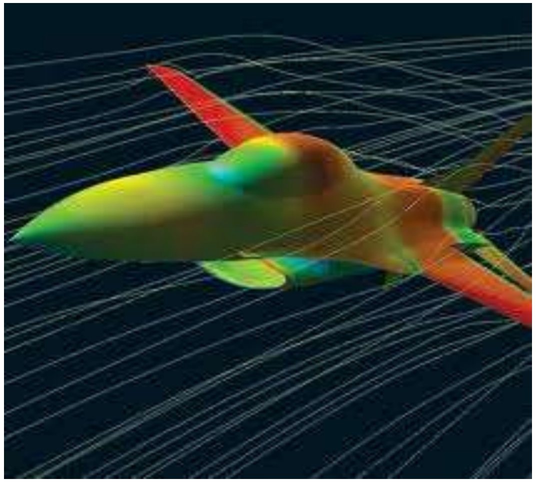

Introduction to Aerodynamics

Dr. Guven

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Aerodynamic Forces

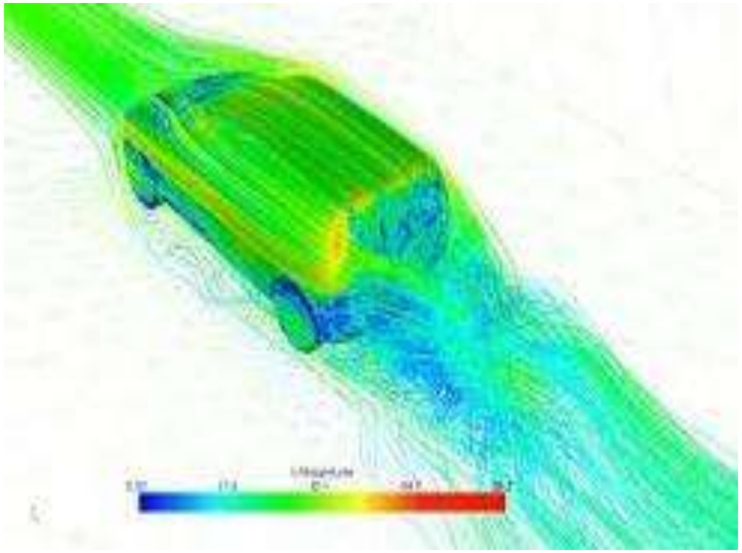
- All aerodynamic forces are generated wither through pressure distribution or a shear stress distribution on a body.
- The most relevant one is the pressure distribution as it is the pressure distribution that causes Lift force to be generated on an airplane. Air will travel from a place of high pressure to low pressure causing a lift to be generated.
- Most airplanes will need to have an area of low pressure on top of the plane.

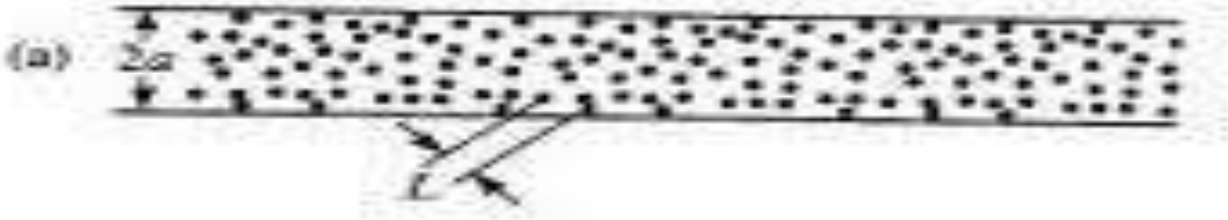
Types of Aerodynamic Flow

- It is essential to understand the types of flow in order to understand the physical phenomena behind them.
- Types of flow include:

  - Continuum vs. Molecular Flow
  - Inviscid vs. Viscous Flow
  - Incompressible vs. Compressible Flow
  - Laminar Flow vs. Turbulent Flow

Continuum Flow – Molecular Flow

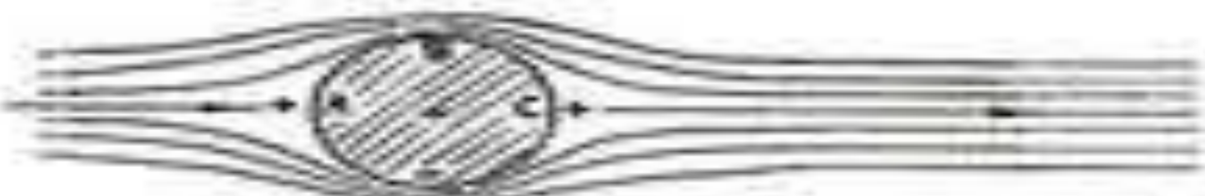




Inviscid Flow vs. Viscous Flow

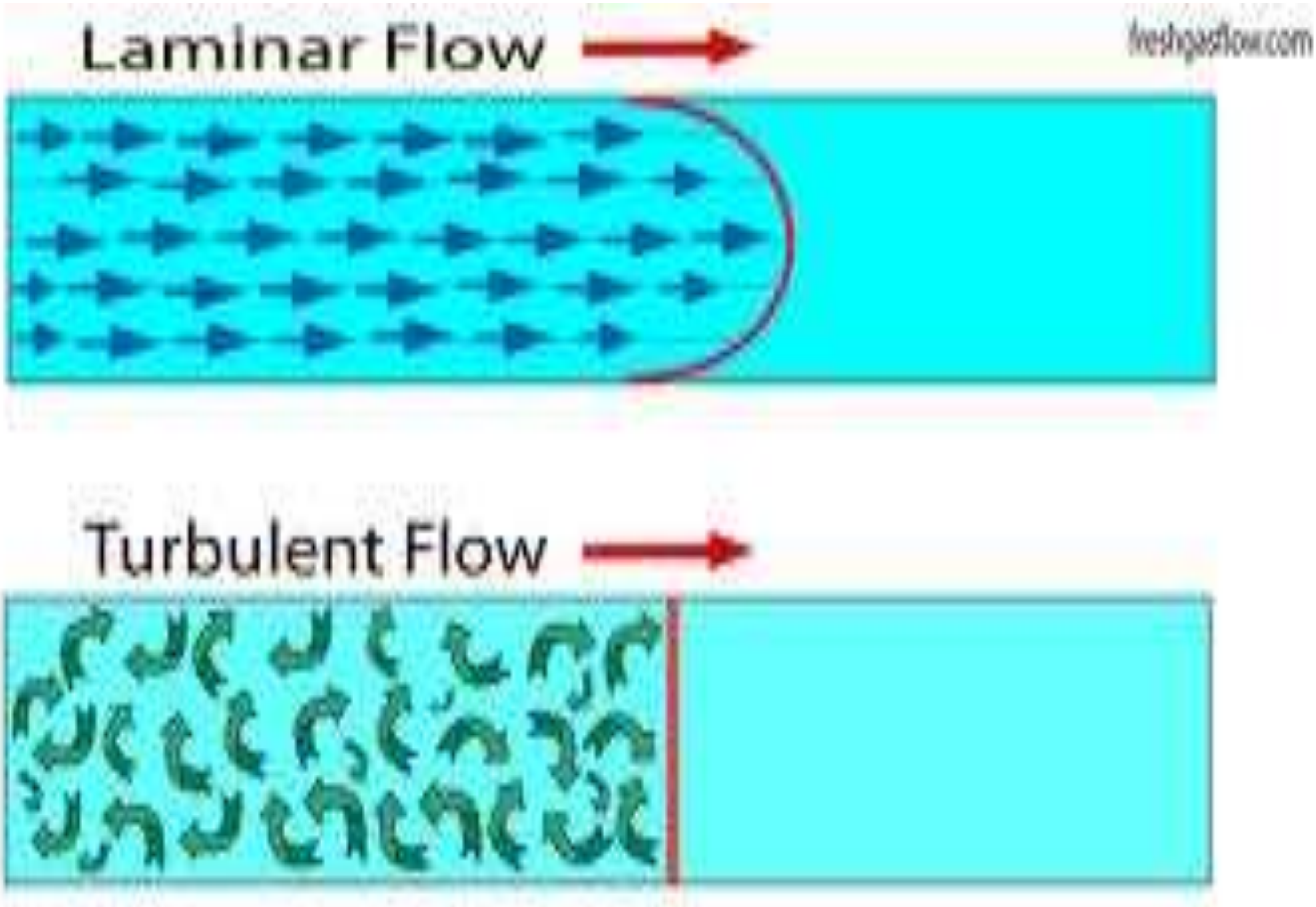
(C) CYLINDER BETWEEN $R_e = 10^4$ AND 10^5: VORTEX STREET WITH $C_{D_0} = 1.2$.

(B) CYLINDER ABOVE CRITICAL REYNOLDS NUMBER WITH $C_{D_0} = 0.3$.

