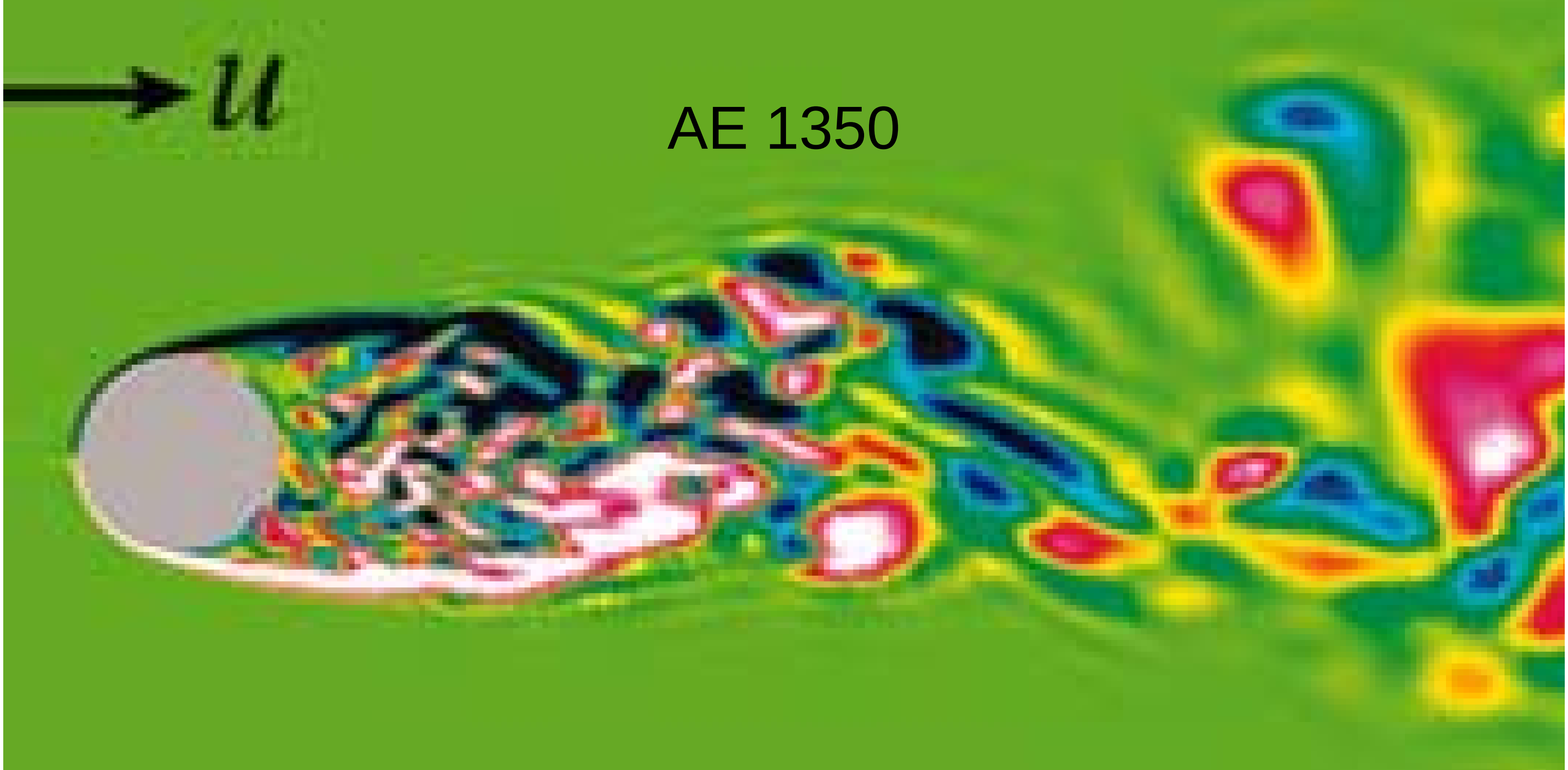
Aerodynamics Introduction

AE 1350



Aerodynamics

- The flow of air over a shape is the fundamental source of the sustaining force (lift) that allows airplanes to fly –
  It also results in drag, and moments (causes rotation)
- The science that deals with these flows is called <u>aerodynamics</u>, applications include:
  – Airplane design
  – Propeller design
  – Design of Rocket or jet engines
  – Planetary entry vehicles
  – Global atmospheric modeling
- The fundamental quantities in aerodynamics are
  – Pressure, P
  – Density, ρ
  – Temperature, T
  – Velocity vector, $\underline{V}$

Motivation

- Knowledge of P, ρ, T and **V** at each point in the flow fully defines the flowfield,

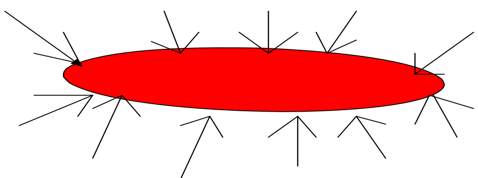
$$P = P(x,y,z)$$

$$\rho = \rho(x,y,z)$$

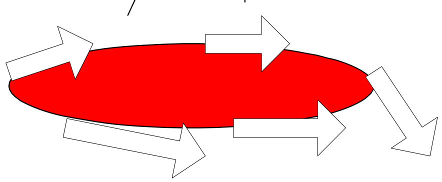
$$T = T(x,y,z)$$

$$\vec{V} = \vec{V}(x,y,z)$$

- The aerodynamic force exerted by the flow on the surface of a vehicle stems from two fundamental sources: pressure and shear stress



Pressure distribution acts normal to the aircraft surface



At the surface, the shear stress distribution acts tangential to the surface

- Each of these distributions can vary in magnitude and direction along the body (they are point properties)
- Integrating the pressure and shear stress distributions across the body yields a resultant force (or forces) – these are the basic sources of all aerodynamic forces and moments

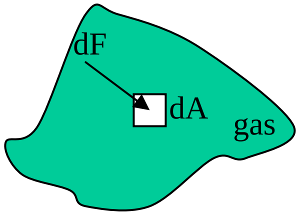
Pressure

- Pressure: Normal force per unit area on a surface
  - When you put your hand outside a car window as it moves down the road, the force you feel tending to push your hand is (mostly) due to pressure
  - Pressure will have units of N/m^2 or lb_f/ft^2, (sometimes Pa or atm units are used)

    1 lb_f = 4.448 N   1 Pa = 1 N/m^2

    1 ft = 0.3048 m 1 atm = 1.01×10^5 N/m^2 = 2116 lb_f/ft^2
  - Mathematically, we can use differential calculus to define:

$$P = \lim\left(\frac{dF}{dA}\right) \text{ as } dA \to 0$$



at a given point. Clearly, *P* is a point property that can have different values at different points in the gas

