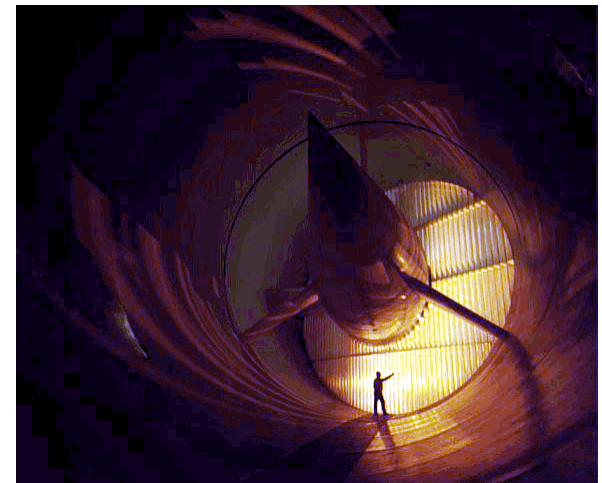
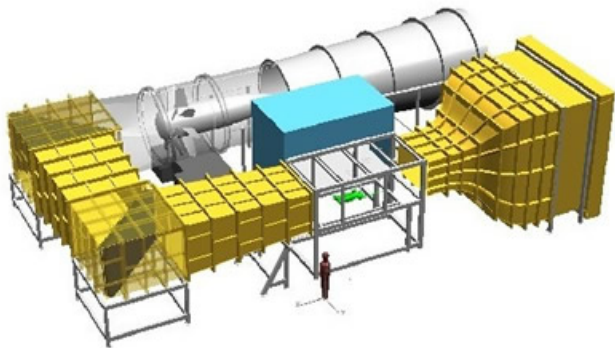




The E80 Wind Tunnel Experiment

the experience will blow you away

by
Professor Duron
Spring 2012



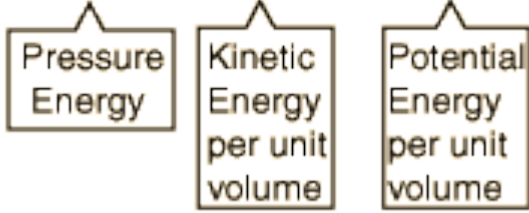
Objectives

- To familiarize the student with the basic operation and instrumentation of the HMC wind tunnel
- To examine the lift and drag forces on standard shapes in a flow field, and obtain a qualitative relationship between lift and drag coefficients
- To evaluate lift and drag forces on a rocket body, evaluate pitot tube measurements, and complete a design problem

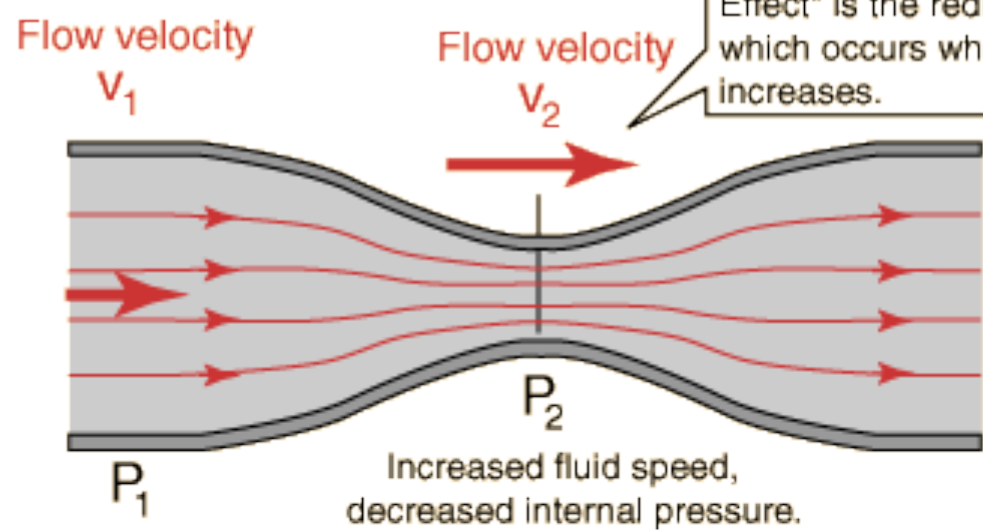
Bernoulli's Equation

Energy per unit volume before = Energy per unit volume after

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$



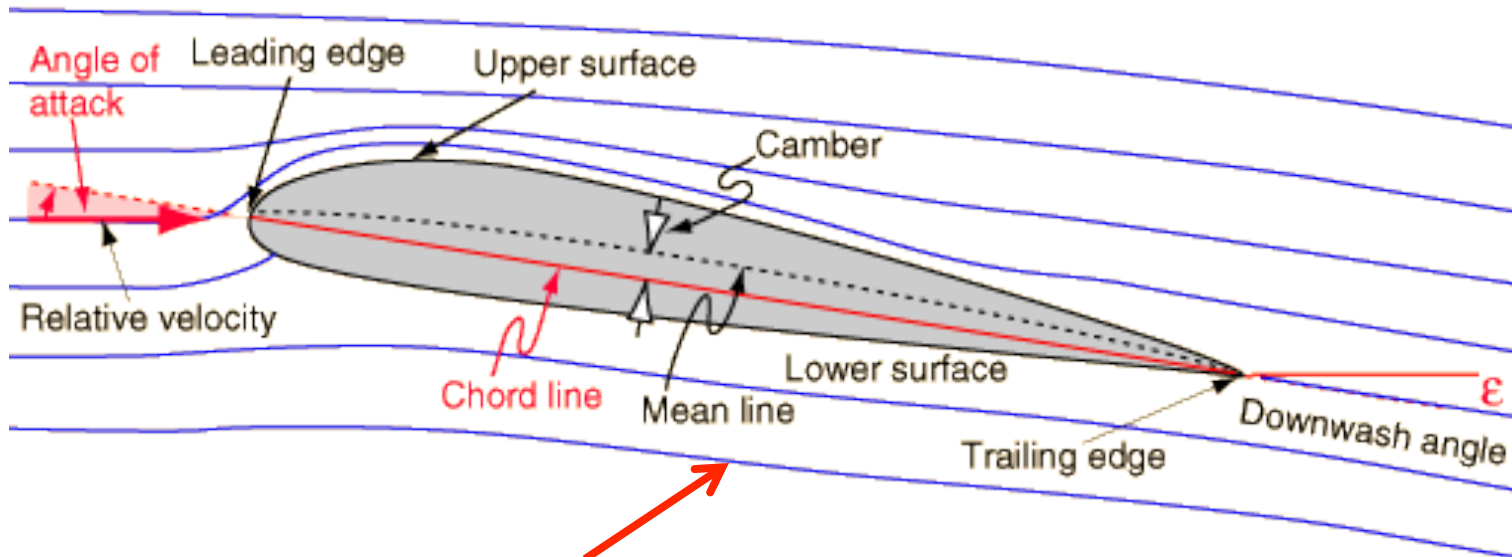
The often cited example of the Bernoulli Equation or "Bernoulli Effect" is the reduction in pressure which occurs when the fluid speed increases.