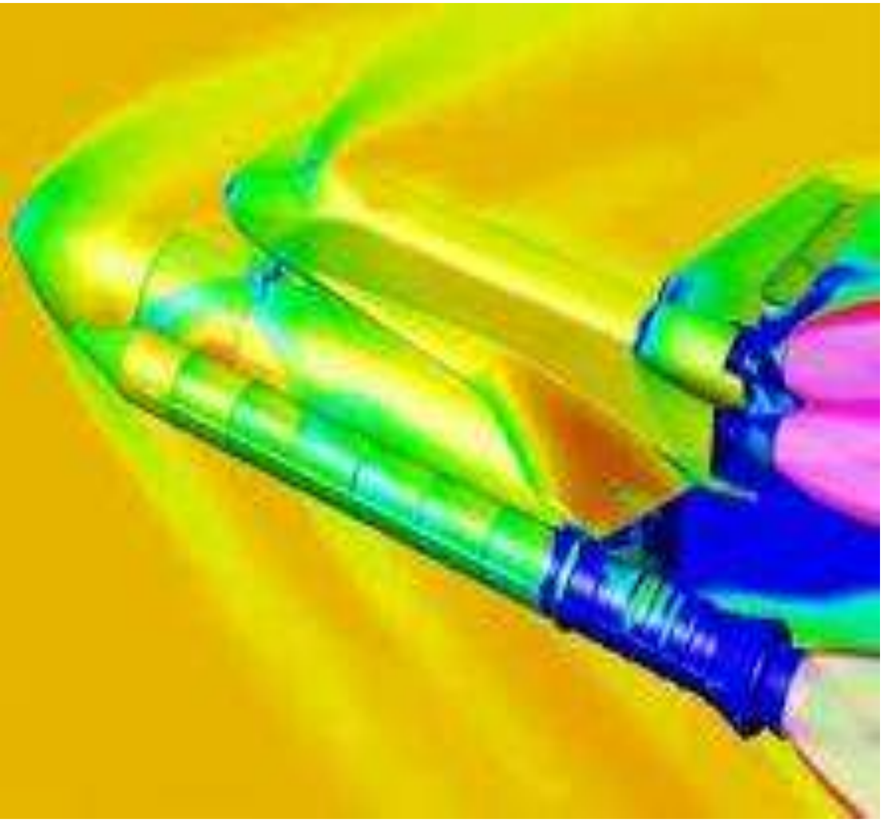


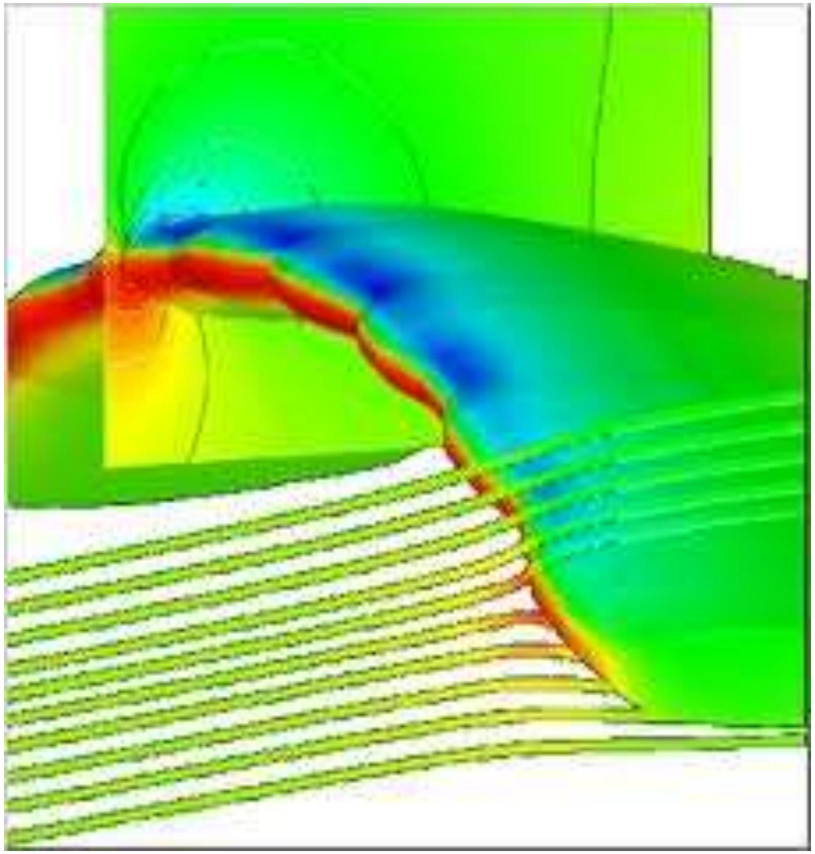
(A) FLOW PATTERN OF CIRCULAR CYLINDER IN NON-VISCOUS FLOW; NO DRAG.

Laminar Flow – Turbulent Flow



Compressible Flow – Incompressible Flow





Laws of Aerodynamics

- Several principles or physical laws will govern aerodynamic equations. These include:
- Equation of state
- Conservation of Mass
- Newton’s Second Law (Conservation of Momentum)
- Conservation of Energy

Equation of State

- Equation of State for ideal gases state how parameters such as pressure, density and temperature relate to each other.
- The equation of state is:

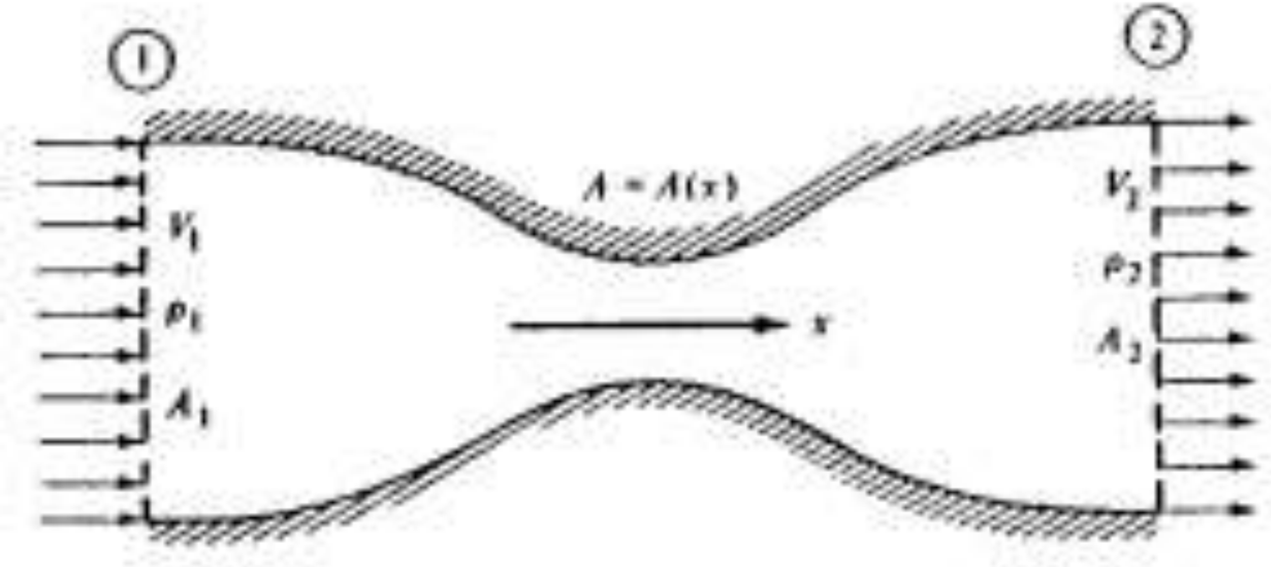
$$\rho RT = P$$

Conservation of Mass

Mass can be neither created or destroyed. Hence, if we take a streamtube, the amount of fluid entering the tube and exiting it will be the same.

Mass of the flow sweeping through A is: dm=ρ(AVdt)

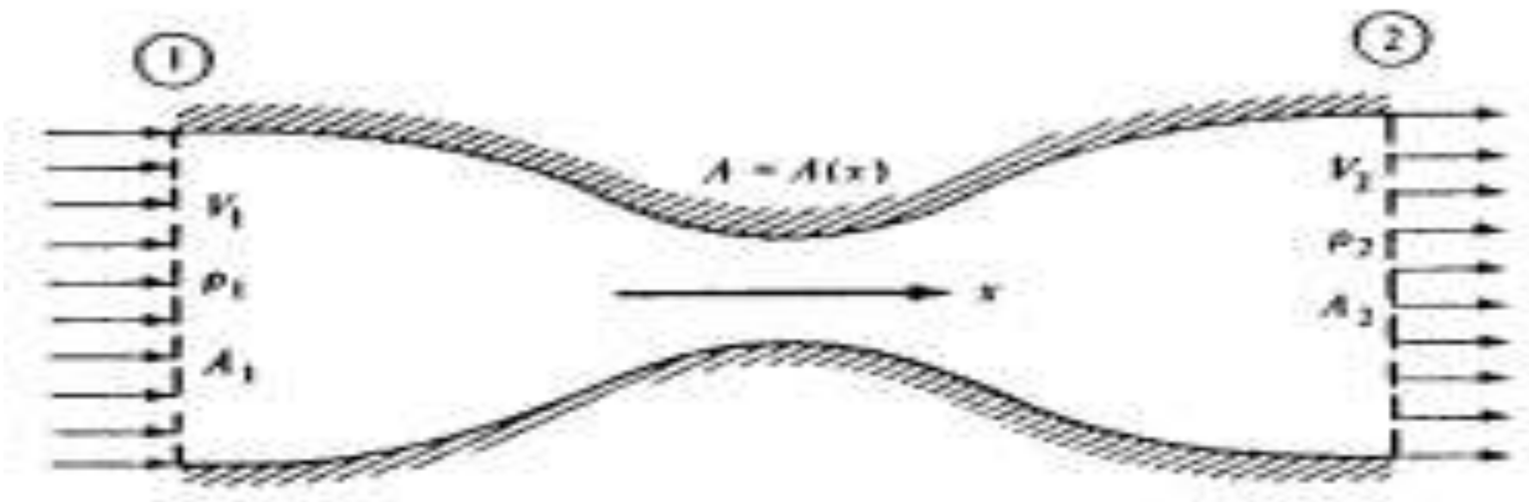
Mass Flow can be derived as dm/dt



Continuity Equation

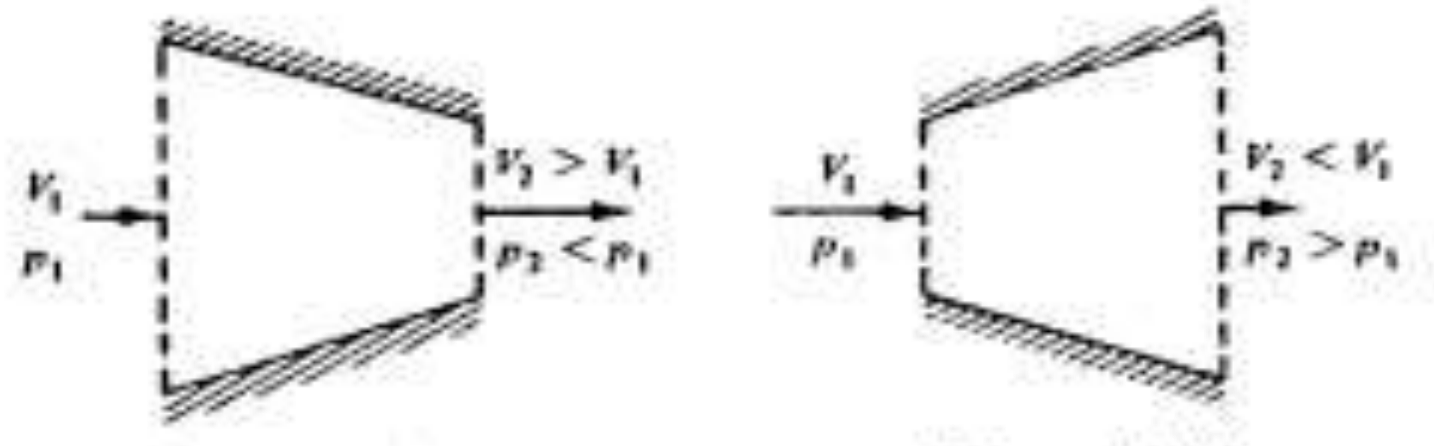
- Since mass can neither be created or destroyed, mass flow on entrance and exit will equal to each other.
- Thus the Continuity Equation becomes:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$



