Fluid Dynamics

IV B. Tech III semester (Autonomous IARE R-18)

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FLUID DYNAMICS

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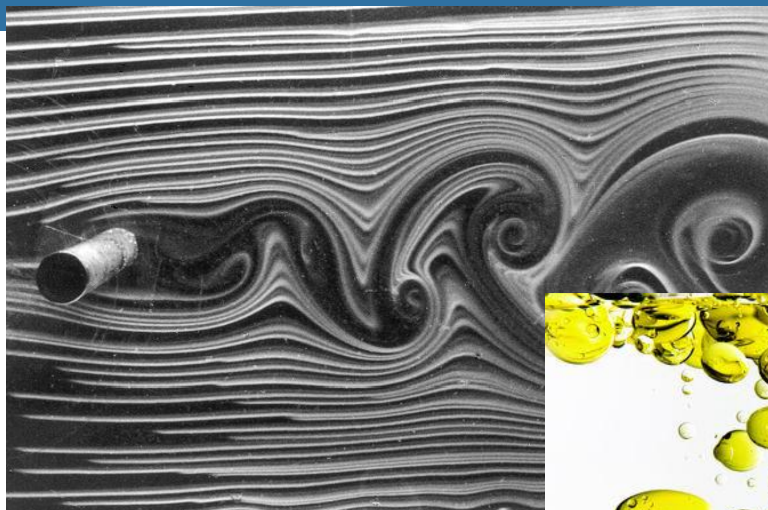
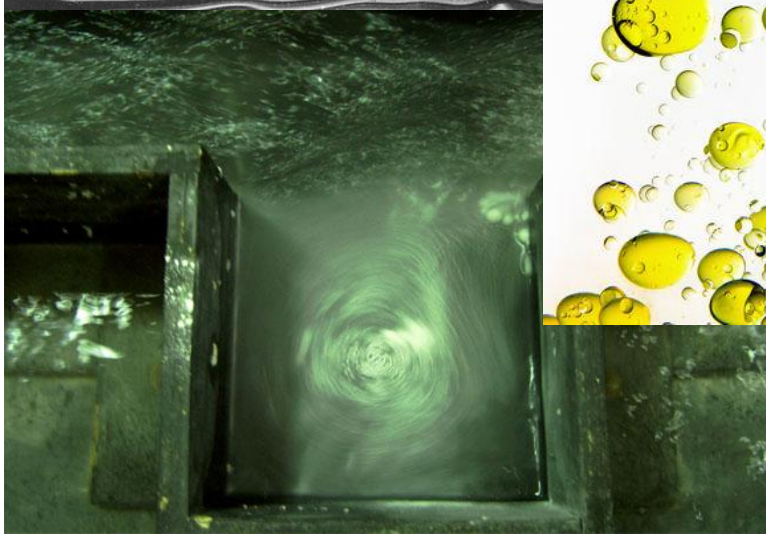
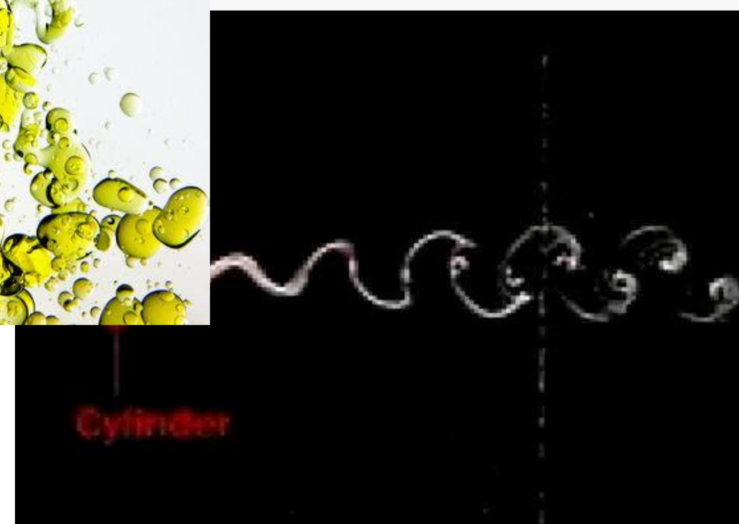
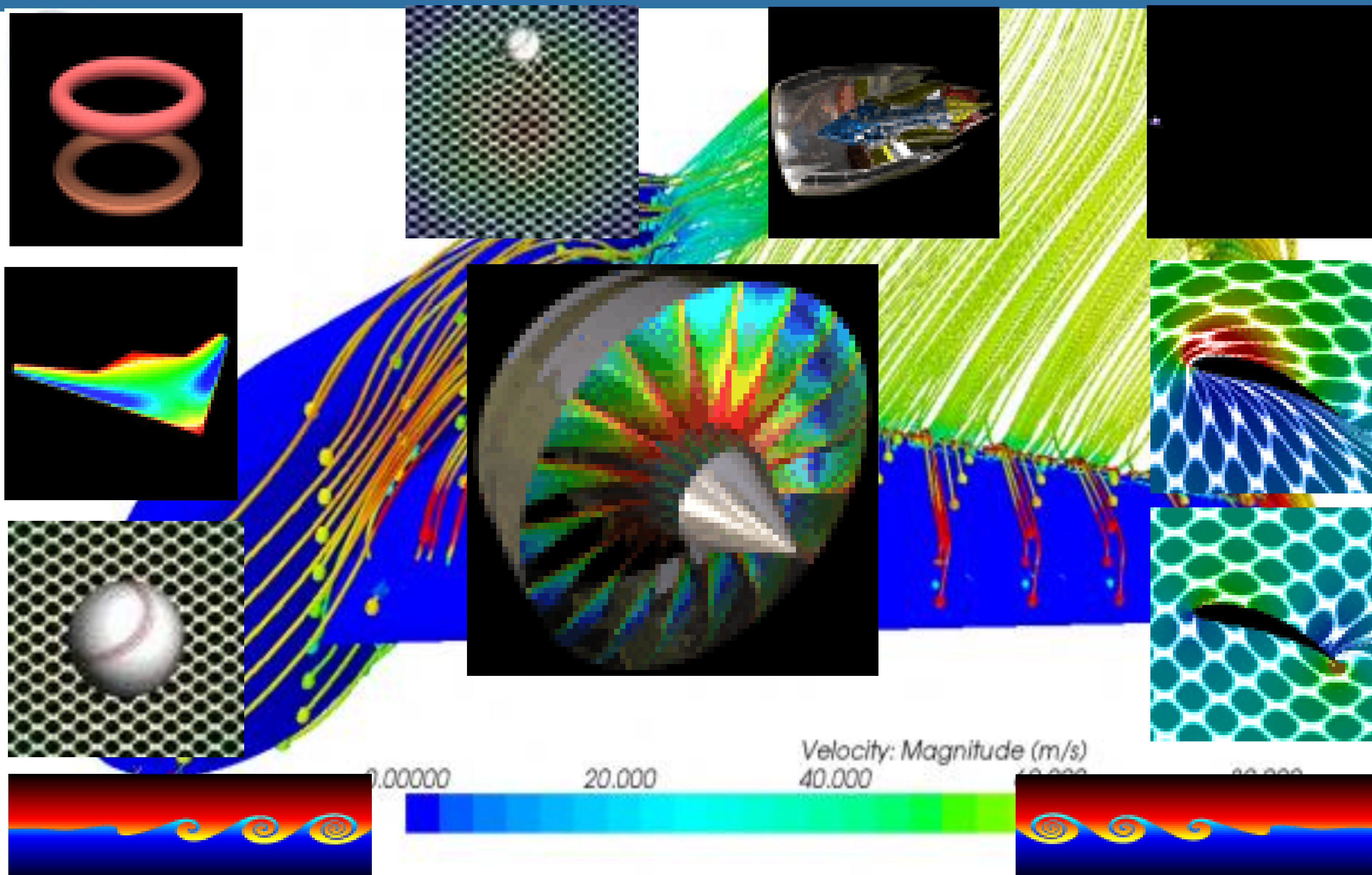
COs	Course outcome
CO1	Understand the basic fluid properties and fluid dynamic concepts with its applications of fluid statics to determine forces of buoyancy and stability; and to fluids in rigid-body motion.
CO2	Use of conservation laws in differential forms and Understand the dimensional methods and kinematics of fluid particles.
CO3	Use Euler's and Bernoulli's equations and the conservation of mass to determine velocities, pressures, and accelerations for incompressible and inviscid fluids.
CO4	Understand the concepts of viscous boundary layers, mechanics of viscous flow effects on immersed bodies and its forces.
CO5	Apply principles of fluid mechanics to the operation, design, and selection of fluid machinery and to understand the ethical issues associated with decision making.






Cylinder


Velocity: Magnitude (m/s)
20.000
40.000

Fluid Properties and Fluid Statics

CLOs	Course Learning Outcome
CLO1	Define the properties of fluids and its characteristics, which will be used in aerodynamics, gas dynamics, marine engineering etc.
CLO2	Explain the hydrostatic forces on submerged bodies, variation with temperature and height with respect to different types of surfaces.
CLO3	Define different types of manometers and explain buoyancy force, stability of floating bodies by determining its metacentre height.

Syllabus

Density, specific weight, specific gravity, surface tension and capillarity, Newton's law of viscosity, incompressible and compressible fluid, numerical problems; Hydrostatic forces on submerged bodies - Pressure at a point, Pascal's law, pressure variation with temperature and height, center of pressure plane, vertical and inclined surfaces; Manometers - simple and differential Manometers, inverted manometers, micro manometers, pressure gauges and numerical problems. Buoyancy - Archimedes principle, meta-center, Meta centric height calculations; Stability.

Introduction

- Fluid mechanics is a study of the behavior of fluids, either at rest (fluid statics) or in motion (fluid dynamics).
- The analysis is based on the fundamental laws of mechanics, which relate continuity of mass and energy with force and momentum.
- An understanding of the properties and behavior of fluids at rest and in motion is of great importance in engineering.

Fluid Mechanics

- **Fluid:** Fluids are substance which are capable of flowing and conforming the shapes of container.

  Fluids can be in gas or liquid states.

- **Mechanics:** Mechanics is the branch of science that deals with the state of rest or motion of body under the action of forces.

- **Fluid Mechanics:** Branch of mechanics that deals with the response or behavior of fluid either at rest or in motion.

Branches of Fluid Mechanics

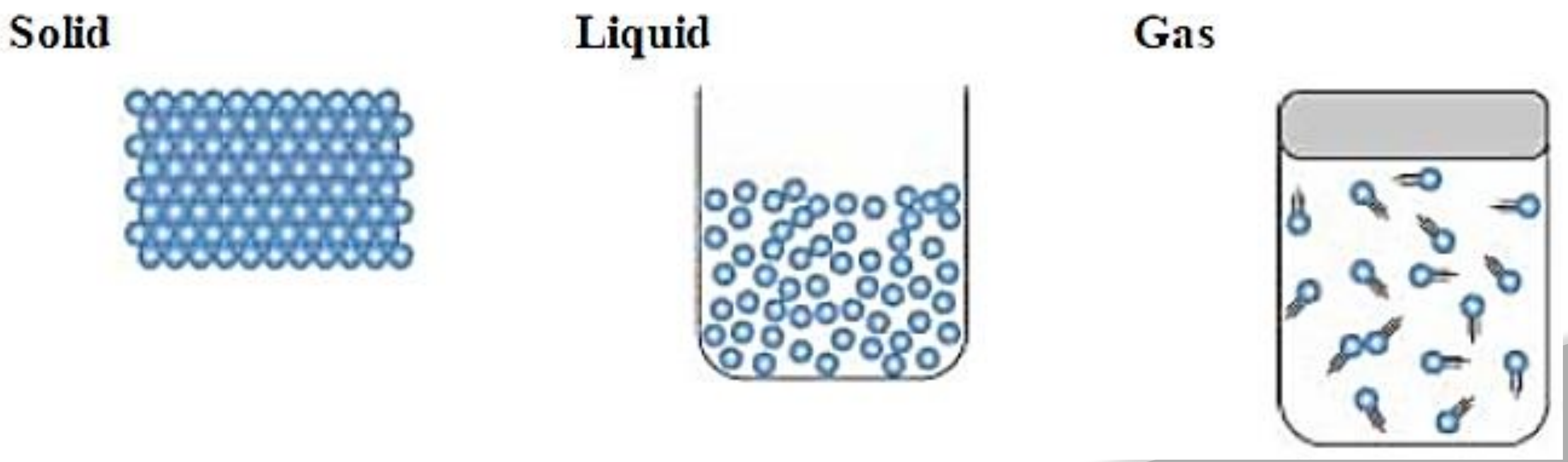
- **Fluid Statics:** It is the branch of fluid mechanics which deals with the response/behavior of fluid when they are at rest.
- **Fluid kinematics:** It deals with the response of fluid when they are in motion without considering the energies and forces in them.
- **Hydrodynamics:** It deals with the behavior of fluids when they are in motion considering energies and forces in them.
- **Hydraulics:** It is the most important and **practical/experimental** branch of fluid mechanics which deals with the behavior of water and other fluid either at rest or in motion.

Significance of Fluid Mechanics

- Fluid is the most abundant available substance e.g., air, gases, ocean, river and canal etc.

- 1. gas
- 2. Liquid
- 3. Solid

(1 and 2) → fluid



Comparison Between Liquids and Gases

Liquids	Gases
Liquids have definite volume at any particular temperature	Gases do not have any definite volume
Liquids have free level surface	Gases do not have free level surface
Molecules of liquid are close to each other	Molecules of gases are far apart
Liquids have relatively more molecular attraction	Gases have less molecular attraction
Liquids are slightly compressible	Gases are highly compressible
Rate of diffusion of liquid is less	Gases have higher rate of diffusion

Comparison Between Liquids and Solids

Liquids	Solids
Liquid conform the shape of any container	Do not conform the shape of container
Liquid can flow	Solids cannot flow
Molecules of liquid are distinctly apart	Molecules of solids are very close to each other
Liquid have relatively less molecular attraction	Solids have more molecular attraction
Liquid are slightly compressible	Solids are highly incompressible
Liquids cannot sustain shear forces	Solids can sustain shear

Dimension and Units

- **System of Units**

System International (SI)

- Fundamental dimensions: length, mass and time
- Units: (meter, kilogram and second)

British Gravitation System (BG)

- Fundamental dimension: length, force and time
- Units: (ft, slug and second)

CGS System

- Fundamental dimensions: length, mass and time
- Units: (centimeter, gram and second)

Dimension and Units

- **Dimension**

Fundamental/Primary Dimension

length(L), mass (M) and time (T)

Derived/Secondary Dimensions

e.g., force, velocity, acceleration etc

Fundamental/Primary Dimension

Dimension	Symbol	Unit (SI)
Length	L	meter (m)
Mass	M	kilogram (kg)
Time	T	second (s)
Temperature	θ	kelvin (K)
Electric current	i	ampere (A)
Amount of light	C	candela (cd)
Amount of matter	N	mole (mol)

Units of Some Dimensions in Different Systems

Fundamental Units

- length(L), mass (M) and time (T)

Derived Units

- e.g., force(F), velocity(L/T), acceleration (L/T/T) etc

System	Length	Time	Force	Velocity	Acceleration	Energy	Power	Temperature
SI	m	s	N	m/s	m/s/s	N-m	kg-m/s	°C
BG	ft	s	lb	ft/s	ft/s/s	ft-lb	ft-lb/s	°F
CGS	cm	s	dyne	cm/s	cm/s/s	dyne-cm	dyne-cm/s	°C

Conversions

Length

- $1m=1000mm=100cm$
- $1ft=12inch$
- $1m=3.281ft$
- 1Mile=5280ft=________km

Time

- 1day=24hours
- 1 hour=60min
- 1 min=60s

Mass

- 1kg=1000g
- 1kg=2.204lb
- 1kg=9.81N
- 1N=______lb ?

Volume

- $1m^3$=1000liters =________cm^3 $1m^3=35.32ft^3$

Properties of Fluids- Mass Density, Specific Weight, Relative Density, Specific volume

Properties of Fluids

- The properties outlines the general properties of fluids which are of interest in engineering.
- The symbol usually used to represent the property is specified together with some typical values in SI units for common fluids.

Density

The density of a substance is the quantity of matter contained in a unit volume of the substance. It can be expressed in three different ways.

- **Mass Density**
- **Specific Weight**
- **Relative Density**

Mass Density

- **Mass Density:** Mass Density, ρ , is defined as the mass of substance per unit volume.

Units: Kilograms per cubic metre, (or)

Dimensions: ML^{-3}

Typical values:

Water = 1000 kgm^{-3}, Mercury = 13546 kgm^{-3}, Air = 1.23 kgm^{-3}, Paraffin Oil = 800 kgm^{-3}.

(at pressure =1.013x 10^{-5} Nm^{-2} and Temperature = 288.15 K.)

Specific Weight

- **Specific Weight:** Specific Weight ω, (sometimes , and sometimes known as *specific gravity*) is defined as the weight per unit volume.

or

- The force exerted by gravity, g, upon a unit volume of the substance.

The Relationship between g and ω can be determined by Newton's 2ndLaw, since

weight per unit volume = mass per unit volume g

$$\omega = \rho g$$

- Units: Newton's per cubic metre, N/m^3 (or) Nm^{-3}
- Dimensions: $ML^{-2}T^{-2}$

Typical values:

- Water =9814 Nm^{-3}
- Mercury = 132943Nm^{-3}
- Air =12.07 Nm^{-3}
- Paraffin Oil =7851 Nm^{-3}

Relative Density

- **Relative Density :** Relative Density,σ, is defined as the ratio of mass density of a substance to some standard mass density.
- For solids and liquids this standard mass density is the maximum mass density for water (which occurs at 4°C) at atmospheric pressure.

$$\sigma = \frac{\rho_{substance}}{\rho_{H_2O(at\,4^\circ c)}}$$

- Units: None, since a ratio is a pure number.
- Dimensions: 1.
- Typical values: Water = 1, Mercury = 13.5, Paraffin Oil =0.8.

Specific Volume

- **Specific volume:** Specific volume is a property of materials, defined as the number of cubic meters occupied by one kilogram of a particular substance.
- The standard unit is the meter cubed per kilogram (m^3/kg or $m^3 \cdot kg^{-1}$).
- Specific volume is inversely proportional to density. If the density of a substance doubles, its specific volume, as expressed in the same base units, is cut in half. If the density drops to 1/10 its former value, the specific volume, as expressed in the same base units, increases by a factor of 10.

Dynamic viscosity, Kinematic viscosity, Newtonian and Non-Newtonian Fluids

Viscosity

- Viscosity, μ, is the property of a fluid, due to cohesion and interaction between molecules, which offers resistance to shear deformation. Different fluids deform at different rates under the same shear stress. Fluid with a high viscosity such as syrup, deforms more slowly than fluid with a low viscosity such as water.
- All fluids are viscous, "Newtonian Fluids" obey the linear relationship given by Newton's law of viscosity.

$$\tau = \mu \frac{du}{dy}$$

- where τ is the shear stress,
- Units Nm^{-2}; $Kgm^{-1}s^{-2}$
- Dimensions $ML^{-1}T^{-2}$.
- du/dy is the velocity gradient or rate of shear strain,
- μ is the "coefficient of dynamic viscosity"

Coefficient of Dynamic Viscosity

- **Coefficient of Dynamic Viscosity** The Coefficient of Dynamic Viscosity,μ, is defined as the shear force, per unit area, (or shear stress τ), required to drag one layer of fluid with unit velocity past another layer a unit distance away.

$$\mu = \tau \Big/ \frac{du}{dy} = \frac{\text{Force}}{\text{Area}} \Big/ \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{Force} \times \text{Time}}{\text{Area}} = \frac{\text{Mass}}{\text{Length x Time}}$$

- Units: Newton seconds per square metre, or Kilograms per meter per second,.

- (Although note that is often expressed in Poise, P, where 10 P = $1 kgm^{-1}s^{-1}$.)

Typical values:

- Water $=1.14 \times 10^{-3} kgm^{-1}s^{-1}$,
- Air $=1.78 \times 10^{-5} kgm^{-1}s^{-1}$,
- Mercury$=1.552 kgm^{-1}s^{-1}$,
  Paraffin Oil $=1.9 kgm^{-1}s^{-1}$.

Kinematic Viscosity

- **Kinematic Viscosity :**Kinematic Viscosity, υ , is defined as the ratio of dynamic viscosity to mass density.

$$\nu = \frac{\mu}{\rho}$$

- Units: square metres per second, m^2s^{-1}
- (Although note that υ is often expressed in Stokes, St, where 10^4 St = $1m^2s^{-1}$.)
- Dimensions: L^2T^{-1}.

Typical values:

- Water =1.14 10^{-6} m^2s^{-1}
- Air =1.46 10^{-5} m^2s^{-1}
- Mercury =1.145 10^{-4} m^2s^{-1}
- Paraffin Oil =2.375 10^{-3} m^2s^{-1}

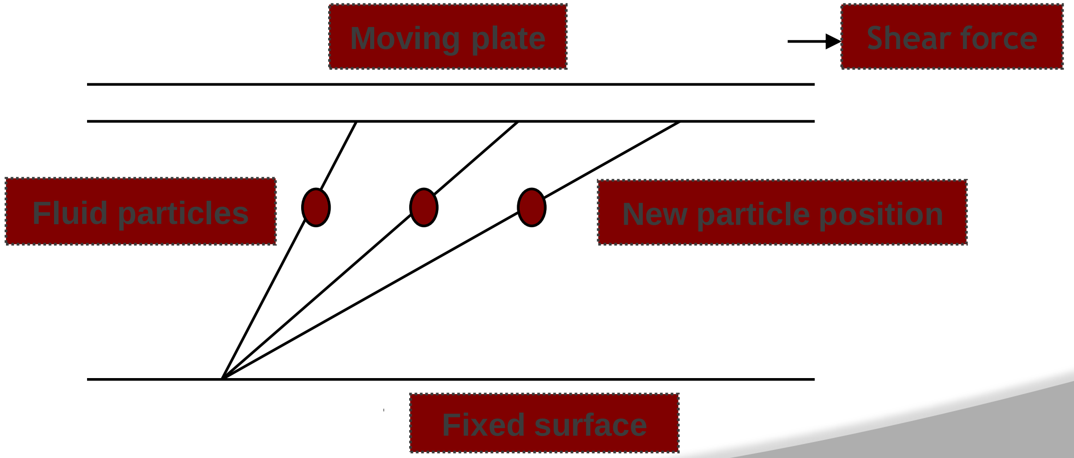
- A fluid is a substance, which deforms continuously, or flows, when subjected to shearing force
- In fact if a shear stress is acting on a fluid it will flow and if a fluid is at rest there is no shear stress acting on it.

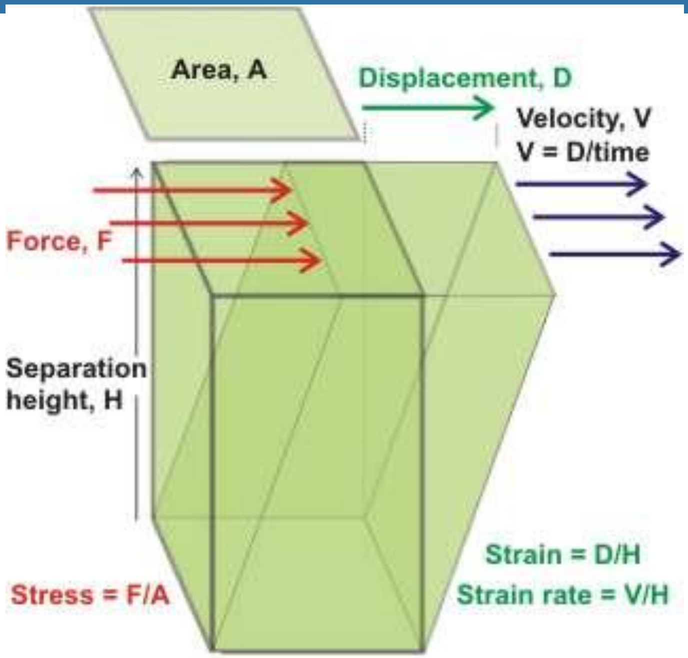
Fluid Flow → Shear stress – Yes

Fluid Rest → Shear stress – No

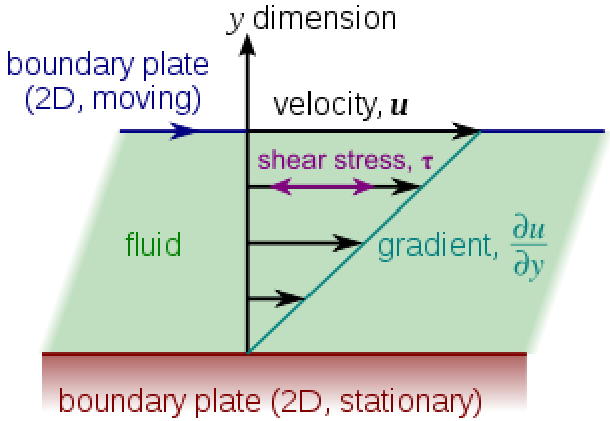
Shear stress in moving fluid

- If fluid is in motion, shear stress are developed if the particles of the fluid move relative to each other. Adjacent particles have different velocities, causing the shape of the fluid to become distorted.
- On the other hand, the velocity of the fluid is the same at every point, no shear stress will be produced, the fluid particles are at rest relative to each other.





Area, A
Displacement, D
Velocity, V
V = D/time
Force, F
Separation height, H
Strain = D/H
Stress = F/A
Strain rate = V/H



y dimension
boundary plate (2D, moving)
velocity, u
shear stress, τ
fluid
gradient, ∂u/∂y
boundary plate (2D, stationary)

Newtonian and Non-Newtonian Fluid

Fluid → Newton's law of viscosity → Newtonian fluids

Newton's' law of viscosity is given by;

$$\tau = \mu \frac{du}{dy}$$

τ = shear stress
μ = viscosity of fluid
du/dy = shear rate, rate of strain or velocity gradient

Example:
Air
Water
Oil
Gasoline
Alcohol
Kerosene
Benzene
Glycerine

- The viscosity μ is a function only of the condition of the fluid, particularly its temperature.
- The magnitude of the velocity gradient (du/dy) has no effect on the magnitude of μ.

• Newtonian and Non-Newtonian Fluid

Fluid - - -> Newton's law of viscosity - - - -> Non- Newtonian fluids

- The viscosity of the non-Newtonian fluid is dependent on the *velocity gradient* as well as the *condition of the fluid*.

Newtonian Fluids

- a linear relationship between shear stress and the velocity gradient (rate of shear),
- the slope is constant
- the viscosity is constant

Non-newtonian fluids

- slope of the curves for non-Newtonian fluids varies

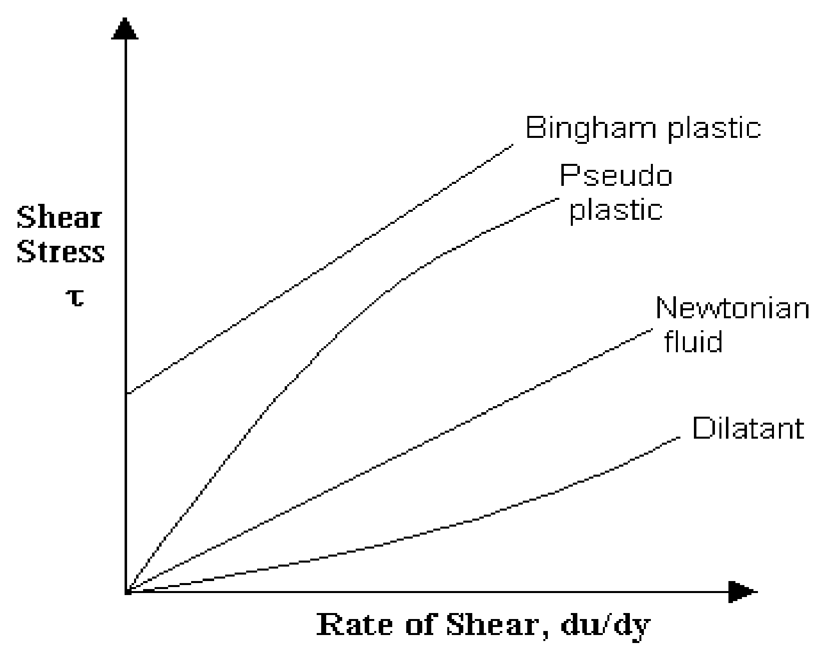


Figure
Shear stress vs. velocity gradient

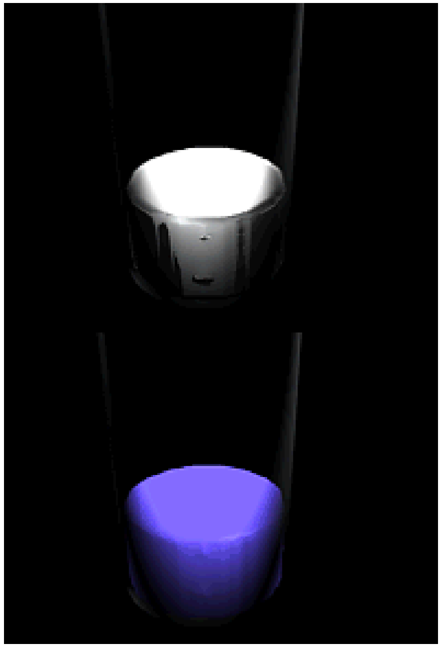
Bingham plastic : resist a small shear stress but flow easily under large shear stresses, e.g. sewage sludge, toothpaste, and jellies.

Pseudo plastic : most non-Newtonian fluids fall under this group. Viscosity decreases with increasing velocity gradient, e.g. colloidal substances like clay, milk, and cement.

Dilatants : viscosity decreases with increasing velocity gradient, e.g. quicksand.

Viscosity

Newtonian & Non Newtonian fluids



Numericals

1. If $5.6m^3$ of oil weighs 46800 N, what is the mass density in kg/m^3?
2. What is the relative density of the oil in question 1?
3. A fluid has absolute viscosity, μ, of 0.048 Pa s. If at point A, 75mm from the wall the velocity is measured as 1.125 m/s, calculate the intensity of shear stress at point B 50mm from the wall in N/m^2. Assume a linear (straight line) velocity distribution from the wall.
4. Calculate the specific weight, density and specific gravity of one liter of a liquid which weighs 7N.

