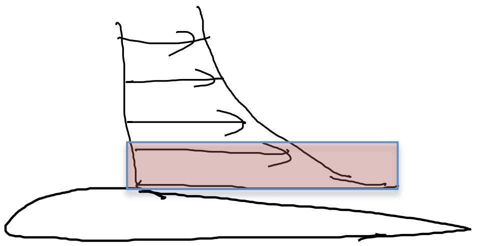
Chapter 7: Flow Past Immersed Bodies

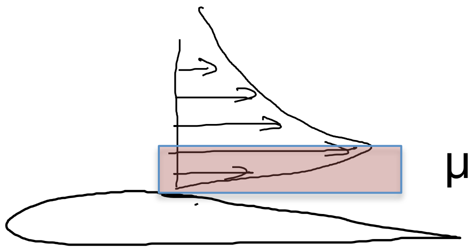
Intro

Resolving D'Alembert's Paradox

- Two missing pieces of physics
  - No fluid has $\mu=0$ exactly
  - Because of no-slip condition, V=0 on body



Ideal Fluid
Velocity Profile



$\mu\, du/dy$ is important here

Real Fluid
Velocity Profile

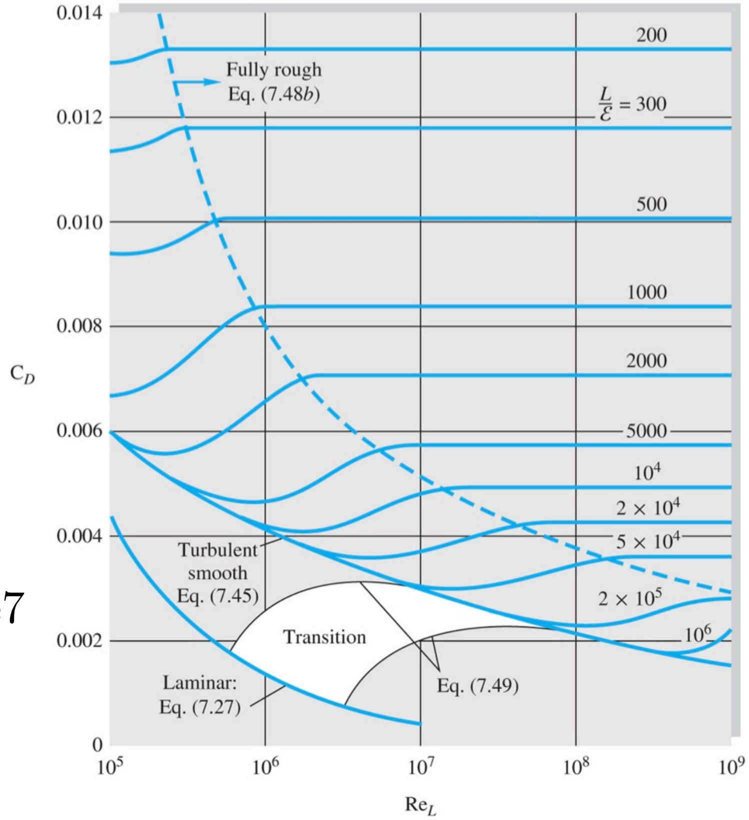
Note the "outer flow" is still correct!
(Chapter 8 -> Calculate Outer Flow)

Other Effects on Drag: Roughness

- Look familiar?