$$A_2 < A_1$$
$$v_2 > v_1$$
$$P_2 < P_1!$$

A Standard Shape (airfoil)

- Airfoils provide lift



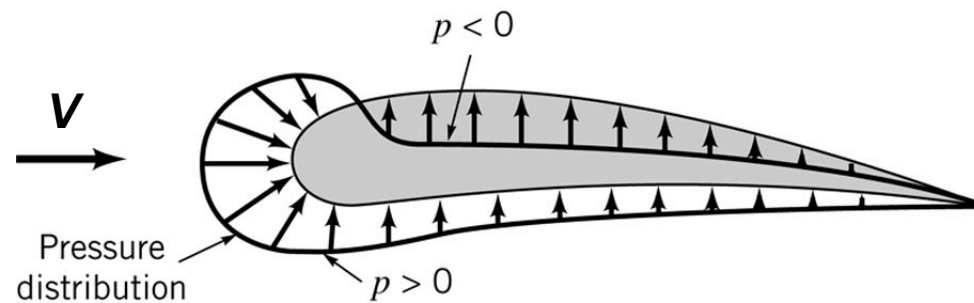
Streamlines

Flow over a curved surface is faster and the Bernoulli effect results in lower pressure over the upper surface

Aerodynamic Forces

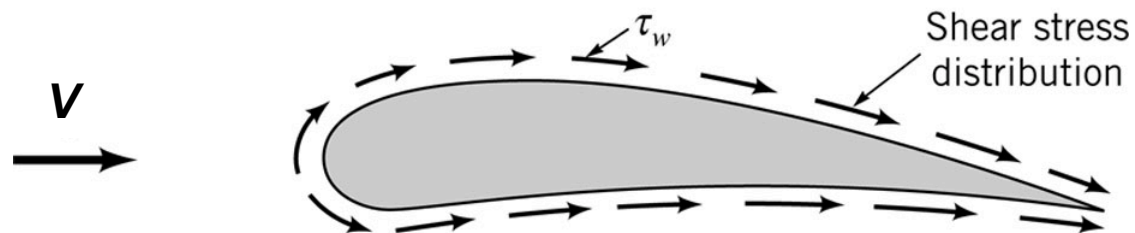
1. Pressure

Acts perpendicular to surface



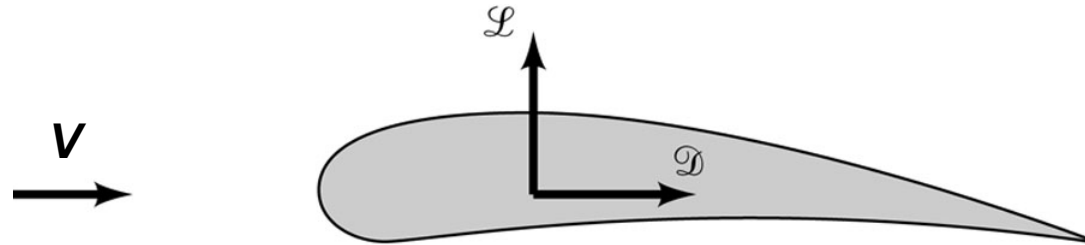
2. Shear stress (friction)

Acts tangentially to surface



Lift and Drag

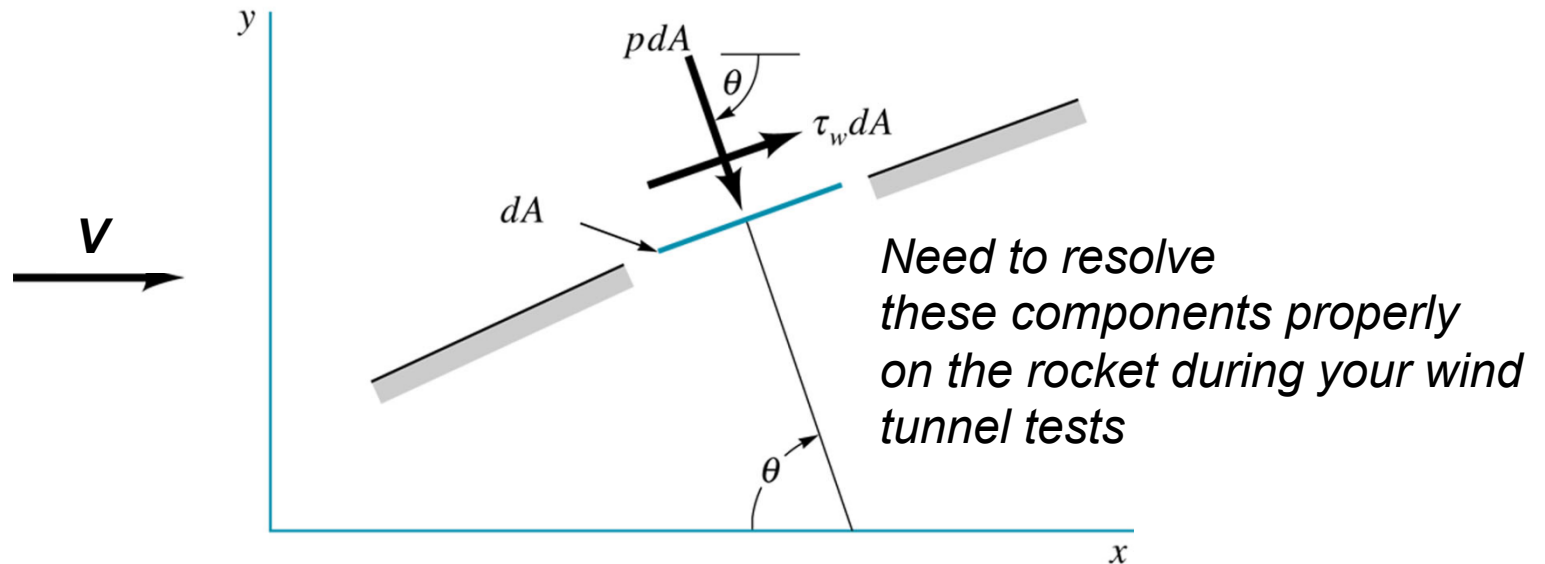
- The sum of pressure and shear stress is the *resultant force*. It is split into two components:
 1. **Lift:** The component of resultant force that is *perpendicular* to the *incoming velocity vector* (free stream).
 2. **Drag:** The component of resultant force that is *parallel* to the *incoming velocity vector* (free stream).