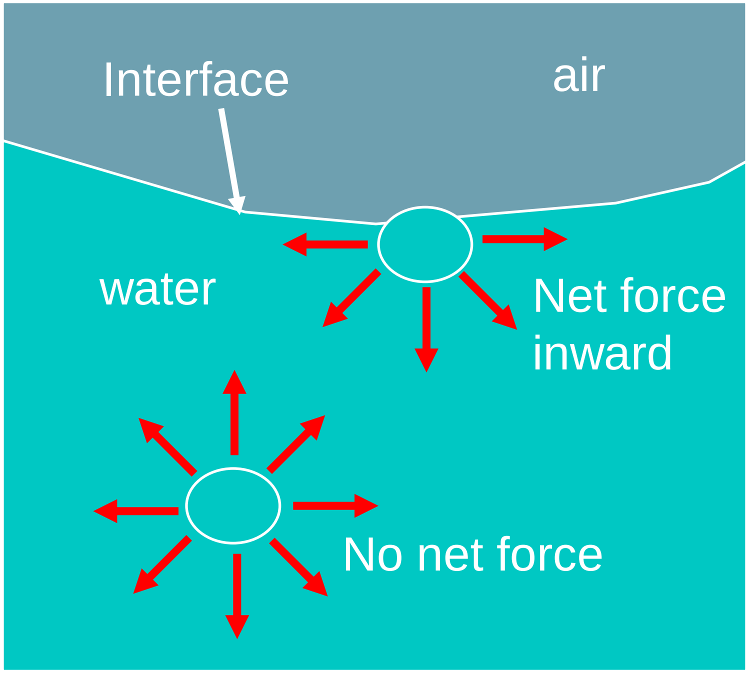
Answers

1. 852 kg/m^3
2. 0.852
3. 0.72 Pa
4. 7000N/m^3, 713.5kg/m^3,0.7135

Surface Tension, Capillarity, Bulk Modulus (Compressibility)

Surface Tension

- Below surface, forces act equally in all directions
- At surface, some forces are missing, pulls molecules down and together, like membrane exerting *tension* on the *surface*
- If interface is curved, higher pressure will exist on concave side
- Pressure increase is balanced by surface tension, σ
- $\sigma = 0.073$ N/m (@ 20^{o}C)



Surface Tension

- Molecular attraction forces in liquids:

– *Cohesion*: enables liquid to resist tensile stress

– *Adhesion*: enables liquid to adhere to another body

- Liquid-fluid interfaces:

– Liquid-gas interface: *free surface*

– Liquid-liquid (immiscible) interface

- At these interfaces, out-of-balance attraction forces forms imaginary surface film that exerts a tension force in the surface » *surface tension*

- Computed as a force per unit length

- Surface tension of various liquids

– Cover a wide range

– Decrease slightly with increasing temperature

- Values of surface tension for water between freezing and boiling points

– 0.00518 to 0.00404 lb/ft or 0.0756 to 0.0589 N/m

- Surface tension is responsible for the curved shapes of liquid drops and liquid sheets as in this example

Figure 1

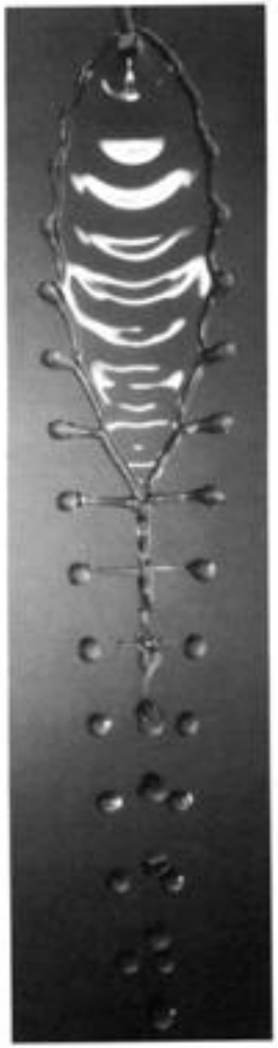


Figure 2

Figure 3

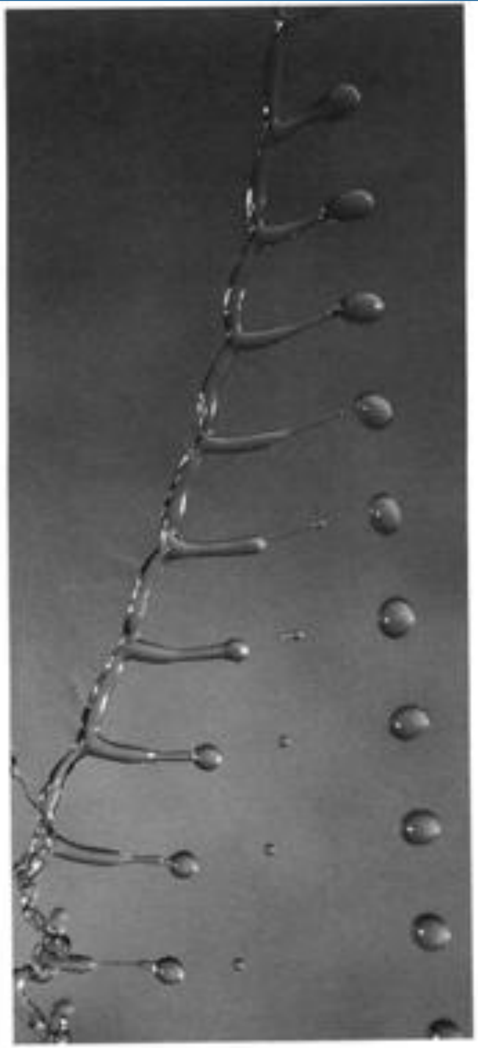
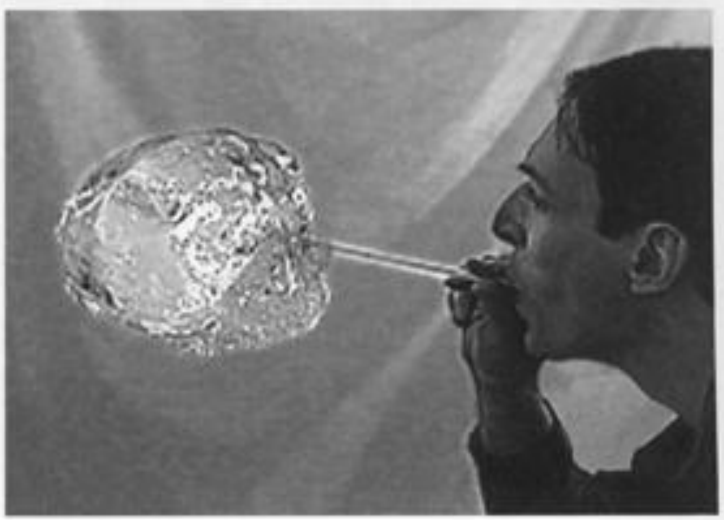


Figure 4

Figure 1

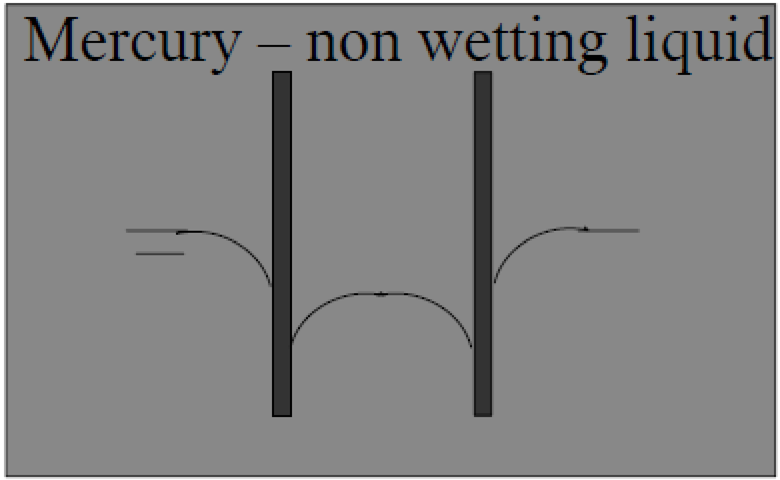
Figure 3

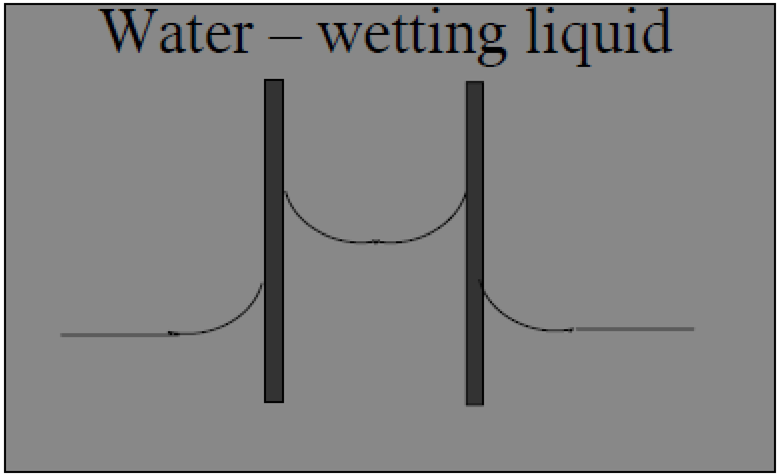


Surface Tension - Capillarity

- Property of exerting forces on fluids by fine tubes and porous media, due to both cohesion and adhesion
- Cohesion < adhesion, liquid wets solid, rises at point of contact
- Cohesion > adhesion, liquid surface depresses at point of contact
- Meniscus: curved liquid surface that develops in a tube

Surface Tension - Meniscus





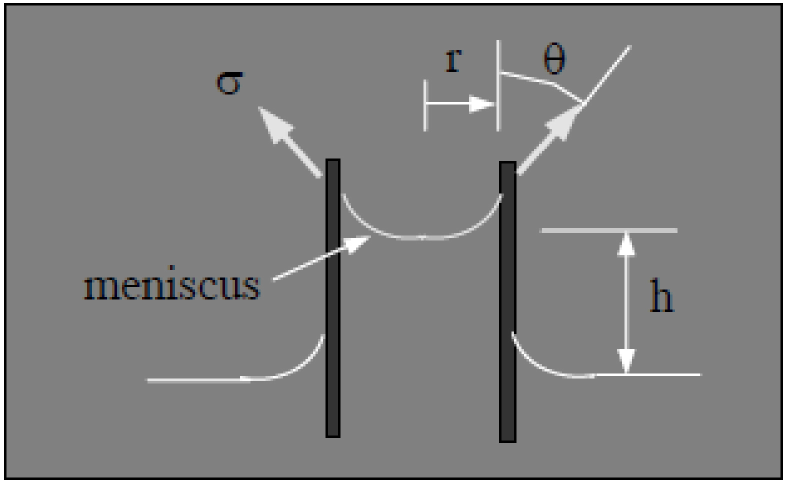
σ = surface tension,

θ = wetting angle,

γ = specific weight of liquid,

r = radius of tube,

h = capillary rise

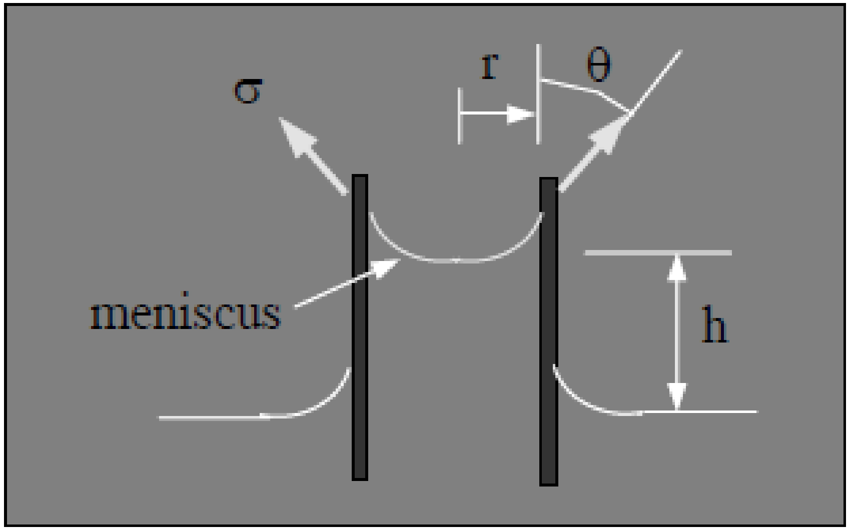


Surface Tension - Capillary Rise

- Equilibrium of surface tension force and gravitational pull on the water cylinder of height *h* produces:

$$2\pi r\sigma\cos\theta = \pi r^2 h\gamma$$

$$h = 2\sigma\cos\theta / (\gamma r)$$



Surface Tension

- Expression in previous slide calculates the *approximate* capillary rise in a small tube
- The meniscus lifts a small amount of liquid near the tube walls, as *r* increases this amount may become significant
- Thus, the equation developed *overestimates* the amount of capillary rise or depression, particularly for large *r*.
- For a clean tube, $\theta = 0^o$ for water, $\theta = 140^o$ for mercury
- For $r > ¼$ *in* (*6 mm*), capillarity is negligible

Surface Tension - Applications

- Its effects are negligible in most engineering situations.
- Important in problems involving capillary rise, e.g., soil water zone, water supply to plants
- When small tubes are used for measuring properties, e.g., pressure, account must be made for capillarity
- Surface tension important in:

– Small models in hydraulic model studies

– Break up of liquid jets

– Formation of drops and bubbles

Elasticity (Compressibility)

- Deformation per unit of pressure change

$$E_v = -\frac{dp}{dV/V} = \frac{dp}{d\rho/\rho}$$

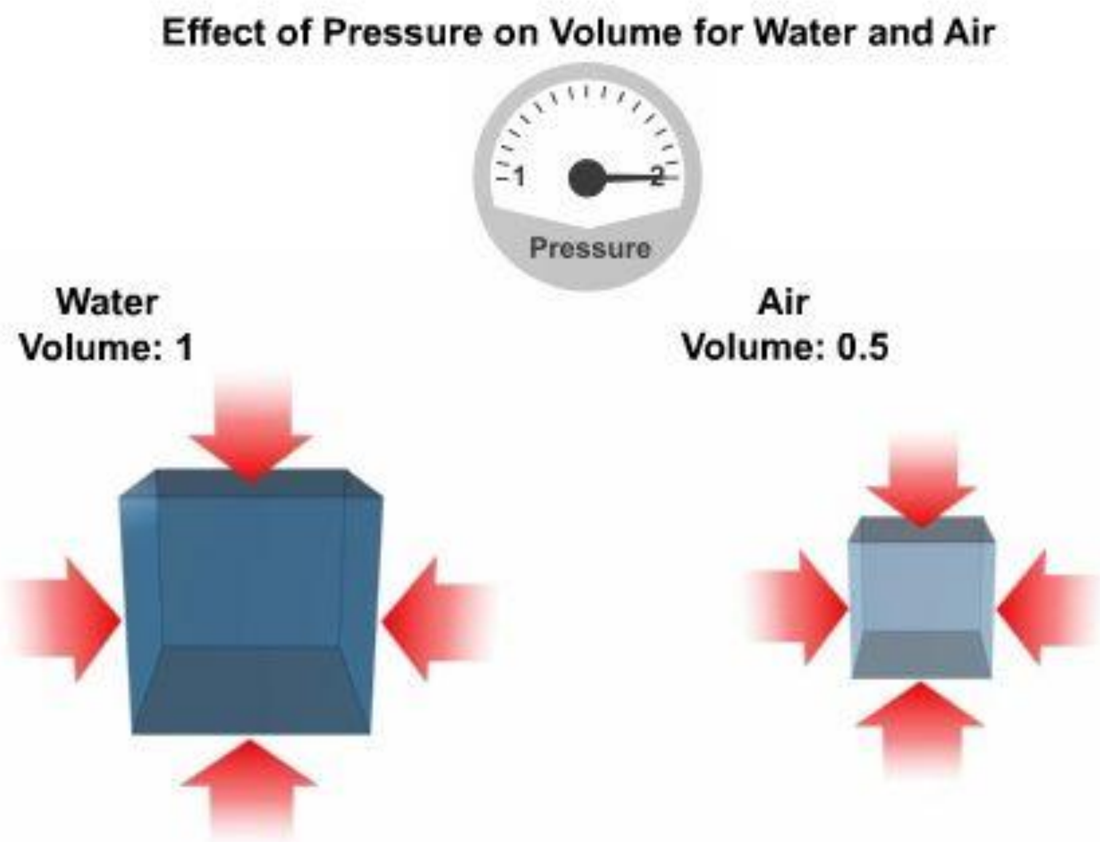
- For water E_v = 2.2 G Pa,

  1 M Pa pressure change = 0.05% volume change

  Water is relatively incompressible

Compressibility

- Compressibility is the fractional change in volume per unit increase in pressure. For each atmosphere increase in pressure, the volume of water would decrease 46.4 parts per million. The compressibility k is the reciprocal of the Bulk modulus, B.


Effect of Pressure on Volume for Water and Air
1
2
Pressure
Water
Volume: 1
Air
Volume: 0.5

Numerical

- Determine the viscosity of a liquid having kinematic viscosity 6 stokes and specific gravity 1.9.
- The velocity distribution for flow over a flat plate is given by $u = 3/4y - y^2$ in which u is the velocity in metre per second at a distance y metre above the plate. Determine the shear stress at y = 0.15 m. Take Dynamic viscosity of fluid as 8.6 poise.
- If the velocity profile of a fluid over a plate is a parabolic with the vertex 20cm from the plate, where the velocity is 120cm/sec. Calculate the velocity gradients and shear stresses at a distance of 0, 10 and 20 cm from the plate, if the viscosity of the fluid is 8.5 poise.

Answers

- 11.40 poise
- 0.3825 N/m^2
- 10.2 N/m^2 ; 5.1 N/m^2, 0 N/m^2

Numerical

- Determine the bulk modulus of elasticity of a liquid, if pressure of the liquid is increased from 70 N/cm^2 to 130 N/cm^2. The volume of the liquid decreases by 0.15 percent.
- The surface tension of water in contact with air at 20^oC is 0.0725 N/m. The pressure inside a droplet of water is to be 0.02 N/cm^2 greater than the outside pressure. Calculate the diameter of the droplet of water.
- Find the surface tension in a soap bubble of 40mm diameter when the inside pressure is 2.5 N/m^2 above atmospheric pressure.

- $4x\ 10^4\ N/cm^2$
- 1.45 mm
- 0.0125 N/m

Numerical

- Calculate the capillary rise in a glass tube of 2.5 mm diameter when immersed vertically in a (a) water and (b) mercury. Take surface tension $\sigma = 0.0725$ N/m for water and $\sigma = 0.52$ N/m for mercury in contact with air. The specific gravity for mercury is 13.6 and angle of contact = 130^{o}.
- Find out the minimum size of glass tube that can be used to measure water level if the capillarity rise in the tube is to be restricted to 2mm. Consider surface tension of water in contact with air as 0.073575 N/m.

Answers

- 1.18cm ; -0.4cm
- 1.5cm

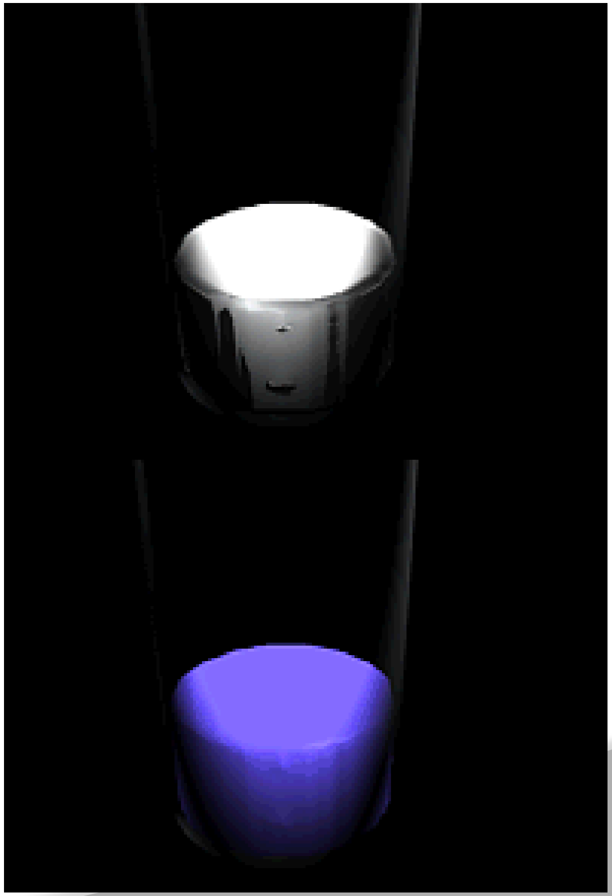
1. Determine the absolute pressure in Pa at a depth of 6m below the free surface of a tank of water when a barometer reads 760mm mercury (relative density 13.57)
2. Determine the pressure in *bar* at a depth of 10m in oil of relative density 0.750.
3. What depth of oil (in m), relative density 0.75, will give a gauge pressure of 275000 Pa.

Answers

1. 160 032 N/m^2
2. 0.736*bar*
3. 37.38m

Viscosity

- Viscosity is defined as the property of a fluid which offers resistance to the movement of one layer of fluid over another adjacent layer of the fluid.
- Viscosity is also defined as the shear stress required to produce unit rate of shear strain.
- Units of viscosity are(SI) Ns/m^2.



Density and Buoyant Force

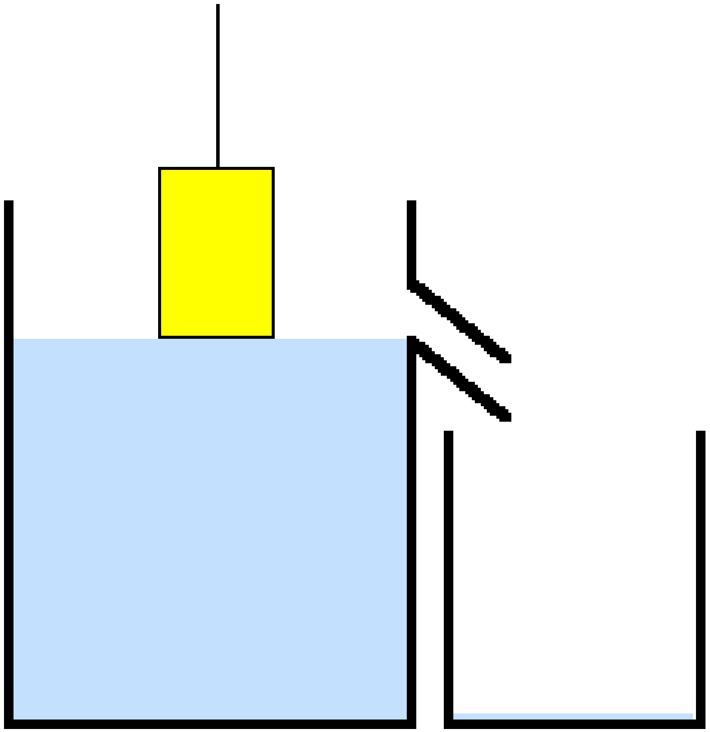
- The **buoyant force** is the upward force exerted by a liquid on an object immersed in or floating on the liquid.

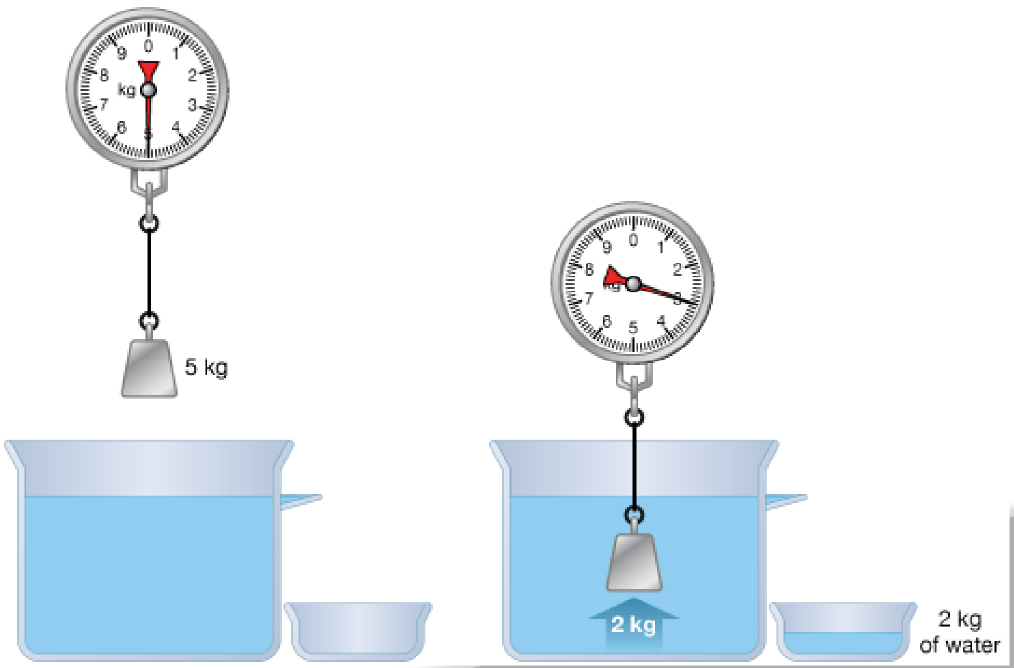
- Buoyant forces can keep objects afloat.

Buoyant Force

- For a floating object, the buoyant force equals the object's weight.
- The apparent weight of a submerged object depends on the density of the object.
- For an object with density ρ_O submerged in a fluid of density ρ_f, the buoyant force F_B obeys the following ratio:

$$\frac{F_g(object)}{F_B} = \frac{\rho_O}{\rho_f}$$




Archimedes' principle
5 kg
2 kg
2 kg
of water

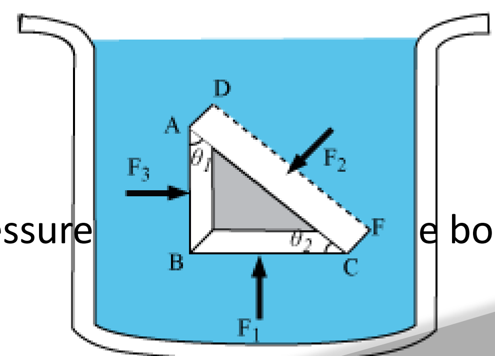
Fluids statics

- The general rules of statics (as applied in solid mechanics) apply to fluids at rest.

From earlier :

- a static fluid can have **no shearing force** acting on it, and that

- any force between the fluid and the boundary must be acting at right angles to the boundary.



Pressure

e boundary

Pressure

- Deep sea divers wear atmospheric diving suits to resist the forces exerted by the water in the depths of the ocean.
- You experience this pressure when you dive to the bottom of a pool, drive up a mountain, or fly in a plane.

Pressure

- **Pressure** is the magnitude of the force on a surface per unit area.

$$P = \frac{F}{A}$$

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

- Pascal's principle states that pressure applied to a fluid in a closed container is transmitted equally to every point of the fluid and to the walls of the container.

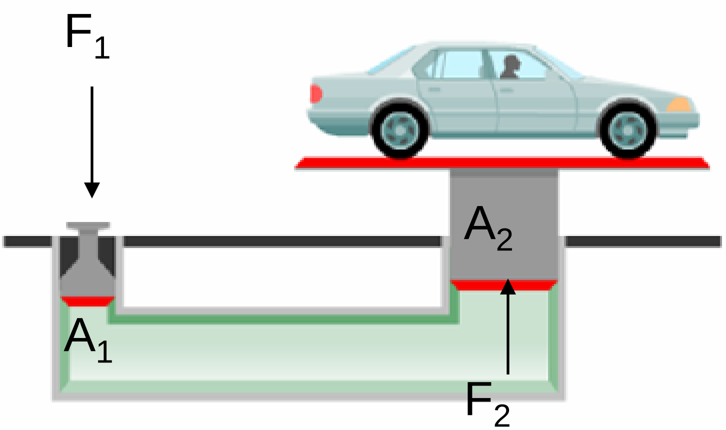
- The SI unit for pressure is the pascal, Pa.
- It is equal to 1 N/m^2.
- The pressure at sea level is about 1.01×10^5 Pa.
- This gives us another unit for pressure, the atmosphere, where 1 atm = 1.01×10^5 Pa

Pascal's Principle

- When you pump a bike tire, you apply force on the pump that in turn exerts a force on the air inside the tire.
- The air responds by pushing not only on the pump but also against the walls of the tire.
- As a result, the pressure increases by an equal amount throughout the tire.

Pascal's Principle

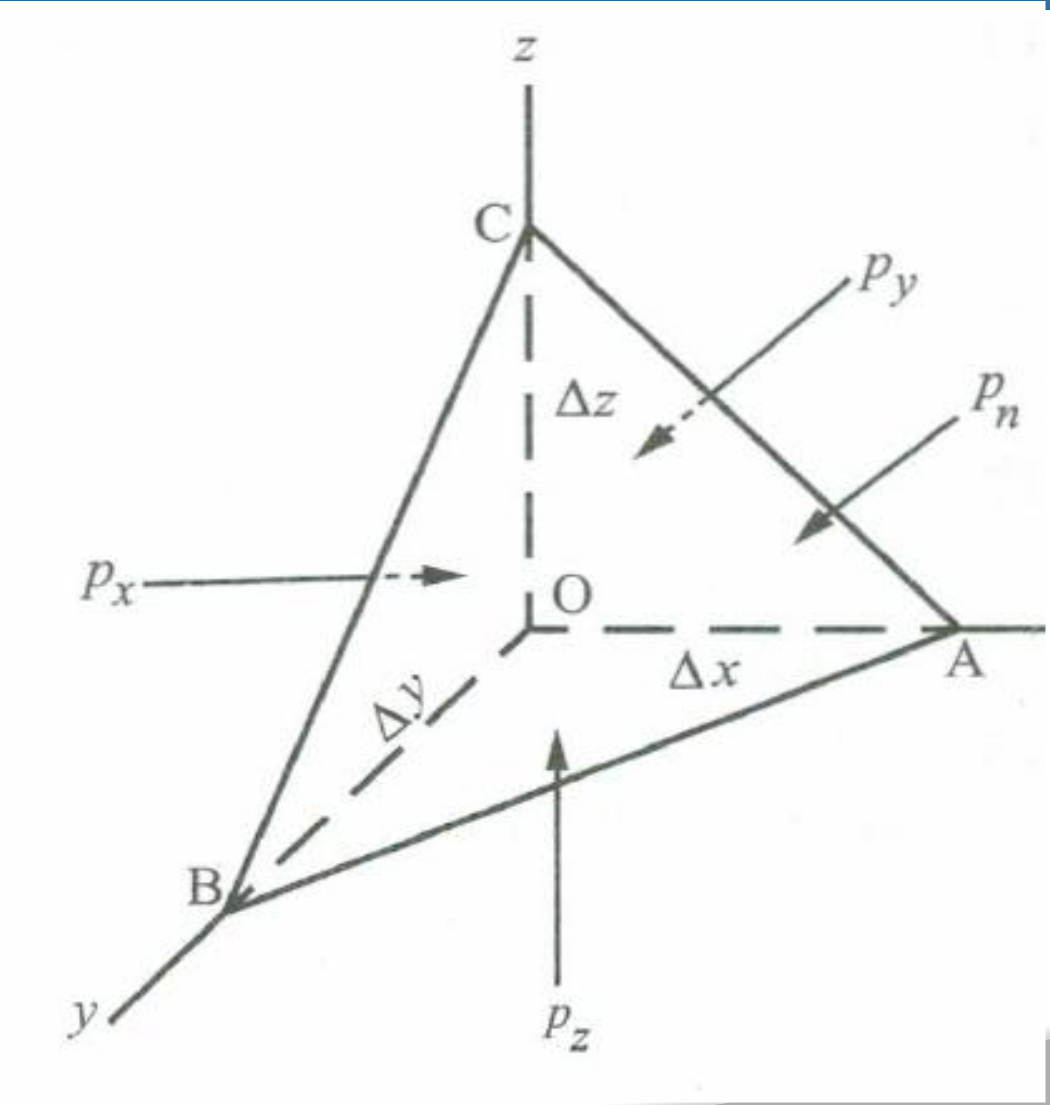
- A hydraulic lift uses Pascal's principle.
- A small force is applied (F_1) to a small piston of area (A_1) and cause a pressure increase on the fluid.
- This increase in pressure (P_{inc}) is transmitted to the larger piston of area (A_2) and the fluid exerts a force (F_2) on this piston.



$$P_{inc} = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$F_2 = F_1 \frac{A_2}{A_1}$$

- **Pascal's Law:** Pascal's law states the pressure intensity at a point, in a static fluid, is equal in all directions. It can be proved in the following way.
- Consider a tetrahedron of sides Δx, Δy and Δz inside a shown in fig. Let 'O' a point inside the fluid be the origin.
- Let area ABC = ΔA and pressure on ΔA equal to p_n. The weight of a fluid element in the tetrahedron = $(\gamma. \Delta x. \Delta y. \Delta z)/6$.
- The weight is proportional to the third order of magnitude of very small quantities like Δx, Δy, Δz, whereas the pressure forces are proportional to the second order of magnitude.
- Hence the weight can be neglected in comparison to the pressures when Δx, Δy, Δz, tend to zero. Since the element is in static condition, the net forces in the x, y and z directions are zero.


z
C
p_y
Δz
p_n
p_x
O
A
Δx
Δy
B
y
p_z

- The component of p_n dA in the x direction = P_n. dA. cos(n,x), where cos(n,x) is the cosine of the angle between the normal to the surface and the x direction.
- Resolving forces in the x direction and equating the net force to zero, for static equilibrium conditions,

$$P_n . dA. \cos(n,x) = P_x 1/2\, dzdy.$$

But geometrically,

dAcos(n,x) = area OBC = 1/2dzdy.

So $P_n = P_x$.