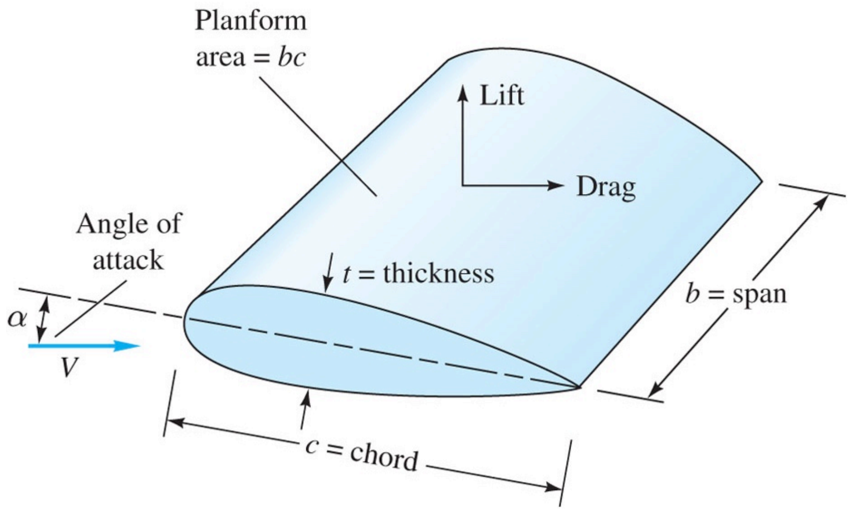
- Transition region
- Suggested Formula

$$C_D = 1.328 Re_L^{-1/2} \text{ for } \mathrm{Re}_L < 5e5$$
$$C_D = 0.031 Re_L^{-1/7} - 1440 Re_L^{-1} \text{ for } 5e5 < \mathrm{Re}_L < 1e7$$
$$C_D = 0.031 Re_L^{-1/7} \text{ for } \mathrm{Re}_L > 1e7$$



Airfoil Terminology

- C_D is based on ***Planform Area***
- Chord length = length from front to back
- Span = side-to-side
- Angle-of-attack = tilt



Airfoils: Terminology

- Camber = asymmetry w.r.t chord line
- NACA airfoil numbers
  - NACAXYZZ (ex. NACA0030)
  - X = max chamber (in % of chord)
  - Y = location of max camber (% chord x 10)
  - ZZ = maximum thickness (% chord)
  - Example NACA 2412 Airfoil means
    - 2% maximum camber @ location 40% from front
    - 12% maximum thickness
  - Example NACA 0030 Airfoil (Thule AeroBar)
    - Symmetric airfoil (0% camber)
    - Max. thickness = 30% of chord length
- Standardized shapes to use (i.e. $y_{top}(x/c)$, $y_{bottom}(x/c)$ based on the XYZZ designation.
- Other (more complicated) NACA designations are avialable, too.