Continuity Equation in Incompressible Flow

- In incompressible flow, the density is treated as constant. For most type of flows, it is possible to treat as incompressible especially for small commercial planes.
- Hence the continuity equation for incompressible flow is: $A_1 V_1 = A_2 V$



Convergent duct

Divergent duct

Momentum Equation

- Newton's Second Law guides the flow of fluid and helps us to find the equation of momentum
- Force = mass x acceleration (F=ma)
- Force is caused by pressure, frictional shear and by gravity acting on the mass inside the element.
- Hence, by integrating these forces and by neglecting friction and gravity we get the Euler’s equation.

$$dp = -\rho V\, dV$$

Bernoulli Equation

- If we integrate the Euler equation for a frictionless and incompressible flow (density constant)

$$dp = -\rho V\,dV$$

$$\int_{p_1}^{p_2} dp = -\rho \int_{V_1}^{V_2} V\,dV$$

$$p_2 - p_1 = -\rho\left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right)$$

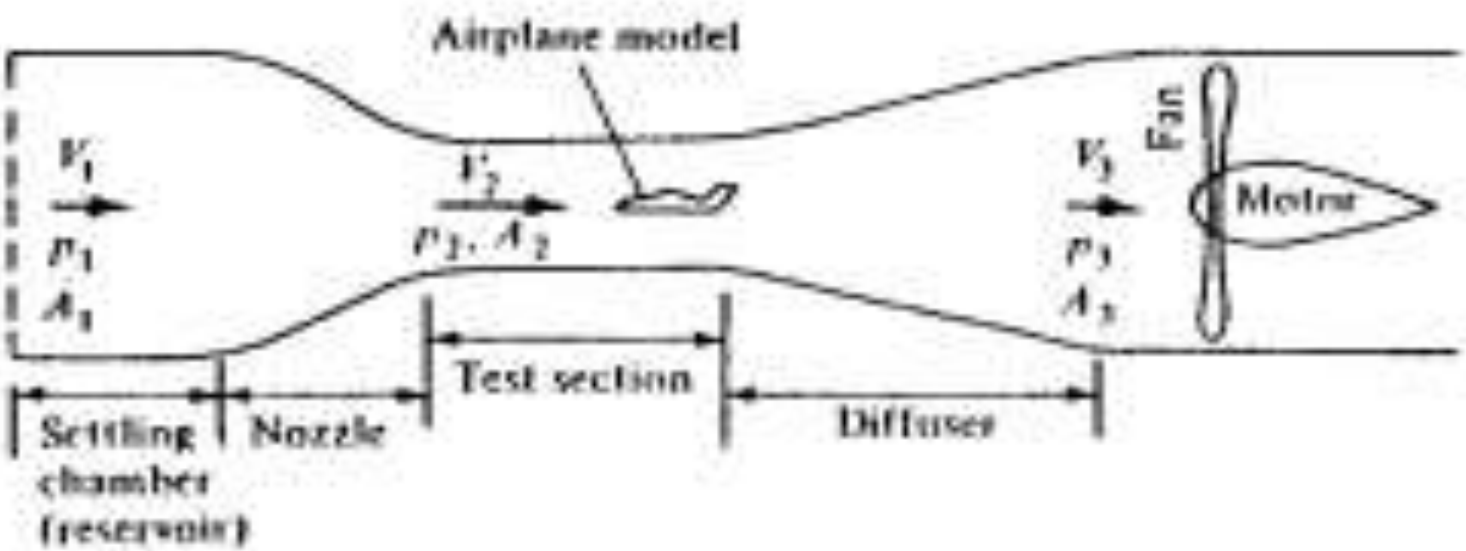
$$\boxed{p_1 + \tfrac{1}{2}\rho V_1^2 = p_2 + \tfrac{1}{2}\rho V_2^2}$$

Wind Tunnel Speed Determination

- Using Bernoulli equation, it is possible to find that the velocity of the test object depends in the pressure difference in the wind tunnel.

$$V_1^2 = \frac{2}{\rho}(p_2 - p_1) + V_2^2 \qquad V_2 = \frac{A_1}{A_2}V_1 \qquad V_1^2 = \frac{2}{\rho}(p_2 - p_1) + \left(\frac{A_1}{A_2}\right)^2 V_1^2$$

$$V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho[1 - (A_2/A_1)^2]}}$$

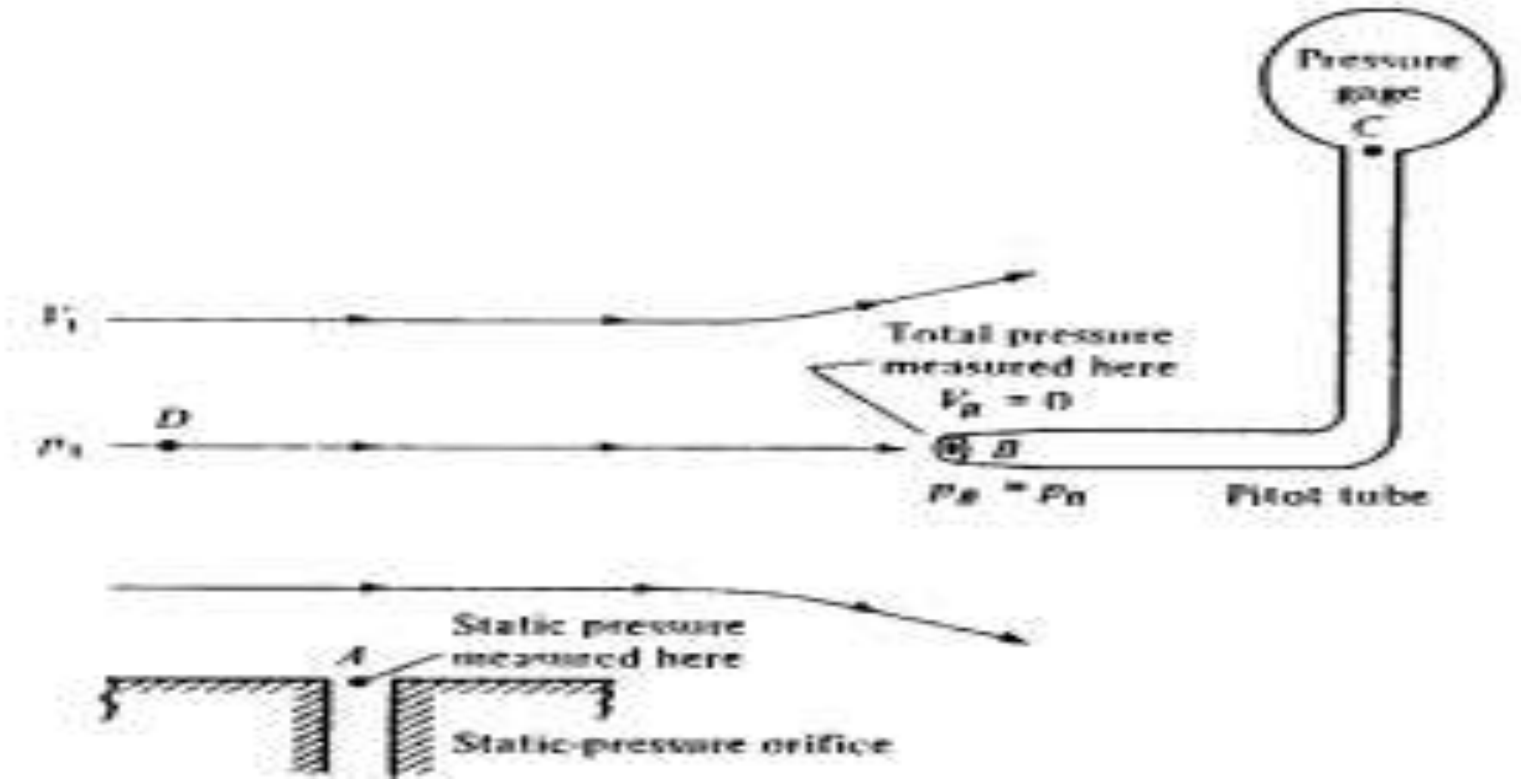


Measurement of Airspeed – Pitot Tube

- Especially for aircraft, measurement of air speed is a very important thing. For any type of flow (even for flows that are not constant), we can measure air speed by using a device called the Pitot Tube.
- In order to analyze Pitot Tube, we need to understand static pressure and total pressure.
- Static pressure is the pressure caused by the random motion of the gas particles. Type of flow doesn’t change static pressure.
- Total pressure is the pressure caused by the flow itself and hence its pressure, density and temperature values effect total pressure. Total pressure is also defined as a pressure that would exist even if the flow was slowed down to zero velocity.

Pitot Tube

- Pitot tube uses static pressure as well as the total pressure of the flow in relation with the Bernoulli equation to measure air speed.