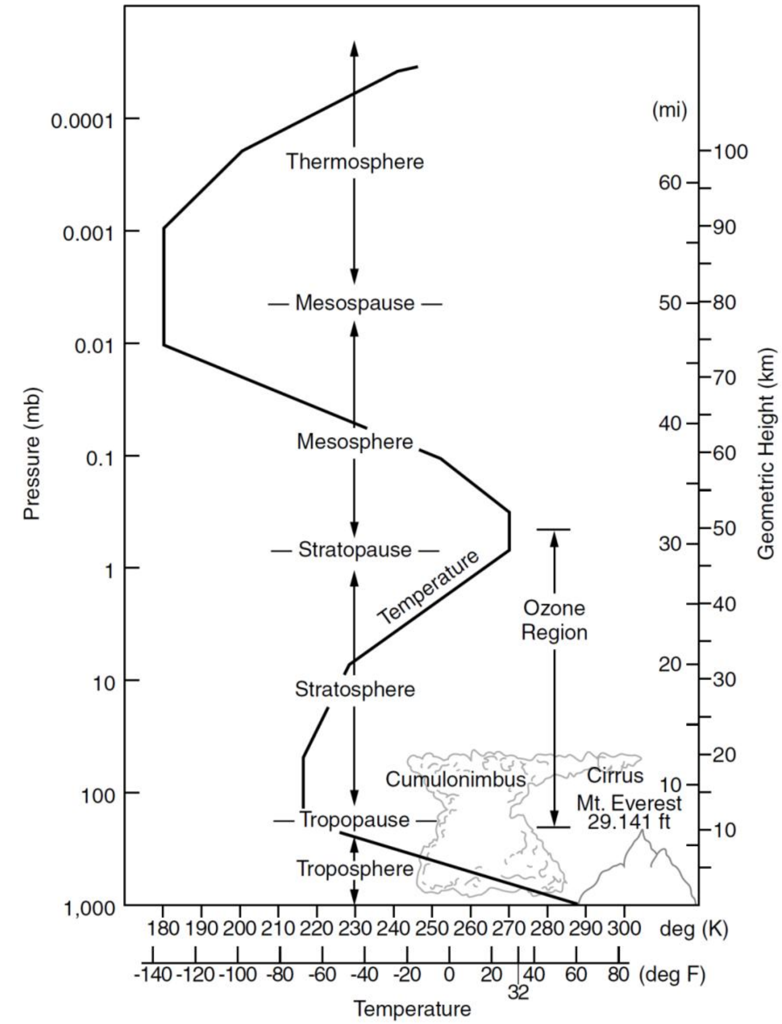
Similarily, resolving forces in the y and z directions and equating the net forces to zero for the static condition, it can be proved that $P_n = P_y$ and $P_n = P_z$.

- Thus $P_n = P_x = P_y = P_z$, which proves pascal's law. Pascal's law does not hold good in the flows having shearing layers. In such cases, pressure p is defined as $p = \frac{p_x + p_z + p_y}{3}$, where P_x, P_y, P_z are pressure intensities in three mutually perpendicular directions.

Hydro static Law

- A **Hydrostatics Law** state that rate of increase of pressure in a vertically downward direction in fluid/liquid is equal to weight density of the liquid.

Figure of standard atmosphere variation



Mathematical Model

– The standard atmosphere defines the temperature variation with altitude as shown

– Now need to find pressure and density as functions of either T or h

– Begin with the hydrostatic equation, divided by the equation of state for a perfect gas

$$dp / p = g_o dh/RT$$

– Can integrate this equation for pressure when we know the *P* relationship between T and h

Gradient Layers

– Define a **lapse rate**, a, by: $dT/dh = a$

– Define the conditions at the layer base by h1, p1, ρ1, and T1

– In previous equation, replace dh with dT/a and integrate w.r.t. temperature to get:

$$P/P_1 = (T/T_1)^{-g_o/aR}$$

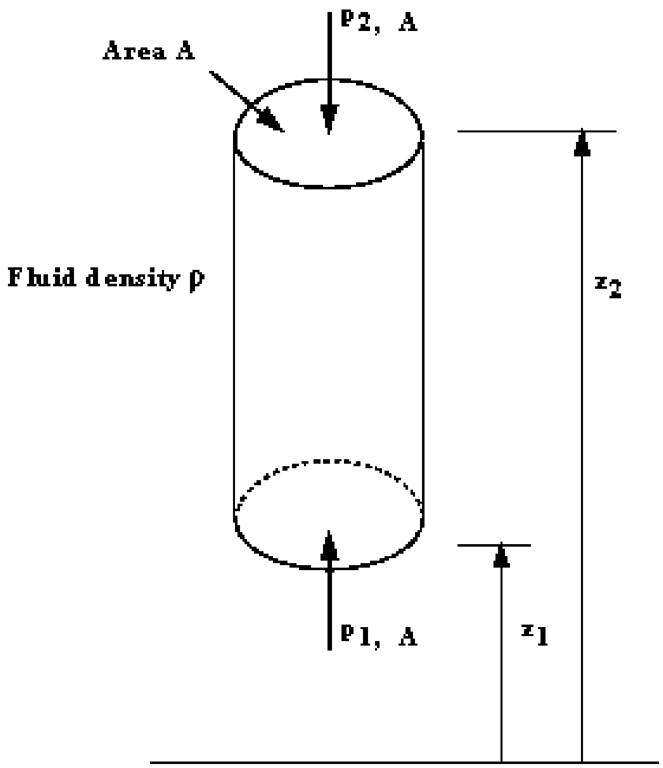
– And since $p/p_1 = (\rho T)/(\rho_1 T_1)$

$$\rho/\rho_1 = (T/T_1)^{-[(g_o/aR)+1]}$$

- Isothermal Layers, T is constant
  - Start at the base of the layer where we will define the conditions as h1, p1, ρ1, and T
  - Integrate the previous equation W.R.T. h holding T Constant

$$P/P_1 = e^{-(go/RT)(h-h1)} = \rho/\rho_1$$

Variation of Pressure Vertically In A Fluid Under Gravity



Vertical elemental cylinder of fluid

- In the previous slide figure we can see an element of fluid which is a vertical column of constant cross sectional area, A, surrounded by the same fluid of mass density ρ.
- The pressure at the bottom of the cylinder is p_1 at level z_1 , and at the top is p_2 at level z_2.
- The fluid is at rest and in equilibrium so all the forces in the vertical direction sum to zero. i.e. we have
- Force due to p_1 on A (upward) $= p_1 A$
- Force due to p_2 on A (downward) $= p_2 A$
- Force due to weight of element (downward) mg

  $\rho g A(z_2 - z_1)$ mass density volume

- Taking upward as positive, in equilibrium we have

$$p_1 A - p_2 A = \rho g A(z_2 - z_1)$$

$$p_2 - p_1 = - \rho g A(z_2 - z_1)$$

- Thus in a fluid under gravity, pressure decreases with increase in height

$$z = (z_2 - z_1)$$

Pressure and Head

- In a static fluid of constant density we have the relationship

$$\frac{dp}{dz} = -\rho g$$

- This can be integrated to gi[illegible] $-\rho g z$ + constant
- In a liquid with a free surface the pressure at any depth z measured from the free surface so that $z = -h$

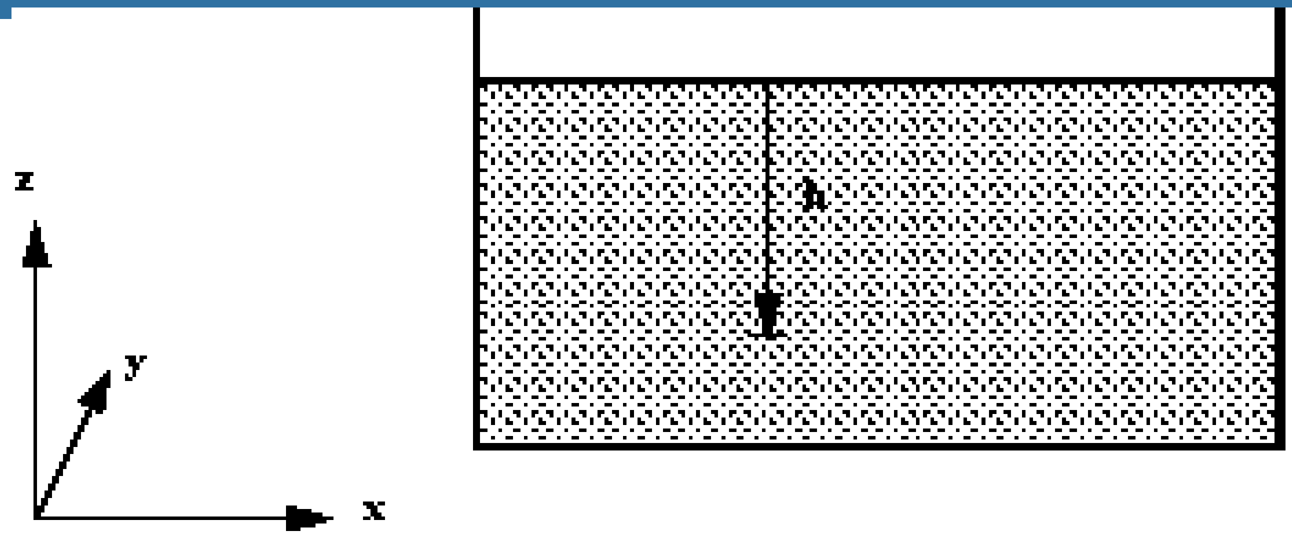


Fig. Fluid head measurement in a tank

This gives the pressure $p = \rho gh + \text{constant}$

- At the surface of fluids we are normally concerned with, the pressure is the atmospheric pressure, $p_{atmospheric}$. So

$$p = \rho gh + p_{atmospheric}$$

- As we live constantly under the pressure of the atmosphere, and everything else exists under this pressure, it is convenient (and often done) to take atmospheric pressure as the datum. So we quote pressure as above or below atmospheric.
- Pressure quoted in this way is known as gauge pressure i.e.
- **Gauge pressure** is $p = \rho g h$
- The lower limit of any pressure is zero - that is the pressure in a perfect vacuum. Pressure measured above this datum is known as absolute pressure i.e.
- **Absolute pressure** is $p = \rho g h + p_{\text{absolute atmospheric}}$
- Absolute pressure = Gauge pressure + Atmospheric pressure

- As g is (approximately) constant, the gauge pressure can be given by stating the vertical height of any fluid of density ρ which is equal to this pressure.

$$p = \rho g h$$

- This vertical height is known as **head** of fluid.

Note: If pressure is quoted in *head*, the density of the fluid *must* also be given.

Problem:

- We can quote a pressure of $500K\ N\ m$-2 in terms of the height of a column of water of density, ρ = 1000kgm-3.

Using $p = \rho g h$,

$$h = \frac{p}{\rho g} = \frac{500\times 10^3}{1000\times 9.81} = 50.95m \text{ of water}$$

And in terms of Mercury with density, ρ = 13.6x10³kgm-3.

$$h = \frac{500\times 10^3}{13.6\times 10^3\times 9.81} = 3.75m \text{ of Mercury}$$

Simple and Differential Manometers

- Manometer: manometers are defined as the devices used for measuring the pressure at a point in the fluid by balancing the column of fluid by the same or another column of the fluid.
- They are classified as

  1.Simple manometer   2.Differential manometer

Simple manometer: simple manometer consist of a glass tube having one of its ends connected to a point where pressure is to be measured and other end remains open to atmosphere.

Differential manometer: these are the devices used for measuring the difference of pressures between two points in a pipe or in two different pipes.

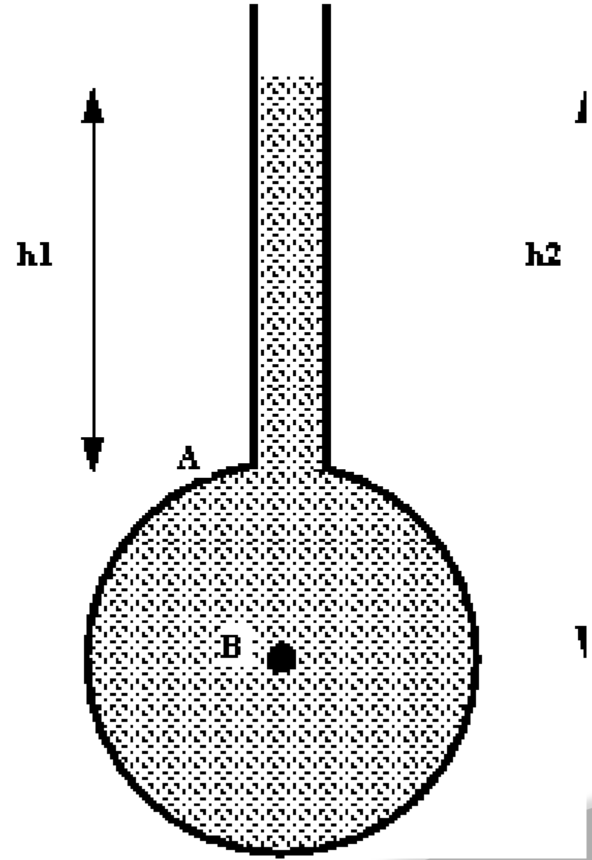
Pressure Measurement By Manometer

- The relationship between pressure and head is used to measure pressure with a manometer (also know as a liquid gauge).

1. Piezometer
2. U-tube Manometer
3. Single Column Manometer

The Piezometer Tube Manometer

- The simplest manometer is a tube, open at the top, which is attached to the top of a vessel containing liquid at a pressure (higher than atmospheric) to be measured.
- An example can be seen in the figure below. This simple device is known as a *Piezometer tube*.
- As the tube is open to the atmosphere the pressure measured is relative to atmospheric so is **gauge pressure**.



ometer tube manometer

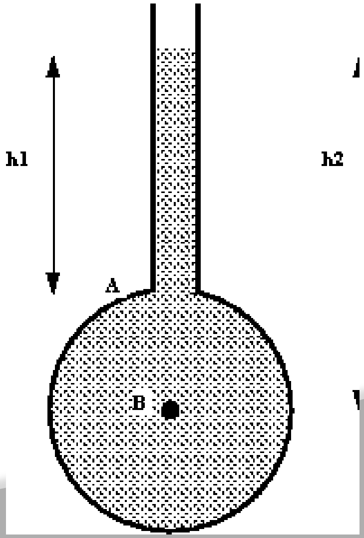
- Pressure at A = pressure due to column of liquid above A

$$p_A = \rho g h_1$$

- Pressure at B = pressure due to column of liquid above B

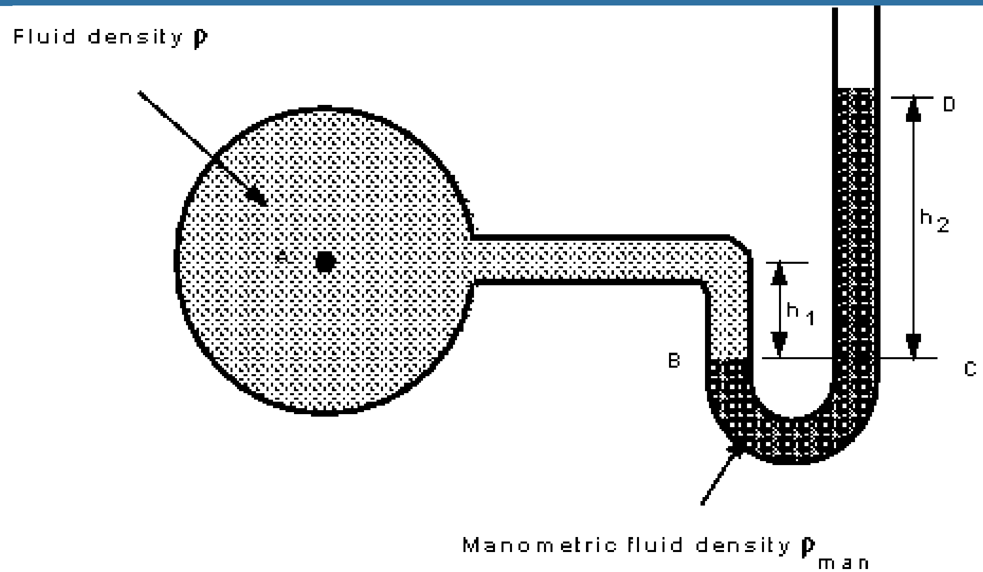
$$p_B = \rho g h_2$$

- This method can only be used for liquids (i.e. **not** for gases) and only when the liquid height is convenient to measure.



The "U"-Tube Manometer

- Using a "U"-Tube enables the pressure of both liquids and gases to be measured with the same instrument.
- The "U" is connected as in the figure and filled with a fluid called the *manometric fluid*.
- The fluid whose pressure is being measured should have a mass density less than that of the manometric fluid and the two fluids should not be able to mix readily - that is, they must be immiscible.



- A “U”-Tube manometer

Pressure in a continuous static fluid is the same at any horizontal level so,

pressure at B = pressure at C

$$p_B = p_C$$

For the **left hand** arm

pressure at B = pressure at A + pressure due to height h of fluid being measured

$$p_B = p_A + \rho g h_1$$

For the **right hand** arm

$$p_C = p_{\text{Amospheric}} + \rho g h_2$$

As we are measuring *gauge pressure* we can subtract $p_{\text{Atmospheric}}$ giving

$$p_B = p_C$$

$$p_A = \rho_{\text{man}} g h_2 - \rho g h_1$$

- If the fluid being measured is a gas, the density will probably be very low in comparison to the density of the manometric fluid i.e. $\rho_{man} >> \rho$.
- In this case the term $\rho g h_1$ can be neglected, and the gauge pressure given by

$$p_A = \rho_{man} g h_2$$

Single Column Manometer

- Modified form of a U Tube manometer in which a reservoir, having a large cross-sectional area (about 100 times) as compared to tube. Due to large cross-sectional area of the reservoir, the change in the liquid level in this reservoir is negligible and the reading in the limb is taken as the pressure. The limb may be vertical or inclined
- When the fluid starts flowing in the pipe, the mercury level in the reservoir goes down by a very small amount which causes a large rise in the right limb.

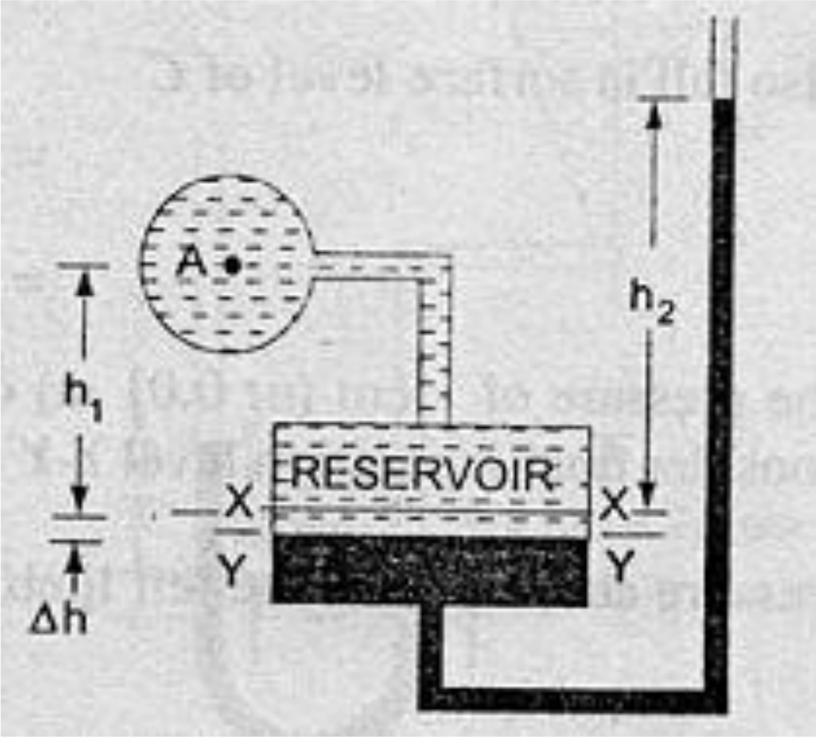
$$P_A + \rho_1 g\,(\Delta h + h_1) = \rho_2 g(\Delta h + h_2)$$

$$P_A = \rho_2 g(\Delta h + h_2) - \rho_1 g\,(\Delta h + h_1)$$

$$= \Delta h\,(\rho_2 g - \rho_1 g) + h_2\,\rho_2 g - \rho_1 g h_1$$

As the volume of reservoir liquid remain same, the fall of liquid volume in the reservoir is equals to rise of liquid volume in the limb

$A\Delta h = a\,h_2$ So, $\Delta h = (a/A)\,h_2$

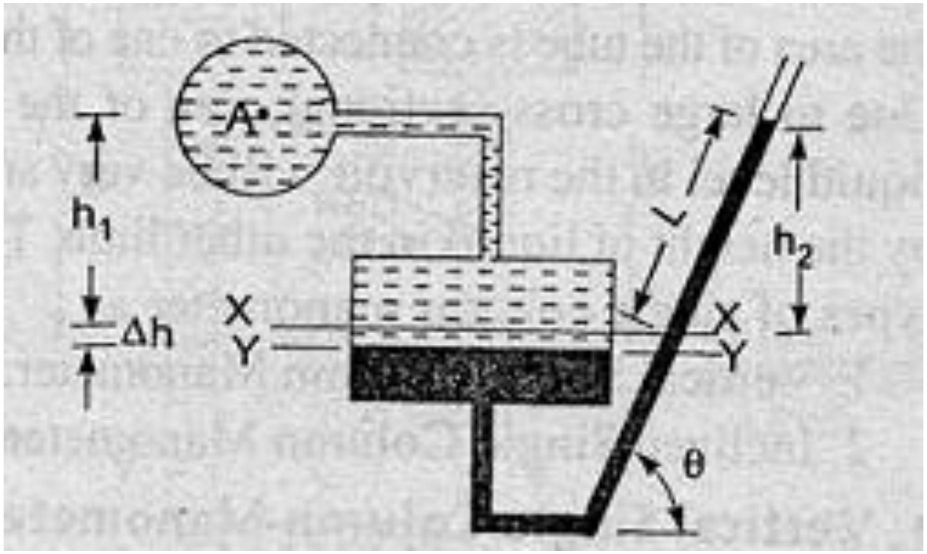


as A is very large and a is very small, a/A is very small and hence may be neglected

That means Δh term is neglected

So, $P_A = h_2\,\rho_2 g - h_1 \rho_1 g$

Inclined Manometers



If, L= length of liquid on right limb above X-X

ɵ= Inclination of right limb to horizontal

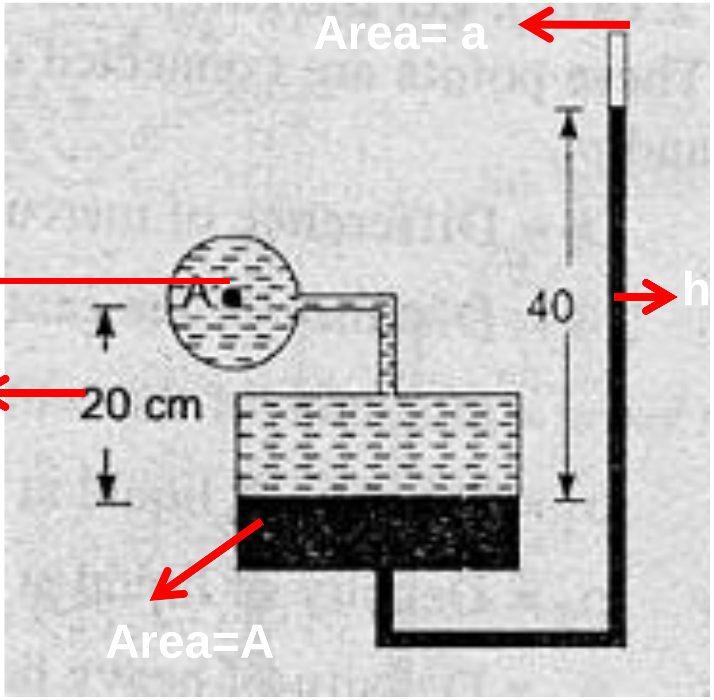
h_2= Vertical rise of liquid in right limb above X-X= L sinɵ

$$P_A = L \sin\theta \rho_2 g - h_1 \rho_1 g$$

A single column manometer is connected to a pipe containing a liquid of sp gravity 0.9, center of the pipe is 20cm from the surface of mercury in the reservoir, which has 100 times more area than that of tube. The mercury on the right limb is 40cm above the level of mercury in the reservoir . Find the pressure in the pipe.

We have, $P_A = (a/A)h_2(\rho_2 g - \rho_1 g) + h_2\rho_2 g - h_1\rho_1 g$

P_A

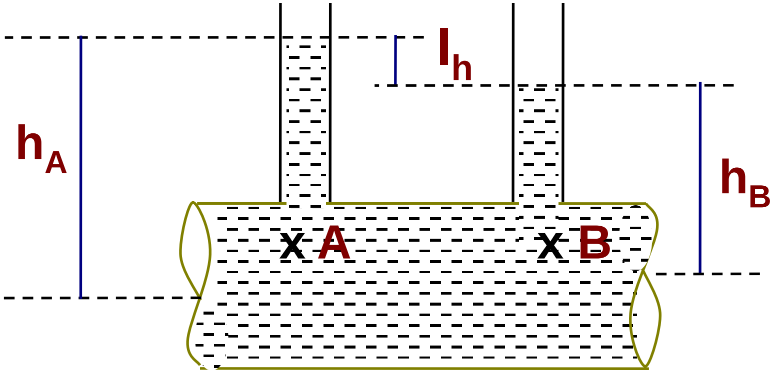


$P_A = (1/100)0.4[13.6X1000X9.81-900X9.81] + 0.4X13.6X1000X9.81 – 0.2X900X9.81$

DIFFERENTIAL MANOMETERS

Differential manometers are used to measure pressure difference between any two points. Common varieties of differential manometers are:

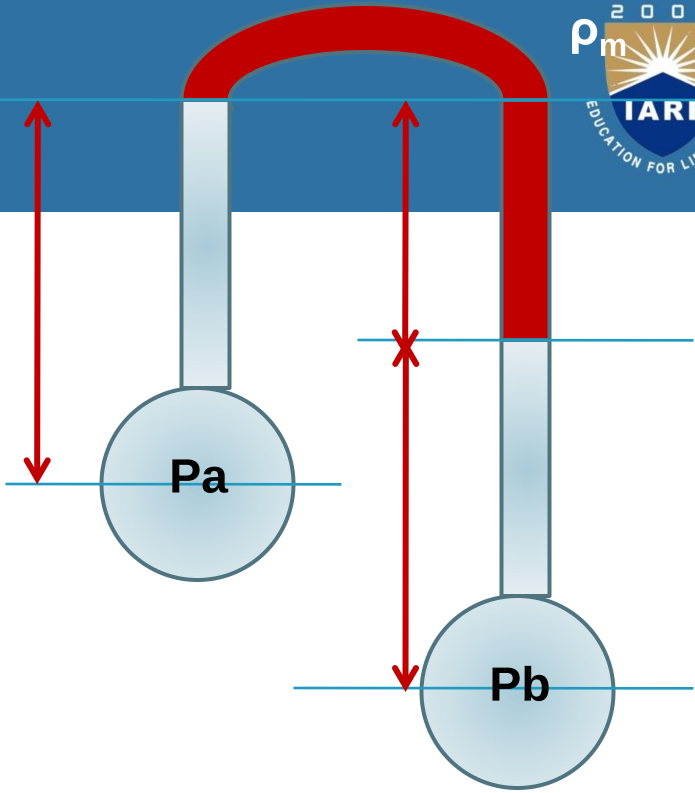
- **Two piezometers.**
- **Inverted U-tube manometer.**
- **U-tube differential manometers.**
- **Micro manometers**



•Two Piezometers

The arrangement consists of two pizometers at the two points between which the pressure difference is required. The liquid will rise in both the piezometers. The difference in elevation of liquid levels can be recorded and the pressure difference can be calculated.

Inverted U-tube Manometers



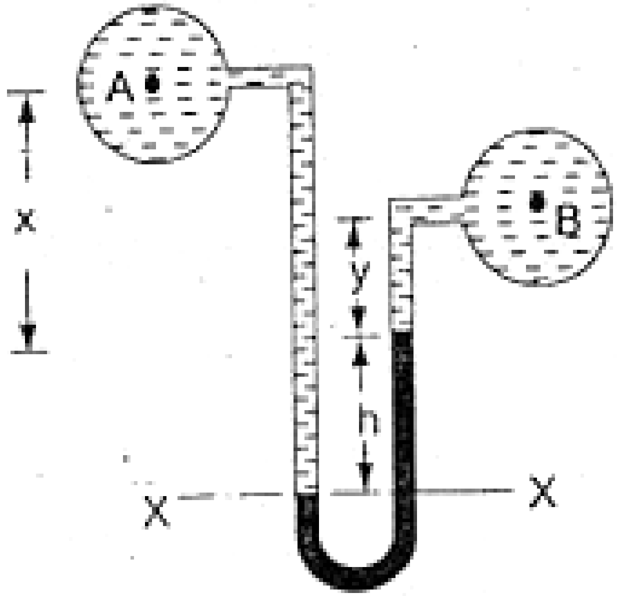
Inverted U-tube manometer is used to measure small difference in pressure between any two points. It consists of an inverted U-tube connecting the two points between which the pressure difference is required. In between there will be a lighter

Let ‘P_A’ and ‘P_B’ be the pressure at ‘A’ and ‘B’

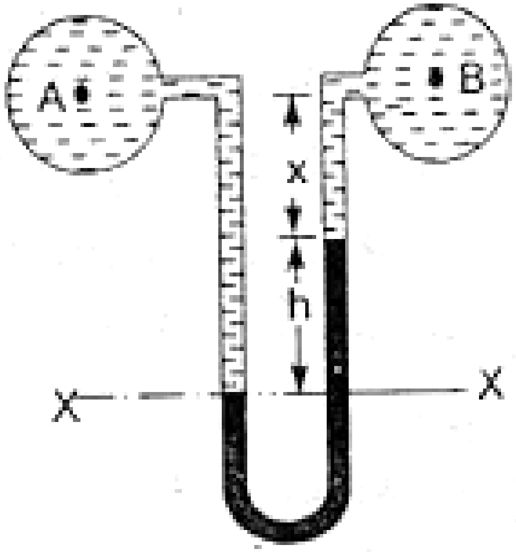
$$P_a - [(y_1\rho_1) + (x\,\rho_m) + (y_2\rho_2)]g = P_b$$

$$P_a - P_b = [\rho_1\; y_1 - \rho_m\, x - \rho_2\, y_2]g$$

Differential U Tube Manometer



(a)Two pipes at different levels



(b) A and B are at the same level

Balancing the pressure on left and right limbs

$$\rho_1 g(h+x) + P_A = \rho_m g h + \rho_2 g y + P_B$$

$$(P_A - P_B) = \rho_m g h + \rho_2 g y - \rho_1 g(h+x)$$

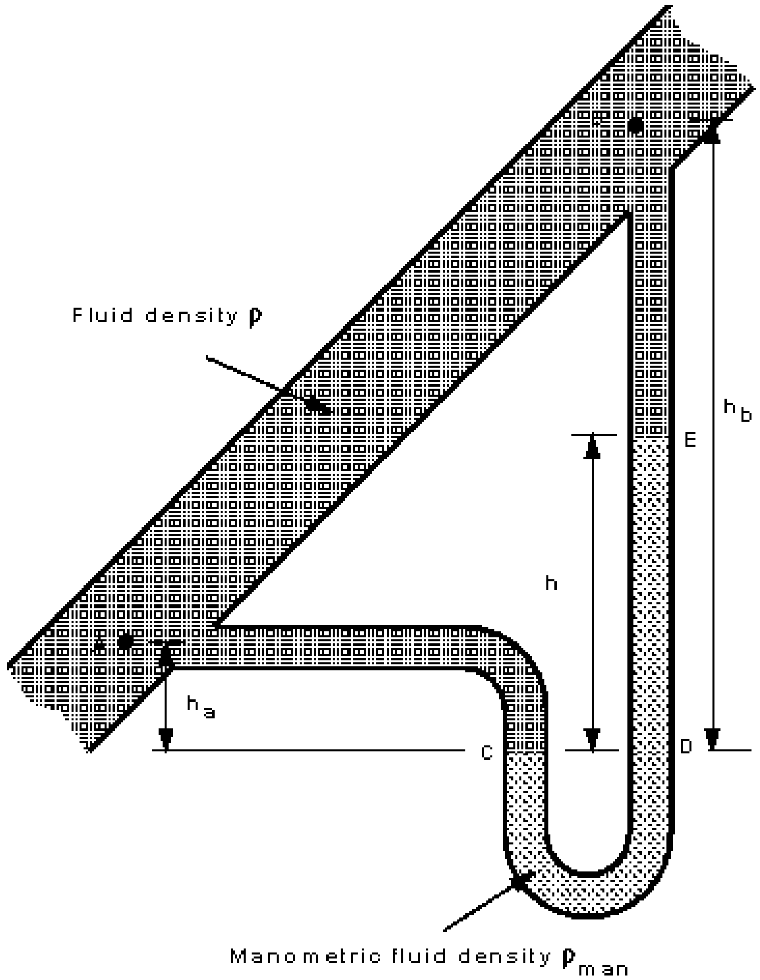
$$(P_A - P_B) = hg(\rho_m - \rho_1) + \rho_2 g y - \rho_1 g x$$

$$\rho_m g h + \rho_1 g x + P_B = \rho_1 g(h+x) + P_A$$

$$(P_A - P_B) = \rho_m g h + \rho_1 g x - \rho_1 g(h+x)$$

$$(P_A - P_B) = hg(\rho_m - \rho_1)$$

Measurement Of Pressure Difference Using a “U”-Tube Manometer



- If the "U"-tube manometer is connected to a pressurized vessel at two points the *pressure difference* between these two points can be measured.
- If the manometer is arranged as in the figure above, then