Density

- <u>Density</u>: Mass of a substance (e.g., a gas) per unit volume
  - Mathematically, we can use differential calculus to define:

$$\rho = \lim\left(\frac{\mathrm{dm}}{\mathrm{dv}}\right) \text{ as } \mathrm{dv} \to 0$$

  - Consider air in a room that has a volume of 250 m^3. If the mass of air in that room is 306.25 kg and is evenly distributed, then throughout the room:

$$\rho = \frac{306.25}{250} = 1.225 \frac{\mathrm{kg}}{\mathrm{m}^3}$$

  - If the air were not uniformly distributed, then like *P*, one can see that ρ can vary from point to point in a gas (also a point property of the flow)
  - Common units of density are kg/m^3, slug/ft^3

1 kg = 2.2 lb_m 1 slug = 32.2 lb_m = 14.6 kg

1 ft = 0.3048 m

Temperature

- <u>Temperature</u>: Measure of the average kinetic energy of the particles in a gas
  - A gas is a collection of molecules and atoms. These particles are in constant motion, and occasionally collide with each other
  - Particles moving more rapidly have higher kinetic energy
  - If kinetic energy of a gas is defined as the average kinetic energy of the particles which make up that gas, then from physics we know that

$$KE = \frac{3}{2} kT$$

    where k is Boltzman's constant = 1.38×10^{-23} J/K

  - Temperature is import primarily in dealing with supersonic or hypersonic flows
  - Common units of temperature are deg Kelvin, Celsius, Rankine or Fahrenheit (usually we like the absolute scales, Rankine or Kelvin)

    0 F = 460 R

    0 C = 273 K = 32 F

    1 K = 1.8 R

Velocity

- Velocity: Connotes both speed and direction
  - It is a vector quantity, $\underline{V}$, where speed represents distance traveled per unit of time
- As with P, ρ and T, the velocity vector is a point property that can vary across the gas
  - Flow can be fast here, slower there…
- Unlike P, ρ and T, velocity is not a scalar quantity
- Common units of velocity are m/s, ft/s, or knots (nautical mile per hour)

Flow Characterization Quantities

- Mach number
- Reynolds number
- Angle of attack

M Rn α

Incompressible vs. Compressible Function of Mach number

- Air is an example of a compressible fluid
  - Its density changes if temperature changes, or if some external force is applied
- A flow is said to be incompressible if there are no changes in density attributable to (or caused by) the velocity or speed of the flow
- Theory and observations in wind tunnels suggest that most flows may be treated as incompressible (i.e., constant density) until the Mach number is sufficiently high (>0.4 or so, depending on shape)
- Mach: *M* = Velocity / Speed of Sound

Speed of Sound

- In thermodynamic and compressible flow applications, the speed of sound will be an important (although not independent) point property, where:

$$\boxed{a = \sqrt{\gamma R T}}$$

$$a = \text{speed of sound}$$

$$\gamma = \text{ratio of specific heats} = 1.4 \text{ for perfect gas air}$$

$$R = \text{gas constant}$$

$$T = \text{temperature in K or R}$$

- Here, *T* must always be expressed as an absolute temperature, K or R
- Mach number is the ratio of the relative velocity magnitude to the speed of sound,

$$\boxed{M = \frac{V}{a}}$$

- A non-dimensional quantity used in scaling
  - M < 1 for <u>subsonic</u> flow
  - M > 1 for <u>supersonic</u> flow

More on the Speed of Sound

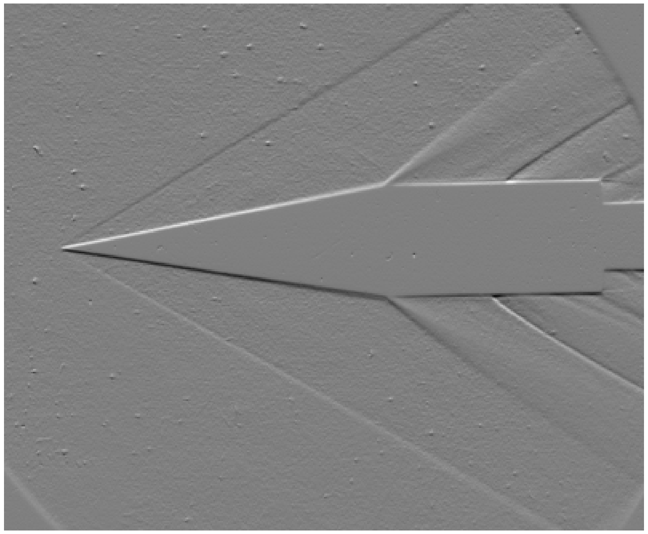
- Using standard atmosphere temperature:
  - Sea level,
    T = 59ºF, a = 340 meters/sec, 761 mph, 661 knots
  - Tropopause (between 11km and 25km),
    T = -70ºF, a = 295 meters/sec, 660 mph, 573 knots

- SR-71 cruise at Mach 3, 80,000 ft, still in tropopause, a = 573 knots
  - Speed = M*a =
    3*573 knots = 1719 knots

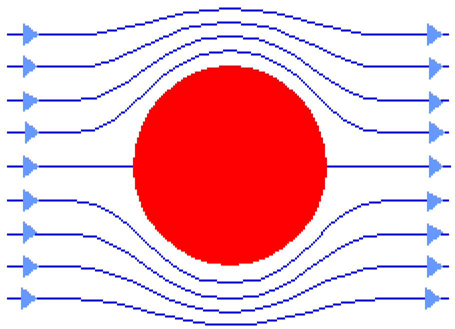
Dryden Flight Research Center EC97-43933-4 Feb1997
This head-on view is what the aerial tanker boom operator or "boomer" sees as NASA Dryden's SR-71A #844 approac efueling. (NASA/Jim Ross)

Why of function of M?