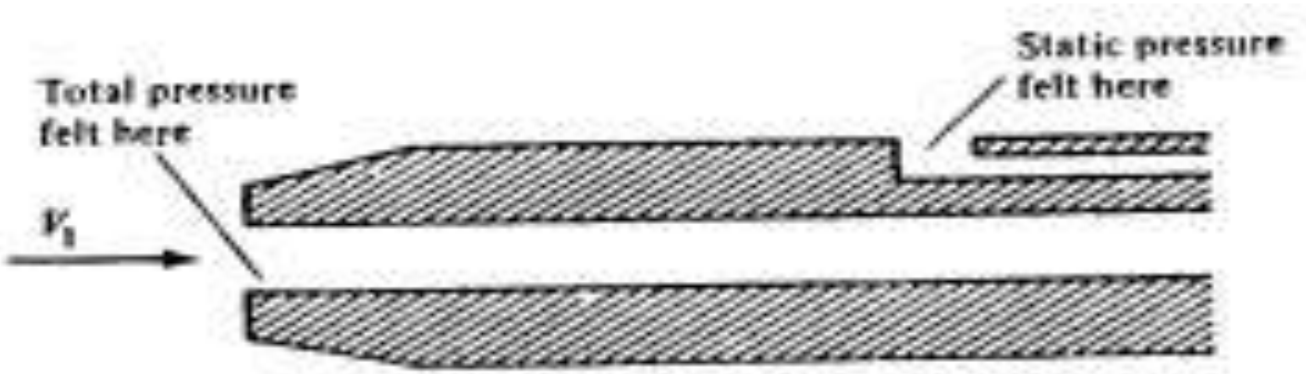
Pitot Tube

- Pitot tube is found frequently on the airplanes to measure air speed constantly.

$$p_A + \frac{1}{2}\rho V_A^2 = p_B + \frac{1}{2}\rho V_B^2$$

$$p_1 + \frac{1}{2}\rho V_1^2 = p_0 + 0$$

$$V_1 = \sqrt{\frac{2(p_0 - p_1)}{\rho}}$$



Conservation of Energy and Flows

- Especially in high speed flows near or above the speed of sound, you will have to take in the energy equations into account.
- A high speed flow is also a high energy flow due to the definition of velocity and kinetic energy.
- When high speed flows are slowed down, the consequent reduction in kinetic energy appears as an increase in temperature.
- Hence, high speed flows, compressibility and energy changes are inter related.

Thermodynamics Terminology

- In order to understand high speed flows, we need to understand basic terms in thermodynamics.
- Specific Heat (c) is the heat added per unit change in temperature of the system.
- Specific heat (C_v) at constant volume is calculated pe constant volume
- Specific heat at constant pressure (C_p) is calculated at constant pressure.
- $\gamma = c_p/c_v$ is termed as the ratio of specific heats

Laws of Thermodynamics

- There are four laws of thermodynamics that govern our universe:
- Zeroth law: Heat equilibrium
- First Law: Energy remains the same
- Second Law: Entropy always increases
- Third Law: As you reach absolute zero, entropy will decrease

Thermodynamic Equations for Perfect Gas

$$de = c_v dT$$

$$dh = c_p dT$$

$$e = c_v T$$

$$h = c_p T$$

Isentropic Flow

- One of the most important concepts of thermodynamics and compressible aerodynamics is isentropic flow.
- Adiabatic process is a process is one in which no heat is added or taken away
- Reversible flow is in which friction and dissipation does not take place
- Isentropic process is both adiabatic and reversible. Hence in isentropic flow entropy is constant.

Isentropic Flow Equations

- Most isentropic flows are applicable to compressible flows.
- Isentropic flow equations create a relationship between pressure, temperature and density.

$$\frac{p_2}{p_1} = \frac{\rho_2}{\rho_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$$

Energy Equation

- Energy equation is the third fundamental law that describes the properties of the flow. Energy equations are useful for compressible flow.
- Energy equation describes the fact that energy can neither be created or destroyed.

Energy Equation for Adiabatic Flow

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$c_p T_1 + \frac{1}{2} V_1^2 = c_p T_2 + \frac{1}{2} V_2^2$$

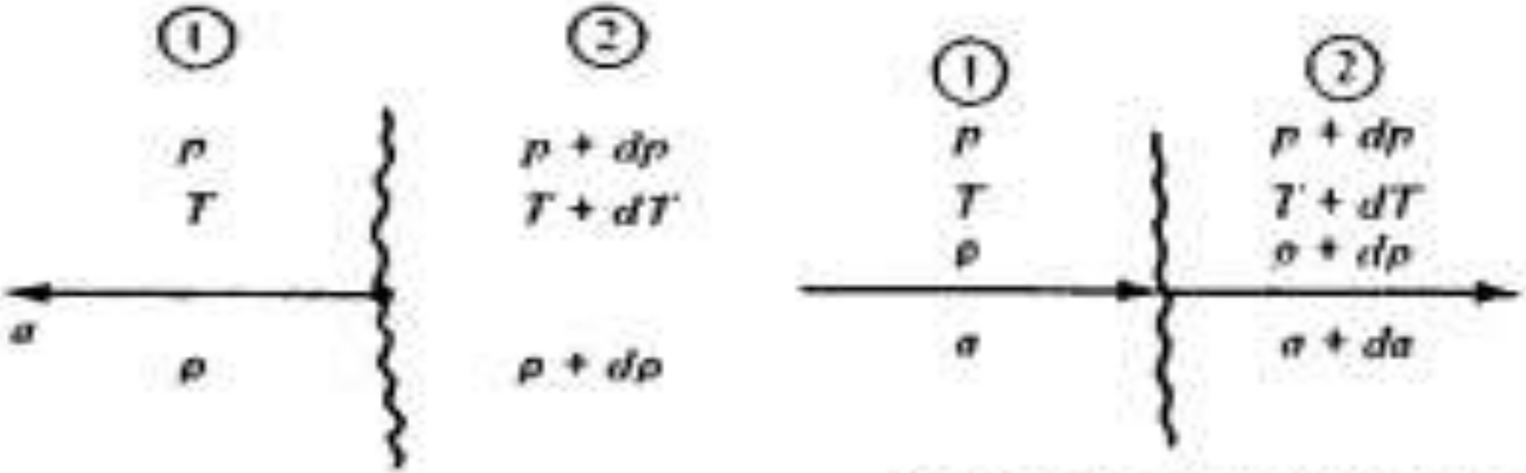
Summary of Equations

- For steady, incompressible and inviscid flow, you need to use the Continuity equation and the Bernoulli equation.
- For isentropic, compressible flow:

  - Continuity Equation
  - Isentropic relations
  - Equation of State
  - Energy Equation

Speed of Sound

- Sound waves travel through the air at definite speed. That speed is called the speed of sound
- Speed of sound is an important variable in analyzing compressible flow



(a) A sound wave propagating with velocity a into a stagnant gas

(b) A stationary sound wave in a moving gas; the upstream velocity relative to the wave is a

Speed of Sound

- On a physical basis, the flow through a sound wave involves no heat addition and the effect of friction is negligible. Thus, the flow through a sound wave is isentropic.
- Thus speed of sound for a gas and also for a perfect gas is:

$$a = \sqrt{\frac{\gamma p}{\rho}} \qquad a = \sqrt{\gamma R T}$$

Why Does Speed of Sound Depend on Temperature?

- Speed of sound is directly dependent on temperature.
- This is due to the fact that propagation of a sound wave through gas takes place via molecular collisions.
- Hence, the energy of a soundwave is transmitted through the air by molecules that collide with each other. The mean kinetic energy associated with these collisions is linked to the temperature of the gas. (More hotter means more faster and thus more kinetic energy)

Mach Number

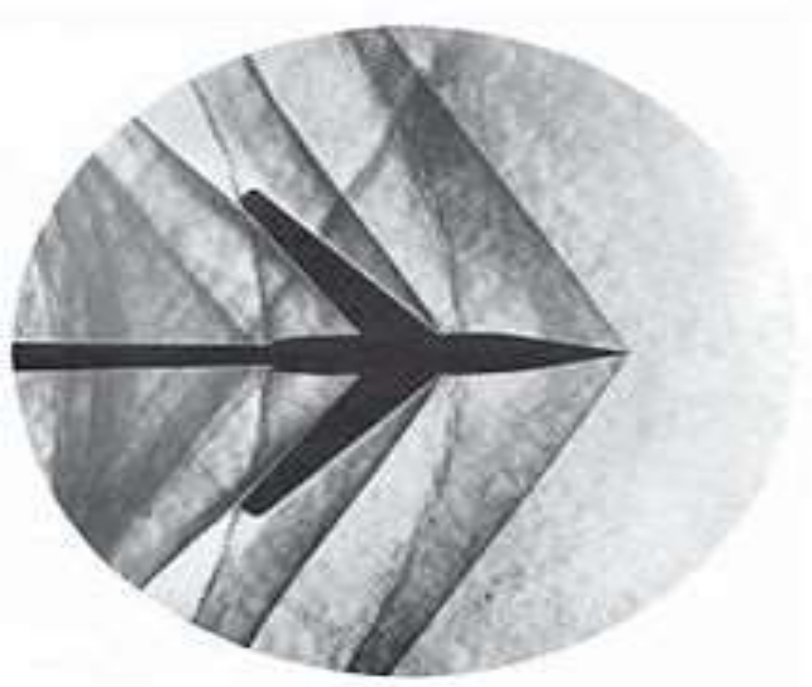
- Mach number denotes the magnitude of the flow as compared to the speed of sound
- If M < 1 the flow is **subsonic**
- If M = 1 the flow is **sonic**
- If M > 1 the flow is **supersonic**
- If M > 5 the flow is **hypersonic**