Pressure at C = Pressure at D

$$p_C = p_D$$

$$p_C = p_A + \rho g h_a$$

$$p_D = p_B + \rho g(h_b - h) + \rho_{man} g h$$

$$p_A + \rho g h_a = p_B + \rho g(h_b - h) + \rho_{man} g h$$

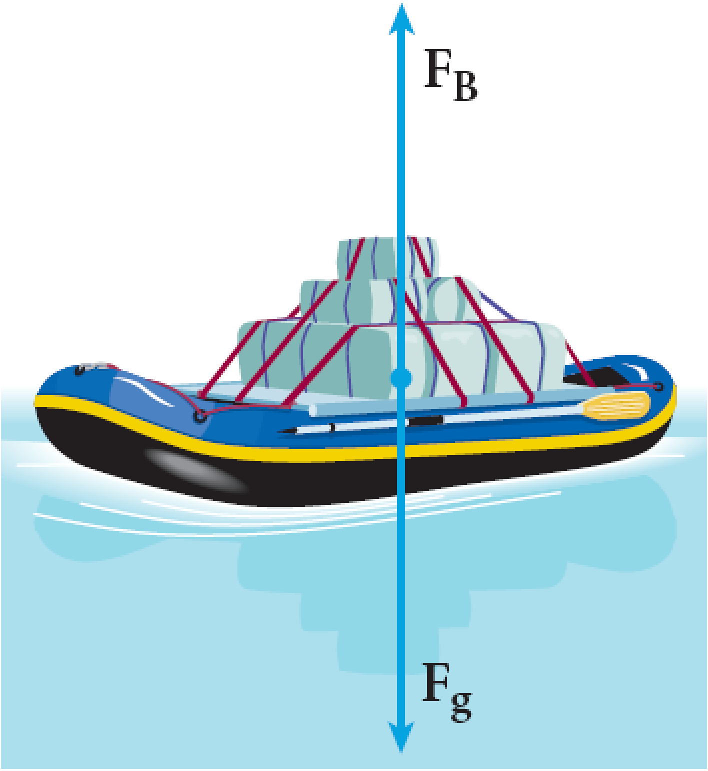
Giving the pressure difference

$$p_A - p_B = \rho g(h_b - h_a) + (\rho_{man} - \rho) g h$$

- Again, if the fluid whose pressure difference is being measured is a gas and $\rho_{man} >> \rho$, then the terms involving ρ can be neglected, so

$$p_A - p_B = \rho_{man} g h$$

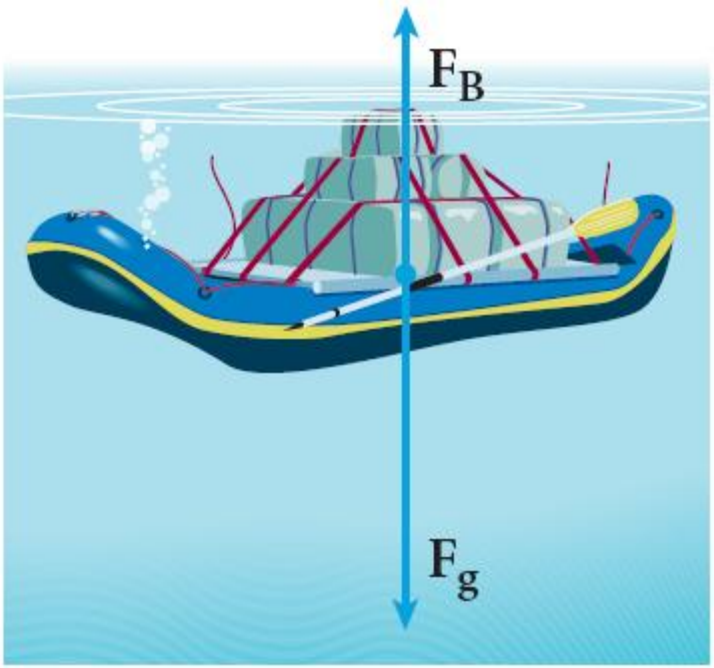
Buoyant Force



- The raft and cargo are floating because their weight and buoyant force are balanced.

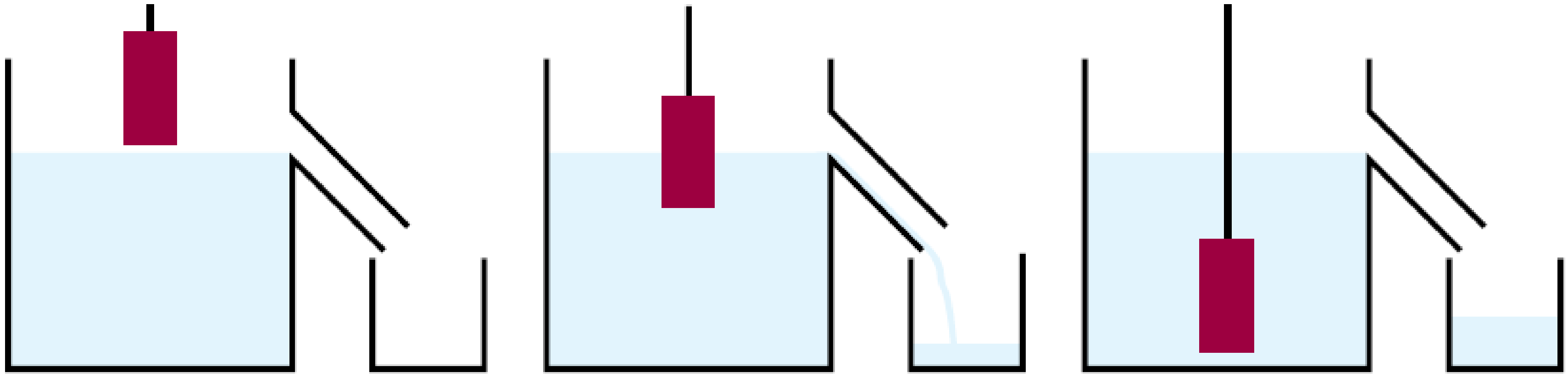
Buoyant Force

- Now imagine a small hole is put in the raft.
- The raft and cargo sink because their density is greater than the density of the water.
- As the volume of the raft decreases, the volume of the water displaced by the raft and cargo also decreases, as does the magnitude of the buoyant force.



Buoyant Force and Archimedes' Principle

- The Brick, when added will cause the water to be displaced and fill the smaller container.
- What will the volume be inside the smaller container?
- The same volume as the brick!

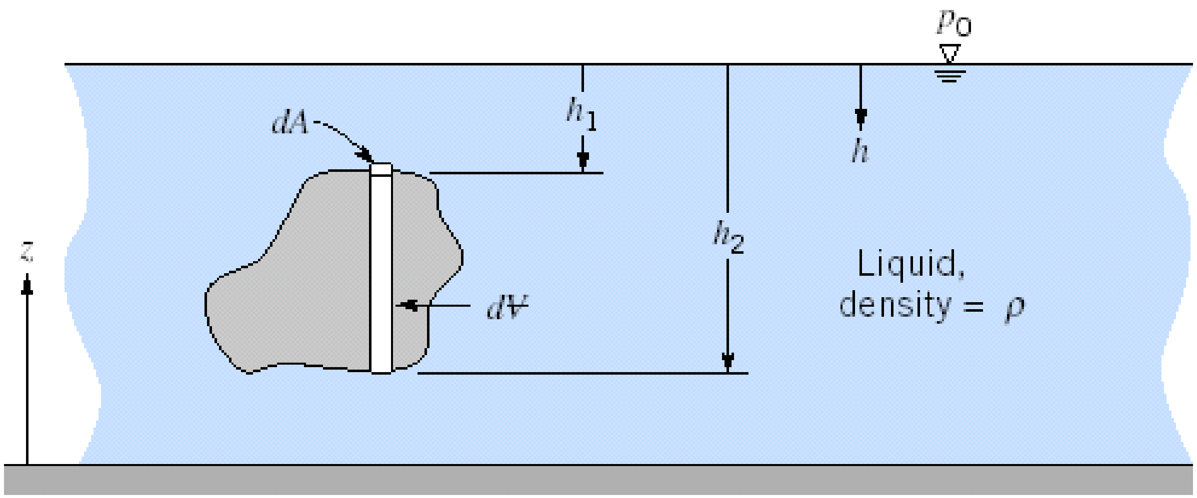


- Archimedes' principle describes the magnitude of a buoyant force.
- Archimedes' principle: *Any object completely or partially submerged in a fluid experiences an upward buoyant force equal in magnitude to the weight of the fluid displaced by the object.*

$$F_B = F_g \text{ (displaced fluid)} = m_f g$$

magnitude of buoyant force = weight of fluid displaced

Buoyancy



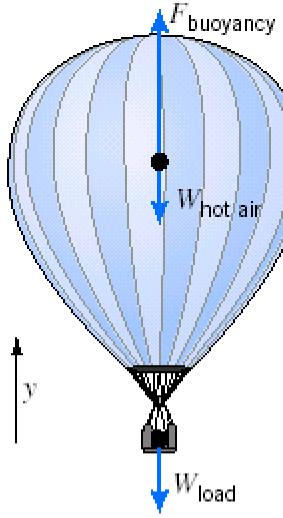
$$dF_z = (p_0 + \rho g h_2)\, dA - (p_0 + \rho g h_1)\, dA$$

$$dF_z = \rho g (h_2 - h_1)\, dA$$

Buoyancy

$$F_{\text{buoyancy}} = \rho g V\!\!\!\!-$$

For example, for a hot air balloon



Archimedes’ Principle and Buoyancy

Why do some things **float** and other things **sink** ?

Buoyancy and Stability

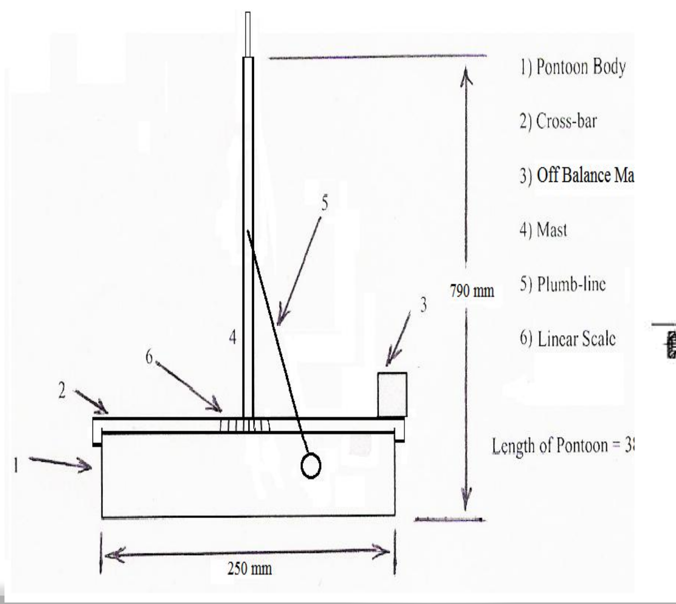
- Buoyancy is due to the fluid displaced by a body. $F_B=\rho_f gV$.
- Archimedes principle : The buoyant force = Weight of the fluid displaced by the body, and it acts through the centroid of the displaced volume.

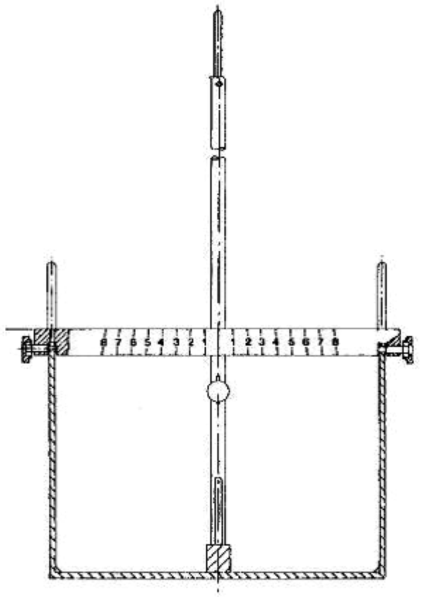
Meta-center

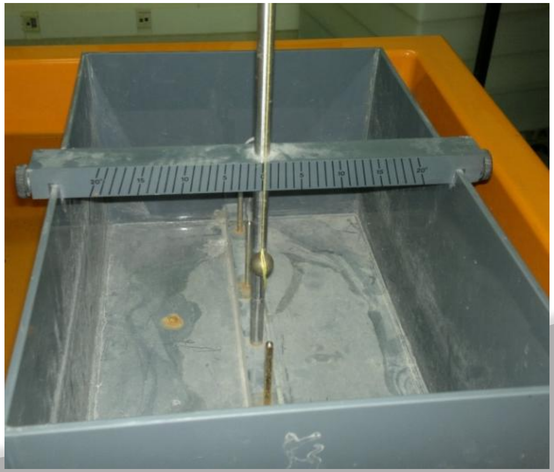
- Metacentre, also spelled metacenter, in fluid mechanics, the theoretical point at which an imaginary vertical line passing through the centre of buoyancy and centre of gravity intersects the imaginary vertical line through a new centre of buoyancy created when the body is displaced, or tipped, in the water, however little.

Meta centric height calculations

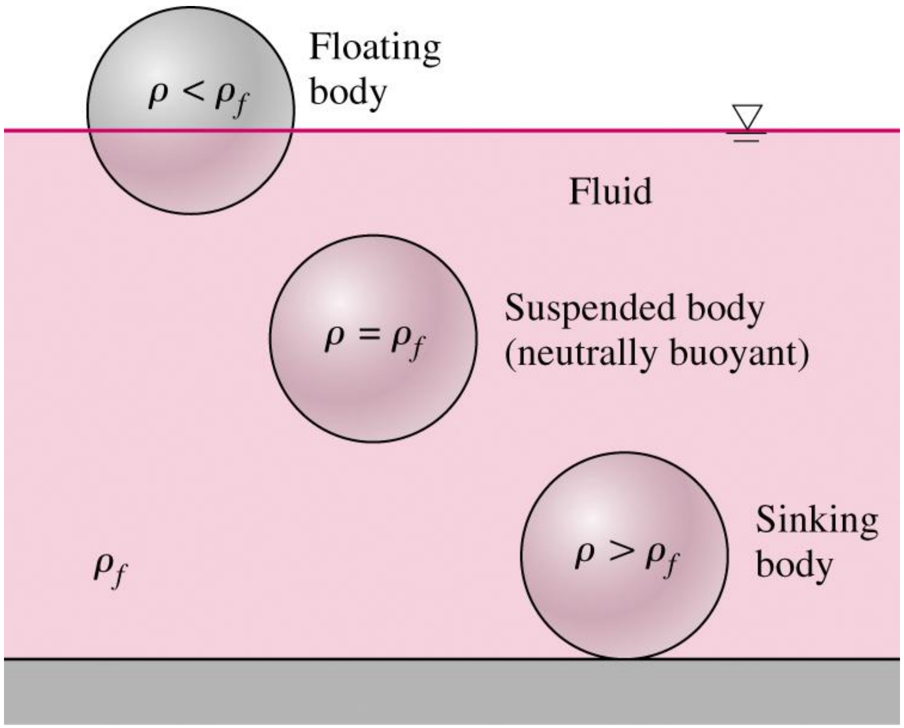
- The set up consists of a small water tank having transparent side walls in which a small ship model is floated, the weight of the model can be changed by adding or removing weights. Adjustable mass is used for tilting the ship, plump line is attached to the mast to measure the tilting angle.





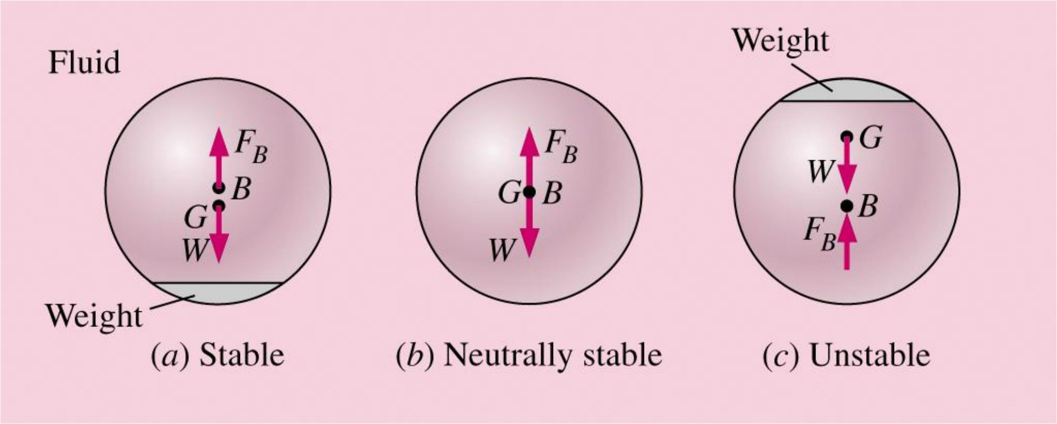


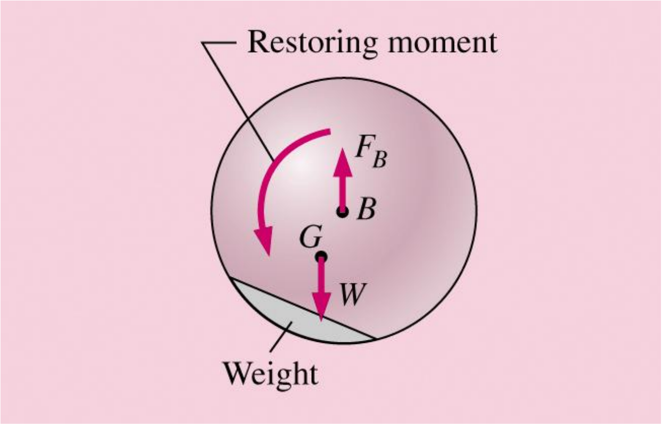
Buoyancy and Stability



- Buoyancy force F_B is equal only to the displaced volume $\rho_f g V_{displaced}$.
- Three scenarios possible
  1. $\rho_{body} < \rho_{fluid}$: Floating body
  2. $\rho_{body} = \rho_{fluid}$: Neutrally buoyant
  3. $\rho_{body} > \rho_{fluid}$: Sinking body

Stability of Immersed Bodies

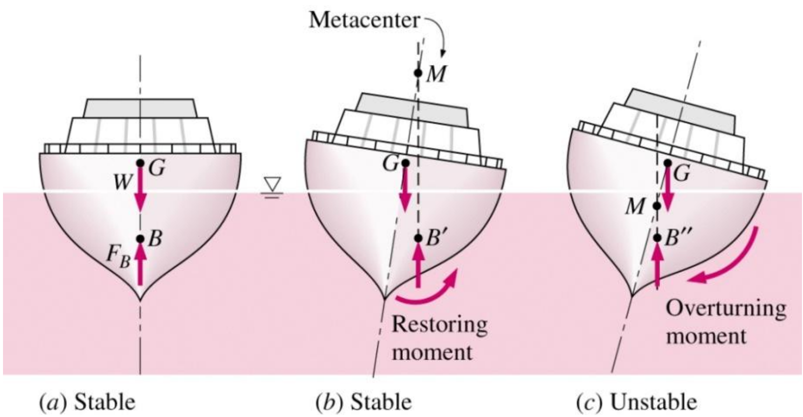




Rotational stability of immersed bodies depends upon relative location of *center of gravity G* and *center of buoyancy B*.

- *G* below *B*: stable
- *G* above *B*: unstable
- *G* coincides with *B*: neutrally stable.

Stability of Floating Bodies

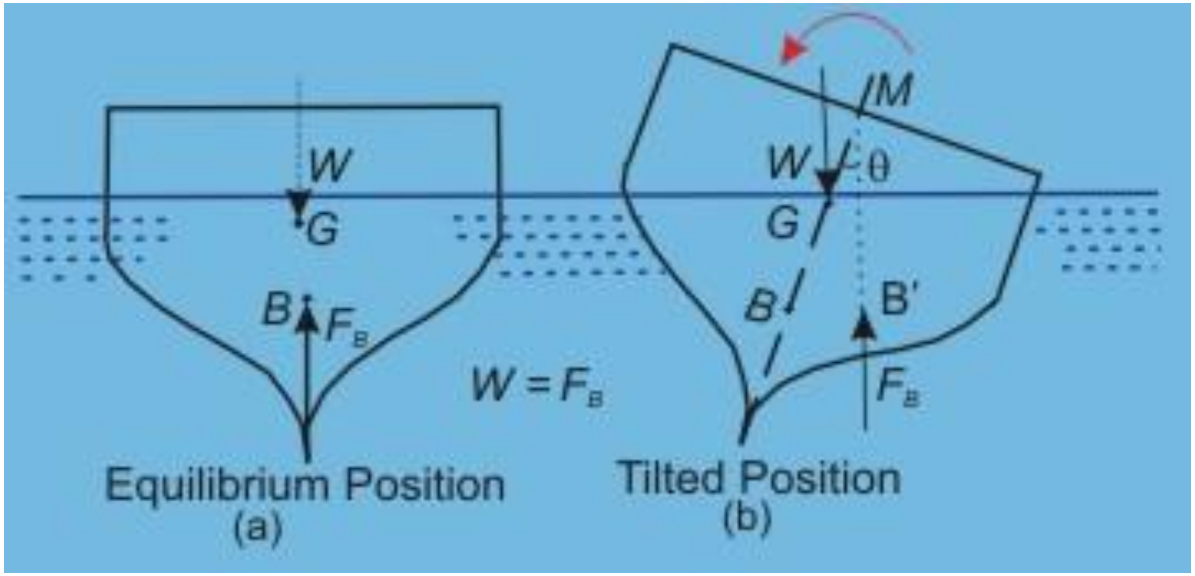


- If body is bottom heavy (*G* lower than *B*), it is always stable.
- Floating bodies can be stable when *G* is higher than *B* due to shift in location of center buoyancy and creation of restoring moment.
- Measure of stability is the metacentric height G*M*. If *GM*>1, ship is stable.

Stability of Floating Bodies in Fluid

- When the body undergoes an angular displacement about a horizontal axis, the shape of the immersed volume changes and so the centre of buoyancy moves relative to the body.
- As a result of above observation stable equilibrium can be achieved, under certain condition, even when G is above B. Figure illustrates a floating body -a boat, for example, in its equilibrium position.
- Let the new **line of action of the buoyant force** (which **is always vertical**) through B' intersects the axis BG (the old vertical line containing the centre of gravity G and the old centre of buoyancy B) at M. For small values of q the **point M is** practically constant in position and is **known as metacentre**

- Floating body in Stable equilibrium



Important points

- The force of buoyancy F_B is equal to the weight of the body W
- Centre of gravity G is above the centre of buoyancy in the same vertical line.
  Figure b shows the situation after the body has undergone a small angular displacement q with respect to the vertical axis.
- The centre of gravity G remains unchanged relative to the body (This is not always true for ships where some of the cargo may shift during an angular displacement).
- During the movement, the volume immersed on the right hand side increases while that on the left hand side decreases. Therefore the centre of buoyancy moves towards the right to its new position B'.

- Hence the **condition of stable equilibrium for a floating body** can be expressed **in terms of metacentric height** as follows:

GM > 0 (M is above G)	**Stable equilibrium**
GM = 0 (M coinciding with G)	**Neutral equilibrium**
GM < 0 (M is below G)	**Unstable equilibrium**

- The angular displacement of a boat or ship about its longitudinal axis is known as 'rolling' while that about its transverse axis is known as "pitching".

Numericals

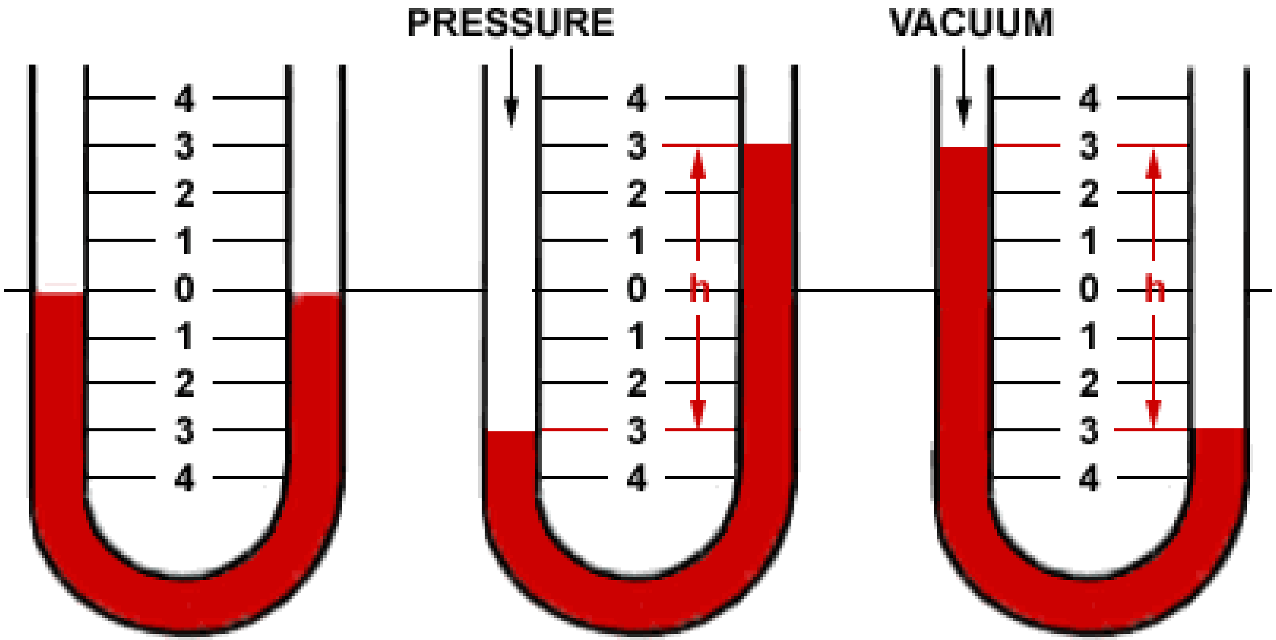
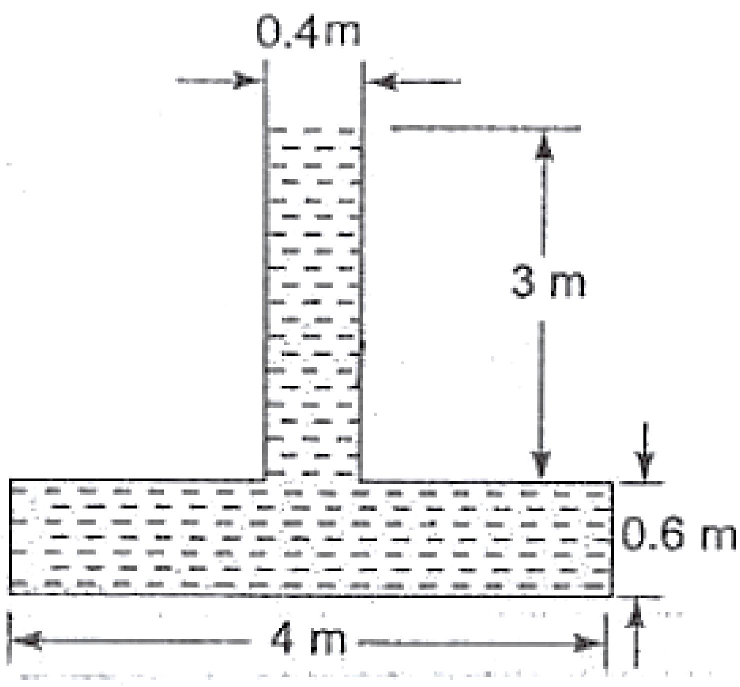


Figure shows a tank full of water. Find;

(i) Total pressure on the bottom of tank.
(ii) Weight of water in the tank.
(iii) Hydrostatic paradox between the results of (i) and (ii). Width of tank is 2 m.



Depth of water on bottom of tank

$$h_1 = 3 + 0.6 = 3.6 \text{ m}$$

Width of tank $= 2$ m

Length of tank at bottom $= 4$ m

$\therefore$ Area at the bottom, $A = 4 \times 2 = 8 \text{ m}^2$

(*i*) Total pressure F, on the bottom is

$$F = \rho g A \bar{h} = 1000 \times 9.81 \times 8 \times 3.6$$

$$= \mathbf{282528\ N.\ Ans.}$$

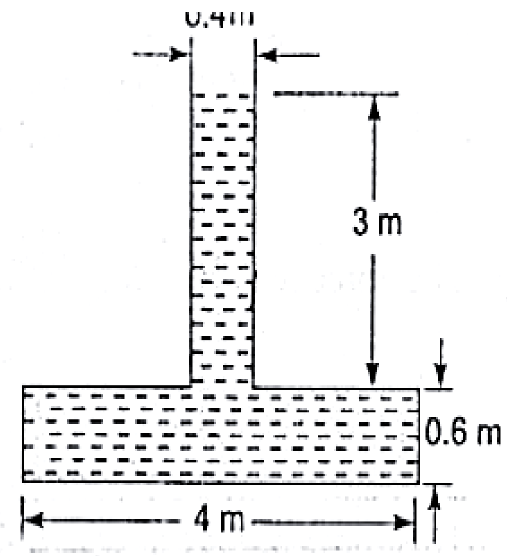


Fig. 3.17

(*ii*) Weight of water in tank $= \rho g \times$ Volume of tank

$$= 1000 \times 9.81 \times [3 \times 0.4 \times 2 + 4 \times .6 \times 2]$$

$$= 1000 \times 9.81\ [2.4 + 4.8] = \mathbf{70632\ N.\ Ans.}$$

iii. From the results of i & ii it is observed that the total weight of water in the tank is much less than the total pressure at the bottom of the tank. This is known as Hydrostatic Paradox.

Unit 2

FLUID KINEMATICS AND BASIC EQUATIONS OF FLUID FLOW ANALYSIS

Syllabus

Statement of Buckingham’s π- theorem, similarity parameters - Reynolds number, Froude number, concepts of geometric, kinematic and dynamic similarity, Types of fluid flows, differential equations of mass and momentum for incompressible flows, inviscid eulers equation and viscous flows- navier stokes equations, concept of fluid rotation, vorticity and stream function, exact solutions of navier stokes equations for coquette flow and poiseuille flow, numericals.

CLO	Course Learning Outcome
CLO4	Dimensional similarity and prediction of flow behaviour using dimensionless numbers.
CLO5	Classification of fluid flows and governing equations of inviscid fluid flows.
CLO6	Conceptual analysis of fluid flow and exact solutions of navier stokes equations for coquette flow and poiseuille flow.

What is fluid kinematics?

- Fluid kinematics is the study on fluid motion in space and time without considering the force which causes the fluid motion.
- According to the continuum hypothesis the local velocity of fluid is the velocity of an infinitesimally small fluid particle/element at a given instant ‘t’. It is generally a continuous function in space and time.

Three Aspects of Kinematics of Fluid

- Development of methods & techniques for describing and specifying the motions of fluids.
- Charecterization of different types of motion and associated deformation rates of any fluid element
- Determination of the conditions for the kinematic possibility of fluid motions.

Buckingham Pi Theorem

- Step 1:

  List all the parameters involved

  Let n be the number of parameters

  Example: For drag on a sphere, F, V, D, ρ, μ ; $n = 5$
- Step 2:

  Select a set of primary dimensions

  For example M *(kg)*, L *(m)*, t *(sec)*.