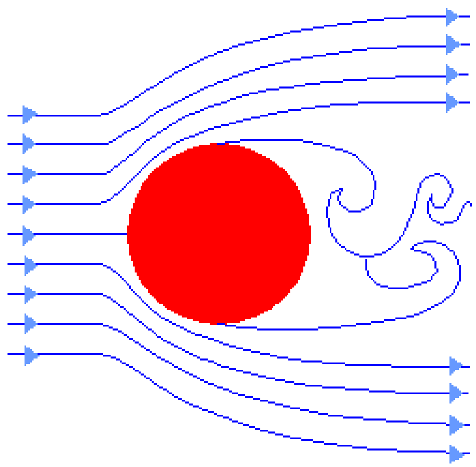
- If there is sufficient time for the sound waves to travel before the fluid particle arrives, the fluid particles downstream will “hear” the message and tend to get out of the way
- Otherwise, there will be a crush (compression), or even a large jump in density (shock wave)



Viscid vs. Inviscid Flow
Function of Reynolds Number (*Rn*)



Inviscid (ideal) flow



Viscous flow

- Streamlines describe the path the fluid particles will take
- Flow velocity is tangential to the streamline
- Engineers inject smoke particles into streamlines to make them visible to the naked eye
- Viscosity can alter the shape of streamlines

Rn

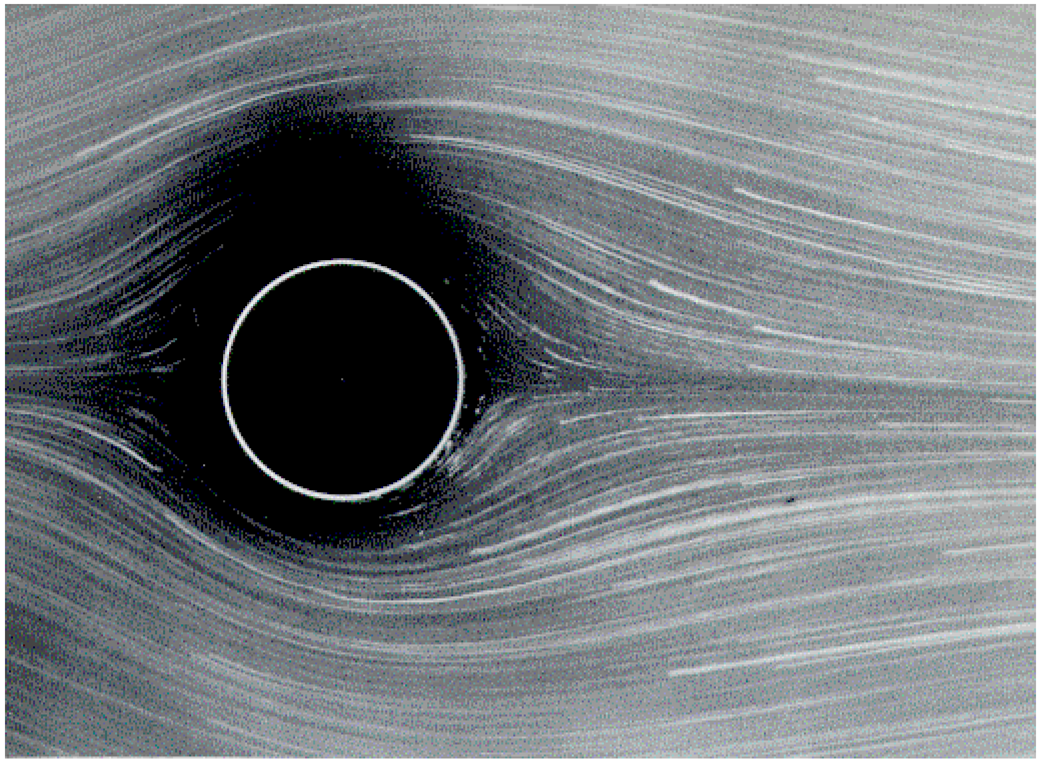
Reynolds Number

$$Rn = \frac{\rho V D}{\mu} = \frac{\text{density velocity distance}}{\text{viscosity}}$$

$$= \frac{\text{importance of pressure forces}}{\text{importance of viscous forces}}$$

Rn

Cylinder at Low Reynolds Number (10)

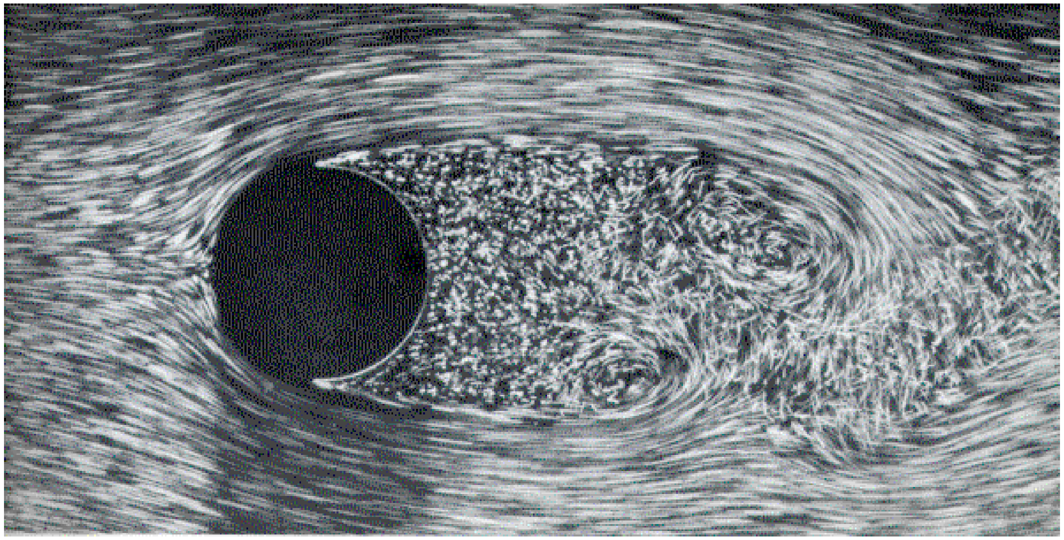


Reynolds Number, $Rn = \dfrac{\rho V D}{\mu}$

where D = Cylinder dia.

