi}{4}(0.03m)^2\right)$$

$$= 1.10\times10^{-2}\,N$$

Similarly, **the drag force is**

$$F_D = C_D \frac{1}{2}\rho V^2 A$$

$$= (0.64)\left(\frac{1}{2}\right)\left(1.2\,kg/m^3\right)\left(10\,m/s\right)^2\left(\frac{\pi}{4}(0.03m)^2\right)$$

$$= 27.1\times10^{-2}\,N$$

Example of Lift & Drag calculation

Problem: A bicyclist travels on a level path. The frontal area of the cyclist and bicycle is 2ft^2 and the drag co-efficient is 0.8. The density of the air is 0.075 lbm/ft^3. The physiological limit of power for this well-trained cyclist is 0.5hp. Neglect the rolling friction, **find the maximum speed of the cyclist**.

Solution: The power is the product of the drag force and the velocity. Therefore

$$P = F_D V = \left[\left(\frac{1}{2}\right) C_D \rho V^2 A\right] V$$

$$\Rightarrow V = \left(2P/\rho C_D A\right)^{1/3}$$

$$= \left[\frac{2\times 0.5hp\times\left(550\ ft.lb/s\right)/hp}{0.075\left(lbm/ft^3\right)\times\frac{1slug}{32.2lbm}0.8\times 2\,ft^2}\right]^{1/3}$$

$$= 52.8\ ft/s = 36.0mph$$

Example of Lift & Drag calculation

Problem: **A baseball is thrown by a pitcher at 95 mph through standard air. The diameter of the baseball is 2.82 in. Estimate the drag force on the baseball.**

$$D = C_D \frac{1}{2} \rho U^2 A$$

$$U = 95mph \frac{88 ft/s}{60mph} = 139.3 ft/s$$

$$\mathrm{Re} = \frac{UD}{\frac{\mu}{\rho}} = \frac{139.3 ft/s \frac{2.82 ft}{12}}{1.57x10^{-4} ft^2/s} = 2.09x10^5$$

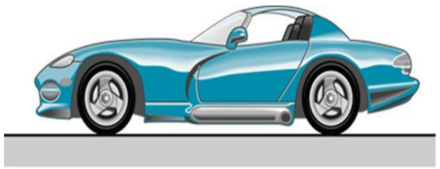
$$Fig.9.25 -> Smooth\ Sphere$$

$$C_D = 0.5$$

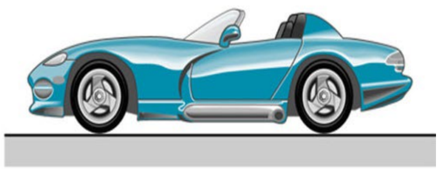
$$D = 0.50 lb$$

Example of Lift & Drag calculation

Problem: **The aerodynamic drag on a car depends on the "shape" of the car. For example, the car shown in the Figure below has a drag coefficient of 0.35 with the windows and roof closed. With the windows and roof open, the drag coefficient increases to 0.45. With the windows and roof open, at what speed is the amount of power needed to overcome aerodynamic drag the same as it is at 65mph with the windows and roof closed? Assume the frontal area remains the same. Recall that power is force times velocity.**



Windows and roof closed: $C_D = 0.35$



Windows open; roof open: $C_D = 0.45$

Solution: **The power is the product of the drag force and the velocity. Therefore,**

$$P = F_D \times V$$

$$F_D = \left(\frac{1}{2}\right) C_D \rho V^2 A$$

Now

$$P_{open} = P_{closed}$$

$$\Rightarrow F_{D|_{open}} \times V_o = F_{D|_{closed}} \times V_c$$

$$\Rightarrow \left(\frac{1}{2}\right) C_{Do} \rho V_o^3 A_o = \left(\frac{1}{2}\right) C_{Dc} \rho V_c^3 A_c; \quad A_o = A_c = same\ frontal\ surface$$

$$\Rightarrow V_o = V_c \left(\sqrt[3]{\frac{C_{Dc}}{C_{Do}}}\right) = 65 mph \left(\sqrt[3]{\frac{0.35}{0.45}}\right) = 59.8 mph$$

Example of Lift & Drag calculation

Problem: **A regulation football is 6.78 inch in diameter and weighs 0.94lb. If its drag coefficient is C_D = 0.2 (based upon projected area), determine its *deceleration* if it has a speed of 20ft/s at the top of its trajectory.**

Solution: **Newton's 2nd law of motion:**

$$F_D = ma; \qquad m_{SOLID} = \frac{w}{g} = \frac{0.94lb}{32.2\ ft/s^2} = 0.0292slugs$$

$$F_D = \left(\frac{1}{2}\right) C_D \rho_{AIR} V^2 A = 0.5 \times 0.2 \times 0.0238\ slugs/ft^3 \times (20\ ft/s)^2 \times \pi/4 (6.78/12\ ft)^2$$