  Example: For drag on a sphere choose *MLT*

Buckingham Pi Theorem

- Step 3

  List the dimensions of all parameters

  Let *r* be the number of primary dimensions

  Example: For drag on a sphere *r* = 3

F	V	D	ρ	μ
$\frac{ML}{t^2}$	$\frac{L}{t}$	L	$\frac{M}{L^3}$	$\frac{M}{Lt}$

Buckingham Pi Theorem

- Step 4

  Select a set of r dimensional parameters that includes all the primary dimensions

  Example: For drag on a sphere ($m = r = 3$) select ϱ, V, D

Buckingham Pi Theorem

- Step 5

  Set up dimensionless groups πs

  There will be *n* – *m* equations

  Example: For drag on a sphere

$$\Pi_1 = \rho^a V^b D^c F$$

$$\left(\frac{M}{L^3}\right)^a \left(\frac{L}{t}\right)^b (L)^c \left(\frac{ML}{t^2}\right) = M^0 L^0 t^0$$

$$\Pi_1 = \frac{F}{\rho V^2 D^2}$$

Buckingham Pi Theorem

- Step 6

  Check to see that each group obtained is dimensionless

  Example: For drag on a sphere

$$[\Pi_1] = \left[\frac{F}{\rho V^2 D^2}\right] \qquad F\,\frac{L^4}{Ft^2}\left(\frac{t}{L}\right)^2\frac{1}{L^2} = 1$$

$\Pi_2 = Re = \rho VD / \mu$

$$\Pi_2 \qquad \frac{F}{\rho V^2 D^2} = f\left(\frac{\rho VD}{\mu}\right)$$

Similitude and Model Studies

For a study on a model to relate to that on a prototype it is required that there be

Geometrical Similarity
Kinematic Similarity
Dynamic Similarity

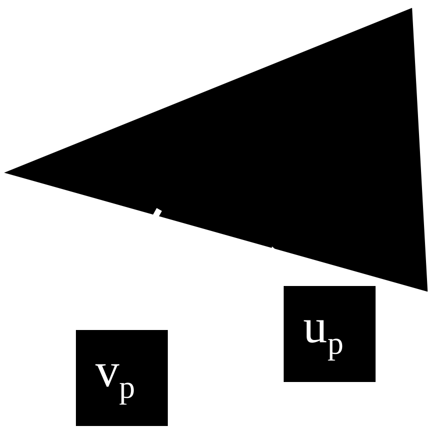
Geometrical Similarity

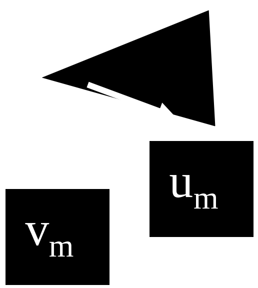
Physical dimensions of model and prototype be similar

$$\frac{Lp}{Hp} = \frac{Lm}{Hm}$$

Kinematic Similarity

Velocity vectors at corresponding locations on the model and prototype are similar

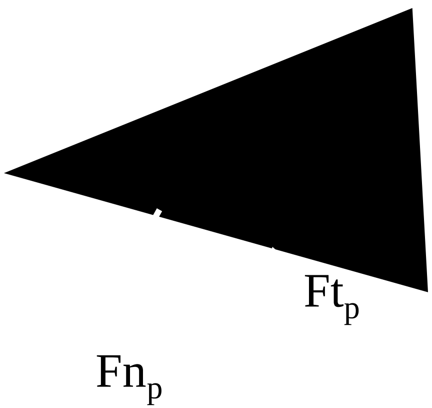


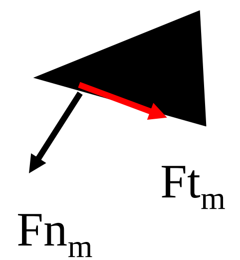


$$\frac{u_p}{v_p} = \frac{u_m}{v_m}$$

Dynamic Similarity

Forces at corresponding locations on model and prototype are similar





$$\frac{Ft_p}{Fn_p} = \frac{Ft_m}{Fn_m}$$


Photo # NH 97206-KN USS Wisconsin (BB-64), ca. 1988-91

Dimensional analysis and similarity

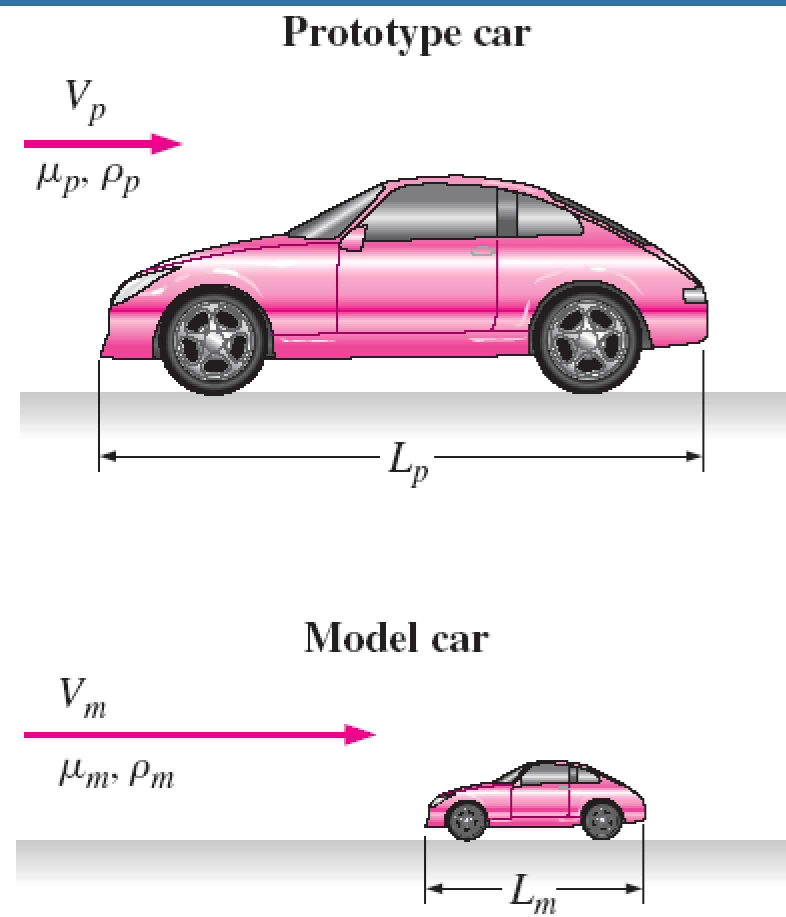
- Consider automobile experiment
- Drag force is $F = f(V, \rho, \mu, L)$
- Through dimensional analysis, we can reduce the problem to

$$\Pi_1 = f(\Pi_2)$$

- where

$$\Pi_1 = \frac{F_D}{\rho V^2 L^2}$$

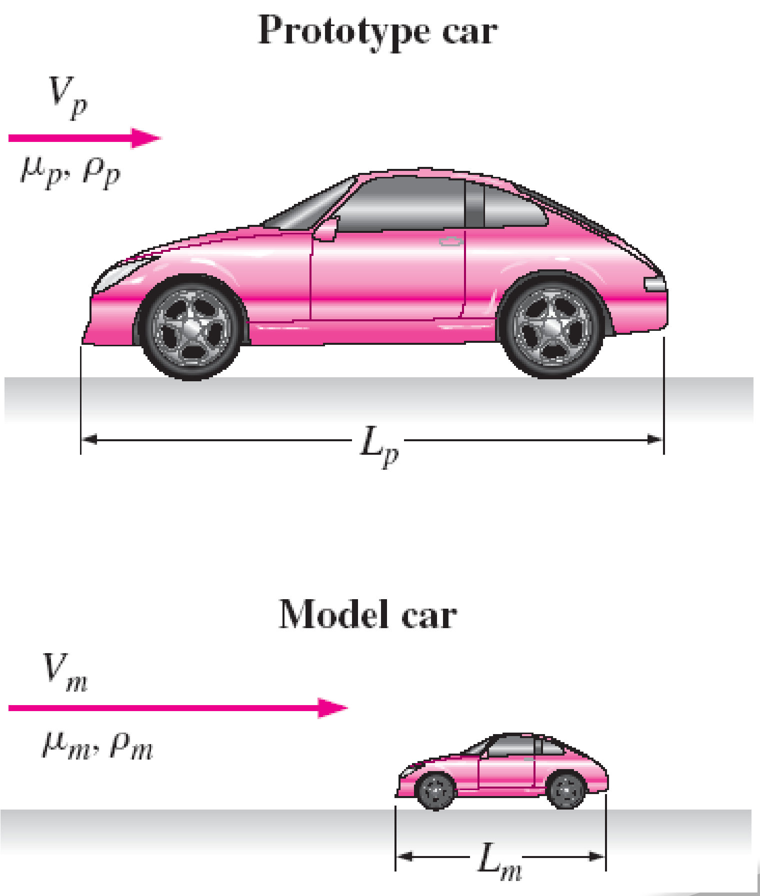
$$\Pi_2 = \frac{\rho V L}{\mu}$$



The Reynolds number is the most well known and useful dimensionless parameter in all of fluid mechanics.

Problem 1: Similarity between Model and Prototype Cars

- The aerodynamic drag of a new sports car is to be predicted at a speed of 50.0 mi/h at an air temperature of 25°C. Automotive engineers build a one-fifth scale model of the car to test in a wind tunnel. It is winter and the wind tunnel is located in an unheated building; the temperature of the wind tunnel air is only about 5°C. Determine how fast the engineers should run the wind tunnel in order to achieve similarity between the model and the prototype.



Solution

$$\Pi_{2,m} = \mathrm{Re}_m = \frac{\rho_m V_m L_m}{\mu_m} = \Pi_{2,p} = \mathrm{Re}_p = \frac{\rho_p V_p L_p}{\mu_p}$$

$$V_m = V_p\left(\frac{\mu_m}{\mu_p}\right)\left(\frac{\rho_p}{\rho_m}\right)\left(\frac{L_p}{L_m}\right)$$

$$= (50.0\ \mathrm{mi/h})\left(\frac{1.754 \times 10^{-5}\ \mathrm{kg/m \cdot s}}{1.849 \times 10^{-5}\ \mathrm{kg/m \cdot s}}\right)\left(\frac{1.184\ \mathrm{kg/m^3}}{1.269\ \mathrm{kg/m^3}}\right)(5) = \mathbf{221\ mi/h}$$

Discussion This speed is quite high (about 100 m/s), and the wind tunnel may not be able to run at that speed. Furthermore, the incompressible approximation may come into question at this high speed.

Methods of Describing the Fluid Flow

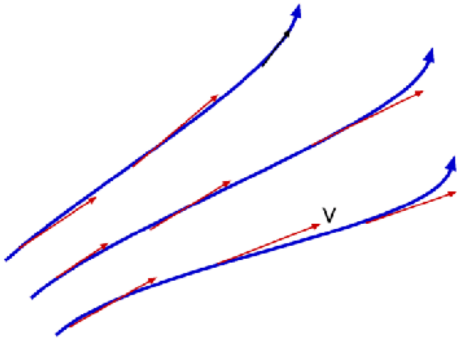
- The fluid motion is described by two methods.

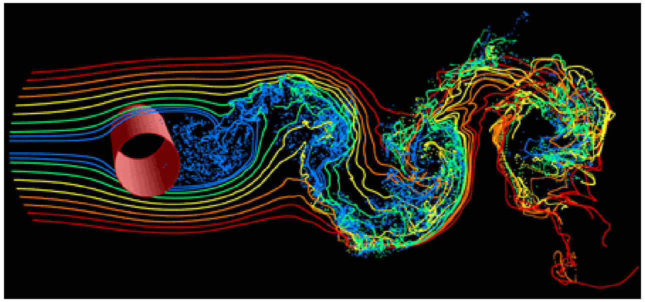
1. Lagrangian Method
2. Eulerian Method

Eularian and Lagrangian approaches

- Eularian and Lagrangian approaches are of the two methods to study fluid motion. The Eularian approach concentrates on fluid properties at a point P (x,y,z,t). Thus it is a field approach.
- In the Lagrangian approach one identifies a particle or a group of particles and follows them with time. This is bound to be a cumbersome method. But there may be situations where it is unavoidable. One such is the two phase flow involving particles.

Streamlines

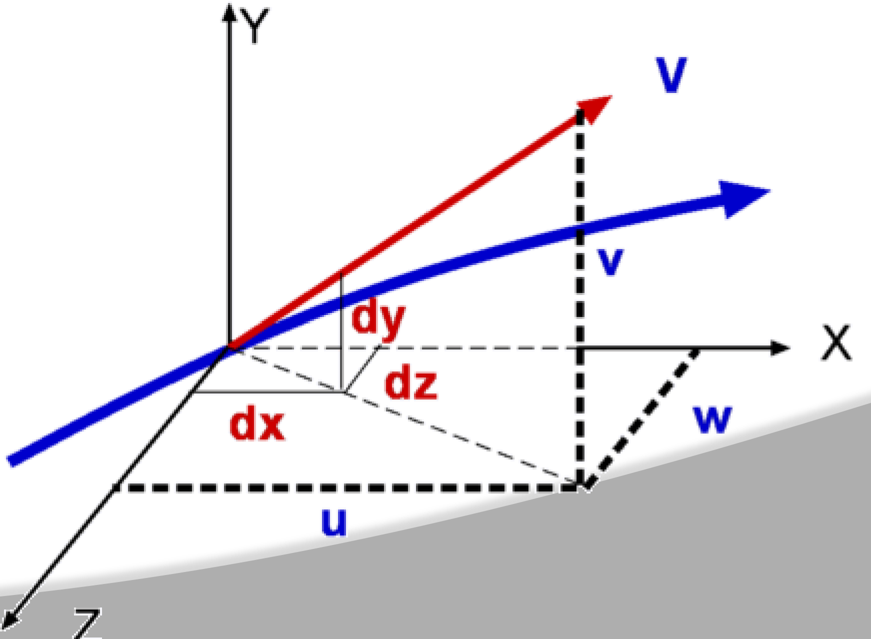




Streamline definition

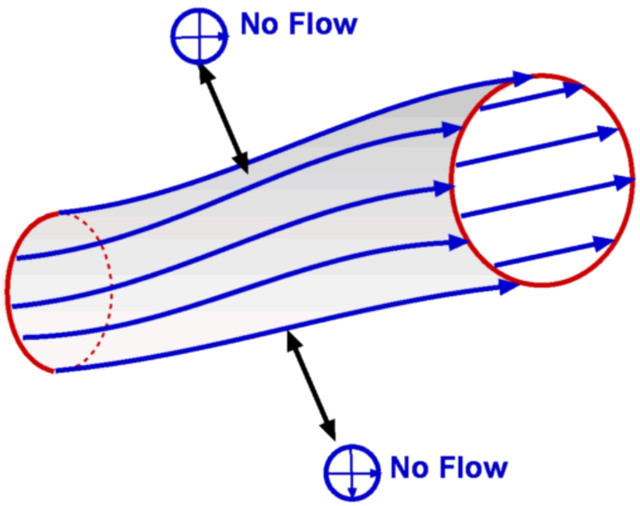
A streamline is one that drawn is tangential to the velocity vector at every point in the flow at a given instant and forms a powerful tool in understanding flows.

$$\frac{du}{u} = \frac{dv}{v} = \frac{dw}{w}$$



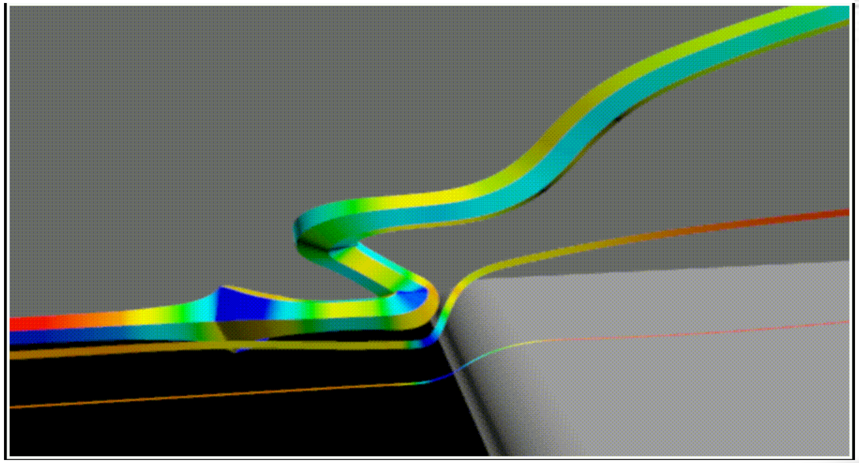
Stream-tube

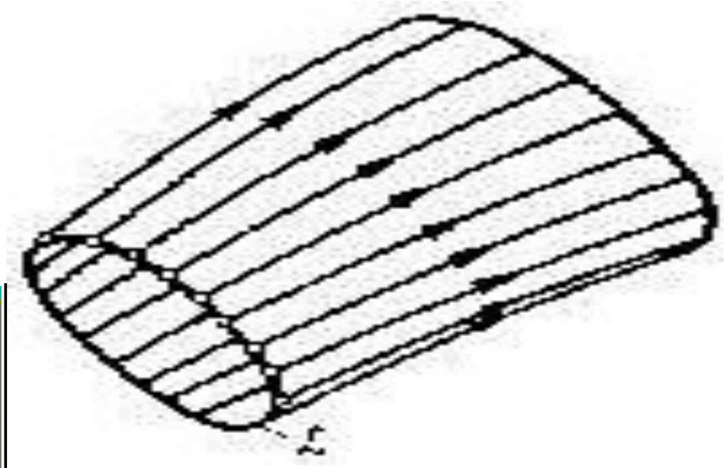
- The definition of streamline is the fact that there cannot be a flow across it; i.e. there is no flow normal to it. Sometimes, as shown in Fig. we pull out a bundle of streamlines from inside of a general flow for analysis. Such a bundle is called stream tube and is very useful in analyzing flows. If one aligns a coordinate along the stream tube then the flow through it is one-dimensional.



Stream-tube

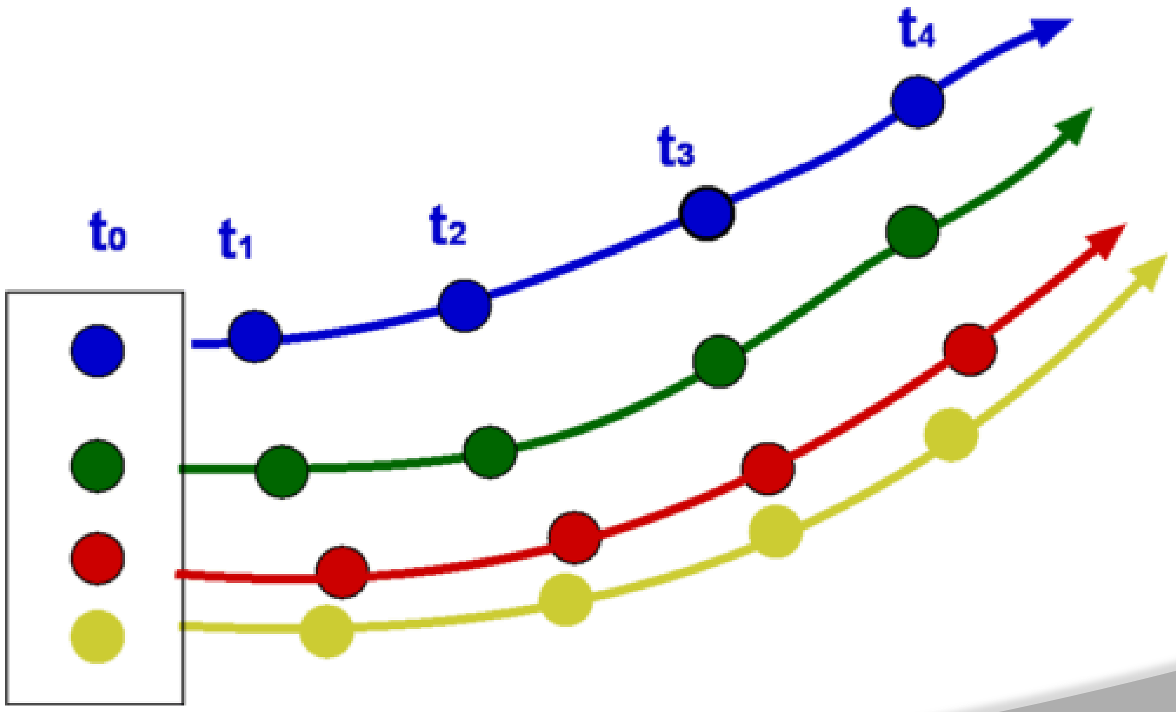
- Is the surface formed instantaneously by all the streamlines that pass through a given closed curve in the fluid.





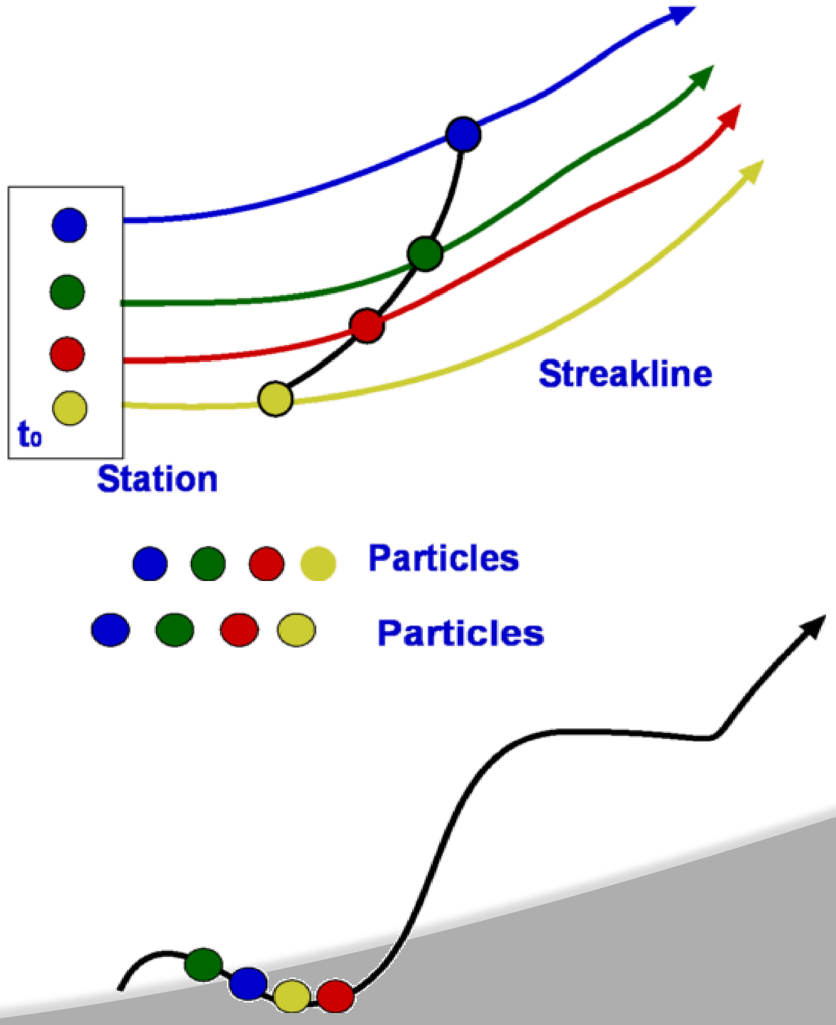
Pathlines

- Pathline is the line traced by a given particle. This is generated by injecting a dye into the fluid and following its path by photography or other means (Fig.)



Streakline

Streakline concentrates on fluid particles that have gone through a fixed station or point. At some instant of time the position of all these particles are marked and a line is drawn through them. Such a line is called a streakline (Fig.).



Timeline

- Timeline is generated by drawing a line through adjacent particles in flow at any instant of time.

- In a steady flow the streamline, pathline and streakline all coincide. In an unsteady flow they can be different. Streamlines are easily generated mathematically while pathline and streaklines are obtained through experiments.

Flow classifications

- Incompressible vs. compressible flow.
  - Incompressible flow: volume of a given fluid particle does not change.
    - Implies that density is constant everywhere.
    - Essentially valid for all liquid flows.
  - Compressible flow: volume of a given fluid particle can change with position.
    - Implies that density will vary throughout the flow field.
    - Compressible flows are further classified according to the value of the Mach number (M), where.
    - $M < 1$ - Subsonic.
    - $M > 1$ - Supersonic.

Types of flows

- Steady
- Unsteady
- Uniform
- Non-uniform
- Laminar
- Turbulent

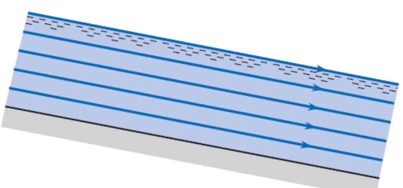
- Rotational
- Irrotational
- One dimensional flows
- Two dimensional flows
- Three dimensional flows

Steady vs. Unsteady Flow

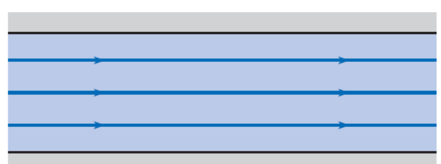
For steady flow, the velocity at a point or along a streamline does not change with time:

$$\frac{\partial \mathbf{V}}{\partial t} = 0$$

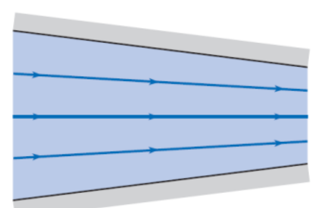
Any of the previous examples can be steady or unsteady, depending on whether or not the flow is accelerating:



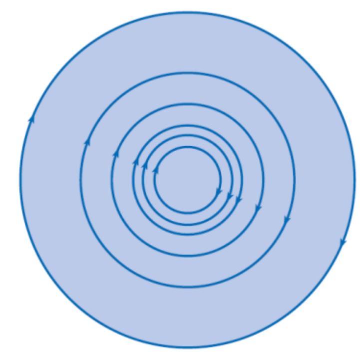
(a)



(b)

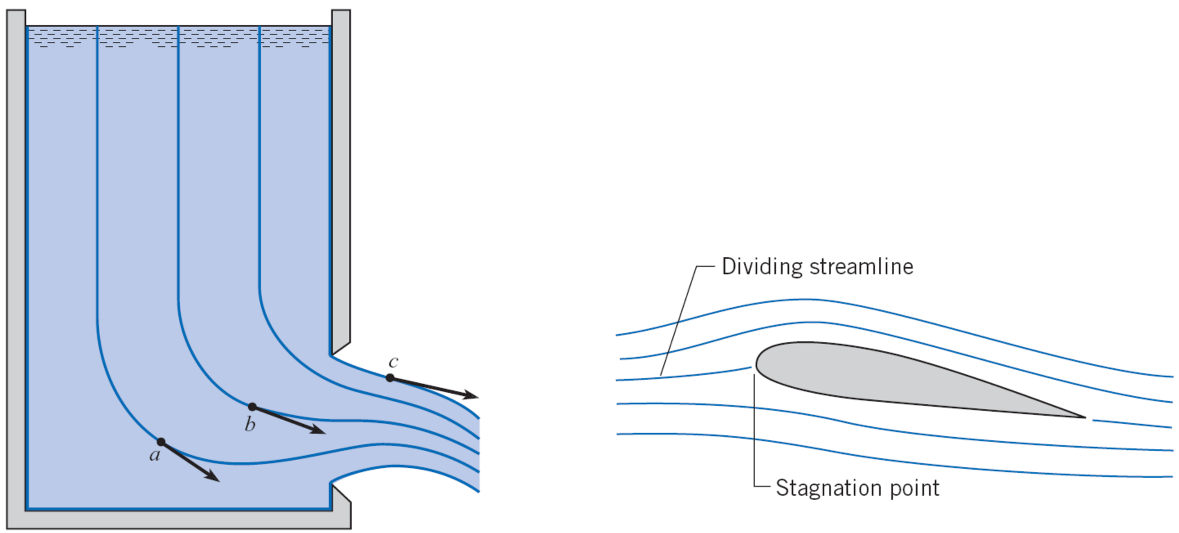


(a)



(b)

Streamlines and Flow Patterns



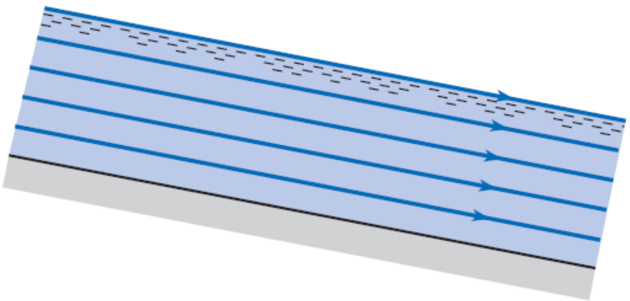
(a) (b)

- Streamlines are used for visualizing the flow. Several streamlines make up a flow pattern.
- A streamline is a line drawn through the flow field such that the flow vector is tangent to it at every point at a given instant in time.

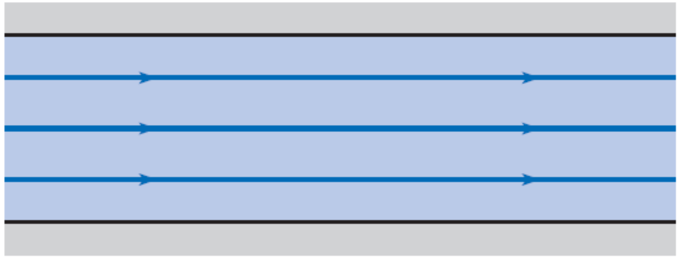
Uniform vs. Non-Uniform Flow

Using s as the spatial variable along the path (i.e., along a streamline):

Flow is uniform if $$\frac{\partial \mathbf{V}}{\partial s} = 0$$



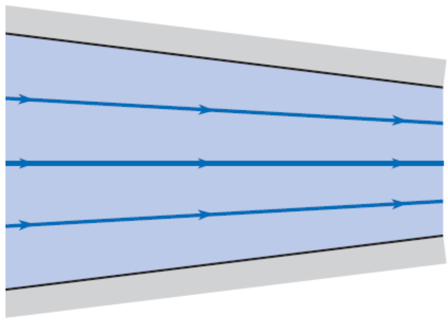
(a)



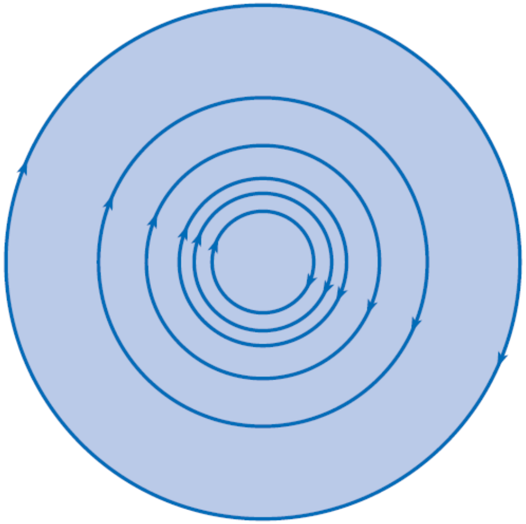
(b)

Note that the velocity along different streamlines need not be the same! (in these cases it probably isn't).