Rn

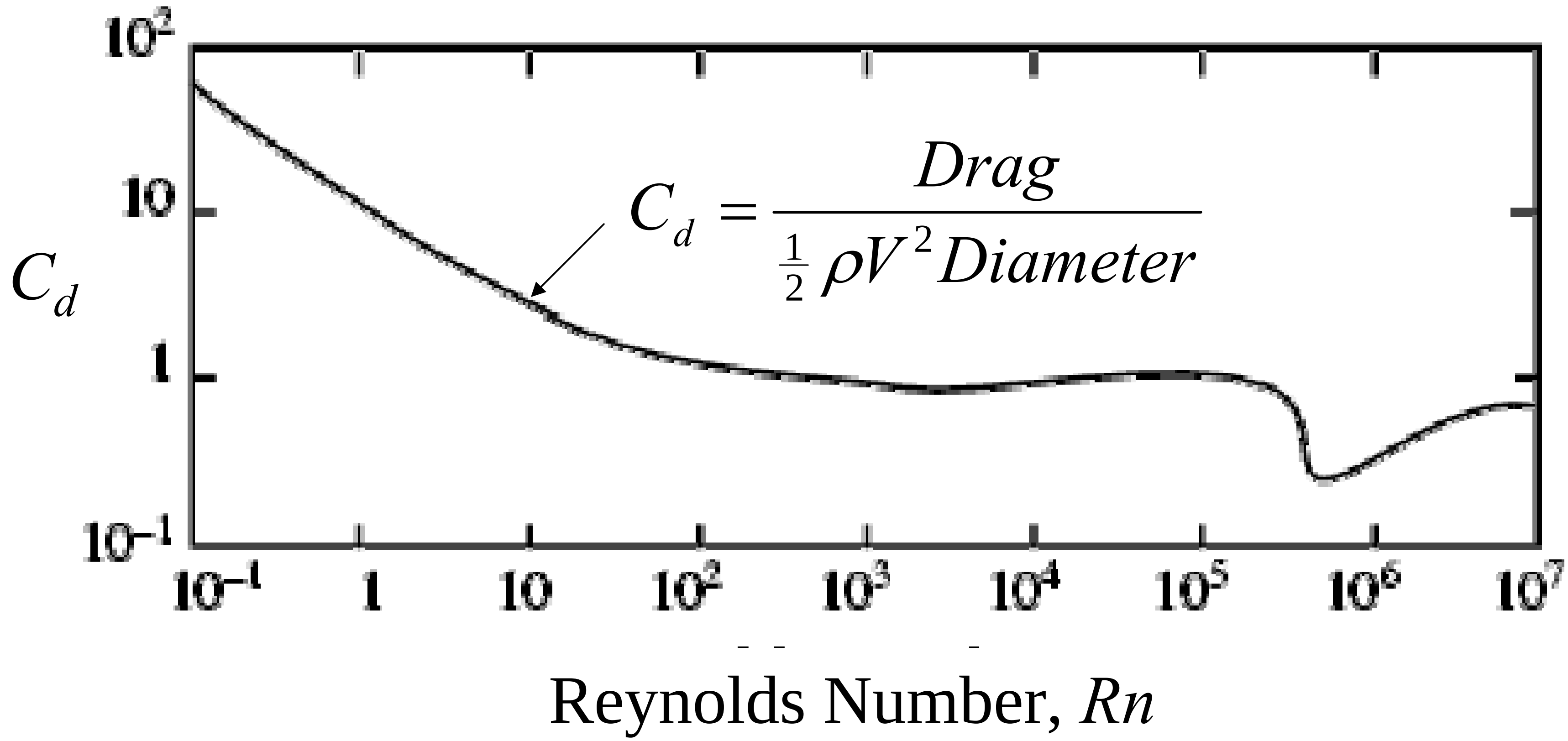
Cylinder at “High” Reynolds Number (2000)



Reynolds Number, $Rn = \frac{\rho V D}{\mu}$

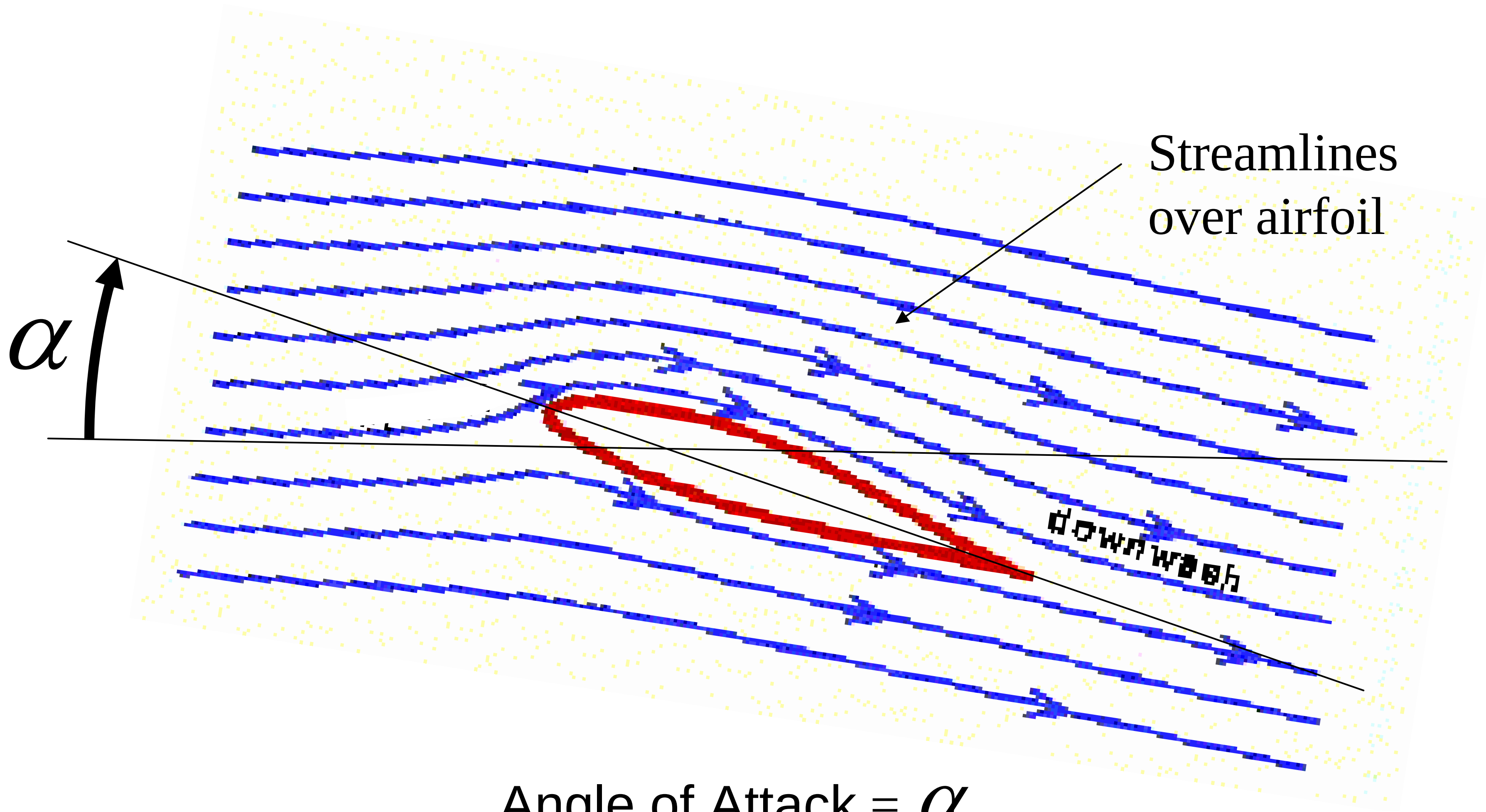
where $D =$ Cylinder dia.