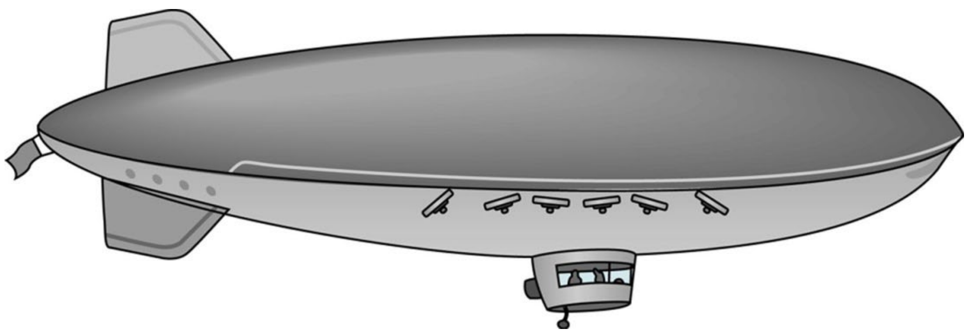
$$\Rightarrow F_D = 0.0239lb$$

Hence

$$a = \frac{F_D}{m} = \frac{0.0239lb}{0.0292slugs} = 0.8187\ ft/s^2$$

Example of Lift & Drag calculation

Problem: **The blimp shown in the Figure below is used at various athletic events. It is 128ft long and has a maximum diameter of 33ft. If its drag coefficient (based on the frontal area) is 0.06, estimate the power required to propel it (a) at its 35mph cruising speed, (b) at its maximum 55mph speed.**



Solution: **The power is the product of the drag force and the velocity. Therefore,**

$$P = F_D \times V$$

$$F_D = \left(\frac{1}{2}\right) C_D \rho V^2 A$$

Now

$$P = \left(\frac{1}{2}\right) C_D \rho V^3 A = 0.5 \times 0.060 \times \left(0.0238\, slugs/ft^3\right) V^3 \times \frac{\pi}{4} \left(33\, ft\right)^2$$

$$\Rightarrow P = 0.0611 V^3\ slugs/ft$$

$$(a) Now\ with\ V = 35\, mile/hour \times 1 hour/3600 s \times 5280\, ft/1 mile = 51.3\ ft/s$$

$$P = 0.0611\, slugs/ft \times \left(51.3\ ft/s\right)^3 \times 1 hp/\left(550\ ft.lb/s\right) = 15.0 hp$$

$$(b)(a) Now\ with\ V = 55\, mile/hour \times 1 hour/3600 s \times 5280\, ft/1 mile = 80.7\ ft/s$$

$$P = 0.0611\, slugs/ft \times \left(80.7\ ft/s\right)^3 \times 1 hp/\left(550\ ft.lb/s\right) = 58.4 hp$$

Example of Lift & Drag calculation

- A 2-mm diameter meteor of specific gravity 2.9 has a speed of 6 km/s at an altitude with an air density of 1.03x10-3 kg/m3. If the drag coefficient is 1.5 (based upon surface area), determine the deceleration of the meteor. (Volume sphere = $\frac{4}{3}\pi r^3$; Area sphere = $4\pi r^2$)

$$F \rightarrow \text{Drag Force} \rightarrow \mathrm{F}_D = ma$$

$$m \rightarrow mass$$

$$m = \rho \bullet Volume$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 A}$$

$$D = 2mm$$

$$Sg = 2.9$$

$$U = 6km/s$$

$$\rho_{air} = 1.03x10^{-3} kg/m^3$$

$$a \rightarrow \text{decleration} = \frac{\mathrm{F}_D}{mass} = \frac{C_D \bullet \frac{1}{2}\rho_{air} U^2 A}{\rho_{sphere} \bullet Volume} \rightarrow \frac{N}{kg} \rightarrow \frac{\cancel{kg} - m/s^2}{\cancel{kg}}$$

$$a = \frac{\mathrm{F}_D}{m} = \frac{C_D \bullet \frac{1}{2} \bullet \rho_{air} \bullet U^2 \pi r^2}{\rho_{sphere} \bullet 4\pi r^3} = \frac{C_D \bullet \frac{1}{2} \bullet \rho_{air} \bullet U^2}{4\rho_{sphere} \bullet r},$$

$$\rho_{sphere} = 2.9\rho_{H_2 0}$$

$$a = \frac{\mathrm{F}_D}{m} = \frac{1.5 \bullet \frac{1}{2} \bullet 1.03x10^{-3} \bullet 6,000^2}{(2.9 \bullet 1000) \bullet 4 \bullet 1/1000} = 2.4x10^3 \frac{m}{s^2}$$