Combined with the right weight and thrust – we can fly!



Calculating Lift and Drag



Drag force $D = \int dF_x = \int p \cos \theta dA + \int \tau_w \sin \theta dA$

Lift force $L = \int dF_y = -\int p \sin \theta dA + \int \tau_w \cos \theta dA$

Lift and Drag

- Lift force L and drag force D cannot be calculated without detailed information about shear stress and pressure distributions on a body and are computationally challenging even with this information.
- Instead, Lift and Drag are represented by nondimensional coefficients defined by the ratio of lift or drag force and fluid kinetic energy.

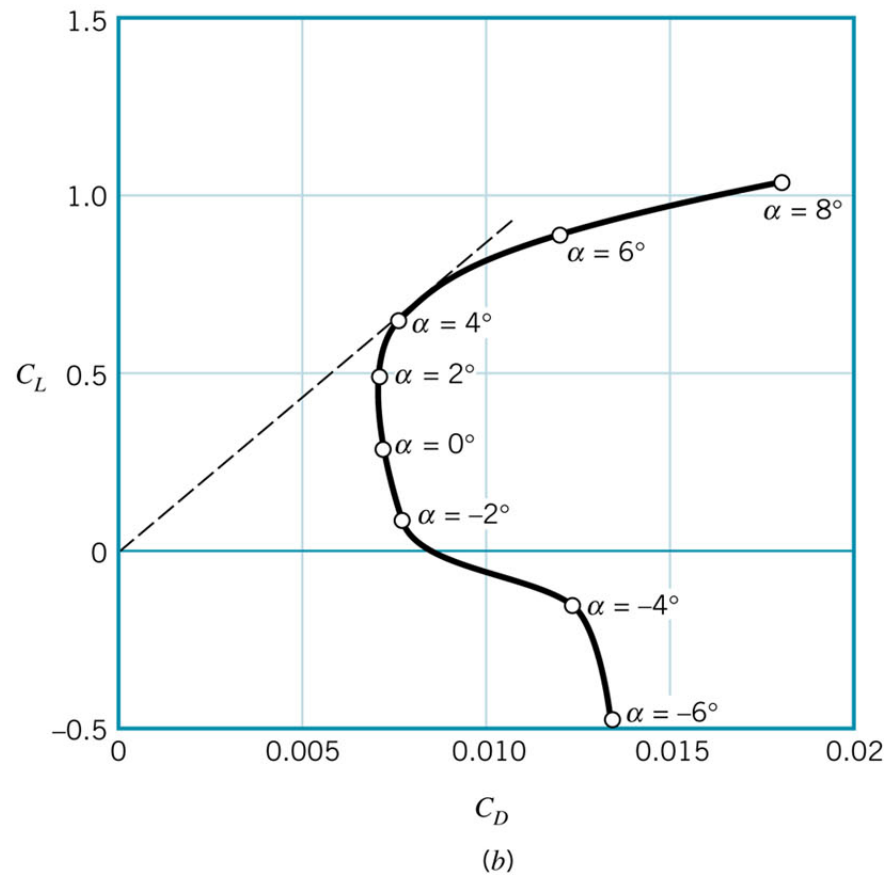
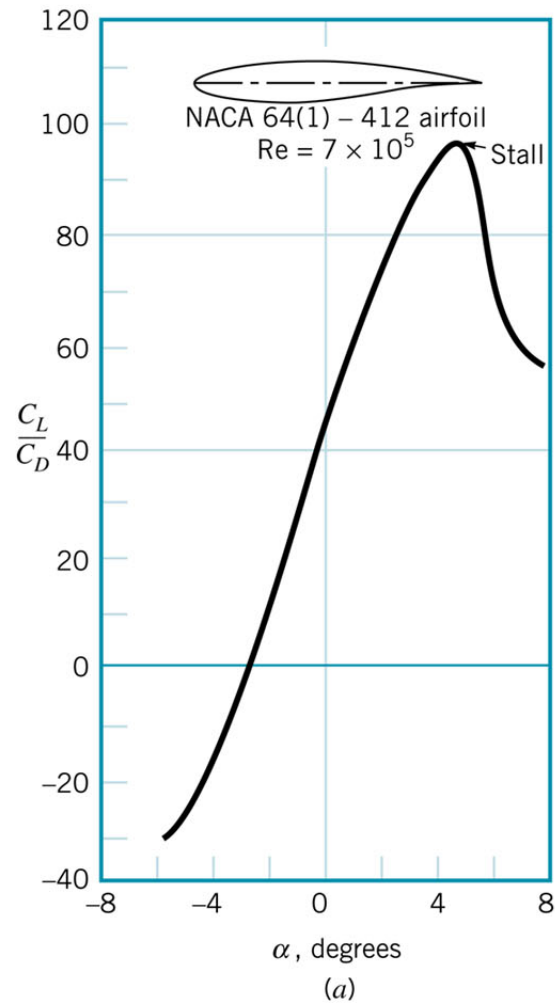
$$C_{L,D} = \frac{F_{L,D}}{\frac{1}{2} \rho V^2 A}$$

where $F_{L,D}$ is the lift or drag force, measured in pounds or Newtons; ρ is the fluid density (in slugs/ft³ or kg/m³), V is the average flow speed (in ft/s or m/s), and A is the area (ft² or m²) normal to the force, or the characteristic area of the object.