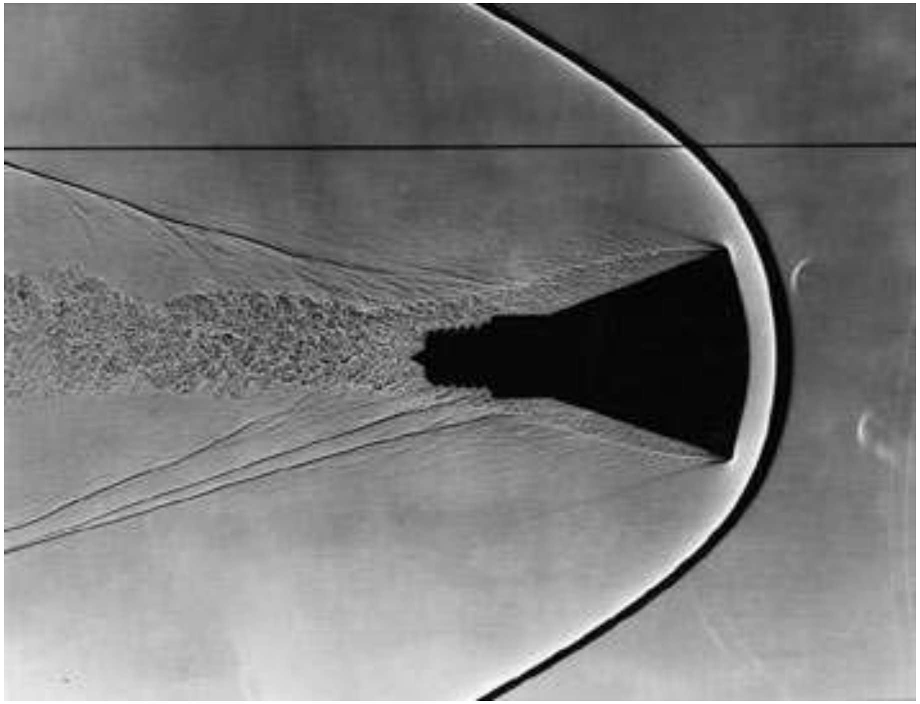
$$M = \frac{V}{a}$$

Shockwaves in Compressible Flow

- Whenever there is a flow that is faster than a speed of sound, then shock waves can occur as the aircraft travels in a compressible region.
- A shockwave is an extremely thin region where the flow properties change drastically. They are usually in the order of 0.00001 cm.
- A shockwave is a explosive compression process where the pressure increases discontinuously across the wave.
- This huge level of compression and pressure increase can have adverse effects if the craft is not made supersonic resistant.

Shockwaves in Compressible Flow



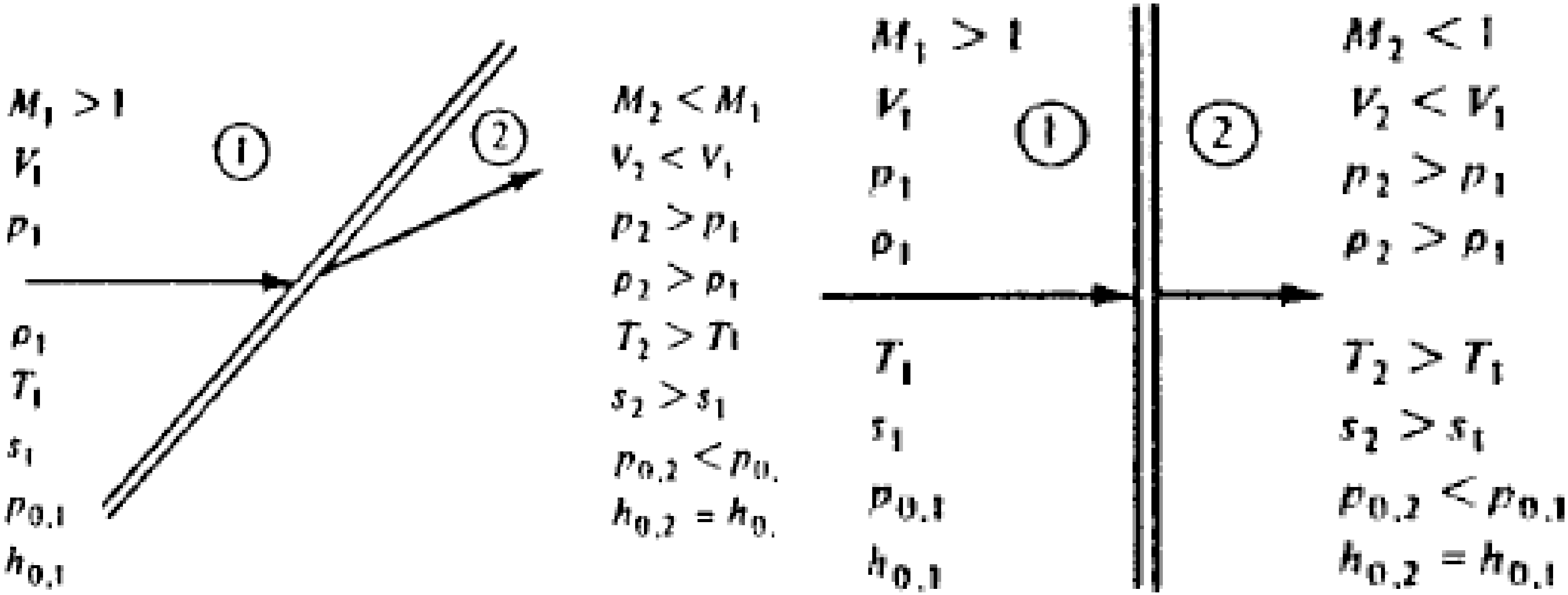


Shockwaves

Characteristics of Shock Waves

- The biggest characteristics of a shockwave is that the pressure will increase greatly as the shockwave is passed.
- When a shock wave passes through matter, the total energy is preserved but the energy which can be extracted as work decreases and entropy increases. This, for example, creates additional drag force on aircraft with shocks

General Properties of Shockwaves



(*a*) Oblique shock wave

(*b*) Normal shock wave

General Properties of Shockwaves

- When you pass across a shockwave:
- Pressure increases $P2 > P1$
- Temperature increases $T2 > T1$
- Density increases
- Entropy increases
- Mach number decreases $M2 < M1$
- Flow velocity decreases

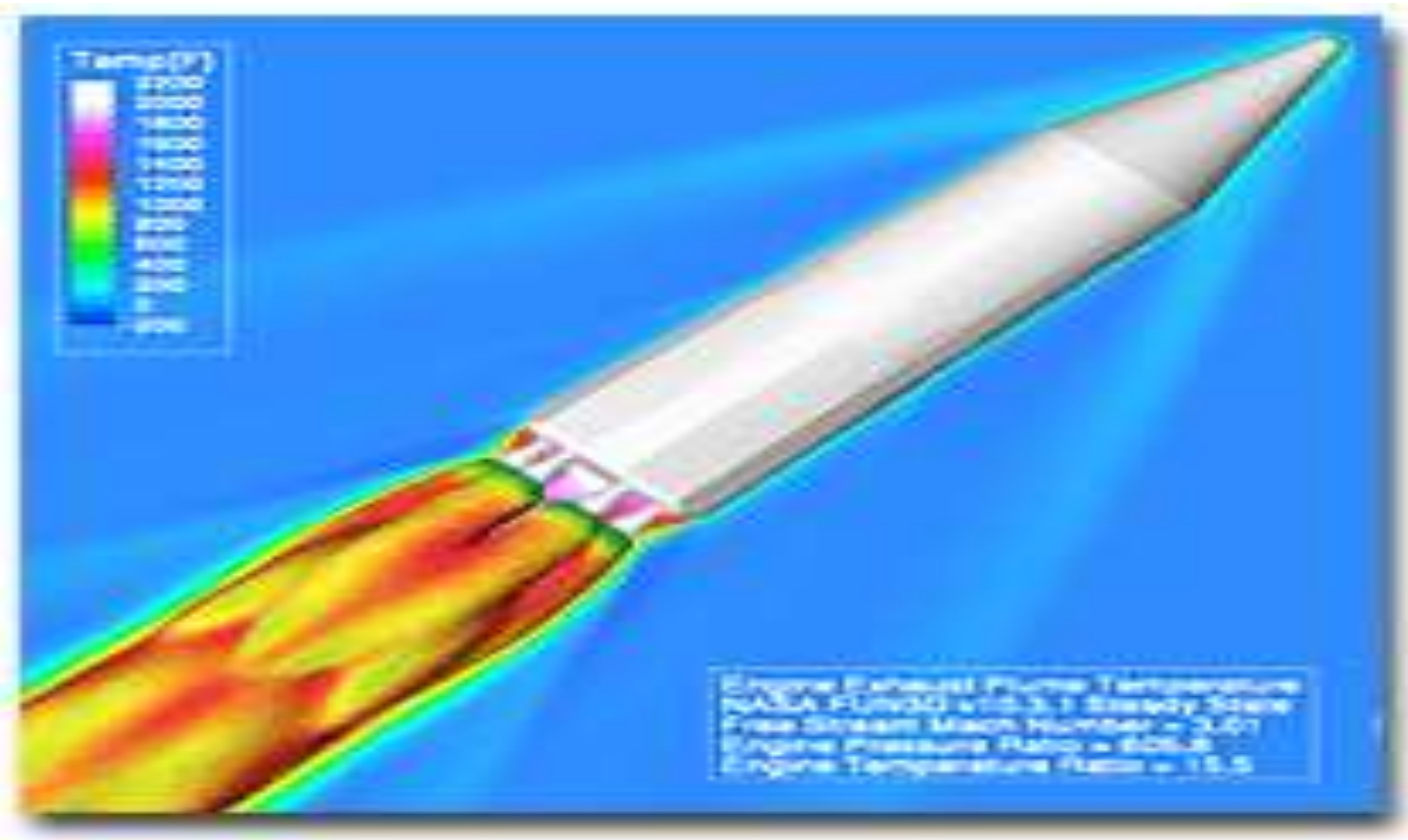
Viscous Flow

- In reality every flow in the world is a viscous flow.
- Viscosity is the phenomena of friction that acts on all objects and fluids.
- In viscous flow, friction of surfaces, heat transfer and energy transfer between molecules and mass transfer (diffusion) takes place.