Drag Coefficient on a Cylinder

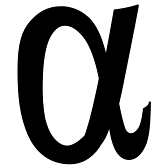


Rn

Angle of Attack



Angle of Attack = α



High Angle of Attack
(High angle with respect to flow)

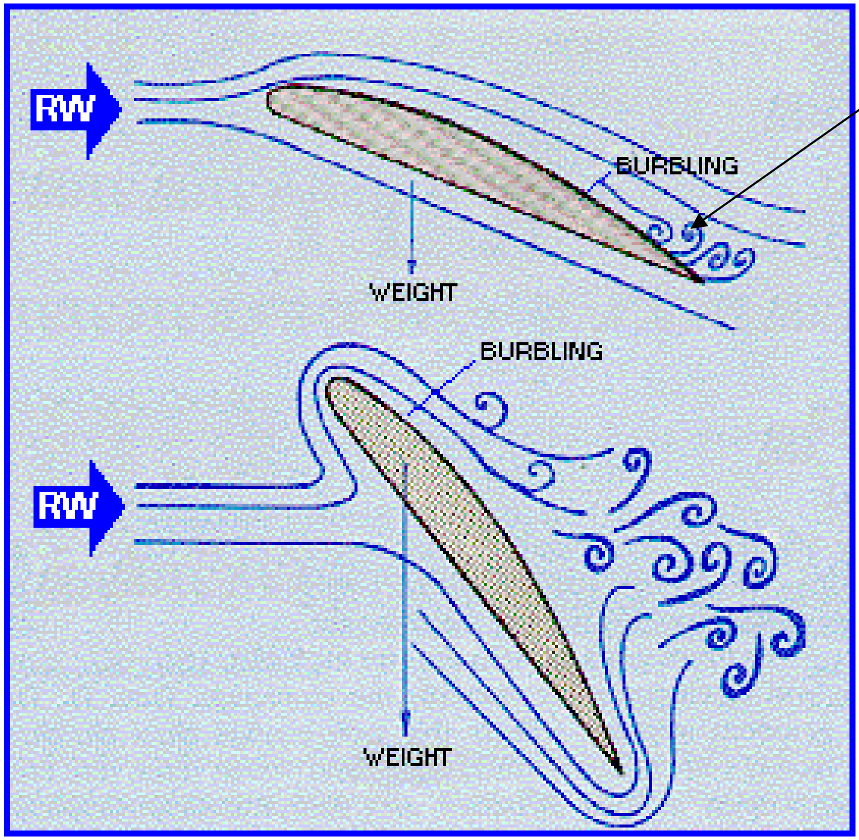
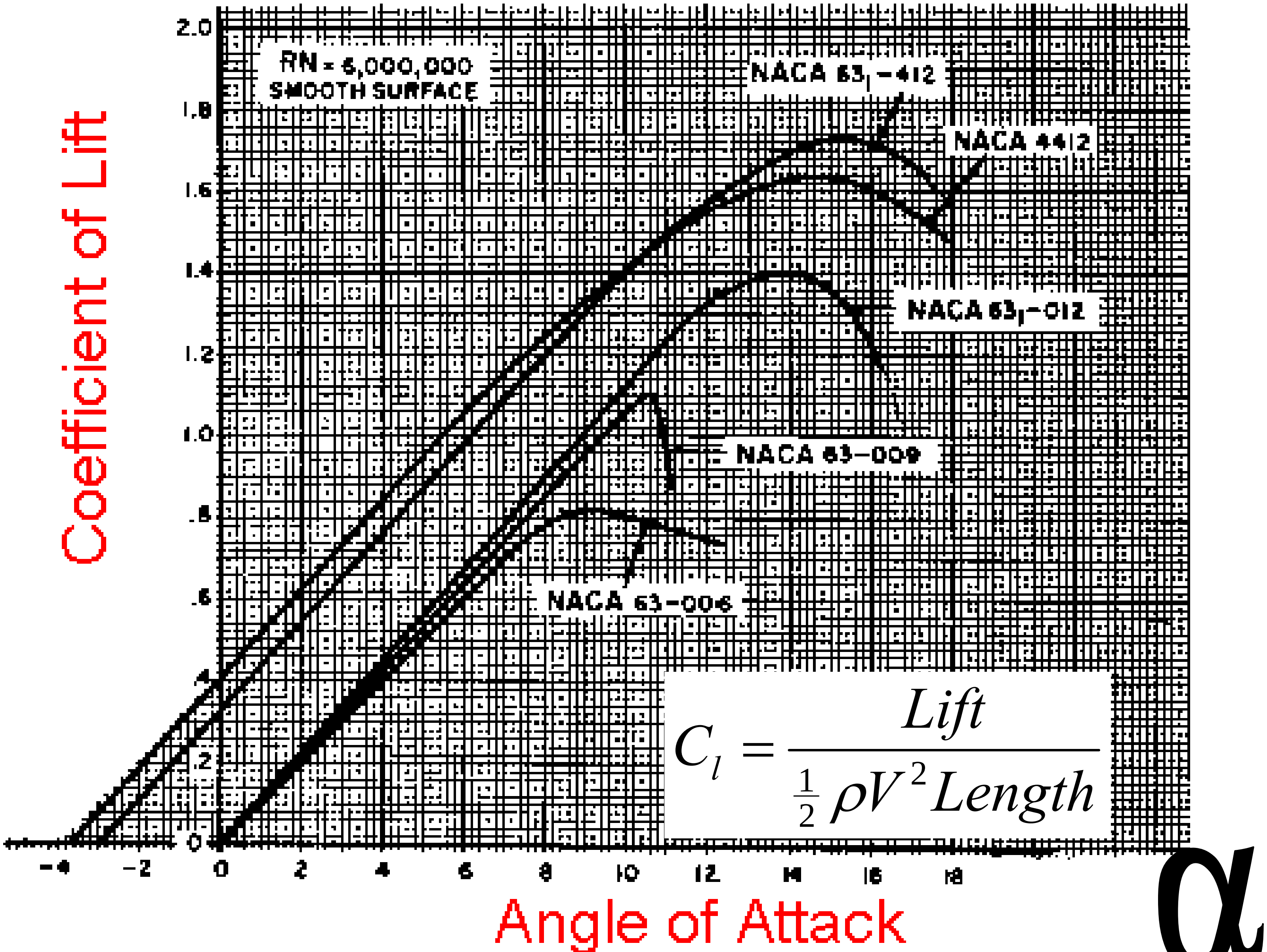