Balancing Lift, Drag - Stall

- <http://www.youtube.com/watch?v=rQAUHSTJIIQ&feature=related>
- <http://www.youtube.com/watch?v=WFcW5-1NP60>

Lift, Drag, Attack Angle



Experimental Fluid Dynamics

- Osborne Reynolds (University of Manchester, 1883) discovered that,
 - if the same atmospheric pressure were used for experiments with wind tunnel models as a full-size airplane would encounter under actual conditions, the results would be invalid.
- For the results to be valid,
 - the air density inside the wind tunnel must be increased by the same proportion as the model is smaller than the actual airplane.
- Practically, if a model is 1/10th the size of a full size plane, the flow velocity must be increased by a factor of 10 to get wind tunnel results that are valid in regular atmospheric conditions with a full size plane.
- **Two similarly shaped but different sized objects would have the same aerodynamics as long as the Reynolds Numbers for the two objects matched.**

Reynolds Number

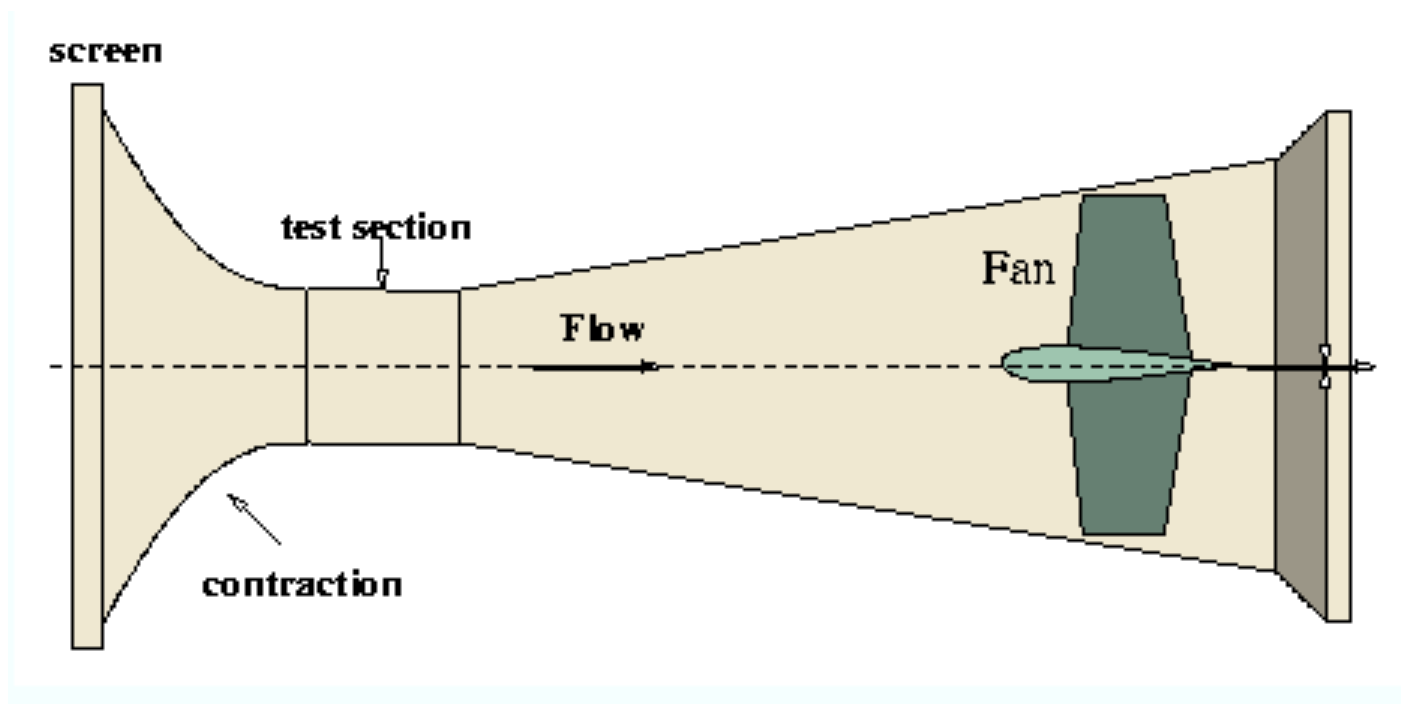
- The Reynolds Number quantifies the relative significance of inertia (fluid acceleration) and viscous effects (e.g. drag force, or boundary layer thickness around an object).
- If a model flow has the same Reynolds Number as the flow it is meant to represent, the flow patterns and quantitative pressures and forces will be equivalent.
- Reynolds Number is defined

$$\text{Re} = \frac{\textit{inertial effects}}{\textit{viscous effects}} = \frac{\rho V d}{\mu}$$

where ρ , μ , V , and d are defined as the fluid density, viscosity (a measure of the fluid's resistance to motion), the average fluid velocity, and some characteristic object length.