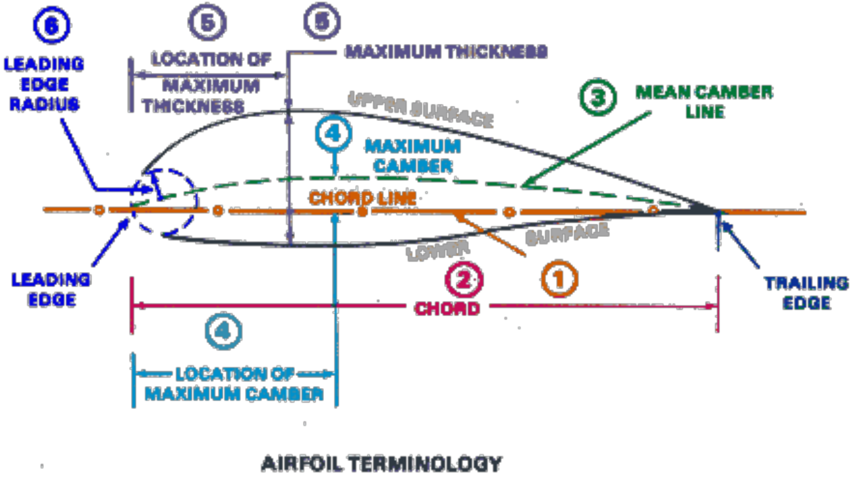


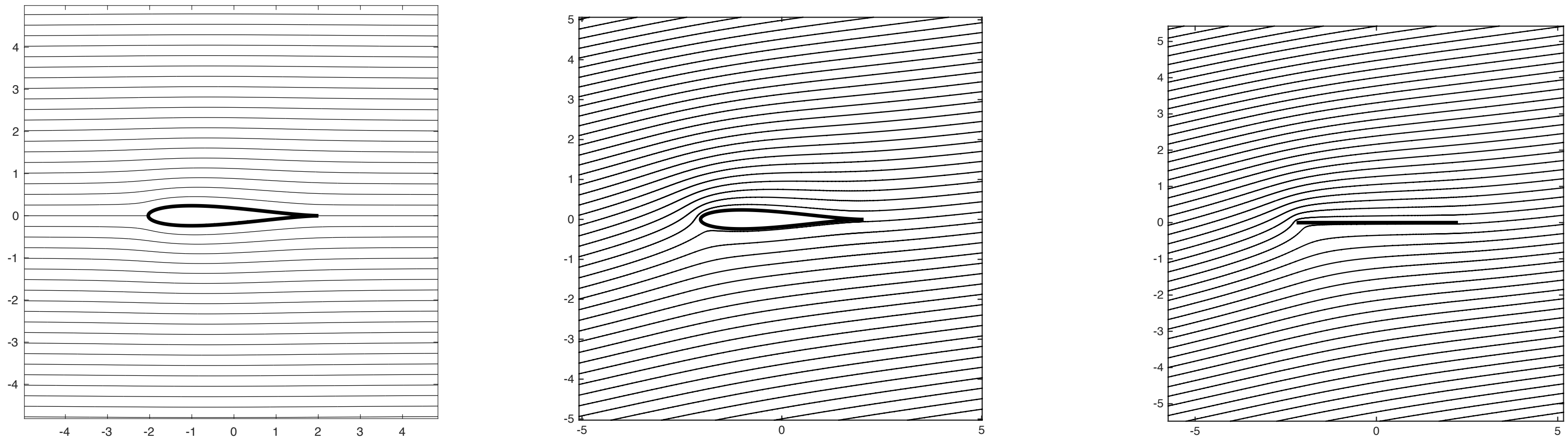
Diagram from dynamicflight.com

Lift for Thin Symmetric Airfoils

$$C_L = 2\pi\alpha$$

Angle of attack (in radians!)

Flow Profiles from Potential Flow Theory (Chapter 8)

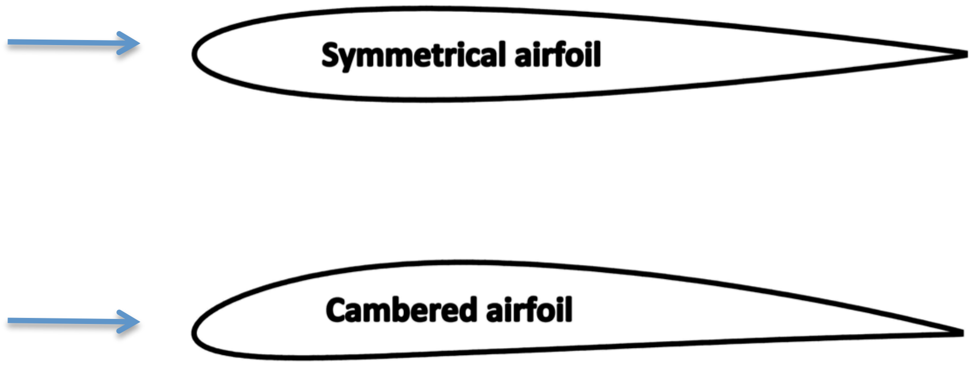


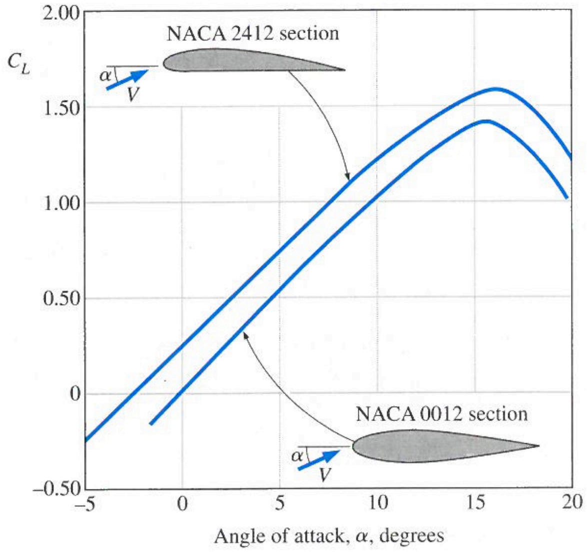
Lift for Thin ***Asymmetric*** Airfoils

$$C_L = 2\pi\alpha + \beta$$

Offset (usually ~2*(h/camber))