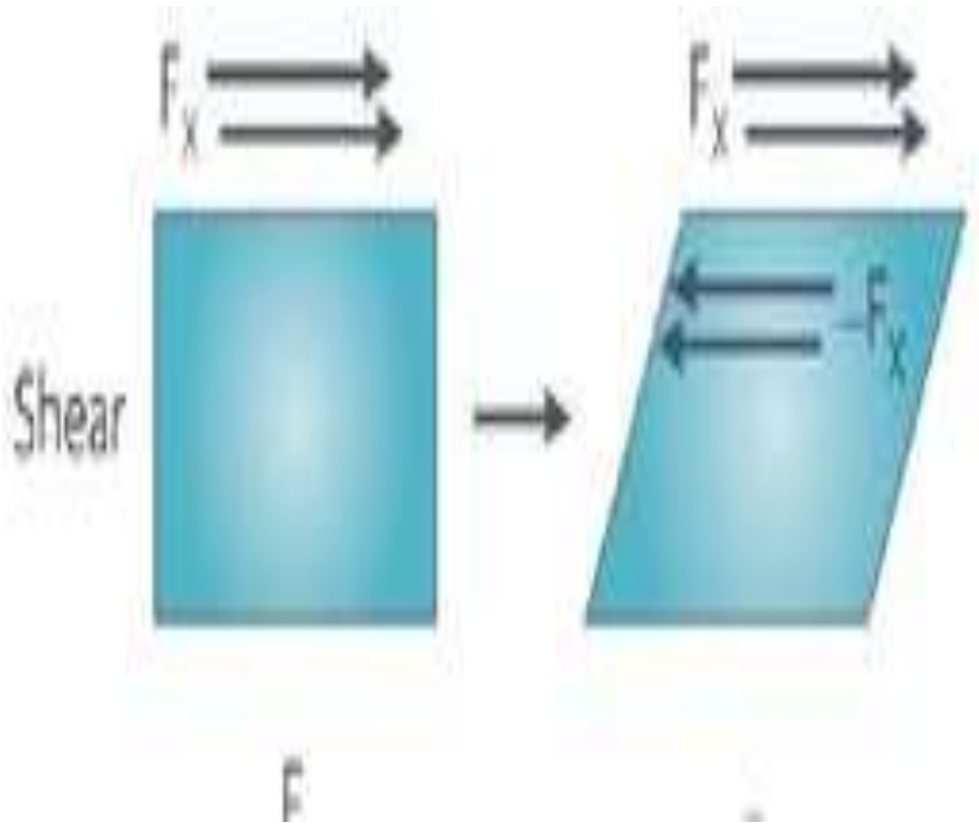
Examples of Viscous Flow

Examples of Viscous Flow

Examples of Viscous Flow



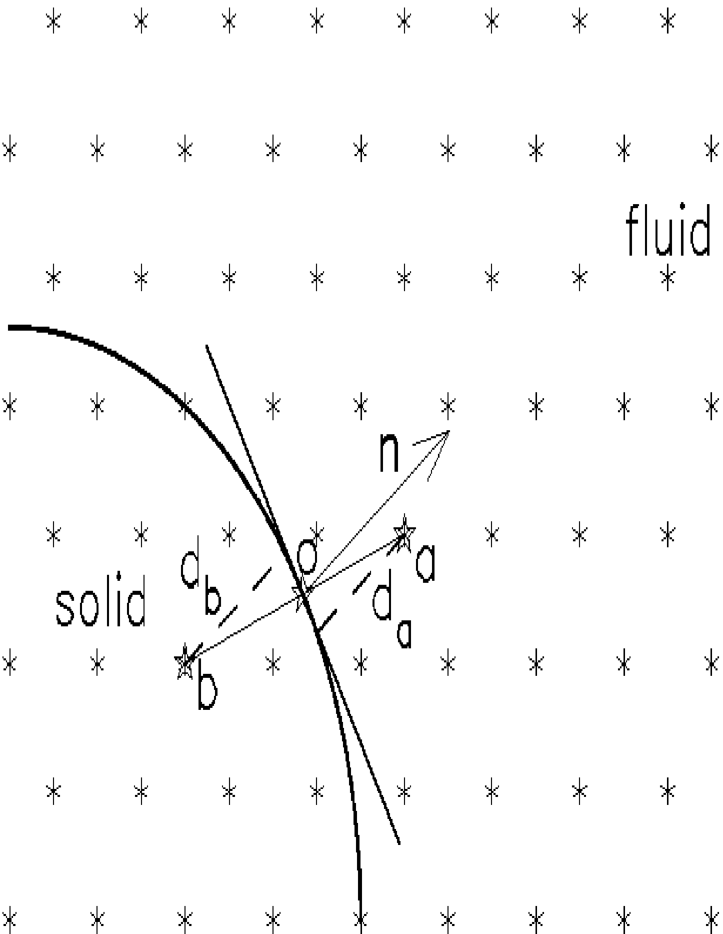
Friction (Viscosity) Creates Shear Stress

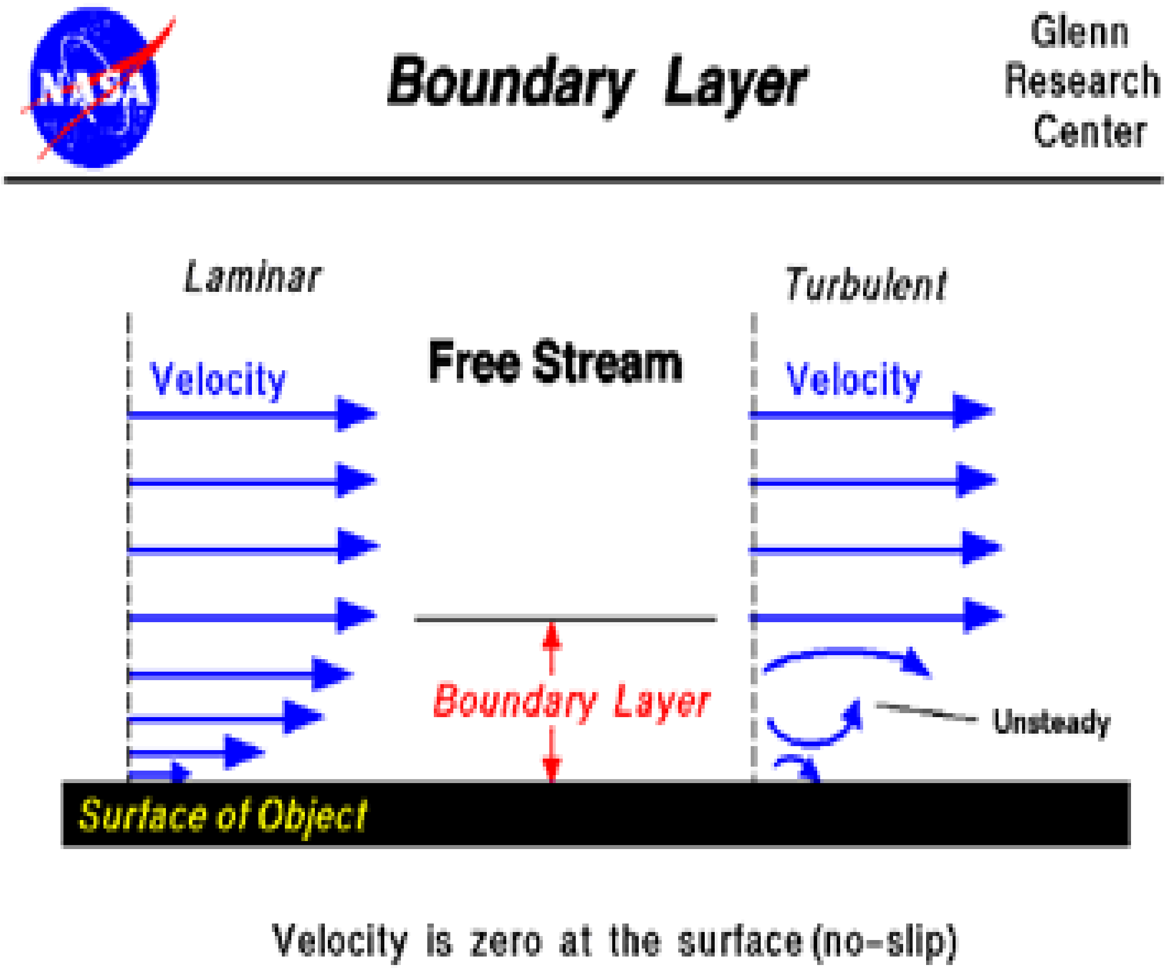


Shear stress is stress applied parallel to the surface of the cell.

No Slip Condition

- The influence of friction creates V=0 at the body surface and this is called no-slip condition.