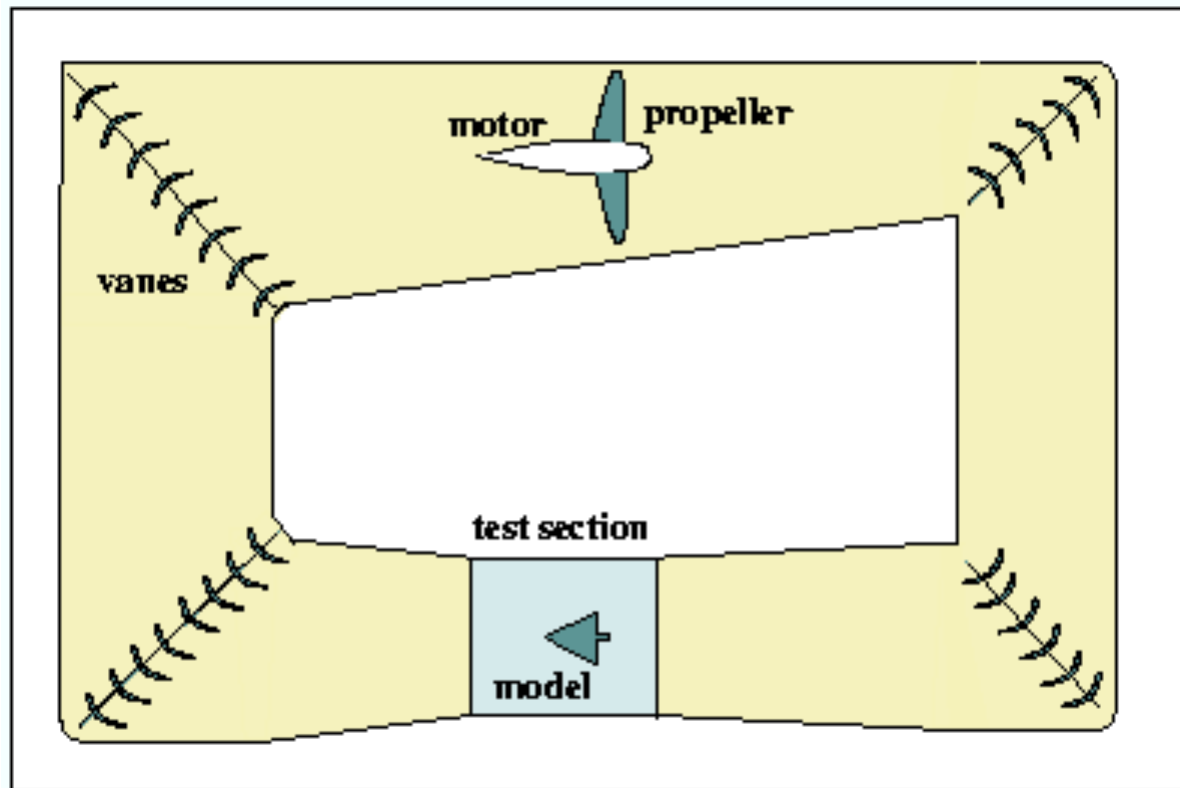
Wind Tunnels (subsonic – less than 250 mph)

- Open Circuit Tunnels
 - the entry and/or exit is open to the lab atmosphere
 - Simple to construct, but use of flow tracers (smoke) is limited
 - Difficult to maintain uniform velocity flow in the test section



Wind Tunnel (cont.)

- Close Circuit Tunnels
 - more uniform flow properties
 - more challenging to construct and maintain



The HMC Wind Tunnel

- Designed and constructed by HMC Students and former HMC Professor Jennifer Rossmann.
- The wind tunnel is a modified open circuit design with a test section that has a 1' x 1' cross section, and can achieve speeds up to 140 mph (Mach 0.2)

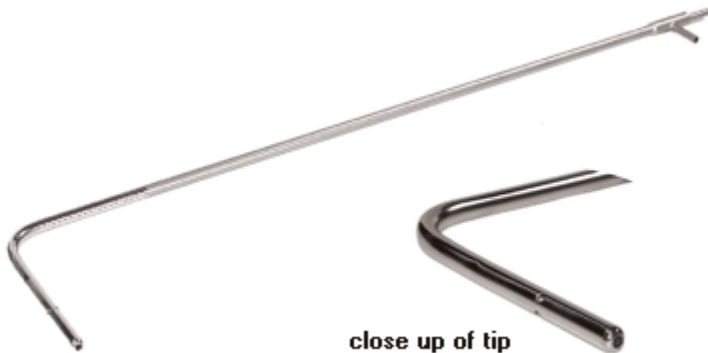
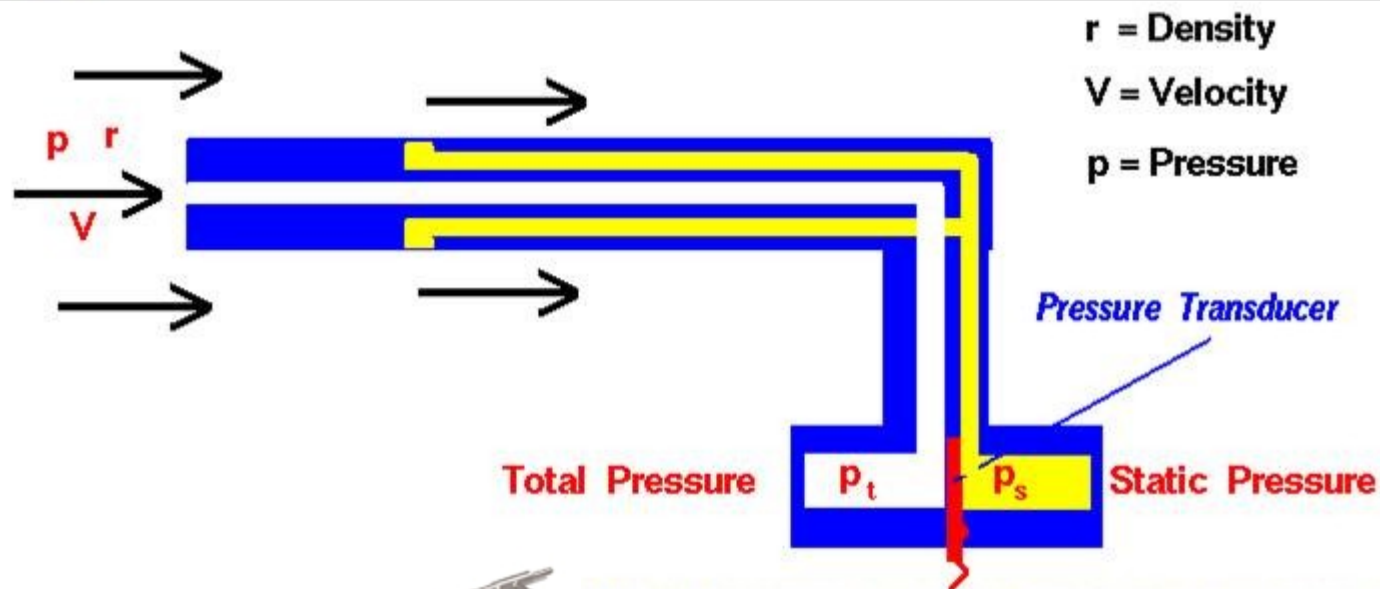