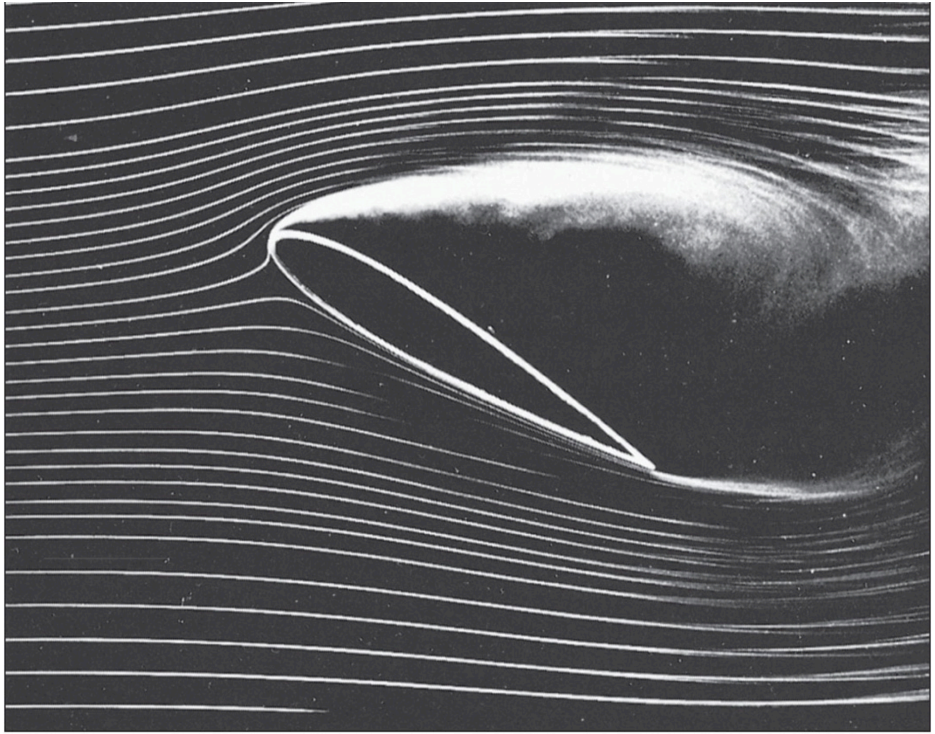
Angle of attack (in radians!)





Flow Separation and Stall

- At high angle of attack, flow streamlines “separate” from the airfoil
- Results in suddedn loss of lift, increase in decrease



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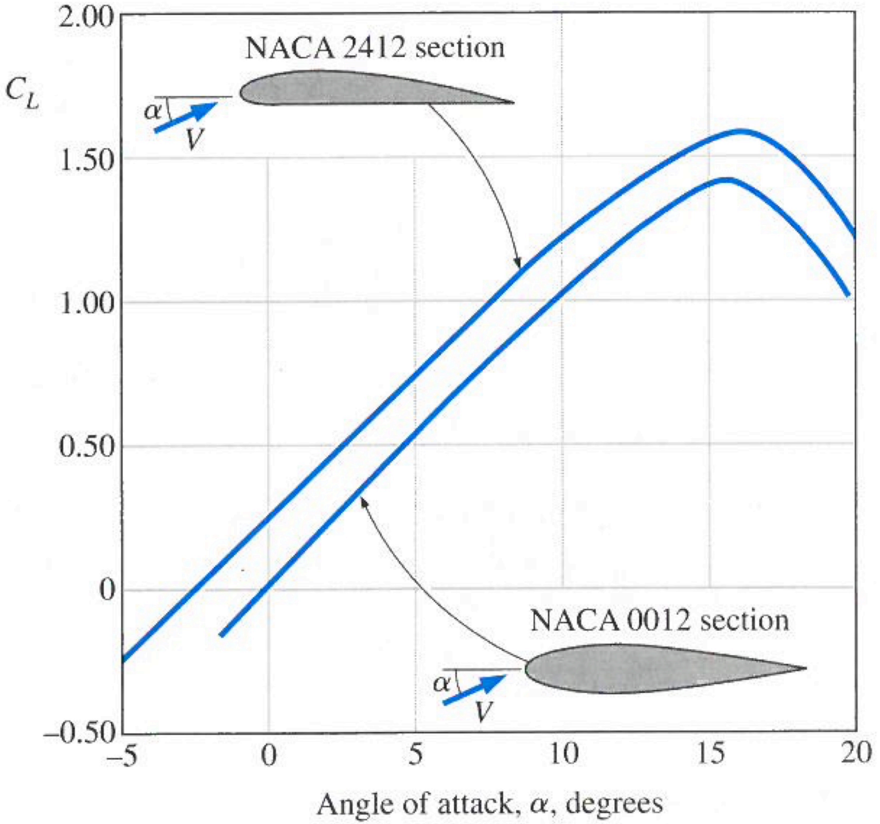
Flow Separation & Stall