Heat Transfer in Viscous Flow

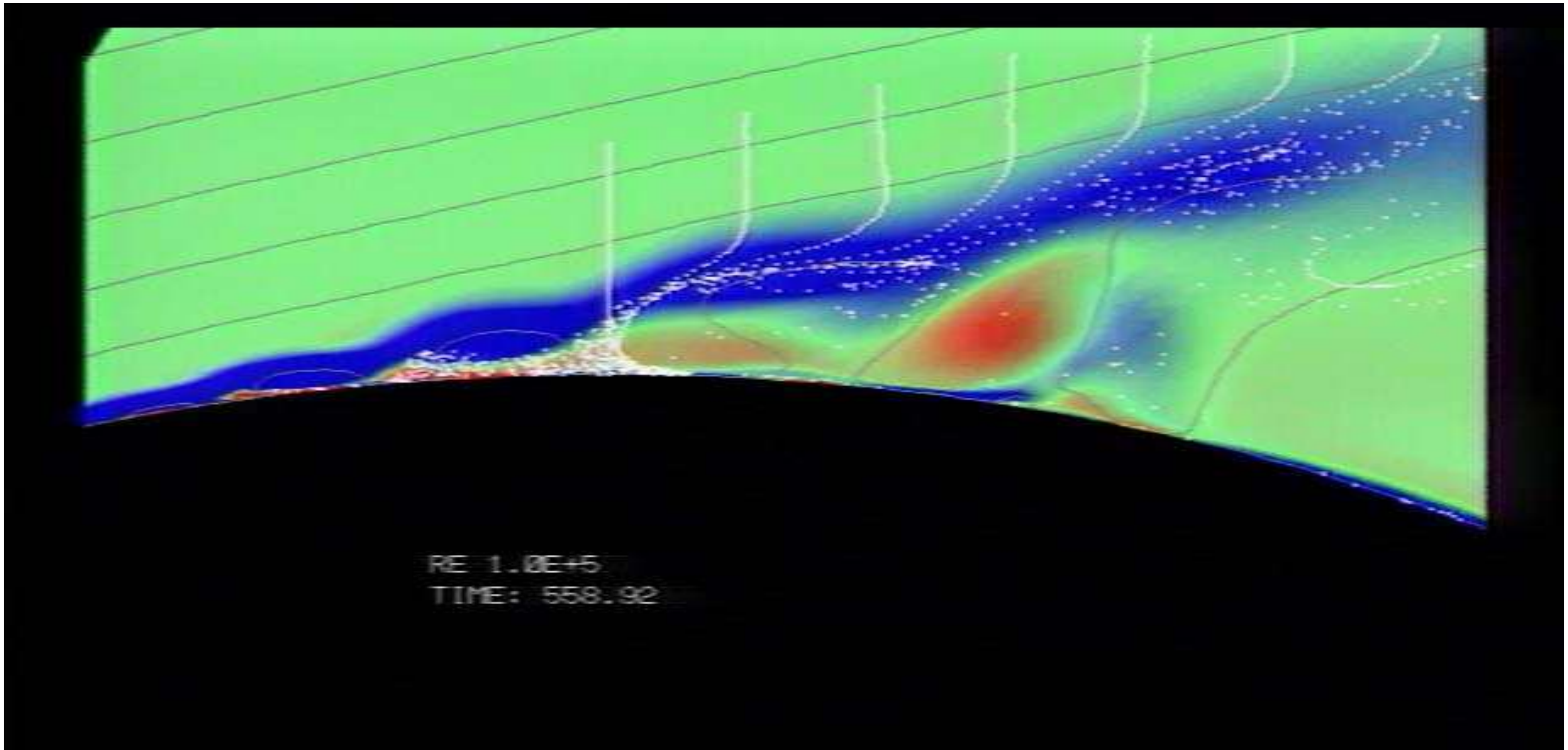
- The moving fluid has a certain amount of energy. As it flows on the surface, the flow velocity is decreased due to friction.
- This decrease in velocity is translated as a decrease in kinetic energy.
- This loss of kinetic energy transforms into internal energy of the fluid. (Conservation of Energy)
- Hence, the temperature of the fluid will rise.

Aerodynamic Heating in Viscous Flow

- As a result, warmer fluid will heat the cooler surface of the body.
- This is called **aerodynamic heating**. This becomes more severe since as flow velocity increases aerodynamic heating will also increase.

Boundary Layer Definition

- ***Boundary Layer*** is the thin boundary region between the flow and the solid surface, where the flow is retarded due to friction between the solid body and the fluid flow.



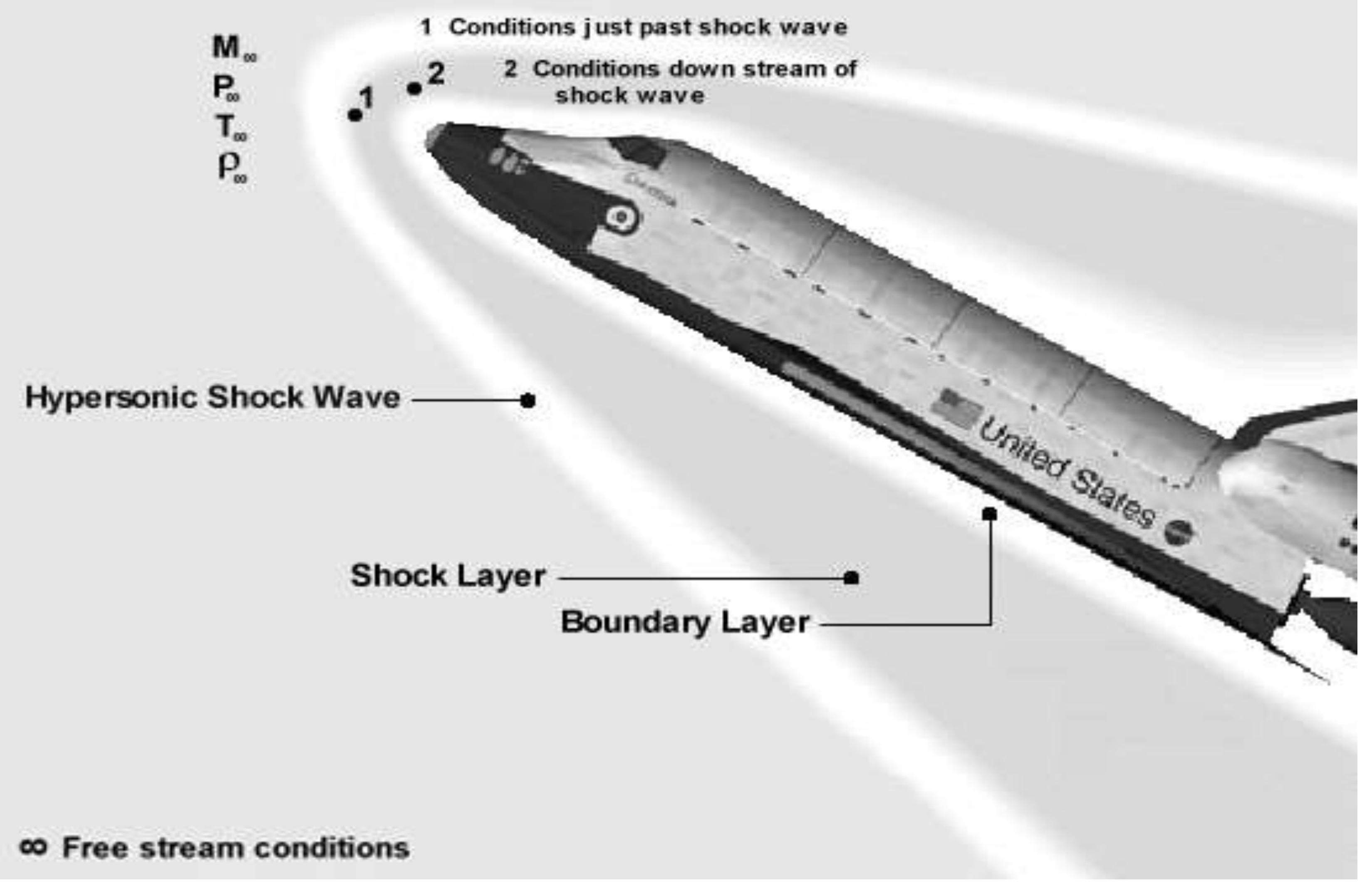
What is the Significance of Boundary Layers?

- Although friction exists in all types of flow, practically it is only of consequence in the thin region separating the flow and the solid body.
- Hence, as far as the physical system is concerned, the boundary layer is the region where mass transfer, momentum transfer, heat transfer, friction effects and all viscosity effects are felt.

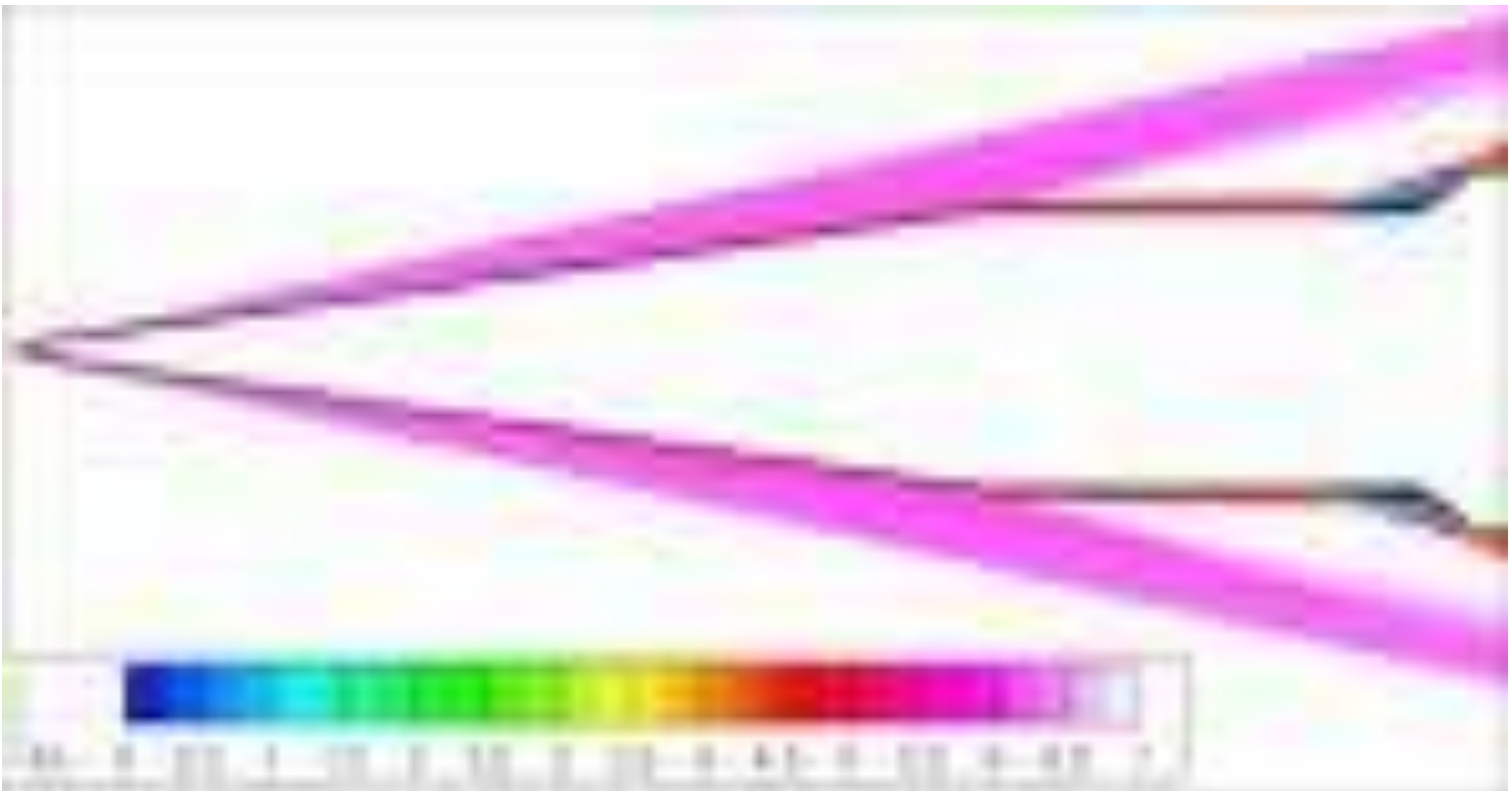
How Does a Boundary Layer Help Engineers!