Instrumentation – Pitot Static Tube



Pitot-Static Tube Prandtl Tube

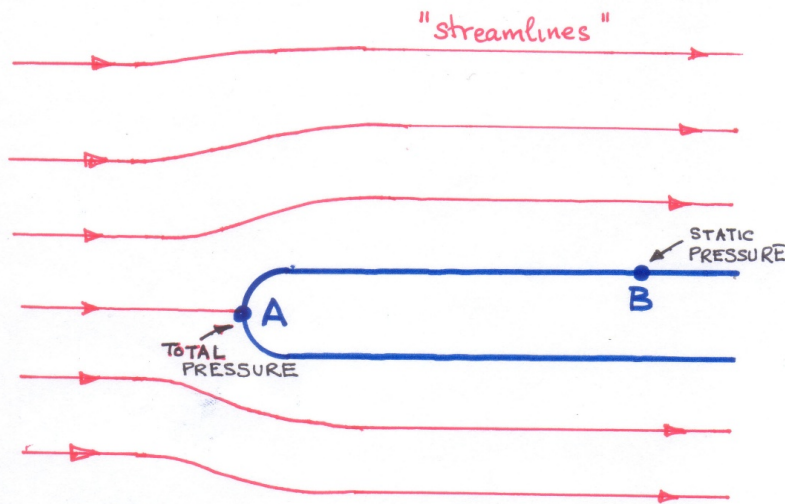
Glenn
Research
Center



Measures Aircraft Speed
(speedometer)

Pitot Tube

- Several small holes are drilled around the outside of the tube, and a center hole is drilled down the tube axis. The outside holes are connected to one side of a manometer, and the center hole is kept separate from the outside holes and is connected to the other side of the manometer.
- Stagnation point A and point B are on the same streamline, so they can be modeled using Bernoulli's equation (neglecting gravity effects)



$$P_A + 0 = P_B + \frac{1}{2} \rho V^2$$

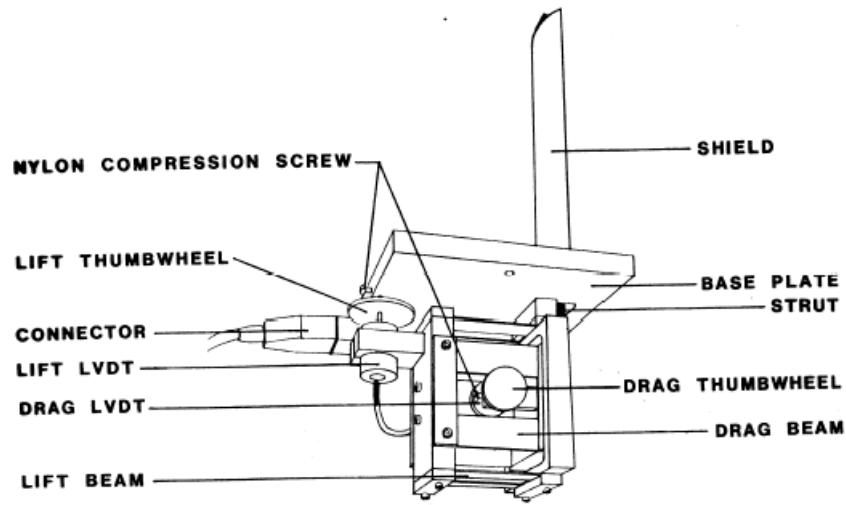
$$\Rightarrow V = \sqrt{\frac{2(P_A - P_B)}{\rho}}$$

From Russia With Love

- <http://www.youtube.com/watch?v=DO3hnYJ7TUw>

Dynamometer

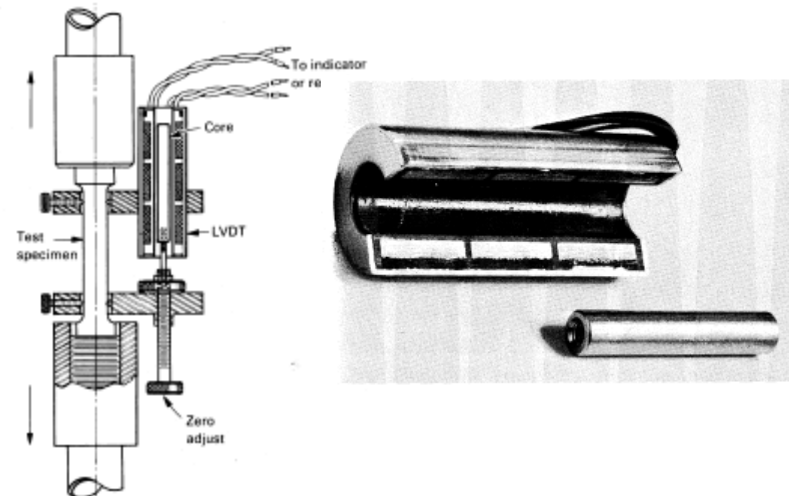
- A two component force balance used to measure lift and drag forces.
- Forces generated by the model under test cause the deflection of two restrained cantilever beams (along the lift axis and the drag axis). Measurements of the resulting deflections can be used to estimate the applied forces.
- Linear Voltage Displacement Transducers (LVDTs) are used to measure the beam displacements.



DYNAMOMETER ASSEMBLY

LVDTs

- A typical LVDT consists of a transformer and a moving core.
- The transformer consists of 3 symmetrically placed coils inside a cylindrical shield of ferro-magnetic material rendering it impervious to humidity and ordinary magnetic interferences.
- The core is made of a nickel-iron alloy and is usually threaded internally to allow attachment to an external actuator (article under test).
- Advantages include
 - Frictionless movement
 - Long mechanical life
 - Infinite resolution
 - Null position stable
 - Frequency range 50Hz-25kHz



Application of an LVDT to an extensometer.

Safety

- Follow the Dress Code for E80 Lab
- Never turn the FAN on without
 - Checking to see that no loose objects are in the test chamber
 - Securing the test chamber cover plate
 - Making sure all test personnel are at a safe distance from the wind tunnel itself (at least 24" in any direction)
 - Making sure the vent is clear
 - Making sure the article under test (AUT) is securely fastened inside the test chamber

