Boundary Layers in a Pressure Gradient

External Flows

Skin Friction vs. Pressure Drag
Drag on Sphere & Cylinders

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

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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.

Turbulent BL

Laminar BL

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 seaward (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
Max value of mean-line ordinate in % chord
Distance from leading edge to the location of max camber in tenths of the 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 $F_L$

\[ C_L = \frac{F_L}{\frac{1}{2} \rho U^2 A} \]

- 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

\[ \frac{F_L}{L} = -\rho U \cdot \Gamma \]

\[ \Gamma = \int \nabla \cdot dl = \iint (\nabla \cdot \vec{A}) dA \]

\[ dl = dx \hat{i} + dy \hat{j} + dz \hat{k} \]

Example Problems:
Figure 9.17 from Fox et al. 2004

Lift/Drag Tradeoff

Symmetric Airfoil Pressure Distributions

Figure from Fox et al. 2004