Examples of non-uniform flow:



(a)



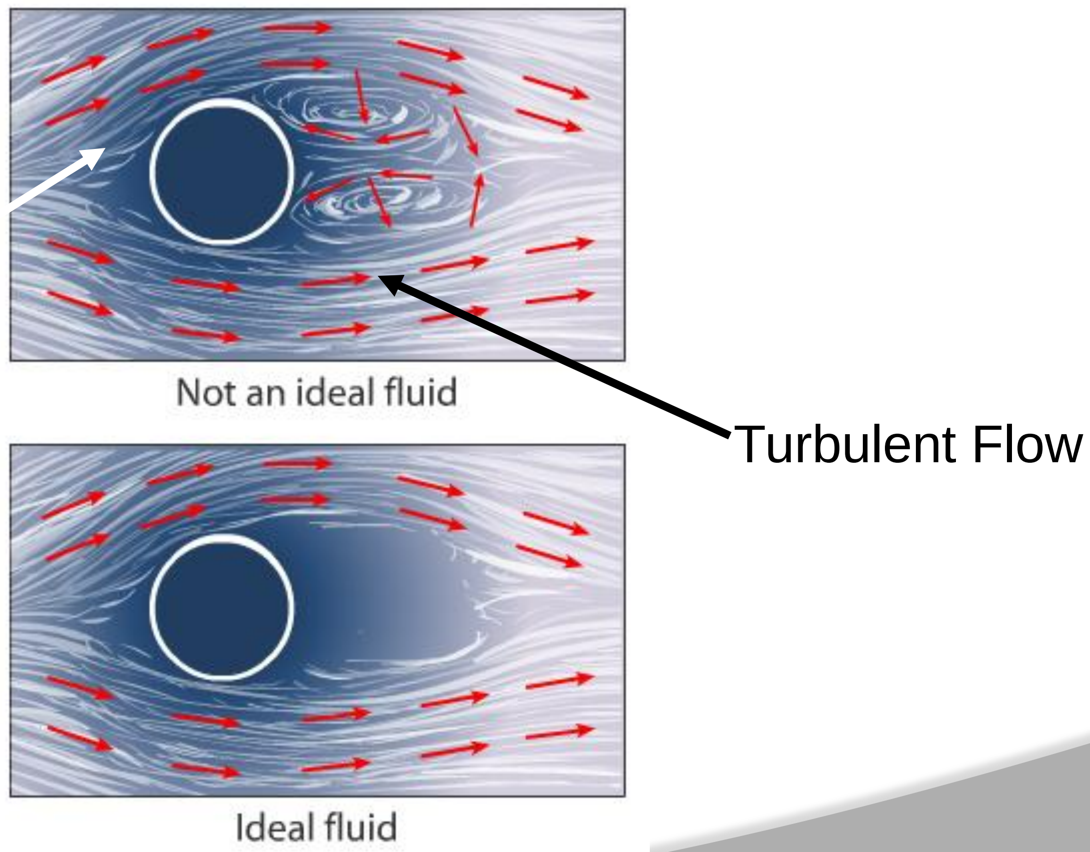
(b)

a) Converging flow: speed increases along each streamline.

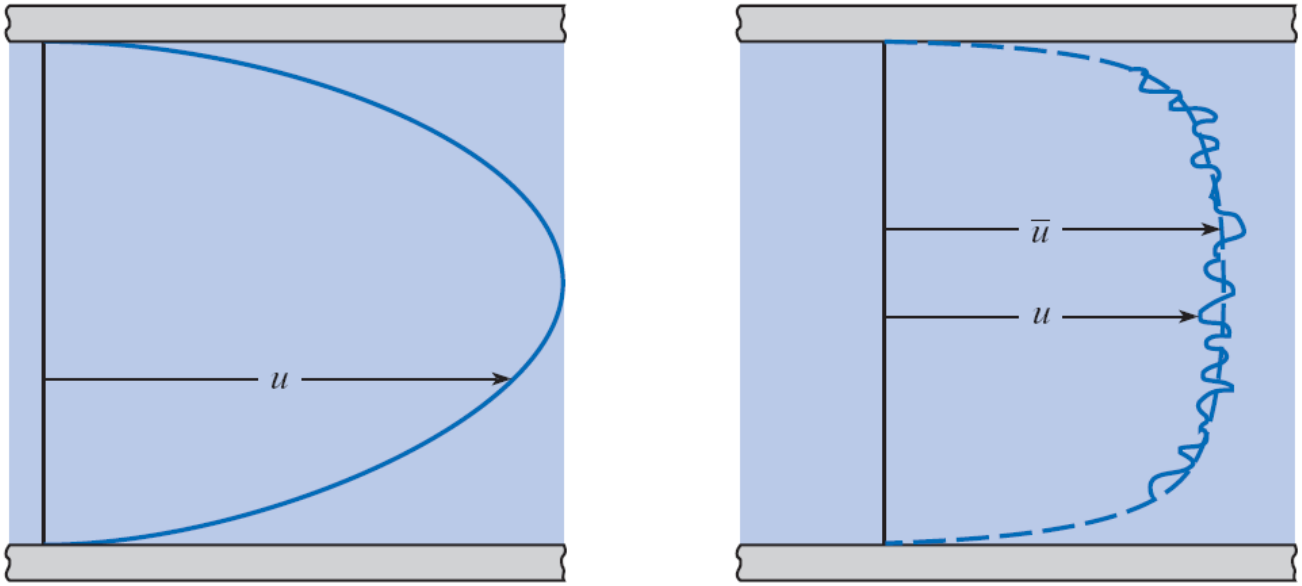
b) Vortex flow: Speed is constant along each streamline, but the direction of the velocity vector changes.

Laminar Turbulent Flow

- Moving fluids can exhibit *laminar* (smooth) flow or *turbulent* (irregular) flow.



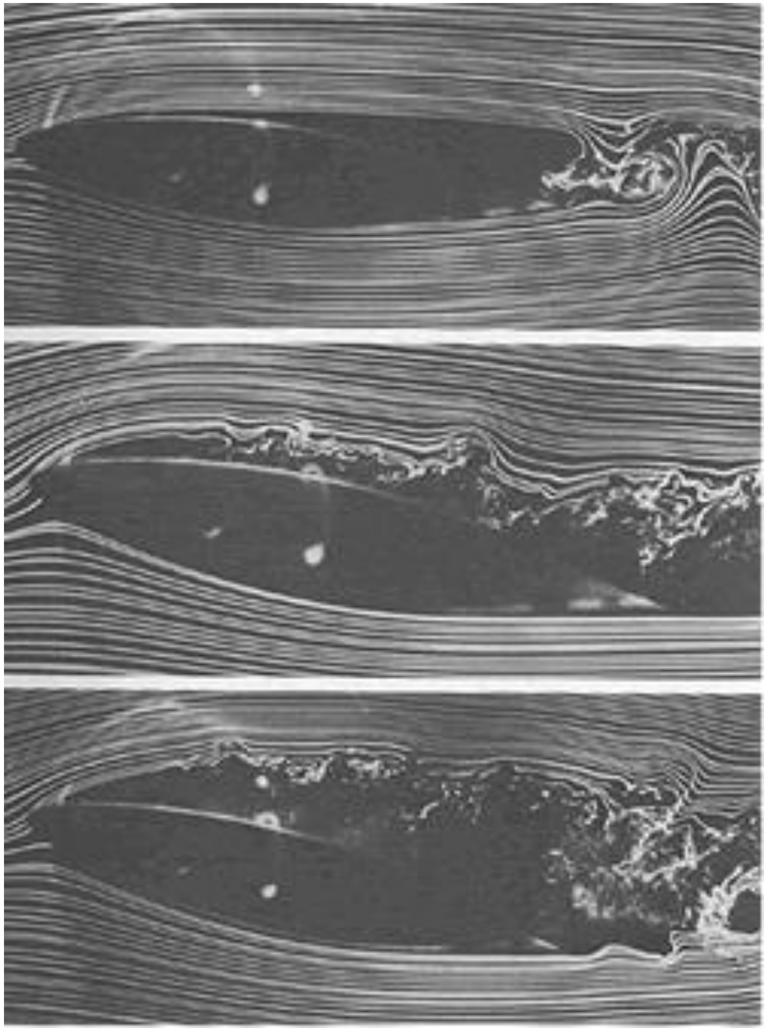
Flow inside a pipe:



(a) (b)

- Turbulent flow is nearly constant across a pipe.
- Flow in a pipe becomes turbulent either because of high velocity, because of large pipe diameter, or because of low viscosity.

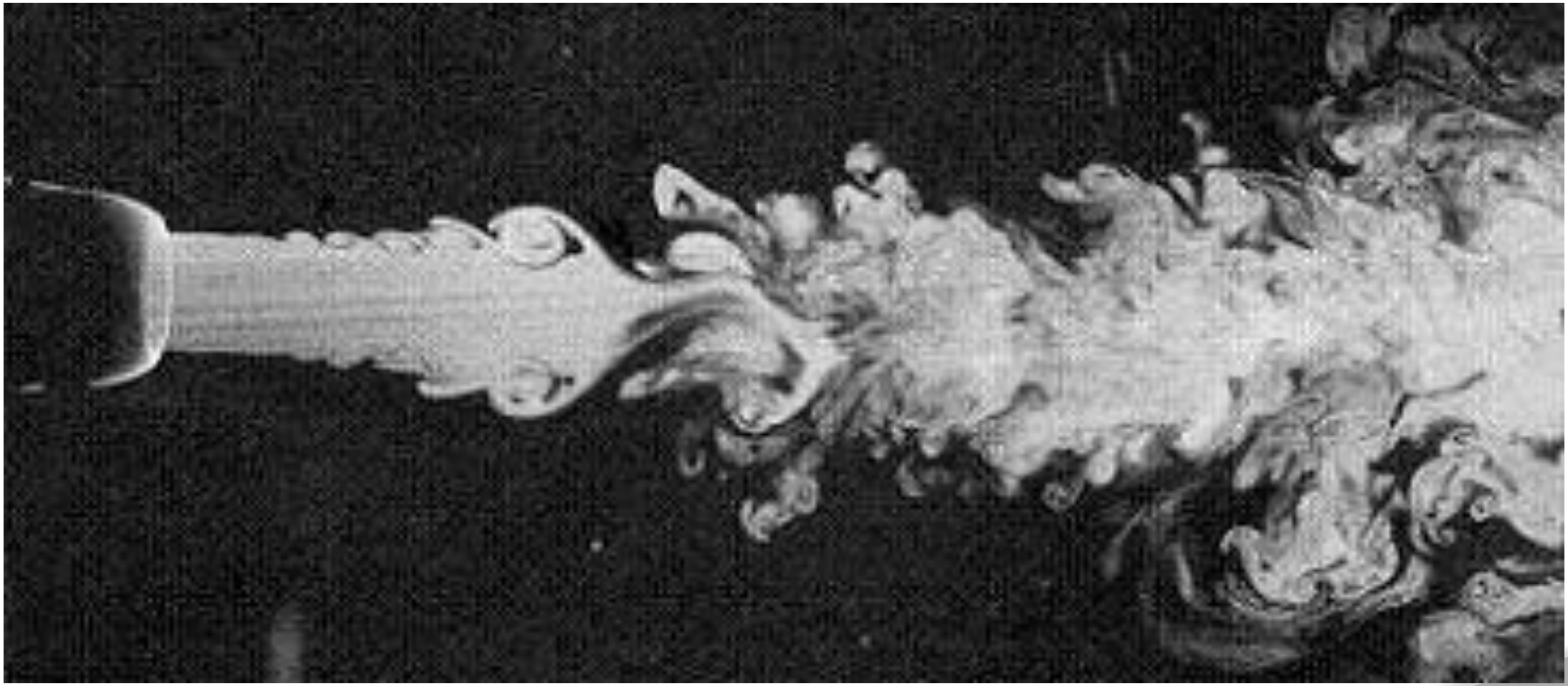
Flow around an airfoil



Partly laminar, i.e., flowing past the object in “layers” (laminar).

Turbulence forms mostly downstream from the airfoil.

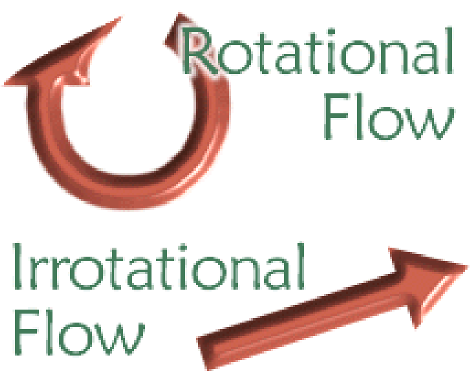
(Flow becomes more turbulent with increased angle of attack.)

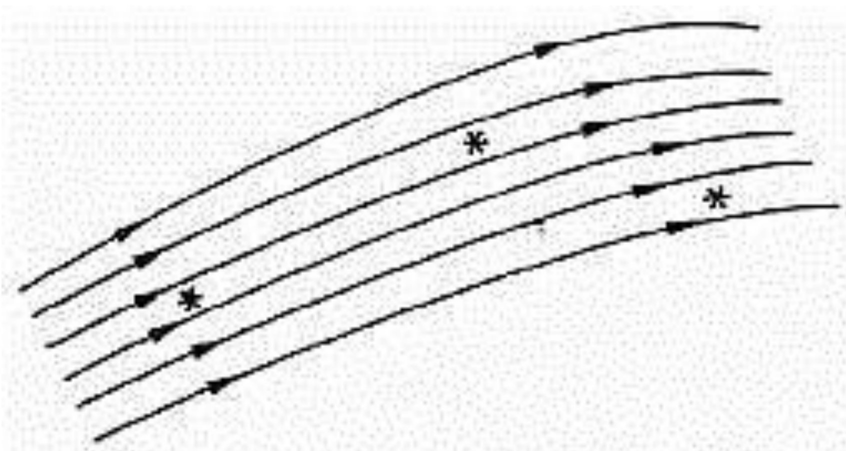


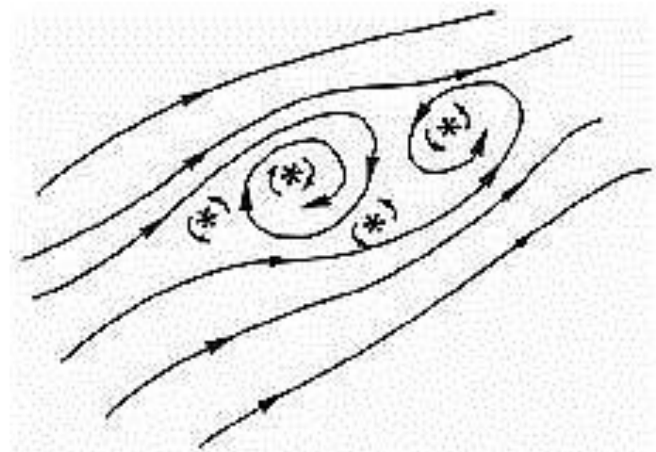
Turbulence is associated with intense mixing and unsteady flow.

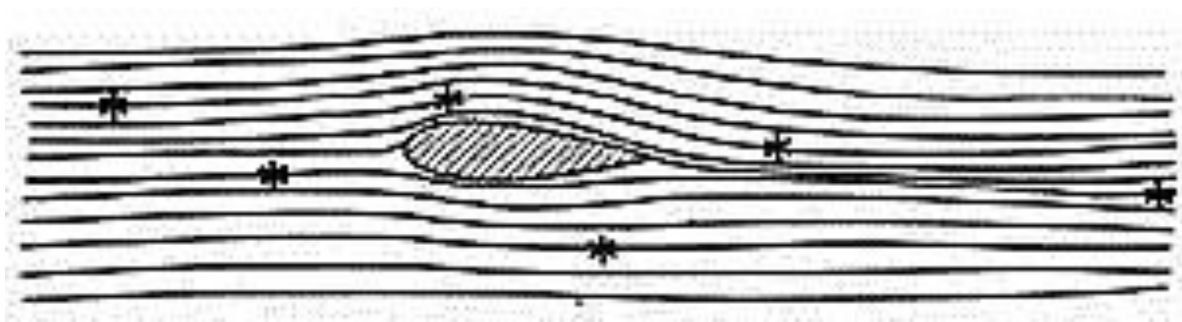
Rotational Vs Irrotational Flows

- Rotational flow is that type of flow in which the fluid particles while flowing along stream lines also rotate about their own axis.
- Irrotational flow is that type of flow in which the fluid particles while flowing along stream lines also do not rotate about their own axis.





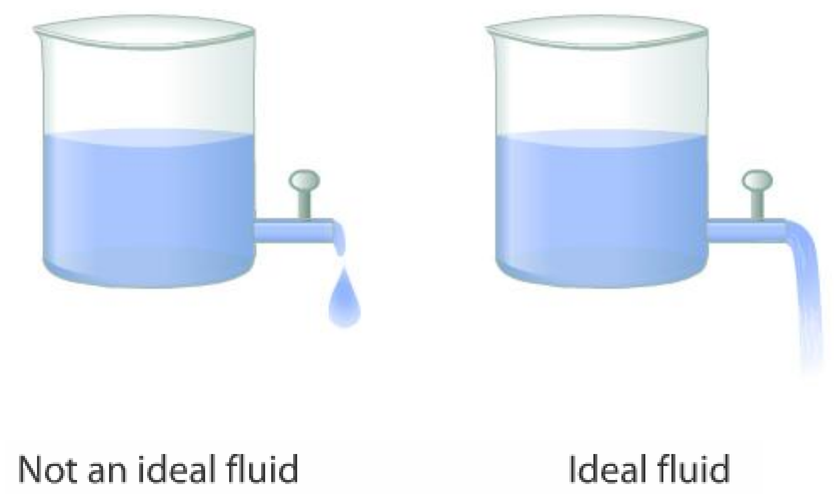


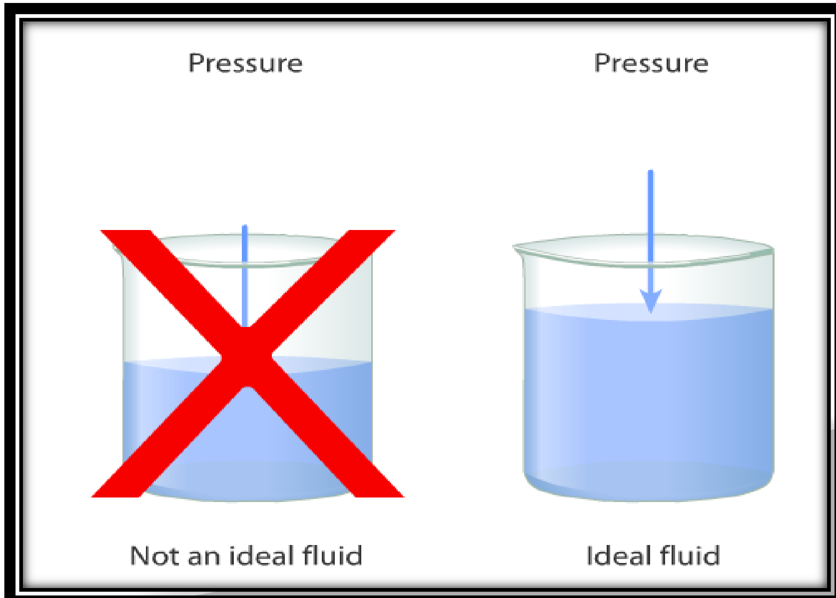


flow about an airfoil.

Fluid Flow

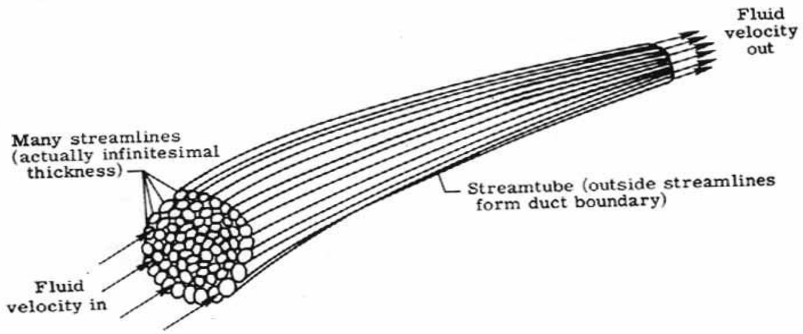
- An **ideal fluid** is a fluid that has no internal friction or viscosity and is incompressible.
- The ideal fluid model simplifies fluid-flow analysis



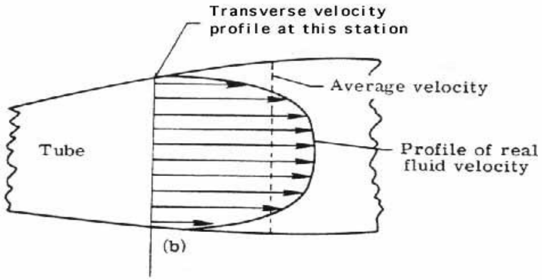


1D,2D,3D flows

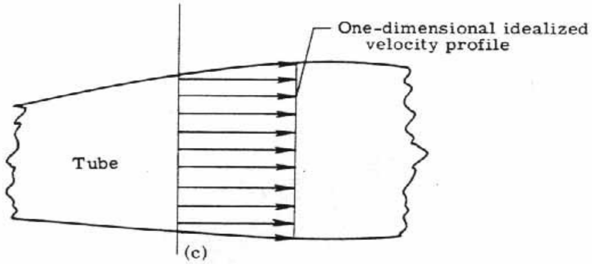
- One dimensional flow: Is that type of flow in which the flow parameter such as velocity is a function of time and one space co-ordinate only.
- Two Dimensional Flow: Is that type flow in which the velocity is a function of time and two rectangular space co-ordinates.
- Three Dimensional flow: Is that type of flow in which the velocity is a function of time and three mutually perpendicular directions.



(a) Stream tubes.



(b) Real velocity flow profile.



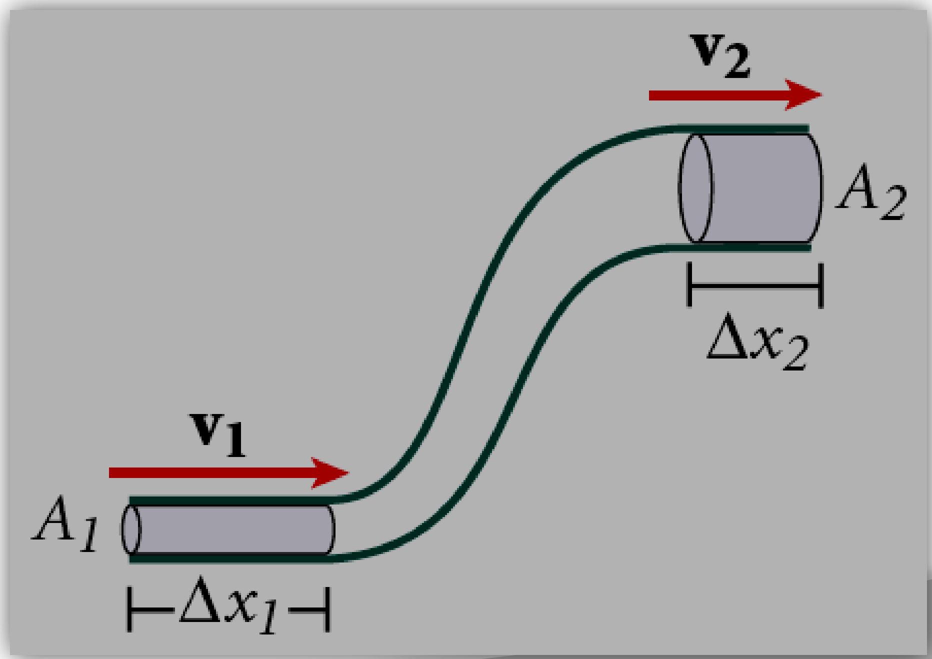
(c) One-dimensional flow profile.

Principles of Fluid Flow

- The continuity equation results from conservation of mass.
- Continuity equation:

$$A_1 v_1 = A_2 v_2$$

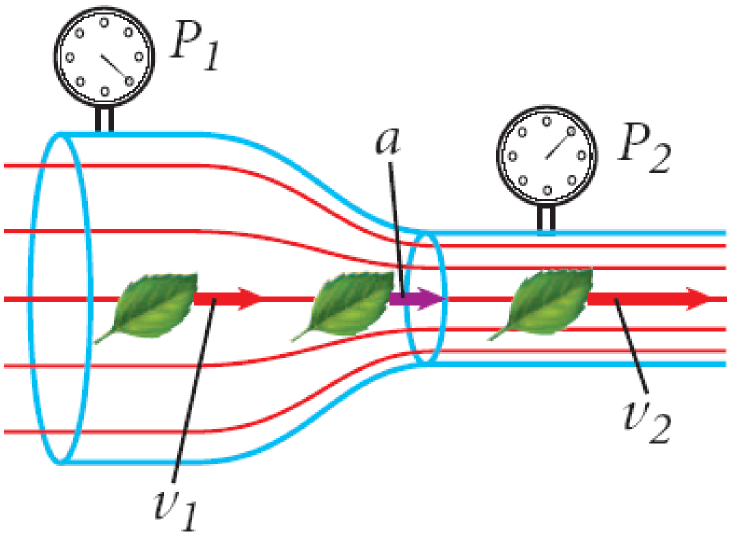
Area × speed in region 1 = area × speed in region 2



Principles of Fluid Flow

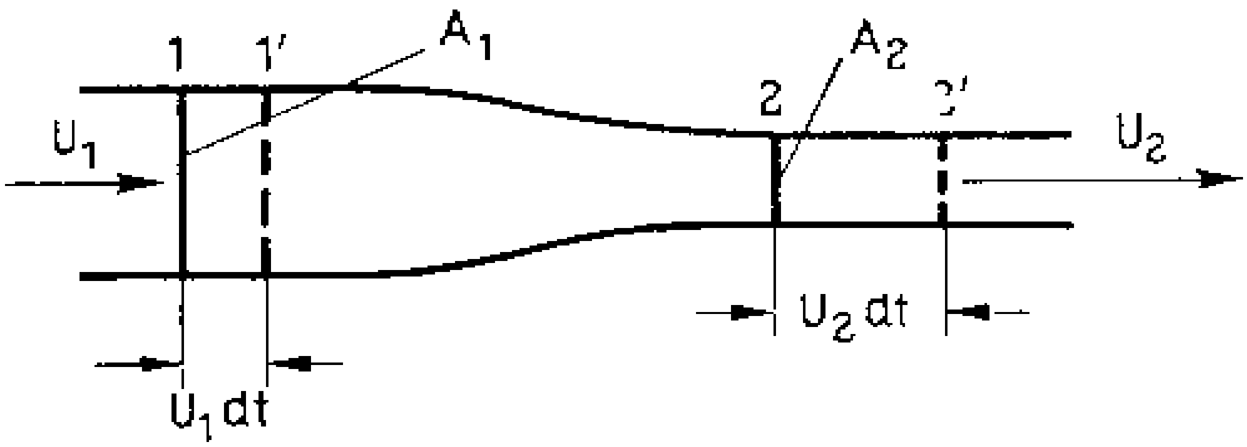
- The speed of fluid flow depends on cross-sectional area.

- Bernoulli's principle states that the pressure in a fluid decreases as the fluid's velocity increases.



Continuity Equation

- For a steady flow the stream-tube formed by a closed curved fixed in space is also fixed in space, and no fluid can penetrate through the stream-tube surface, like a duct wall.



Considering a stream-tube of cylindrical cross sections A_1 and A_2 with velocities u_1 and u_2 perpendicular to the cross sections A_1 and A_2 and densities ρ_1 and ρ_2 at the respective cross sections A_1 and A_2 and assuming the velocities and densities are constant across the whole cross section A_1 and A_2 , a fluid mass closed between cross section 1 and 2 at an instant t will be moved after a time interval dt by $u_1 \cdot dt$ and $u_2 \cdot dt$ to the cross section 1' and 2' respectively.

Because the closed mass between 1 and 2 must be the same $\rho_1 A_1 u_1 dt$ between 1' and 2', and the mass between 1' and 2 for a steady flow can not change from t and t+dt, the mass between 1 and 1' moved in dt, $\rho_2 A_2 u_2 dt$ must be the same as the mass between 2 and 2' moved in the same time dt, :

- Therefore the continuity equation of steady flow :

$$\rho_1 A_1 u_1 = \rho_2 A_2 u_2 \qquad \textbf{(4.1)}$$

Interpretation : The mass flow rate $\dot{m} = \rho A u = const.$

through a steady stream-tube or a duct.

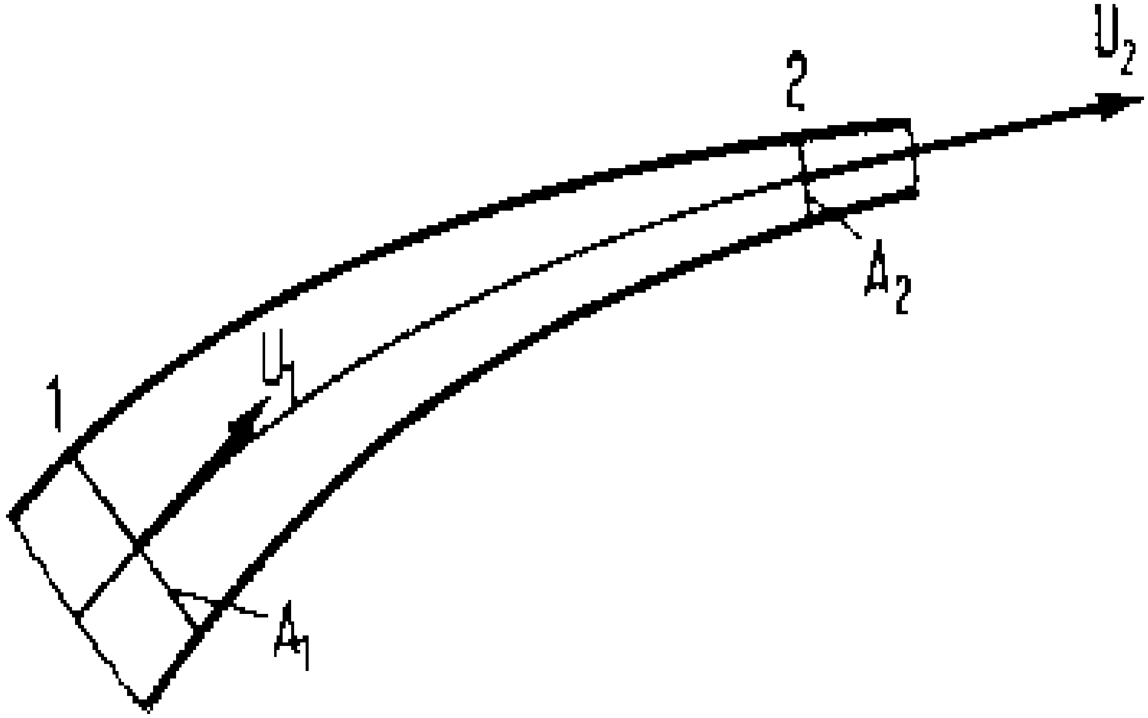
- For incompressible fluid with $\rho_1 = \rho_2$:

$$A_1 u_1 = A_2 u_2 \qquad \textbf{(4.2)}$$

Interpretation : The volume flow rate $\dot{V} = Au = const.$

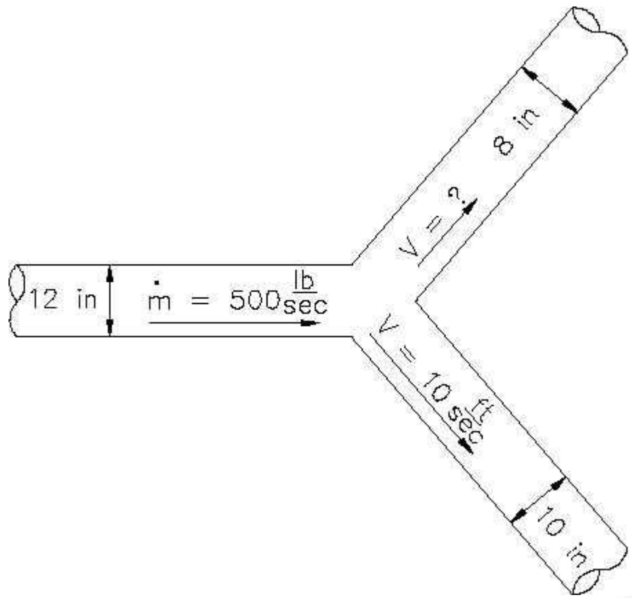
- From the continuity equation for incompressible fluid :

$$\frac{u_1}{u_2} = \frac{A_2}{A_1}$$ for a stream-tube.