- This means that instead of solving for the whole Navier Stokes equation set for the full flow, we can approximate a solution by ***solving for the boundary layer where the viscous effects are felt***.
- Thus, in order to calculate skin friction and aerodynamic heating at the surface, you only have to account for friction and thermal conduction within the thin boundary layer. Hence; you wont need to analyze the large flow outside the boundary layer

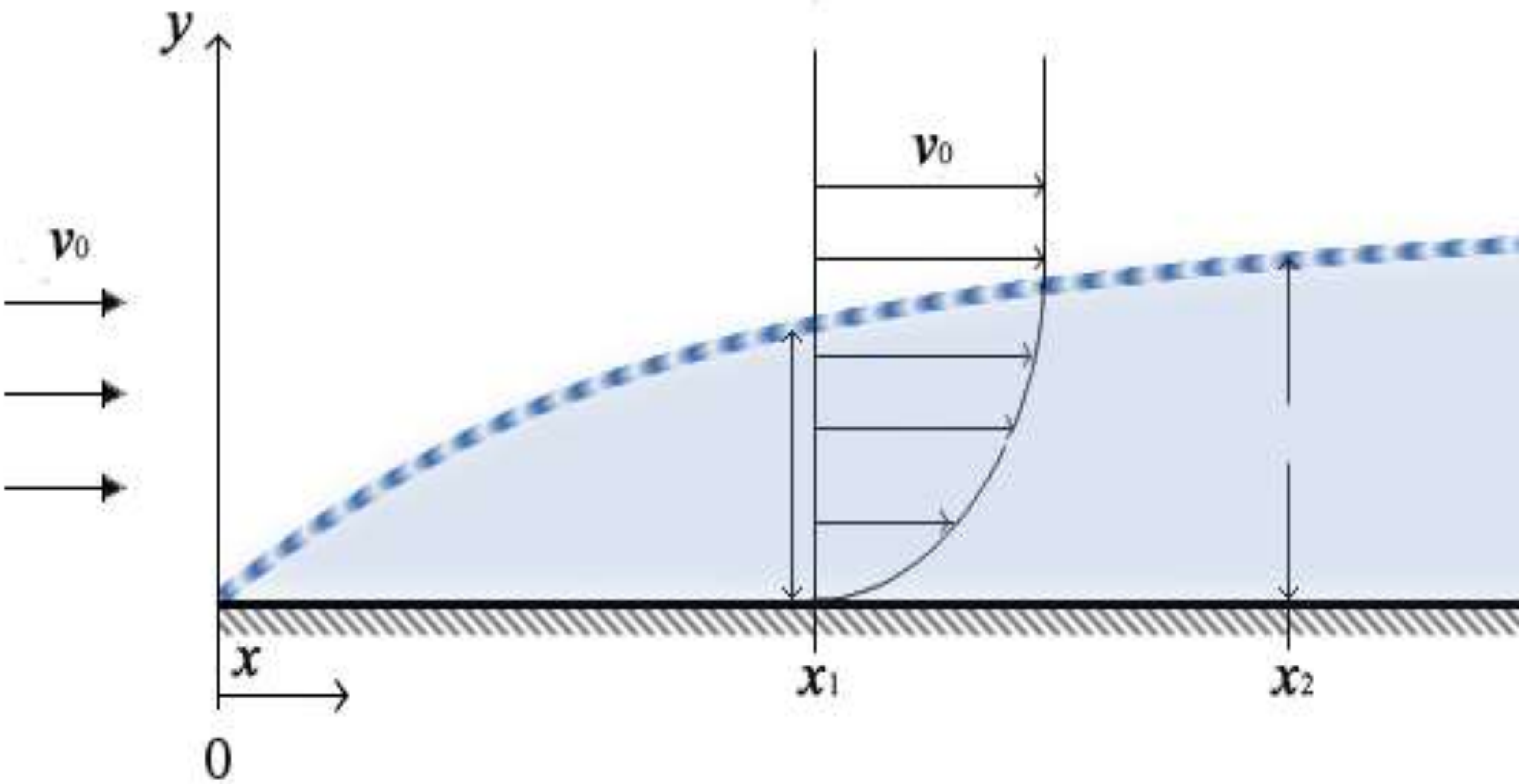
Representation of a Boundary Layer



Representation of a Boundary Layer



Shape of a Boundary Layer



Because of No-Slip condition, the velocity of the fluid is Zero at the surface and it gradually increases.

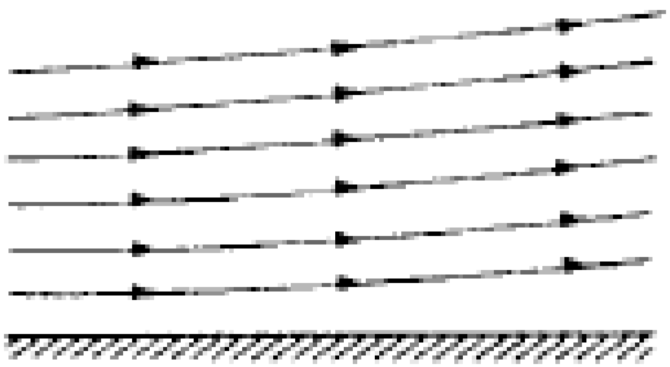
Reynolds Number

- Reynolds Number is the most important parameter in viscous aerodynamics or in fluid mechanics. It determines the type of the flow and it helps to determine the characteristics of the flow.
- Reynolds Number is the ratio between inertial forces to viscous forces

$$\mathrm{Re} = \frac{\rho_\infty V_\infty L}{\mu_\infty}$$

Turbulent Flow

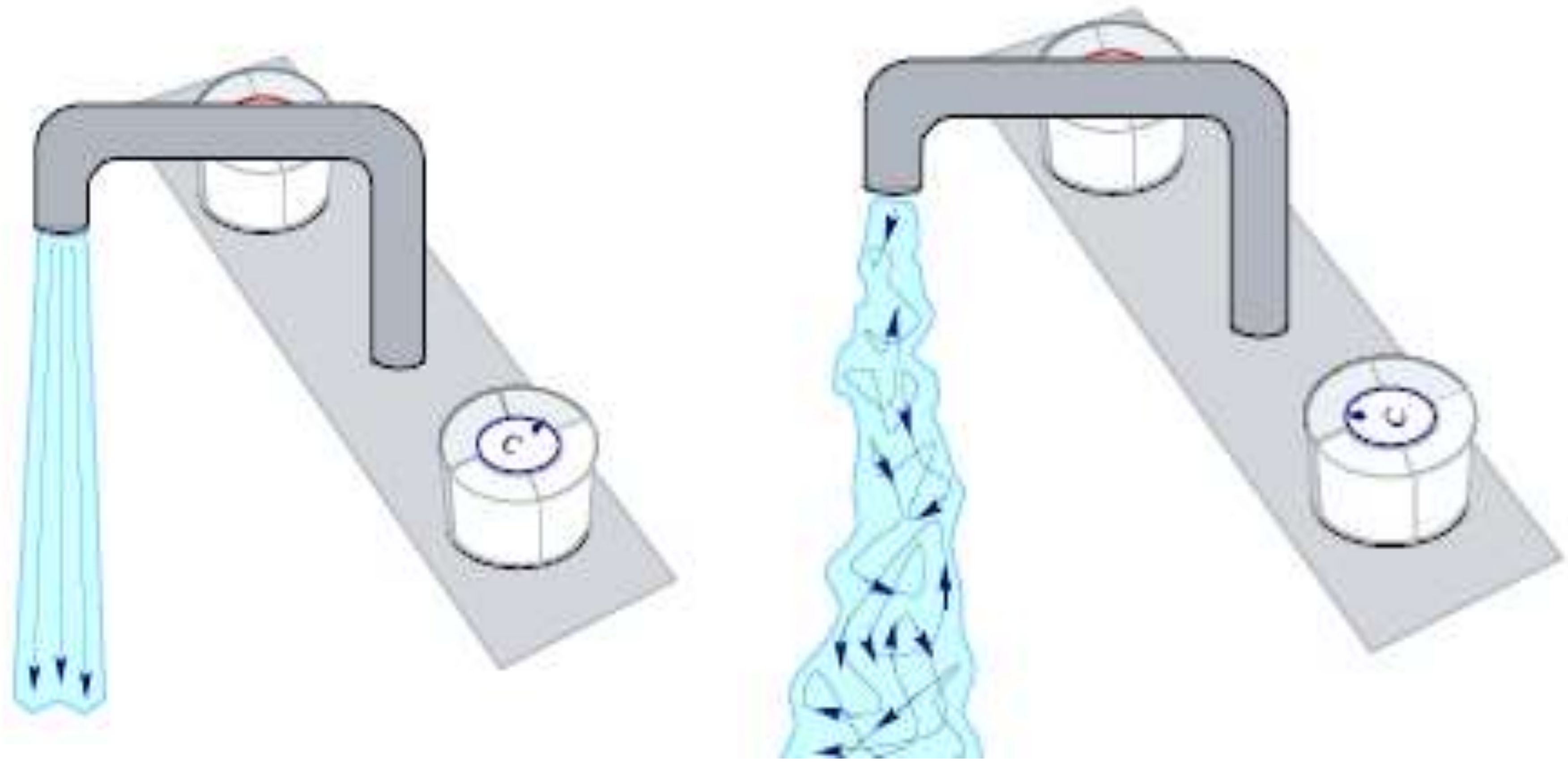
- Higher Reynolds Numbers usually denote turbulent flow.
- Turbulent flow can be desired in certain situations



(a) Laminar flow

(b) Turbulent flow

Laminar and Turbulent Flow



When is Turbulent Flow Desirable?