- Max Lift Coefficient implies min. flight speed
- Called "Stall" Speed

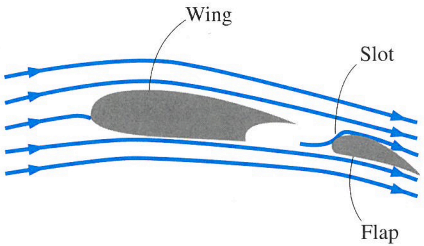
$$C_{L,\max} = \frac{L}{1/2\rho V_{\text{stall}}^2 A_{\text{planform}}}$$

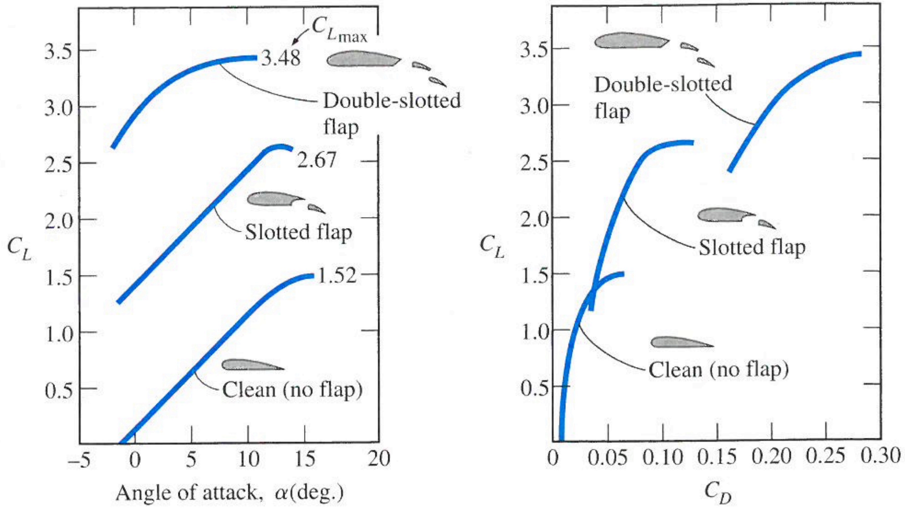
$$V_{\text{stall}} = \sqrt{\frac{L}{1/2\rho C_{L,\max} A_{\text{planform}}}}$$



Slots and Flaps

- Designed to raise the max lift coefficient/ reduce stall speed.
- Penalty: Increased Drag