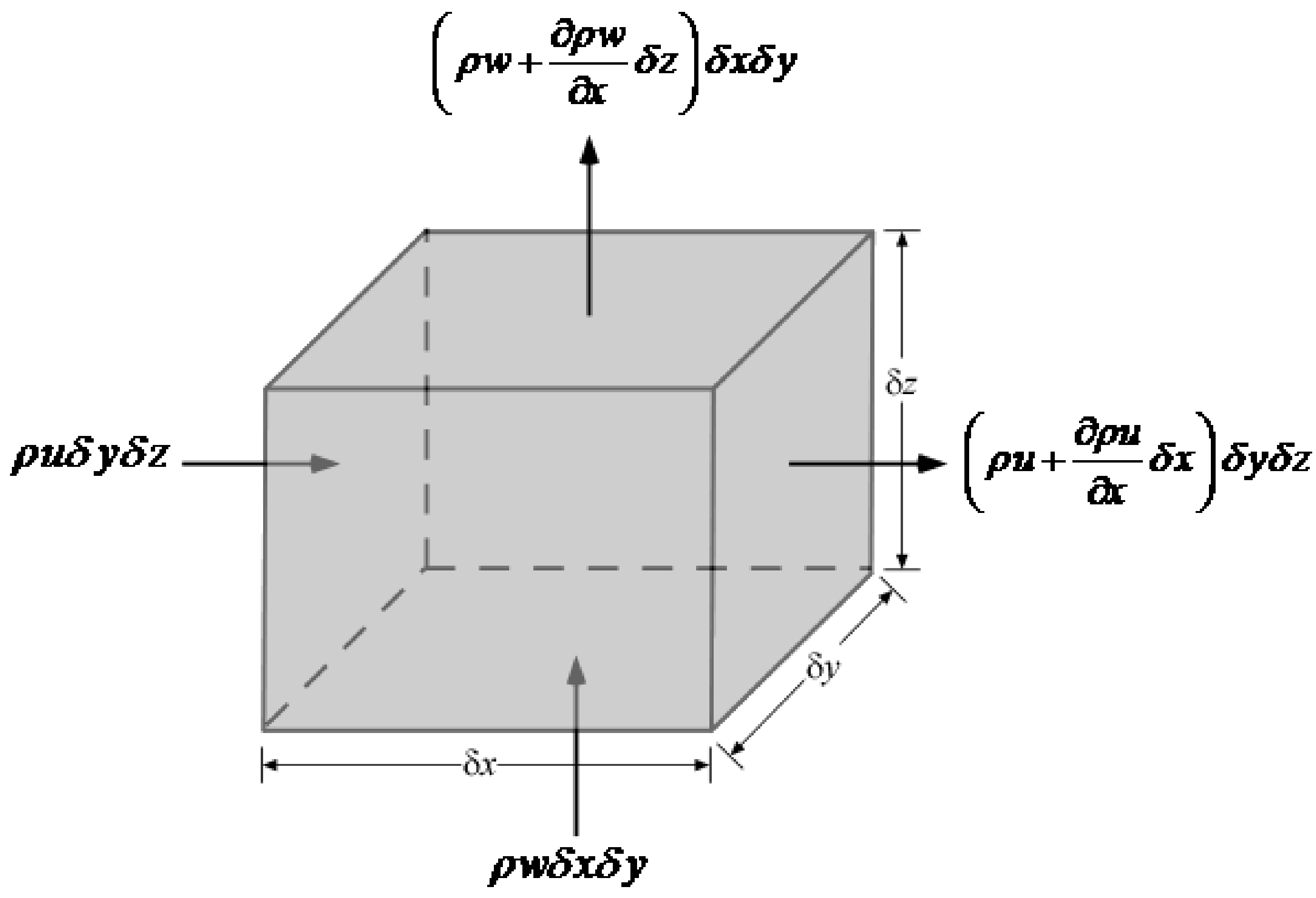


U_2
2
A_2
1
U_1
A_1

Continuity Equation - Multiple Outlets A piping system has a "Y" configuration for separating the flow as shown in Figure. The diameter of the inlet leg is 12 in., and the diameters of the outlet legs are 8 and 10 in. The velocity in the 10 in. leg is 10 ft/sec. The flow through the main portion is 500 Kg.m/sec. The density of water is 62.4 kg/m^3. What is the velocity out of the 8 in. pipe section



Continuity Equation in three Dimensions



Momentum Equation

Moment of momentum equation is derived from moment of momentum principle which states that the resulting torque acting on a rotating fluid is equal to the rate of change of moment of momentum.

Let V_1 = velocity of fluid at section 1

r_1 = radius of curvature at section 1,

Q = rate of flow of fluid,

ρ = density of fluid,

and V_2 and r_2 = velocity and radius of curvature at section 2

Momentum of fluid at section 1 = mass × velocity = $\rho Q \times V_1/s$

∴ Moment of momentum per second at section 1,

$$= \rho Q \times V_1 \times r_1$$

Similarly moment of momentum per second of fluid at section 2

$$= \rho Q \times V_2 \times r_2$$

∴ Rate of change of moment of momentum

$$= \rho Q V_2 r_2 - \rho Q V_1 r_1 = \rho Q[V_2 r_2 - V_1 r_1]$$

According to moment of momentum principle

Resultant torque = rate of change of moment of momentum

or $$T = \rho Q[V_2 r_2 - V_1 r_1]$$

Equation (6.23) is known as moment of momentum equation. This equation is applied :

1. For analysis flow problems in turbines and centrifugal pumps.
2. For finding torque exerted by water on sprinkler.

Euler's equation

$$\frac{1}{\rho}\frac{dp}{ds} + g\frac{dz}{ds} + \frac{du}{dt} = 0$$

By the chain rule, the time derivative of u, which is a function of both s and t, may be expressed as:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + \frac{\partial u}{\partial s}\frac{\partial s}{\partial t}$$

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial s}$$

Euler and Bernoulli

Euler's equation is independent of time, so for $\frac{\partial u}{\partial t} = 0$

$$\frac{1}{\rho}\frac{dp}{ds} + g\frac{dz}{ds} + u\frac{du}{ds} = 0$$

For an incompressible fluid, integrating along the streamline,

$$\frac{p}{\rho g} + \frac{u^2}{2g} + z = \text{const}$$

Navier-Stokes equations

- So far we have separately considered flow
  - in one dimension affected by pressure and gravity
  - in one dimension affected by pressure and viscosity
- Need three dimensions and all forces in order to provide a full solution for any general flow problem
- The following is not rigorous- see Bachelor for a rigorous derivation

Navier-Stokes equations

Looking back to Euler's equation with unsteadiness, the gravity term is simply the component of gravity, g_s. Introducing viscosity as well gives 3 similar equations:

$$\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho \frac{du}{dt}$$

$$\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho \frac{dv}{dt}$$

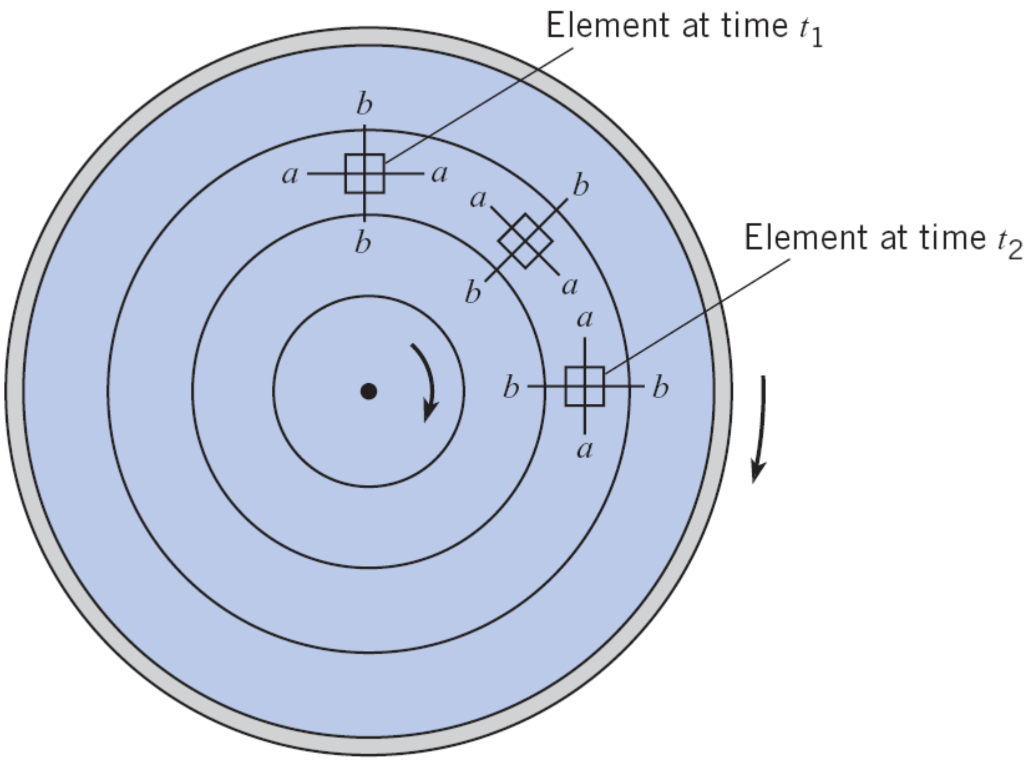
$$\rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho \frac{dw}{dt}$$

Navier-Stokes equations

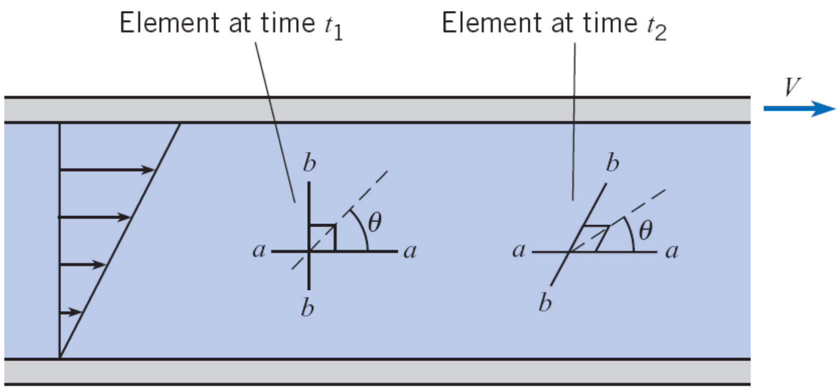
- There is no general solution to the N-S equations
- Some analytical solutions may be obtained by simplification
- The equations may be written in vector (div/grad) notation:

$$\rho \underline{g} - \nabla p + \mu \nabla^2 \underline{u} = \rho \frac{d\underline{u}}{dt}$$

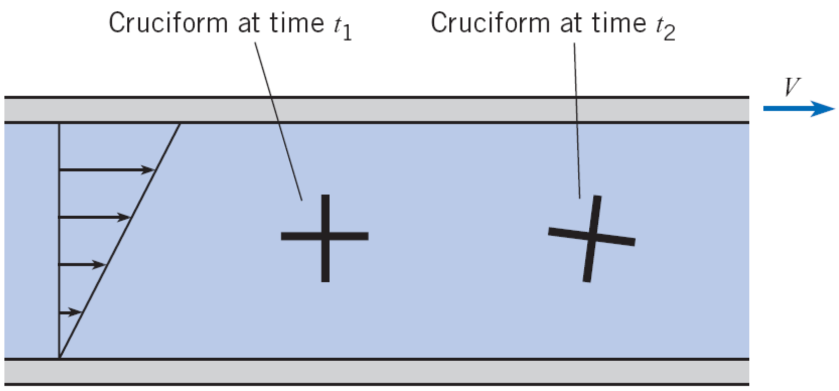
Rotation and Vorticity , forced vertex with free surface



Rotation of fluid element in flow between moving and stationary parallel plates



(a)



(b)

$$\boldsymbol{\omega} = 2\boldsymbol{\Omega}$$

$$= \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)\mathbf{i} + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right)\mathbf{j} + \left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right)\mathbf{k}$$

$$= \boldsymbol{\nabla} \times \mathbf{V}$$

Stream Function

- The idea of introducing stream function works only if the continuity equation is reduced to two terms. There are 4-terms in the continuity equation that one can get by expanding the vector equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

For a steady, incompressible, plane, two-dimensional flow, this equation reduces to,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$u = \frac{\partial \psi}{\partial y}; \quad v = -\frac{\partial \psi}{\partial x}$$

$$\text{or}, \vec{V} = \frac{\partial \psi}{\partial y}\hat{i} - \frac{\partial \psi}{\partial x}\hat{j}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Velocity Potential

- An irrotational flow is defined as the flow where the vorticity is zero at every point. It gives rise to a scalar function (ϕ) which is similar and complementary to the stream function (ψ).
- Let us consider the equations of irrortional flow and scalar function (ϕ). In an irrotational flow, there is no vorticity ($\bar{\xi}$).
- Now, take the vector i $\vec{\xi} = \nabla \times \vec{V} = 0$ calar function (ϕ),

$$\nabla \times (\nabla \phi) = 0$$

- So, the velocity components can be written as,

$$u = \frac{\partial \phi}{\partial x};\ v = \frac{\partial \phi}{\partial y};\ w = \frac{\partial \phi}{\partial z}$$

$$u\hat{i} + v\hat{j} + w\hat{k} = \frac{\partial \phi}{\partial x}\hat{i} + \frac{\partial \phi}{\partial y}\hat{j} + \frac{\partial \phi}{\partial z}\hat{k}$$

$$\nabla . (\nabla \phi) = 0$$

$$\text{or, } \nabla^2 \phi = 0$$

$$\text{or, } \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

For a streamline, $\psi(x,y) = \text{constant}$, and the differential of ψ is zero.

$$d\psi = \frac{\partial \psi}{\partial x} dx + \frac{\partial \psi}{\partial y} dy = 0$$

$$\text{or, } d\psi = -v\,dx + u\,dy = 0$$

$$\text{or, } \left(\frac{dy}{dx}\right)_{\psi=\text{constant}} = \frac{v}{u}$$

Similarly, for an equipotential line, $\phi(x,y) = \text{constant}$, and the differential of ϕ is zero.

$$d\phi = \frac{\partial \phi}{\partial x} dx + \frac{\partial \phi}{\partial y} dy = 0$$

$$\text{or, } d\phi = u\,dx + v\,dy = 0$$

$$\text{or, } \left(\frac{dy}{dx}\right)_{\phi=\text{constant}} = -\frac{u}{v}$$

Combinii

$$\left(\frac{dy}{dx}\right)_{\psi=\text{constant}} = -\frac{1}{(dy/dx)_{\phi=\text{constant}}}$$

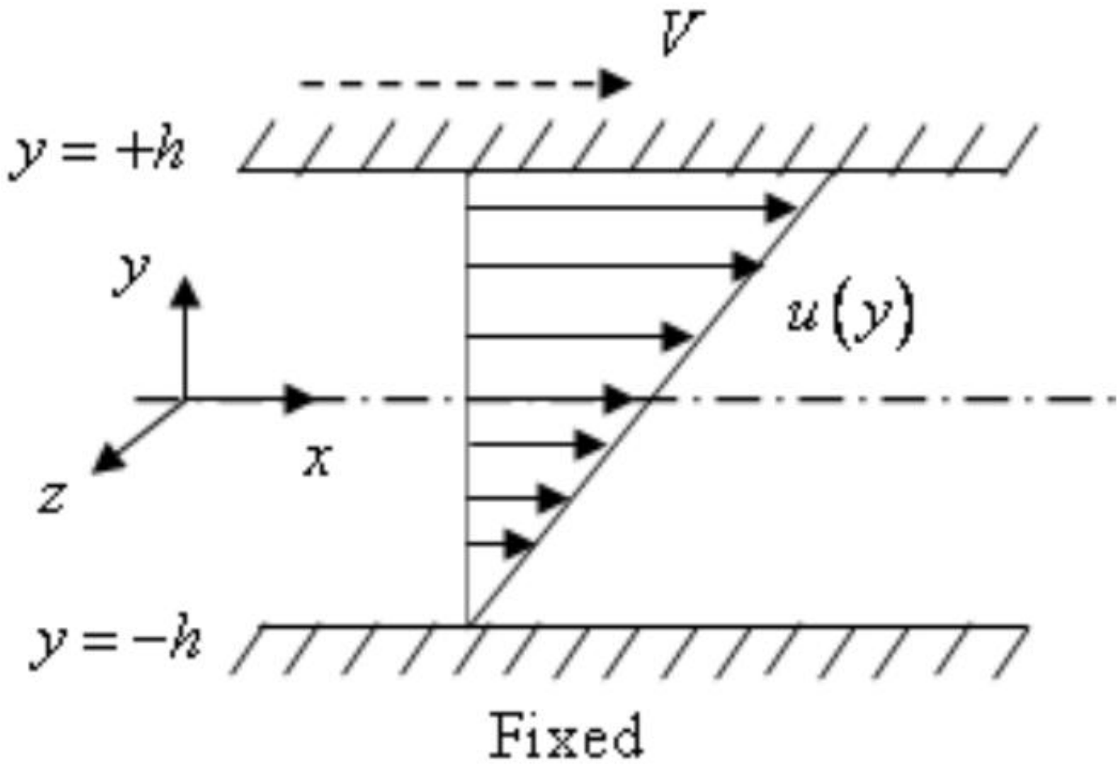
Hence, the streamlines and equipotential lines are mutually perpendicular.

Velocity Potential Vs Stream Function

	Stream Function (ψ)	Velocity Potential (ϕ)
Exists for	only 2D flow	all flows
	viscous or non-viscous flows	Irrotational (i.e. Inviscid or zero viscosity) flow
	Incompressible flow (steady or unsteady)	Incompressible flow (steady or unsteady state)
	compressible flow (steady state only)	compressible flow (steady or unsteady state)

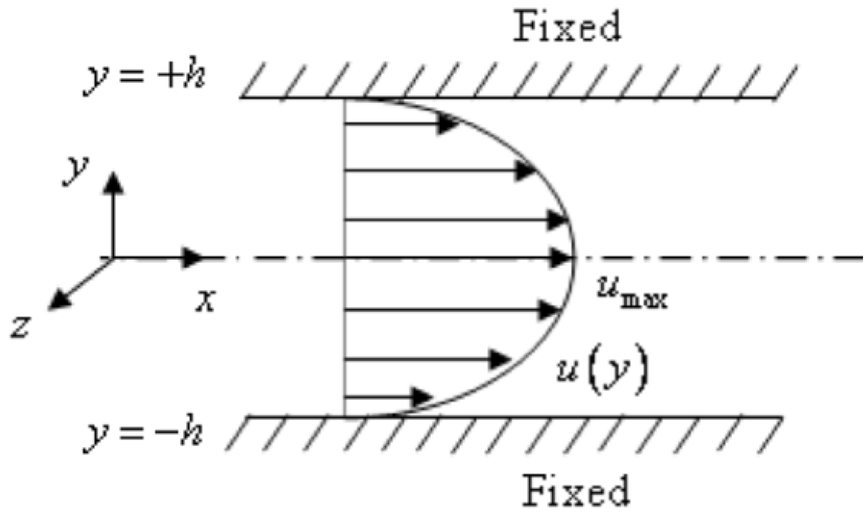
- In 2D inviscid flow (incompressible flow or steady state compressible flow), both functions exist

Viscous Incompressible Flow between Parallel Plates (Couette Flow)



$$\tau_w = \mu \frac{du}{dy} = \frac{\mu V}{2h}$$

Viscous Incompressible Flow with Pressure Gradient (Poiseuille Flow)



$$u = -\left(\frac{dp}{dx}\right)\left(\frac{h^2}{2\mu}\right)\left(1-\frac{y^2}{h^2}\right)$$

Unit 3

Fluid Dynamics

CLO	Course Learning Outcome
CLO7	Define Fluid forces and describe the motion of a fluid particle with fluid deformation.
CLO8	Determine the Euler's and Bernoulli's equation and obtain its phenomenological basis of Naviers-stokes equation.
CLO9	Describe about the flow measurements using different equipment’s of fluid flows.

Syllabus

Fluid forces and Motion of a fluid particle; Fluid deformation; Euler's and Bernoulli's equation, phenomenological basis of Naviers- stokes equation, flow measurements : pressure, velocity and mass flow rate, viscosity, pitot-static tube, venturi meter, orifice meter and V-Notch, numericals.

Fluid Dynamics

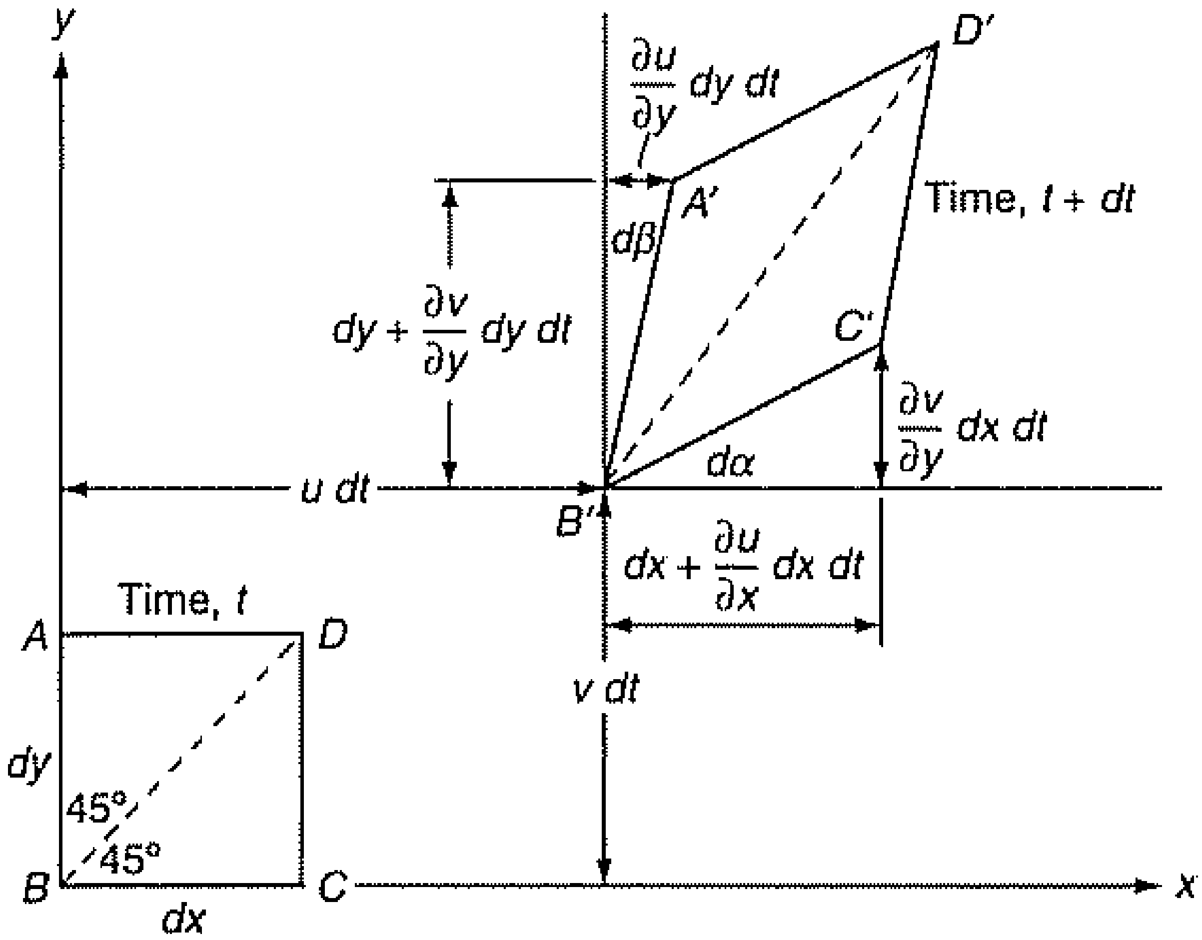
- In some cases, fluid forces have little effect on an object’s motion (e.g., shotput)
- In other cases, fluid forces are significant – badminton, baseball, swimming, cycling, etc.
- Three major fluid forces of interest: – Buoyancy – Drag – Lift

Motion of a fluid particle and Fluid deformation

- In fluid mechanics we are interested in general motion, deformation, and rate of deformation of particles
- Fluid element can undergo 4 types of motion or deformation:
  1. **Translation**
  2. **Rotation**
  3. **Shear strain**
  4. **Extensional strain or dilatation**
- We will show that all kinematic properties of fluid flow
  - Acceleration
  - Translation
  - Angular velocity
  - Rate of dilatation
  - Shear strain

  are directly related to fluid velocity vector **V** = (u, v, w)

DISTORTION OF A MOVING FLUID ELEMENT



COMMENTS ON SHEAR STRAIN

$$\frac{1}{2}(d\alpha + d\beta)$$

$$\varepsilon_{xy} = \frac{1}{2}\left(\frac{d\alpha}{dt} + \frac{d\beta}{dt}\right) = \frac{1}{2}\left(\frac{dv}{dx} + \frac{du}{dy}\right)$$

$$\varepsilon_{yz} = \frac{1}{2}\left(\frac{dw}{dy} + \frac{dv}{dz}\right)$$

$$\varepsilon_{zx} = \frac{1}{2}\left(\frac{du}{dz} + \frac{dw}{dx}\right)$$

$$\varepsilon_{ij} = \varepsilon_{ji}$$

- Recall: defined as the average decrease of the angle between two lines which are initially perpendicular in the unstrained state (AB and BC)
- Shear-strain rates
- Shear-strain rates are symmetric

Energy Conservation (Bernoulli's Equation)

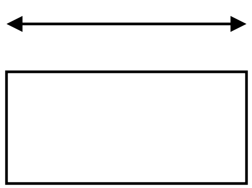
Integration of Euler's equation

$$\int_1^2 \frac{dp}{\rho} + \int_1^2 V dV + \int_1^2 g dz = 0$$

Bernoulli's equation

$$\frac{p_1}{\rho} + \frac{V_1^2}{2} + g z_1 = \frac{p_2}{\rho} + \frac{V_2^2}{2} + g z_2$$

Flow work + kinetic energy + potential energy = constant



Under the action of the pressure, the fluid element moves a distance Δx within time Δt

The work done per unit time ΔW/Δt (flow power) is

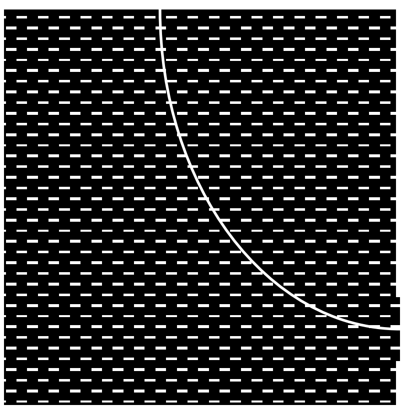
$$\frac{\Delta W}{\Delta t} = \frac{pA\Delta x}{\Delta t} = \left(\frac{p}{\rho}\right)\rho A \frac{\Delta x}{\Delta t} = \rho A V \left(\frac{P}{\rho}\right),$$

$$\frac{p}{\rho} = \left(\frac{1}{\rho A V}\right)\left(\frac{\Delta W}{\Delta t}\right) = \text{work done per unit mass flow rate}$$

Energy Conservation (cont.)

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2, \text{where } \gamma=\rho g \text{ (energy per unit weight)}$$

It is valid for incompressible fluids, steady flow along a streamline, no energy loss due to friction, no heat transfer.



Determine the velocity and mass flow rate of efflux from the circular hole (0.1 m dia.) at the bottom of t water tank (at this instant). The tank is open to the atmosphere and H=4 m

$$V_2=\sqrt{2g(z_1-z_2)}=\sqrt{2gH}$$

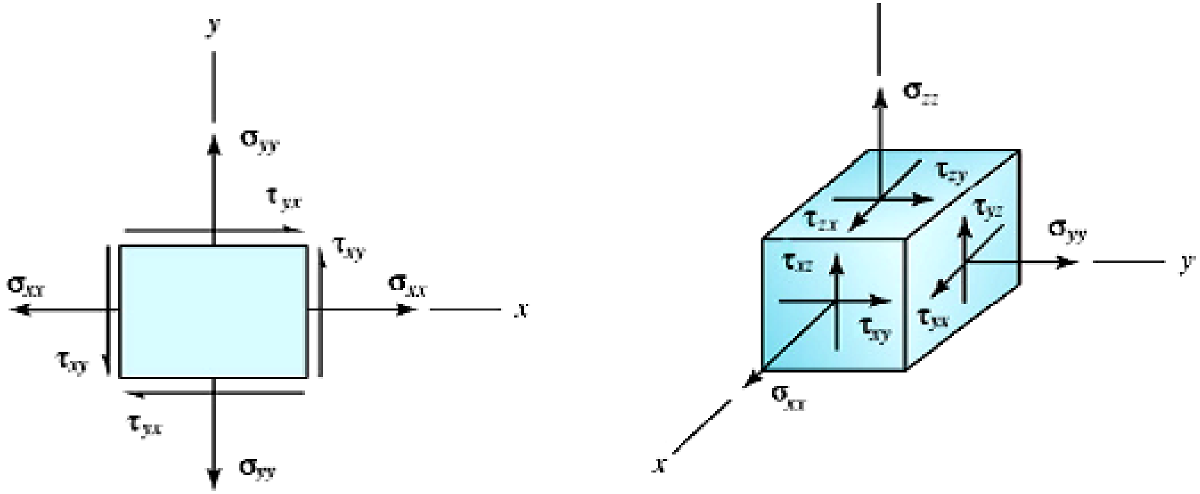
$$=\sqrt{2*9.8*4}=8.85(m/s)$$

$$\dot{m}=\rho AV=1000*\frac{\pi}{4}(0.1)^2(8.85)$$

$$=69.5(kg/s)$$

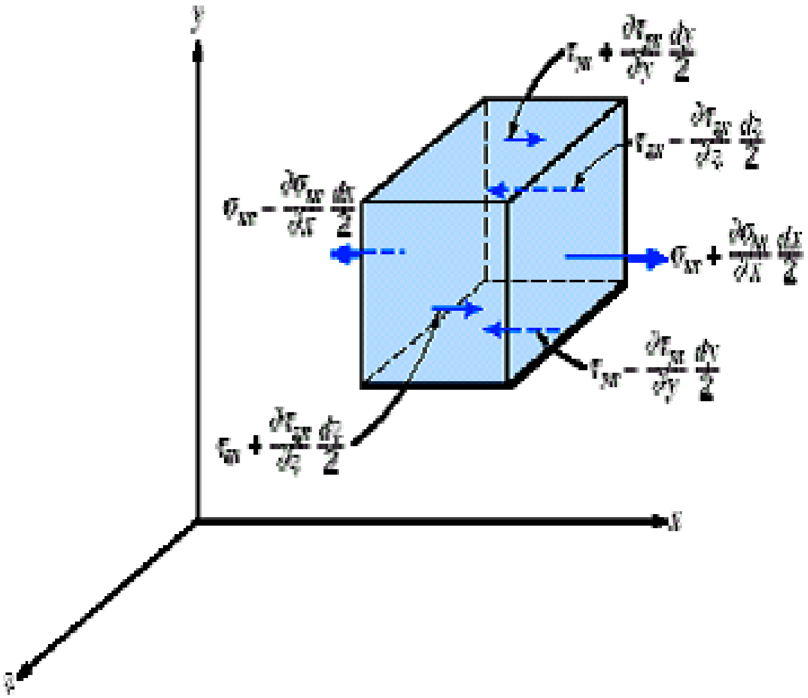
■ Newton's Second Law:

$$d\vec{F} = dm\frac{D\vec{V}}{Dt} = dm\left[u\frac{\partial \vec{V}}{\partial x} + v\frac{\partial \vec{V}}{\partial y} + w\frac{\partial \vec{V}}{\partial z} + \frac{\partial \vec{V}}{\partial t}\right]$$



(a) (b)

Forces Acting on a Fluid Particle:



$$dF_{B_x} + dF_{S_x} = \left(\rho g_x + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \right) dx\, dy\, dz$$

$$dF_{B_y} + dF_{S_y} = \left(\rho g_y + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \right) dx\, dy\, dz$$

$$dF_{B_z} + dF_{S_z} = \left(\rho g_z + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} \right) dx\, dy\, dz$$

Differential Momentum Equation:

$$\rho g_x + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} = \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right)$$

$$\rho g_y + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} = \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right)$$

$$\rho g_z + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = \rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right)$$

or $$\rho\left[\frac{\partial \vec{V}}{\partial t} + \left(\vec{V}\cdot\nabla\right)\vec{V}\right] = \rho\vec{g} + \nabla\cdot\sigma_{ij}$$

■ Newtonian Fluid: Navier-Stokes Equations:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\rho g_x-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