The Lab

- <http://www.eng.hmc.edu/NewE80/WindTunnelLab.html>

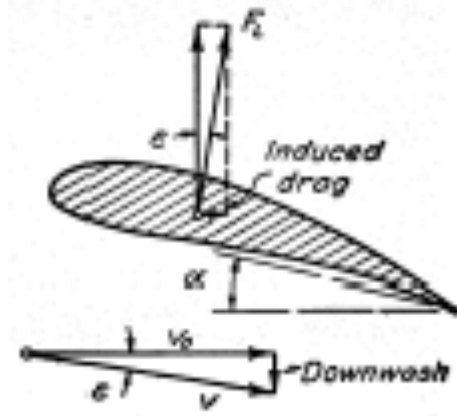
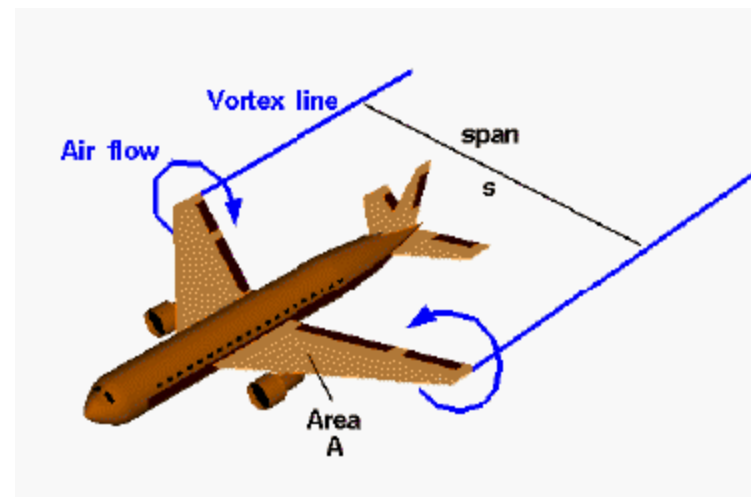
Extras...

Acknowledgements

- Dr. Jennifer Rossmann
- Jake Pinheiro
- NASA web sites

Induced Drag

- For a lifting wing, the pressure on the top of the wing is lower than the pressure below the wing. Near the wing tips, the air can move from the region of high pressure into the region of low pressure.
- Vortices are created at the wing tips.
- If the atmosphere has high humidity, you can sometimes see the vortex lines on an airliner during landing as long thin "clouds" leaving the wing tips.
- The wing tip vortices produce a down wash of air behind the wing which is very strong near the wing tips and decreases toward the wing root.
- The local angle of attack is increased by the induced flow of the down wash, giving an additional, downstream-facing drag force.
- This additional force is called **induced drag** because it faces downstream and has been "induced" by the action of the tip vortices.



Downwash



A sample calculation – Boeing 747-400

- Assume the following
 - Maximum speed = 910km/h
 - Wing Span = 67 m (typ. Area=4600sqft, chord length=21ft)
 - Air temperature = -40°C
- Need to determine properties of air at specified temperature
 - http://users.wpi.edu/~ierardi/FireTools/air_prop.html
 - <http://www.onlineconversion.com>
 - http://www.engineeringtoolbox.com/24_162.html
 - (water properties will be need for your design)
- Reynolds Number associated with one wing

$$\text{Re} = \frac{\rho V d}{\mu} = \frac{1.520 \left[\frac{\text{kg}}{\text{m}^3} \right] * 253 \left[\frac{\text{m}}{\text{s}} \right] * 67 \left[\text{m} \right]}{0.0000148 \left[\frac{\text{kg}}{\text{ms}} \right]} = 1.74E + 9$$

Demo

- FoilSim

The screenshot displays the FoilSim software interface. At the top left, there are view and display options: View: Edge, Top, Side-3D, Find; Display: Streamlines, Moving, Frozen, Geometry. A 3D model of a red wing is shown with streamlines. Below the model is a 'Zoom' control. To the right of the model is a 'Student Version' label and a red 'Reset' button. Below these are three dropdown menus: 'Ideal Flow' (set to 'Ideal Flow'), 'English Units' (set to 'English Units'), and 'Input' (set to 'Flight Test'). Below these is an 'Output' dropdown menu (set to 'Probe'). A 'Lift' dropdown menu shows '41422 lbs'. Below the lift is a 'Probe' dropdown menu (set to 'OFF') and a red 'OFF' button. To the right of the probe is a velocity gauge with a scale from 0 to 10 and a needle pointing to approximately 1.974 x 10² mph. Below the gauge are three buttons: 'Velocity', 'Pressure', and 'Smoke'. On the left side, there are input fields for 'Speed-mph' (250.0), 'Altitude-ft' (30000.0), 'Press-lb/in2' (14.682), and 'Temp-F' (-40). Below these is a 'Density' field showing '0.00293 slug/cu ft'. At the bottom left, there is a 'Flight Test' button and a 'Specify Air T & P' dropdown menu.

Mach Number

- Aerodynamic forces also depend on the compressibility of the air or fluid.
- At low speeds (typically below 200 mph), the density of the fluid remains fairly constant. At high speeds, some of the object's energy compresses the fluid and changes its density and alters the resulting force on the object.
- Near and beyond the speed of sound (approximately 700 mph), shock waves are produced affecting both lift and drag on the object.
- The important similarity parameter for compressibility is the Mach Number defined as the ratio of the object's velocity to the speed of sound

$$M = \frac{V}{c}$$

The Bernoulli Effect

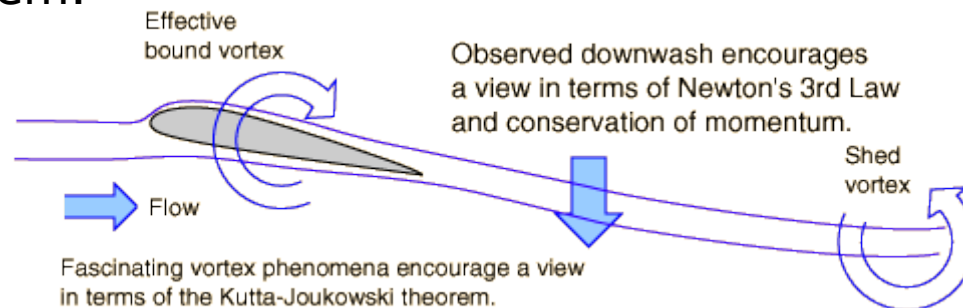
- The air across the top of an airfoil experiences constricted flow lines and increased air speed relative to the wing.
- According to Bernoulli, this results in a decrease in pressure along the top of the airfoil and provides a lift force.

Newton's 3rd Law

- Lift results from the angle of attack.
- The boundary layer of air on the airfoil and resulting downwash of air behind the airfoil gives the air a downward force.
- According to Newton's 3rd Law, the airfoil experiences a force in the opposite direction lifting the airfoil.