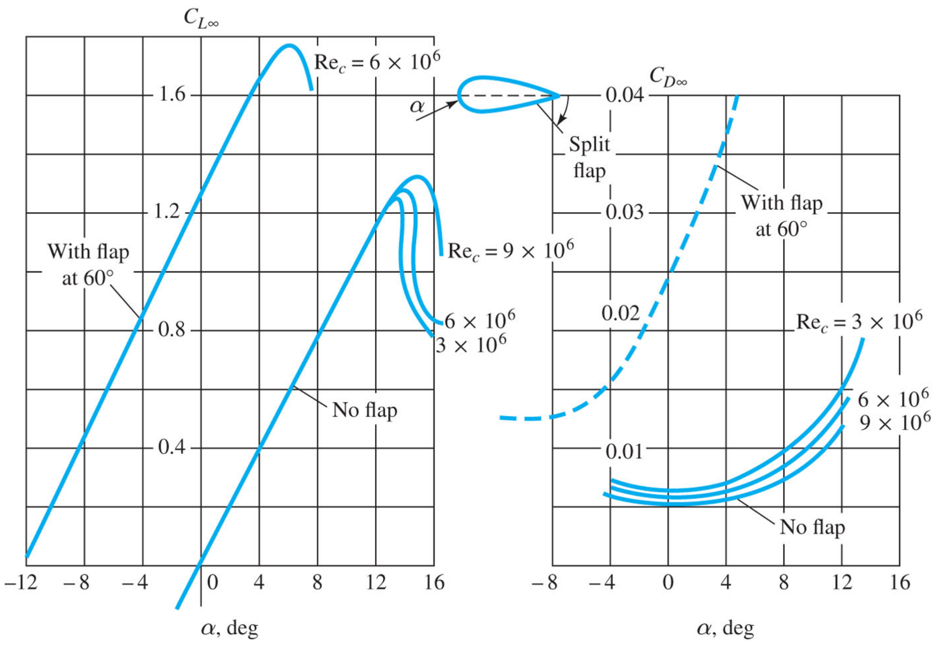




From Abbott and von Doenhoff, for NACA 23012 (1959).

Airfoil Drag

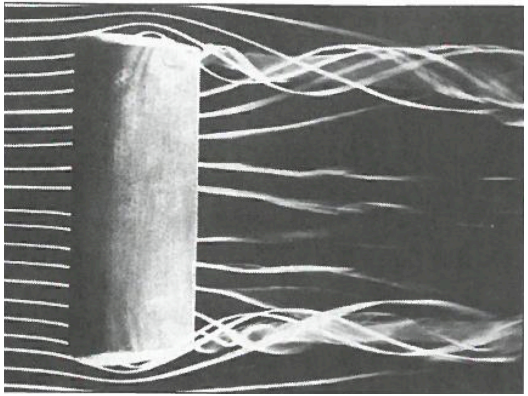
- At Zero Angle of Attack simililar to a flat plate
- At Angles before stall drag increases somewhat (minor flow separation near rear of wing)
- At stall angle, C_D shoots up suddenly (not shown)



Airfoil Theory: 3D Effects

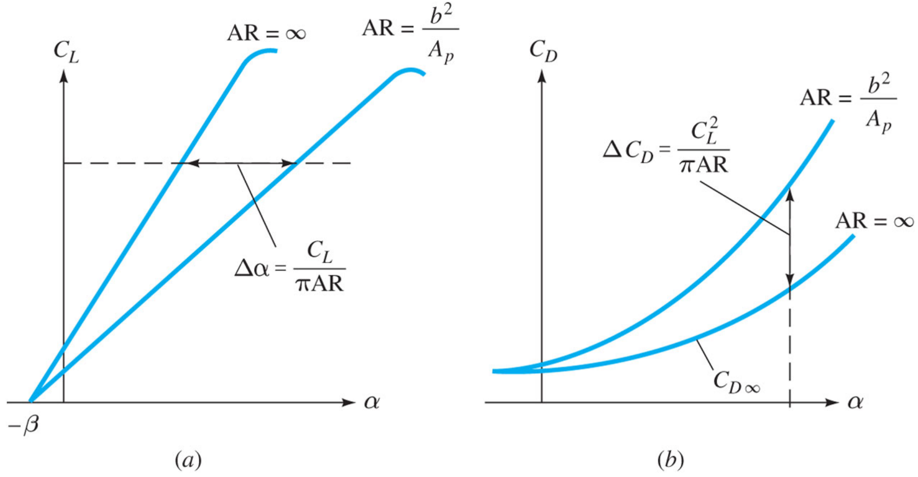
- All previous graphs are for infinitely long wings
- Pressure difference **induces** flow around wing
- Creates both loss of lift and an extra drag component
  - Called **Induced Drag**
- Magnitude depends on Aspect Ratio (AR)

$$AR \equiv \frac{\text{span}}{\text{chord}}$$



Induced Lift and Drag

$$AR \equiv \frac{\text{span}}{\text{chord}}$$



$$\boxed{C_L \approx C_{L,\infty} \frac{1}{1 + 2/\mathrm{AR}}}$$

$$\boxed{C_D \approx C_{D,\infty} + \frac{C_L^2}{\pi \mathrm{AR}}}$$

<u>Mitigation</u>