Figure 5-8 Airfoil approaching and entering a stall

Flow Separation

α

Coefficient of Lift vs Angle of Attack



$$C_l = \frac{Lift}{\frac{1}{2}\rho V^2 Length}$$

The Physics of Fluid Flows

- Equation of State
- Continuity
- Conservation of Momentum
- Conservation of Energy

Equation of State

- A gas in which the particles are widely separated (such that intermolecular forces can be neglected) is called a perfect gas
  - This is a good assumption for air vehicles flying in subsonic and low supersonic conditions
- For such a flow, *P*, ρ, and *T* are related as:

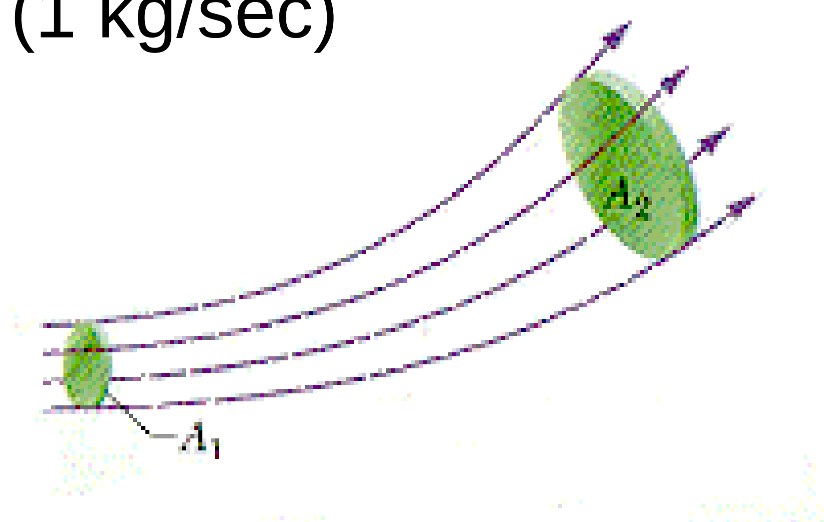
$$\boxed{P = \rho R T}$$

$$R = 287 \frac{\mathrm{J}}{\mathrm{kgK}} = 1716 \frac{\mathrm{ftlb_f}}{\mathrm{slug}^\circ\mathrm{R}}$$

- *T* must be expressed as an absolute temperature, R or K, for this to work

Continuity

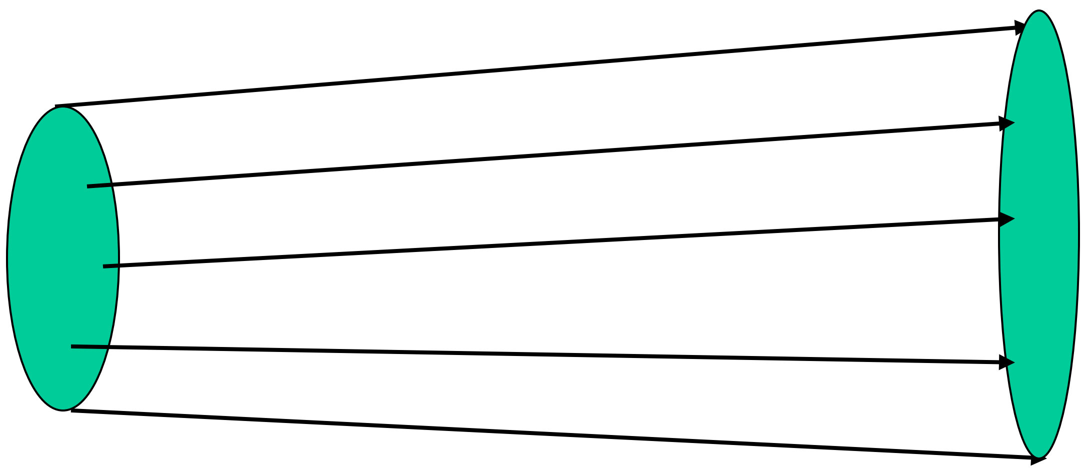
- Consider a stream tube, i.e. a collection of streamlines that form a tube-like shape
- Within this tube mass can not be created or destroyed
- The mass that enters the stream tube from the left (e.g. at the rate of 1 kg/sec) must leave on the right at the same rate (1 kg/sec)



Continuity Equation

Rate at which mass leaves = $\rho_2 A_2 V_2$

Rate at which mass enters = $\rho_1 A_1 V_1$



Area A_1
Density ρ_1
Velocity V_1

Area A_2
Density ρ_2
Velocity V_2

Continuity Equation
2 Versions

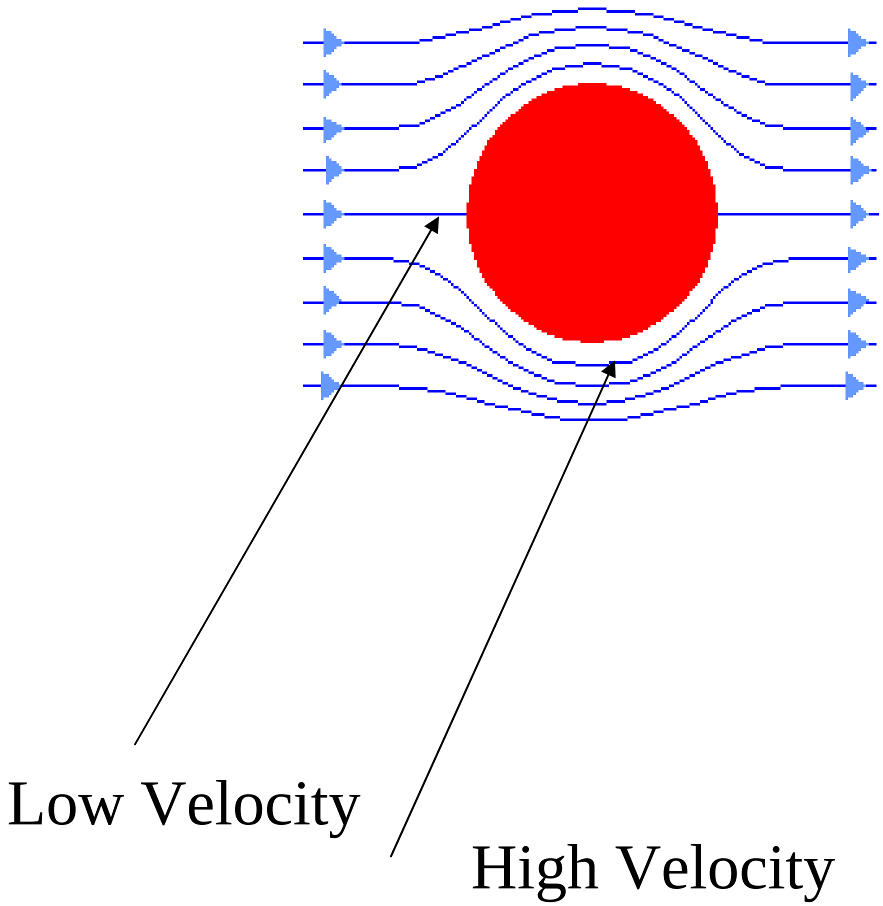
In compressible flow through a "tube"