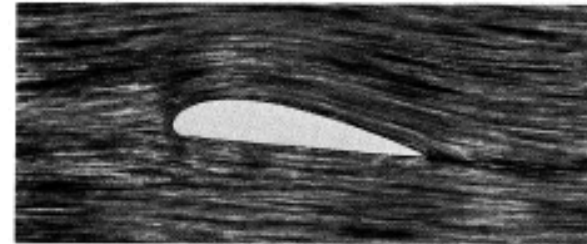
Bernoulli or Newton for Lift?

- Bernoulli's equation is a statement of the principle of conservation of energy in fluids and has been shown to match pressure measurements around airfoils in wind tunnels and in flight.
- Newton's 3rd law and the conservation of momentum are equally valid in the context of lift.
- German mathematician Kutta and Russian physicist Zhukovsky independently developed the mathematical theory of lift that makes the connection between lift on an airfoil and the circulation around them.



Flow Patterns and Length Effect

- Flow patterns are shown on a Joukowski foil of very great span (length).
- At high angles of attack, the boundary layer separates at the leading edge and stalls producing a drop in lift-to-drag ratio.
- Flow around a finite length wing is 3-D. The pressures above and below the wing interact with the surrounding air – particularly as you approach the wing tips.
- Leads to the concept of induced drag

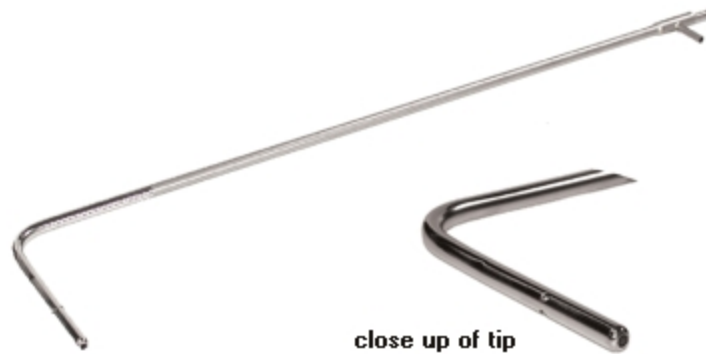


What is a boundary layer?

- Aerodynamic forces depend on the viscosity of the air. As an object moves through the air, air molecules stick to the object's surface.
- A layer of air is created near the surface that is referred to as a boundary layer. This boundary layer, in effect, changes the shape of the object since the flow reacts to the edge of the boundary layer as if it was the physical surface of the object.
- It is also possible for the boundary layer to lift off or even separate from the body creating an effective shape much different than the object's physical shape.
- Boundary layers are very important in determining the lift and drag of an object.
- To determine and predict these conditions, aerodynamicists rely on wind tunnel testing and very sophisticated computer analyses.

Wind Tunnel Instrumentation

- A standard pitot probe measures pressure difference.

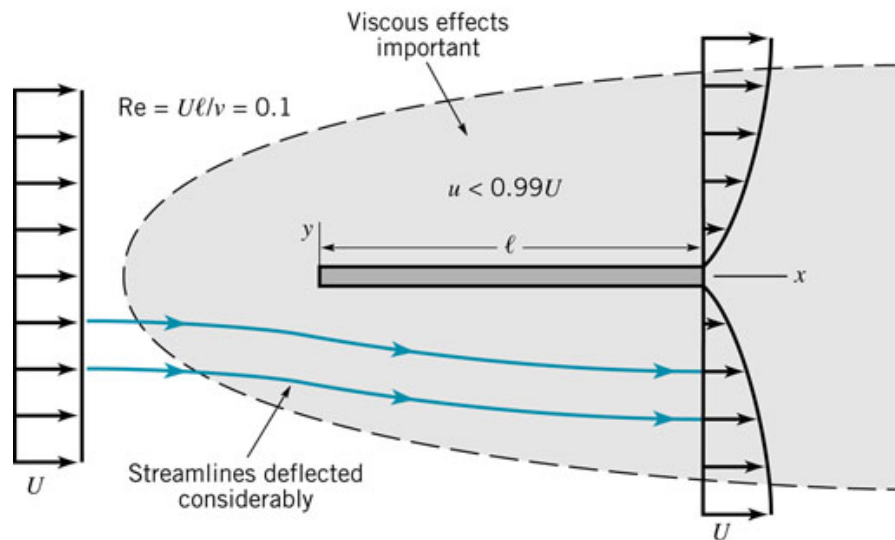


- A stagnation point exists at the nose of the probe where the flow velocity is zero and a small pressure tap measures the pressure p_o at this point.
- Flow generally moves around the probe with some average speed V and pressure p .
- A differential manometer measures the difference between the two pressure which varies according to Bernoulli's equation

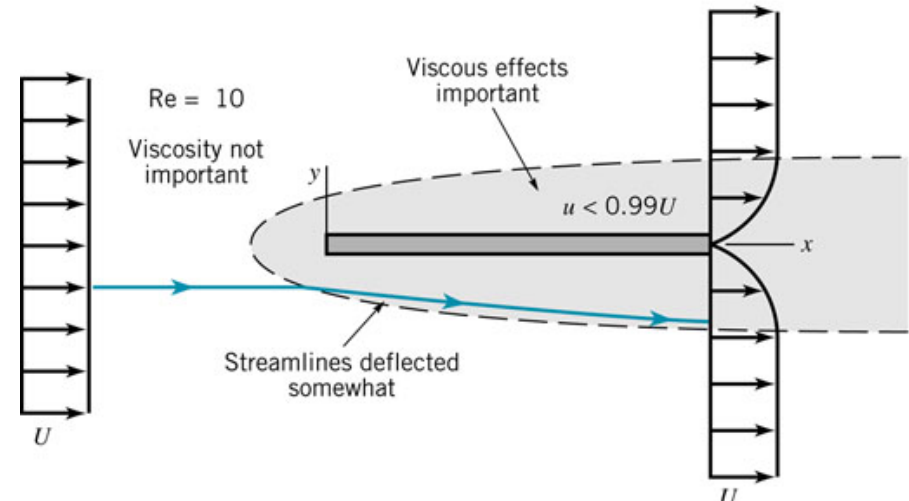
$$p_o - p = \frac{1}{2} \rho V^2$$

Re and Boundary Layer Flow

Low Re



Moderate Re



High Re

