## Boundary Layers in a Pressure Gradient

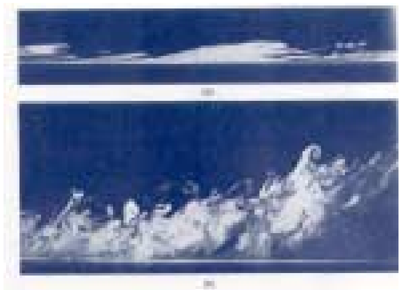


Figure from
Potter & Wiggert 1997

## External Flows

## Skin Friction vs. Pressure Drag

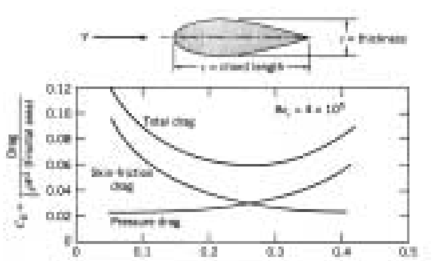
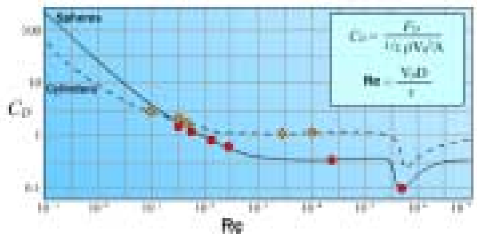



**Fig. 6.14** Drag coefficient on a streamlined strut as a function of thickness ratio, showing contributions of skin friction and pressure to total drag (19).

Figure from Fox et al. 2004

## Drag on Sphere & Cylinders

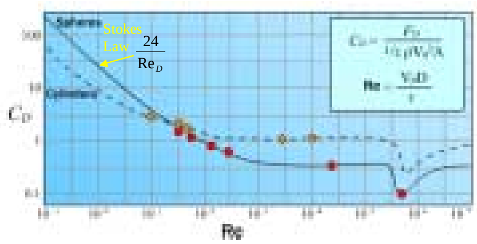
Cylinders & Spheres: Prior to separation both components of drag can be significant.




See MM Video

## Drag

Cylinders & Spheres: Prior to separation both components of drag can be significant.




See MM Video

## Drag

Cylinders & Spheres: Prior to separation both components of drag can be significant.

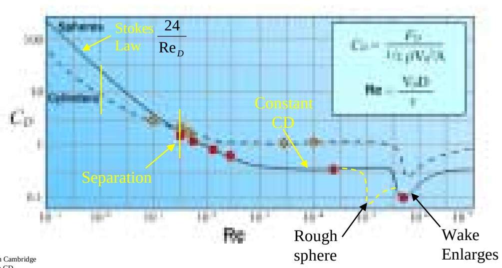
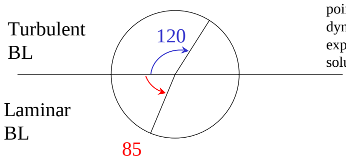



Figure From Cambridge Multi-media CD

# Sphere Flow Separation

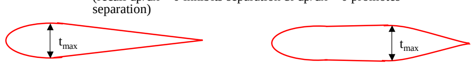



Can not determine Separation point analytically (as it may move dynamically), we must use experiments or numerical solutions to N-S equations

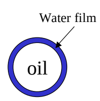
See MM Video

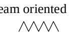
# Method of Drag Reduction

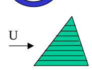
1. Streamlining – reduce pressure drag - reduce regions of dp/dx > 0 (either in size or magnitude) – prevent separation
   - i. Add fairings – prevent buffeting & vortex shedding
   - ii. Contour leading or Trailing edges – for struts, columns, etc
   - iii. For Airfoils – move position of maximum thickness rearward (recall dp/dx < 0 inhibits separation & dp/dx > 0 promotes separation)




2. Reducing Friction Drag
   1. Oil pipeline – introduce a thin film of water around edge of pipe – oil rides over low viscosity water ~ reduces drag ~60%
   2. Vee-Groove micro Riblets – stream oriented and are effective at reducing drag ~8%
   3. Large Eddy Breakup Devices – reduces local friction ~10%

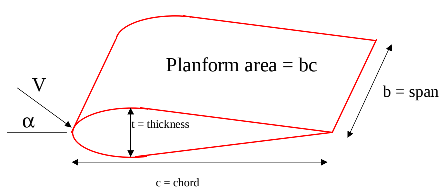




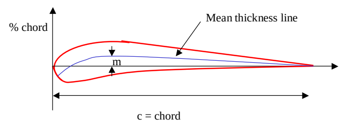

3. Biological Drag Reduction – trees & leaves

# Airfoils - Symmetric




Symmetric Airfoils have no lift at $\alpha = 0$

## Airfoils - Cambered




Cambered Airfoils have lift at $\alpha = 0$

Naming Convention:

NACA 4-digit Series: Example NACA 0012

Distance from leading edge to the location of max camber in tenths of the chord

Max value of mean-line ordinate in % chord

Max Section thickness in % chord

## Lift Force

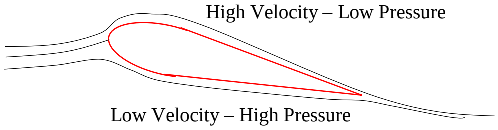
- The purpose of an airfoil is to generate a Force normal to the approach velocity – Lift Force - $F_L$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty^2 A_P}$$

- Lift is generated by an imbalance in pressure along the upper and lower surfaces

$$F_L = \int (p \sin\alpha) dS$$

High Velocity – Low Pressure



Low Velocity – High Pressure

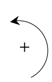
## Lift Force – Circulation - $\Gamma$

Path Dependant

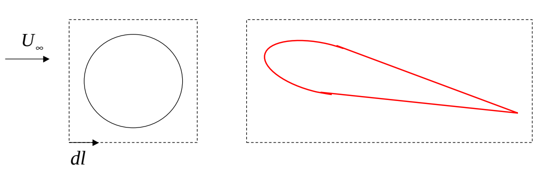
$$\frac{F_L}{L} = -\rho U_\infty \Gamma$$

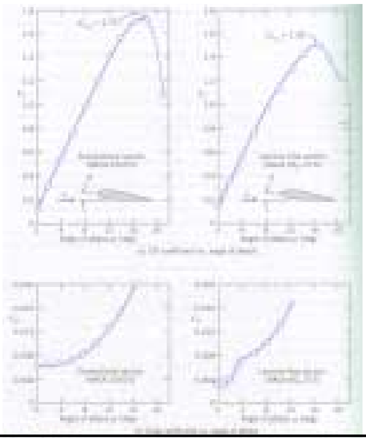
$$\Gamma = \oint_l \vec{V} \bullet d\vec{l} = \int_A (\vec{\omega} \bullet \hat{n}) dA$$

$$d\vec{l} = dx\hat{i} + dy\hat{j} + dzi\hat{k}$$




Example Problems:





Lift/Drag Tradeoff

Figure 9.17 from Fox et al. 2004

## Symmetric Airfoil Pressure Distributions

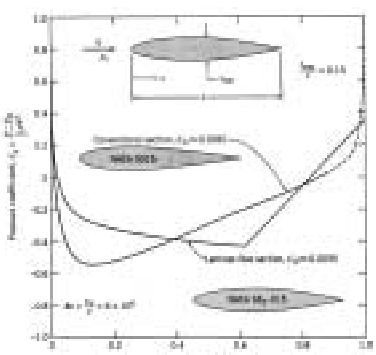


Figure from Fox et al. 2004