$$\rho A V = \text{constant}$$

In incompressible flow, ρ does not change. Thus,

$$A V = \text{constant}$$

More on Continuity

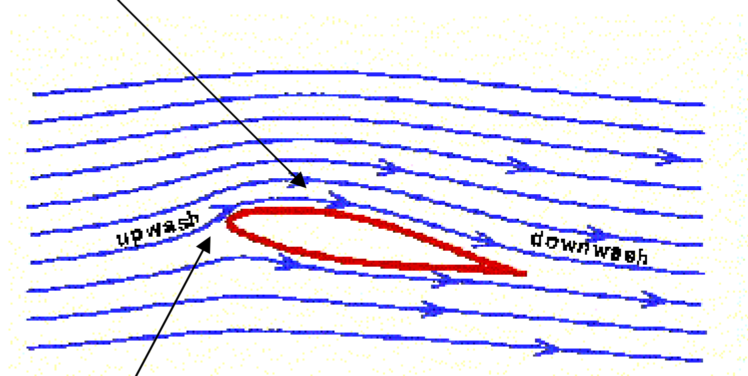


AV = constant

If Area between streamlines is high, the velocity is low and vice versa.

More on Continuity

High Velocity



Low Velocity

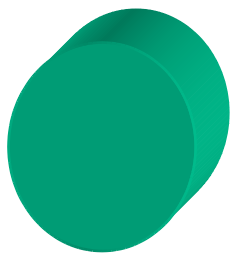
AV = constant

If Area between streamlines is high, the velocity is low and vice versa

In regions where the streamlines squeeze together, velocity is high

Conservation of Momentum

- Newton's 2nd Law
  - Rate of change of momentum is sum of forces, i.e., "F = ma"
- Consider a small slice of stream tube



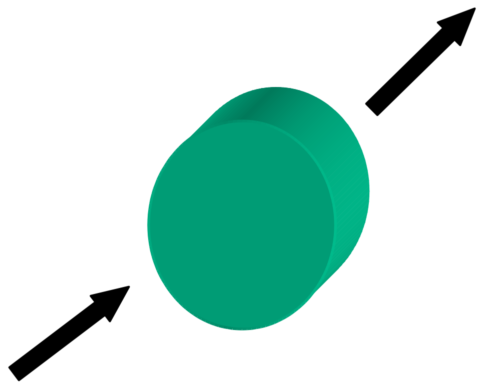
- Rate of change of momentum of the fluid particles within this stream tube slice must be due to forces acting on it
  - Force = time rate of change of Momentum

Momentum Equation:
Rate of Change of Momentum

Mass Flow Rate in = Mass Flow rate out (Continuity)

$\rho VA = (\rho + d\rho)(V + dV)(A + dA)$

Density ρ
velocity V
Area A



Density $\rho + d\rho$
velocity $V + dV$
Area = $A + dA$

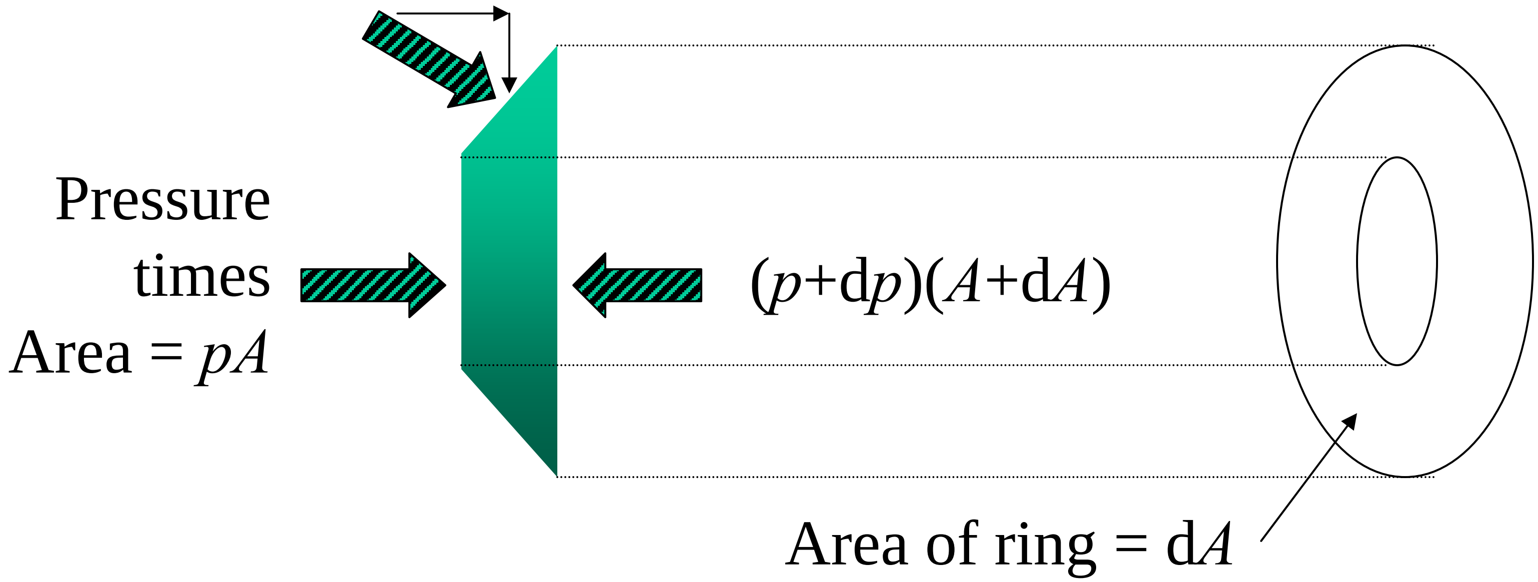
Momentum rate in =
Mass flow rate times velocity
= $\rho V^2 A$

Momentum Rate out =
Mass flow rate times velocity
= $\rho VA (V + dV)$

Rate of change of momentum within this element =
Momentum rate out - Momentum rate in
= $\rho VA (V + dV) - \rho V^2 A = \rho VA\, dV$

Momentum Equation: Forces Acting on Stream Tube

Horizontal Force = Pressure times area of the ring = $(p+dp/2)dA$



Net force = $pA + (p+dp/2)dA-(p+dp)(A+dA)$

$=- Adp - dp \bullet dA/2 \approx -Adp$

Product of two small numbers

Momentum Equation

- Rate of change of momentum = $\rho AVdV$
- Forces acting on the stream tube = $-Adp$
  - Note: We have neglected all other forces: viscous, gravity, electrical and magnetic forces

- Equating the two factors (and divide by A), we get <u>Euler's equation</u>

$$\rho VdV + dp = 0$$

Momentum Equation for Incompressible Flow

- For incompressible flows (ρ constant), Euler's equation can be integrated:

$$\rho V dV + dp = 0$$

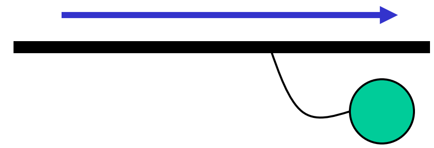
$$\rho \int V dV + \int dp = 0$$

$$\boxed{\frac{1}{2}\rho V^2 + p = Const}$$

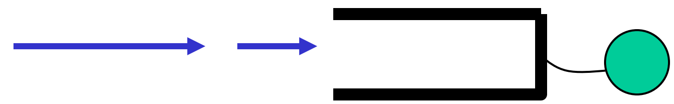
- …called Bernoulli's Equation (we've seen before!)
- This "stagnation pressure" is constant along a streamline, High Reynolds number, low Mach number

Pitot Tube: Measure Airspeed using Bernoulli's Equation

- Measure local pressure of air: p_S, "static pressure"

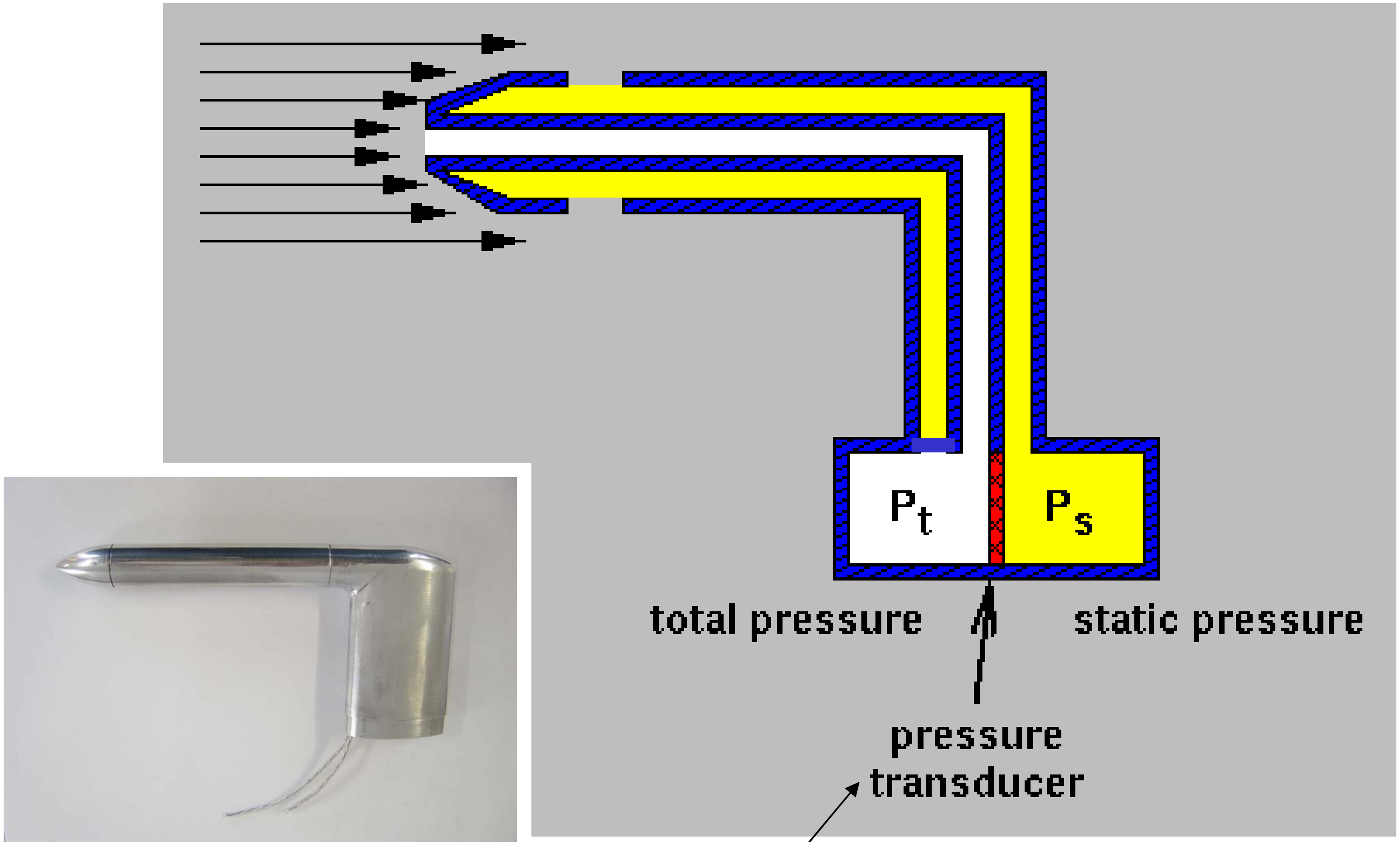


- Measure pressure after bringing to zero speed relative to instrument (i.e., bring to stagnation): p_T, "total pressure"



- From Bernoulli: $$\frac{1}{2}\rho V^2 + p_S = p_T$$
- Determine velocity of flow with respect to instrument: $$V = \sqrt{\frac{2(p_T - p_S)}{\rho}}$$
- Note: really only need difference between p_S and p_T

Pitot Tube



(Wikipedia)

Measure pressure difference

$$V = \sqrt{\frac{2(p_T - p_S)}{\rho}}$$

Pitot-static system

- Total pressure probe(s) not behind propulsion sources, near front of aircraft – usually on sides of fuselage near front or front of a wing
- Static pressure port(s) in location with minimum disturbance from aircraft itself – usually sides of fuselage
- Airspeed indicator shows measured airspeed to pilot

2 on each side of this Boeing 757

Airspeed Indicator

- Mechanically uses Bernoulli's equation to show airspeed – not corrected for density
- Aircraft are typically flown via this so-called indicated airspeed (not corrected for density, mechanical errors, etc.) in knots

$$V = \sqrt{\frac{2(p_T - p_S)}{\rho_{\text{standard}}}}$$