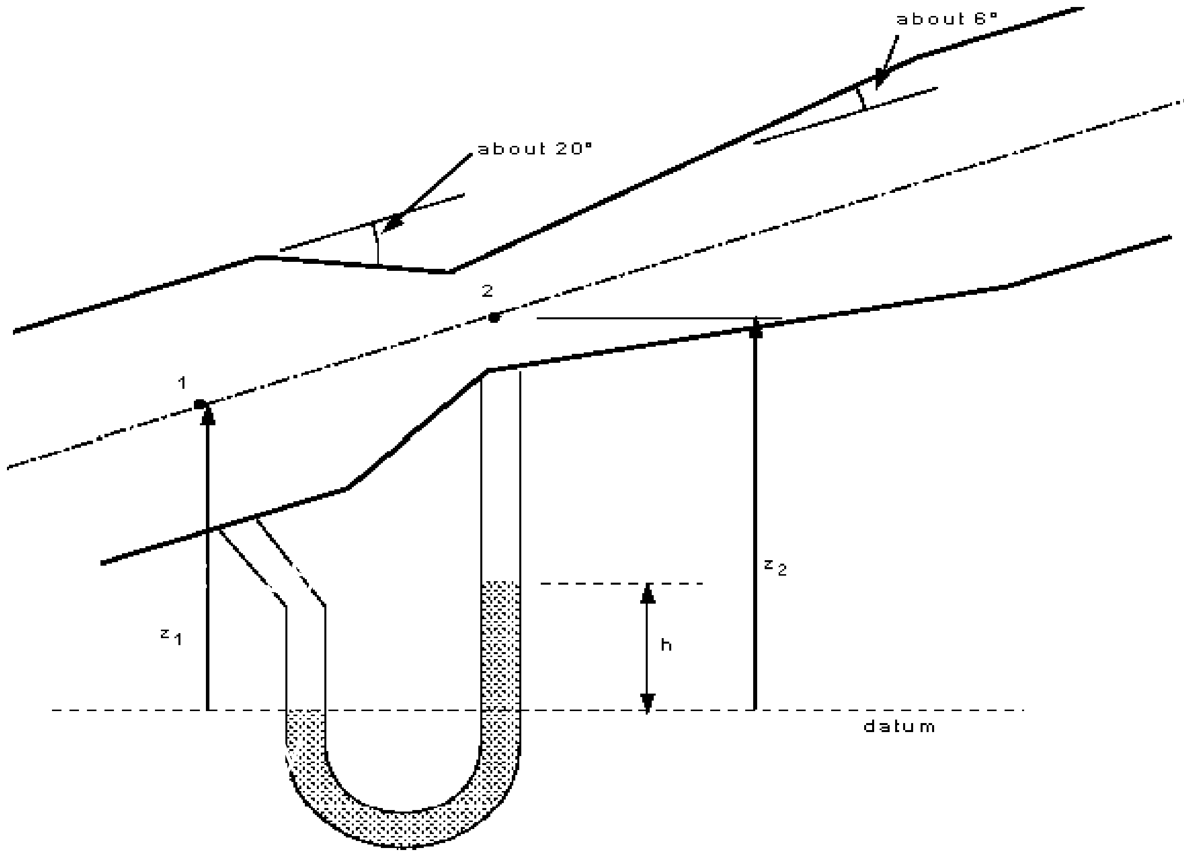
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=\rho g_y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\rho g_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

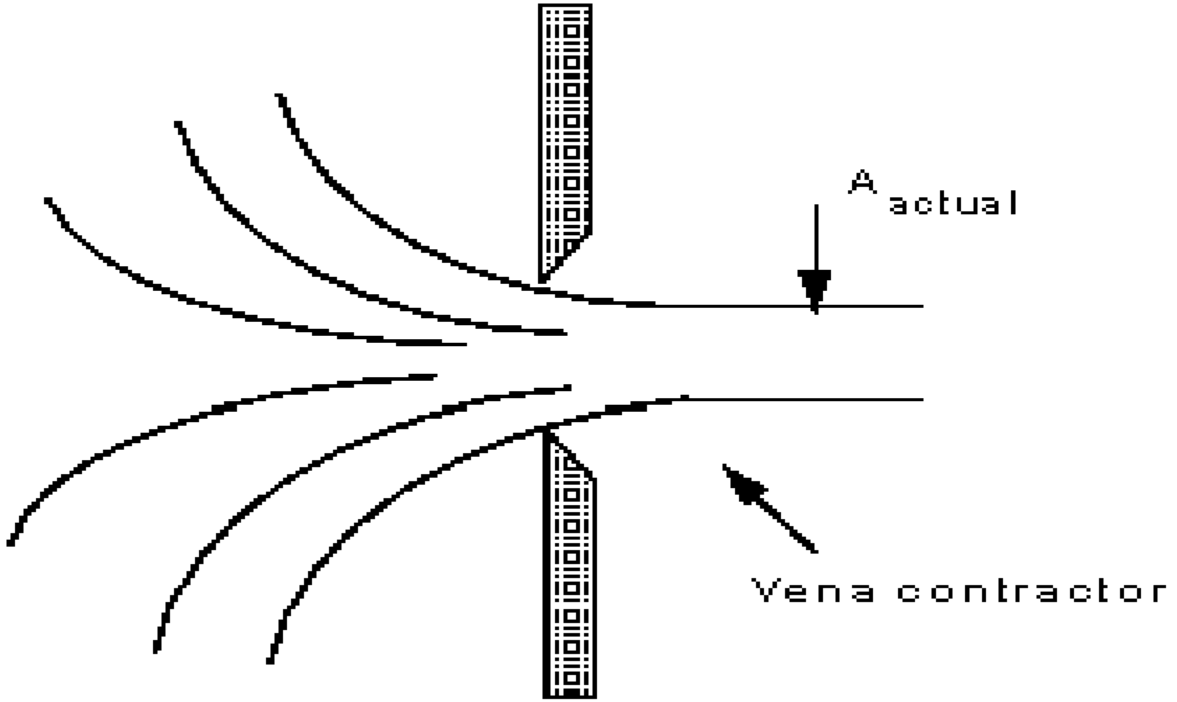
Flow measurements

- Accurate measurement of flow rate of liquids and gases is an essential requirement for maintaining the quality of industrial processes. In fact, most of the industrial control loops control the flow rates of incoming liquids or gases in order to achieve the control objective. As a result, accurate measurement of flow rate is very important.
- Needless to say that there could be diverse requirements of flow measurement, depending upon the situation. It could be volumetric or mass flow rate, the medium could be gas or liquid, the measurement could be intrusive or nonintrusive, and so on. As a result there are different types of flow measuring techniques that are used in industries.

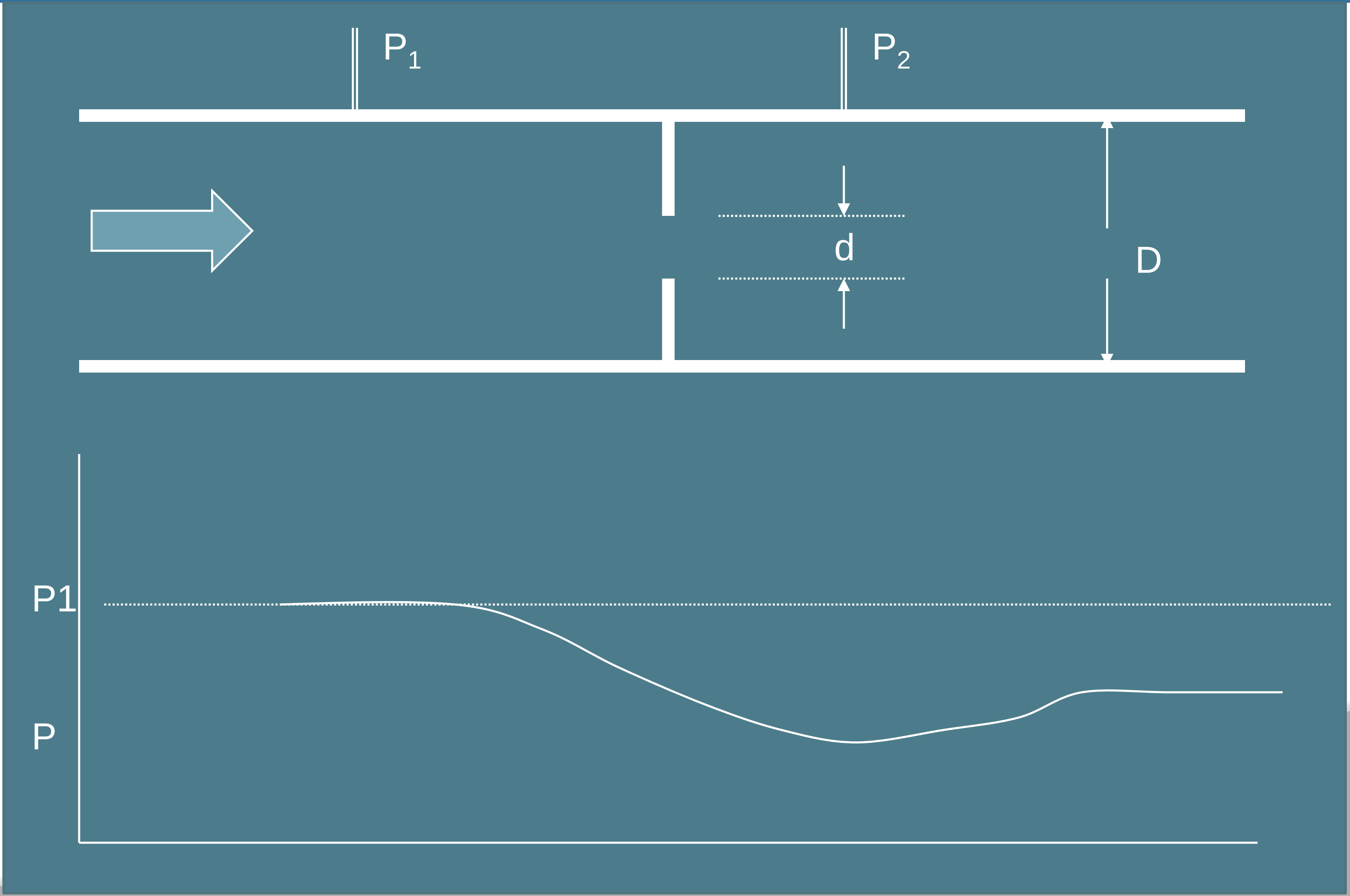
Flow through a Venturi Meter



Flow Through an Orifice Meter



Flow Through an Orifice Meter



Flow Through an Orifice Meter

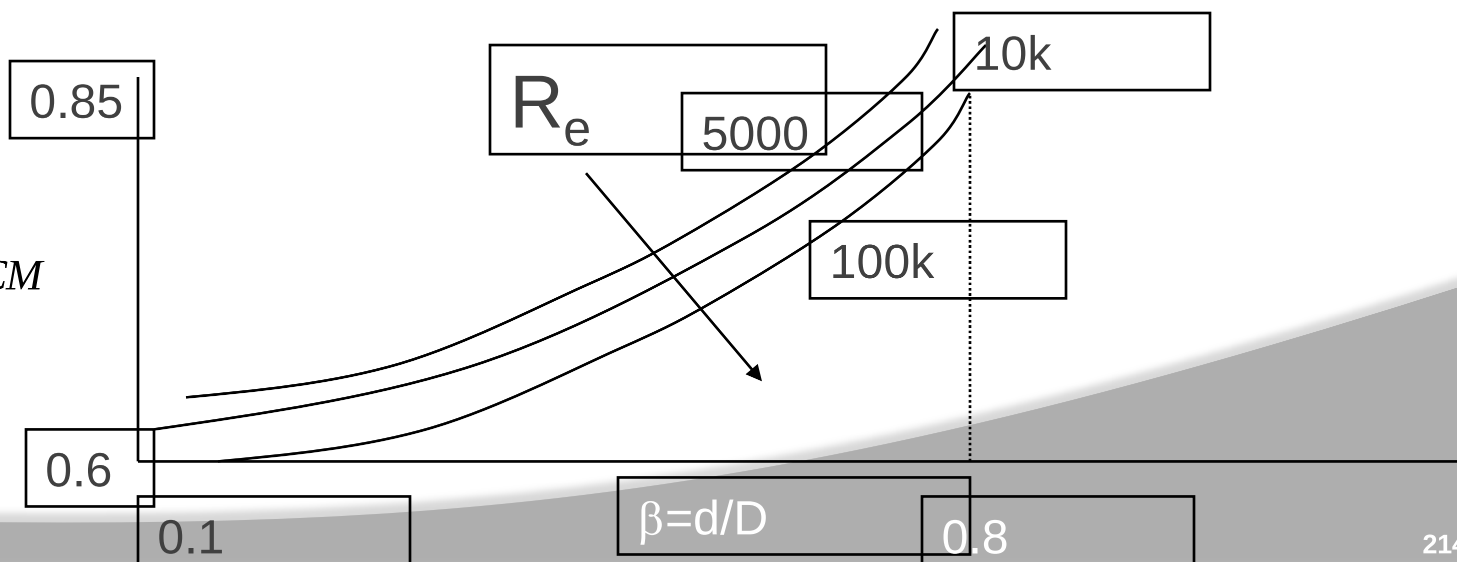
-Cheapest and Simplest

-But biggest pressure drop and power lost (C~0.6 - 0.7)

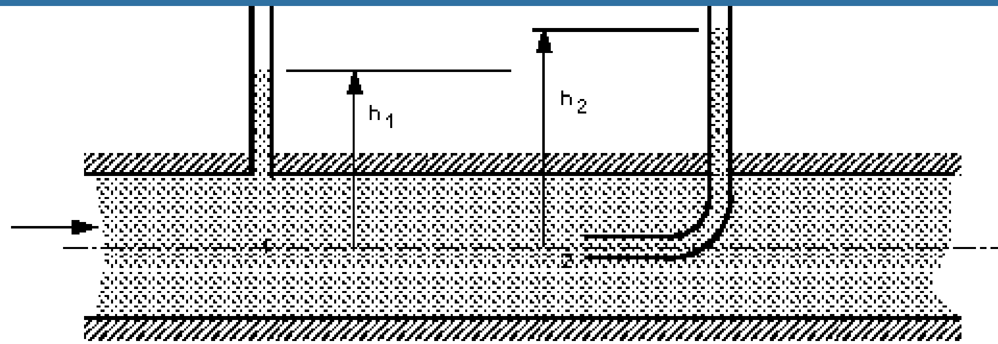
-Side Note:

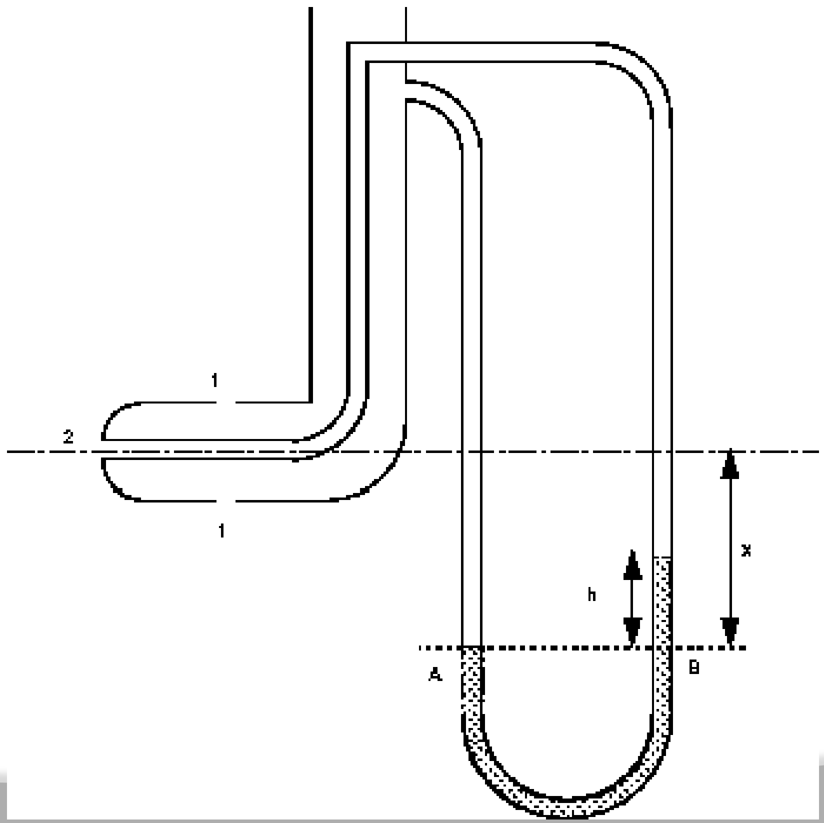
Pressure drop caused by friction and turbulence of shear layer downstream of vena contracta

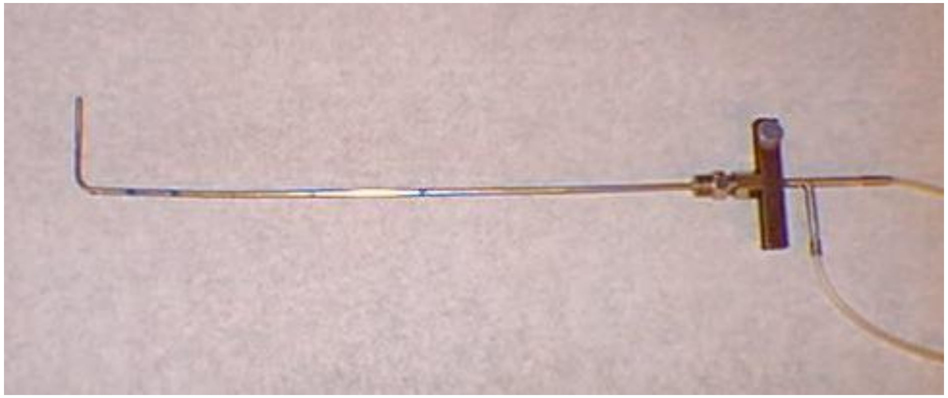
$$C\left[\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\right] = CM$$



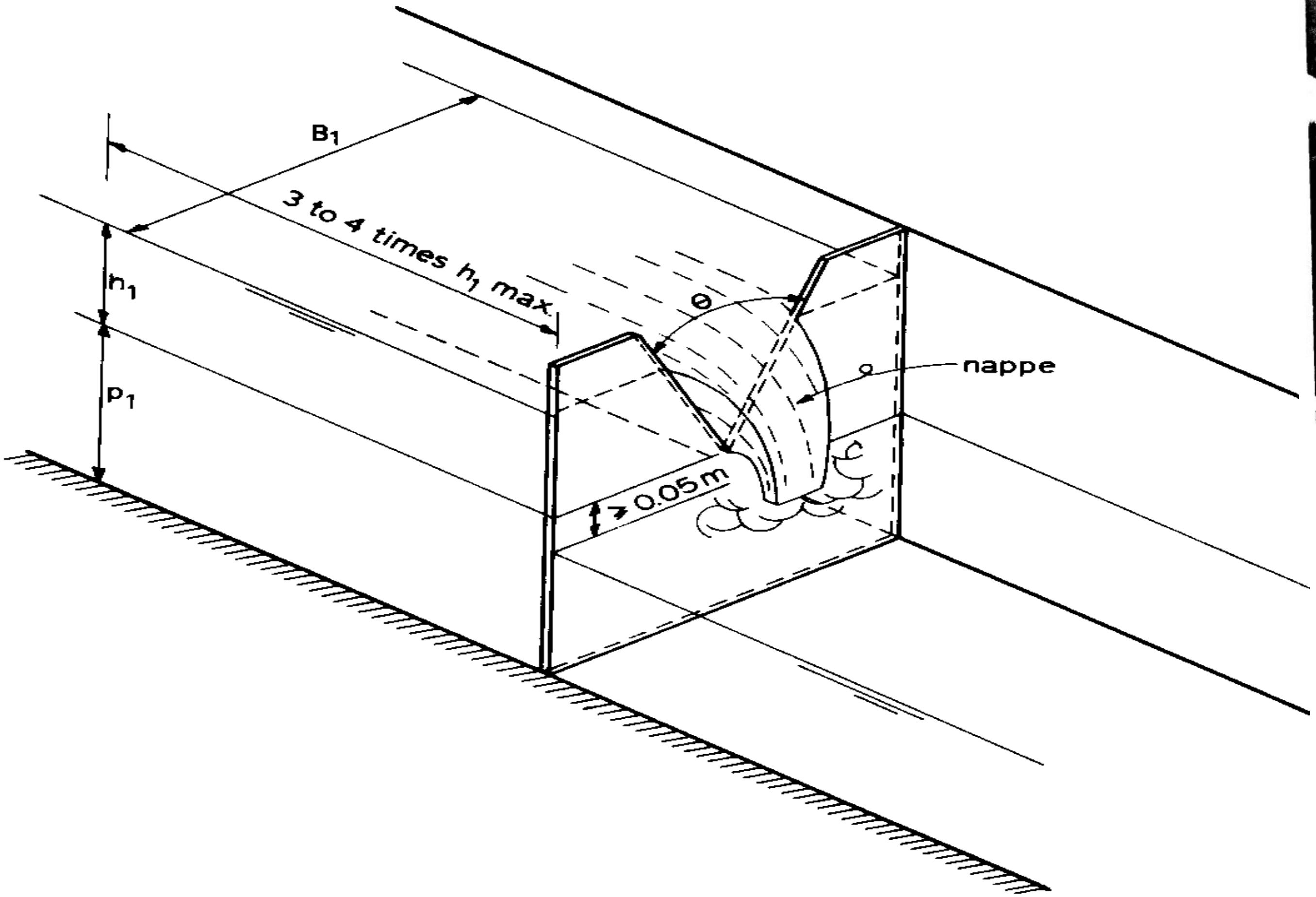
Pitot-Static Tubes







V-Notch



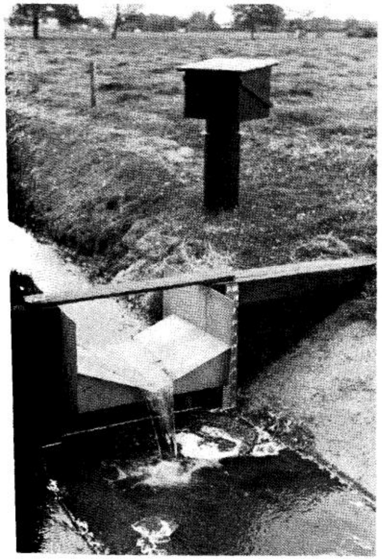
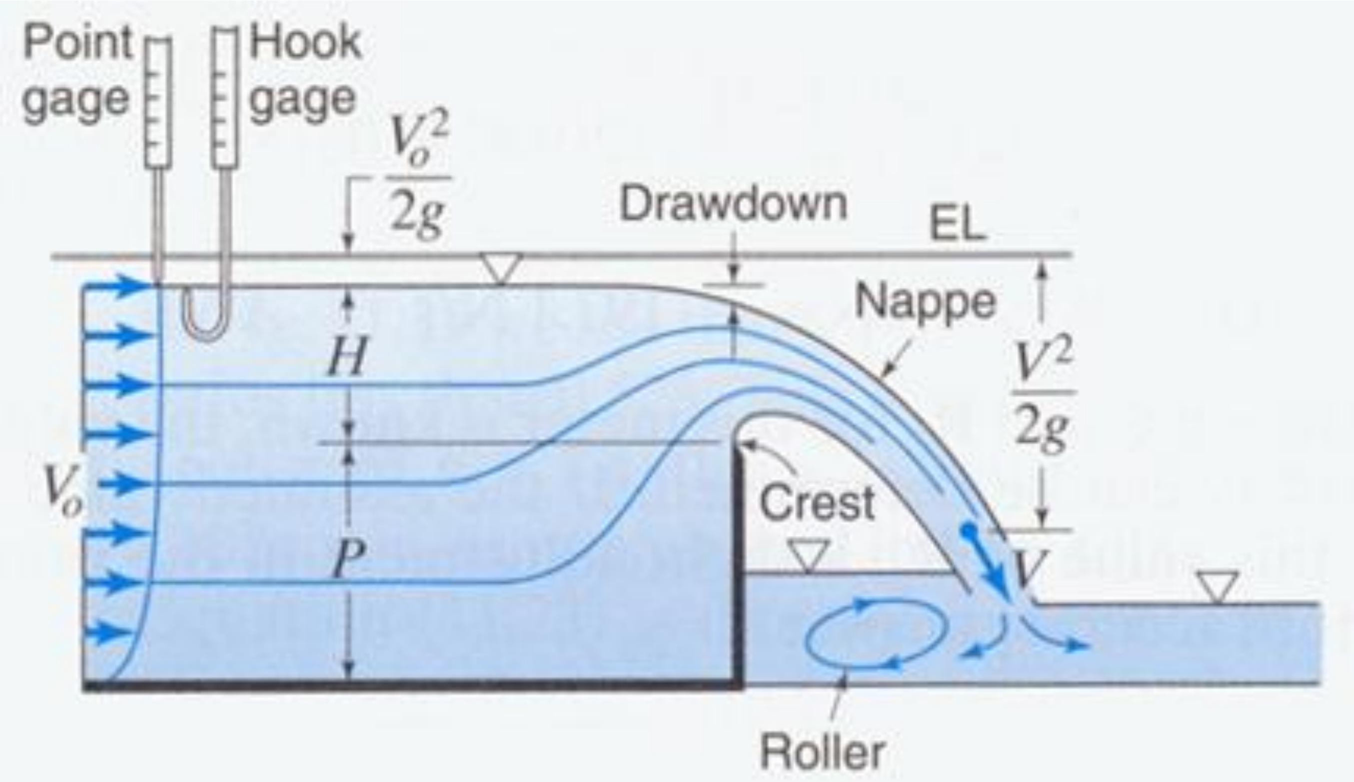
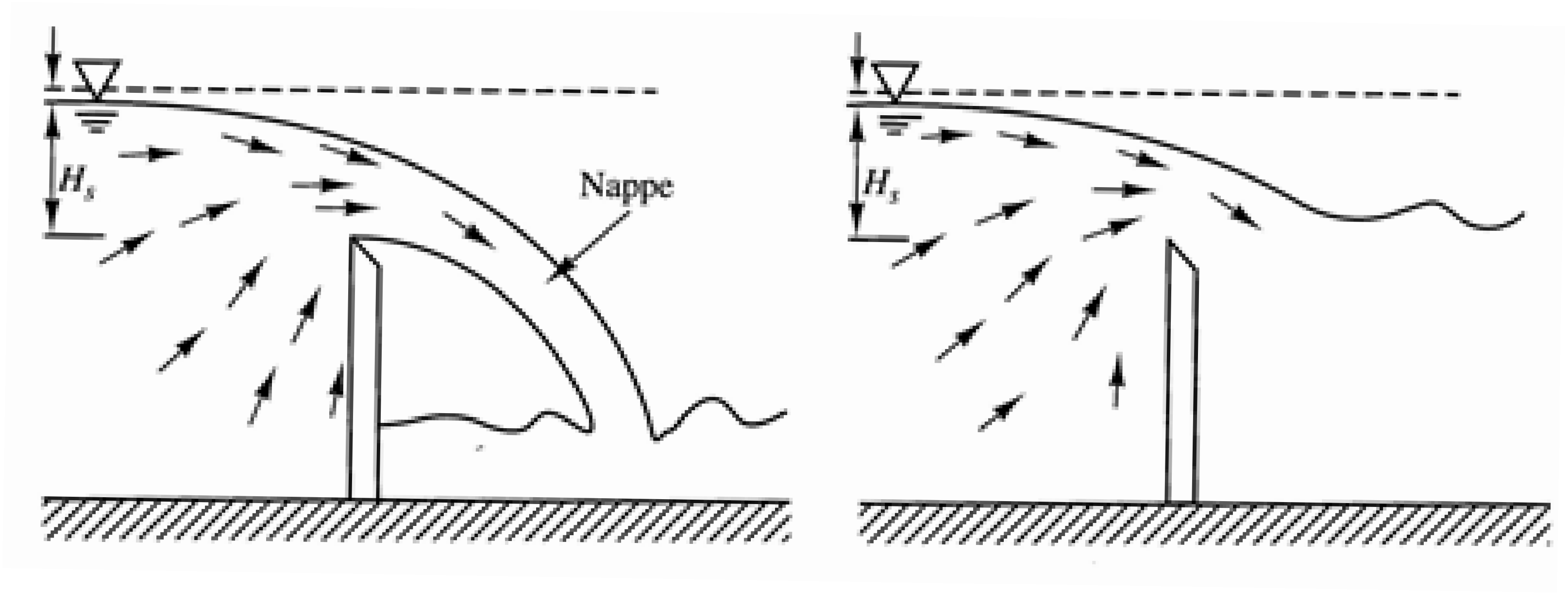


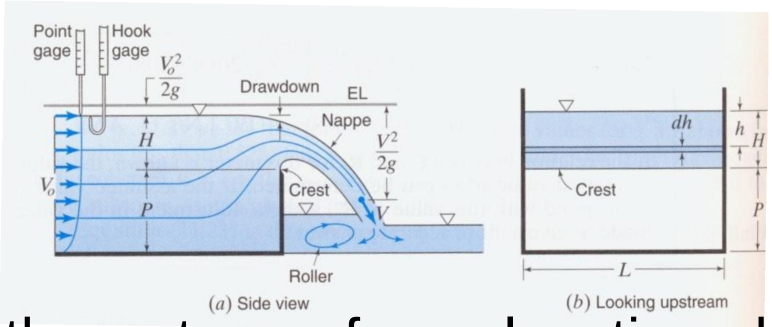
Photo 2 Triangular broad-crested weir

Definition Diagram and Analysis of Sharp - Crested Weirs





Nappe entrains air underneath it and can collapse onto the downstream side of the weir; following analysis assumes that this does not occur (can ventilate this area to assure an air space)



Measurements of the water surface elevation above the weir crest are typically made upstream of the weir, where the water surface has not been significantly affected, and this value of *H* is used instead of H_C in the calculation. To account for this and other approximations, an empirical coefficient is added to the equation:

$$Q = \frac{2\sqrt{2g}}{3} C_{w,rect} b H^{3/2}$$

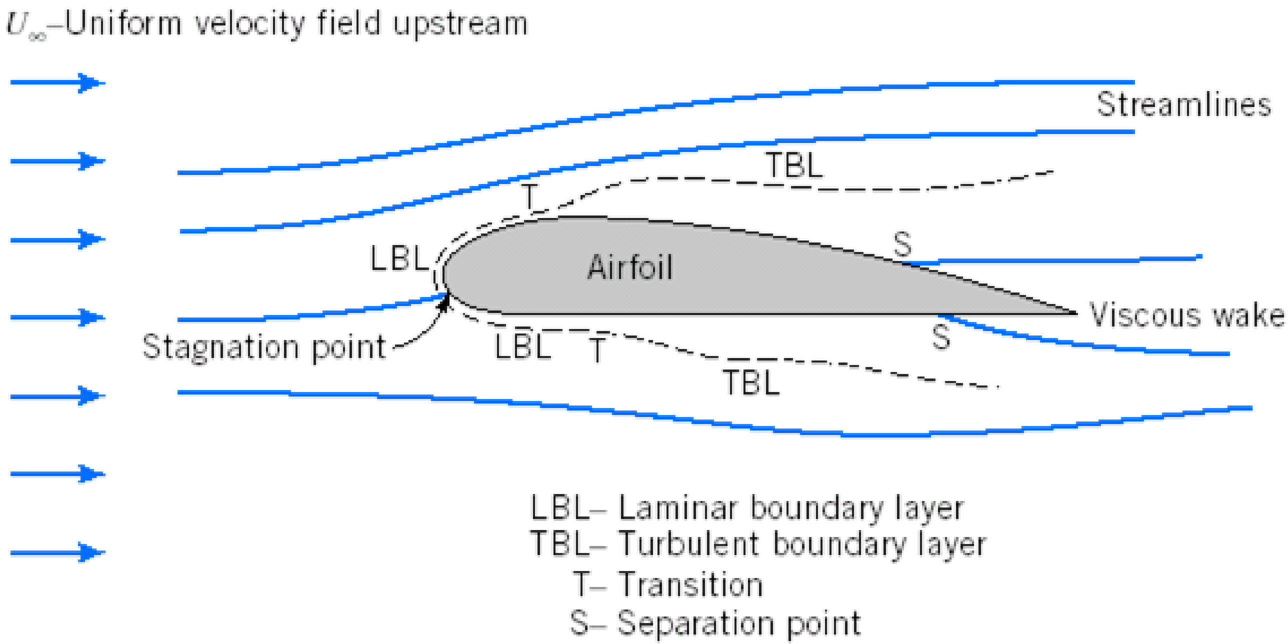
C_w can be approximated by $0.611+0.075(H/P_w)$ and is typically in the range 0.64-0.70.

Unit 4

BOUNDARY LAYER THEORY

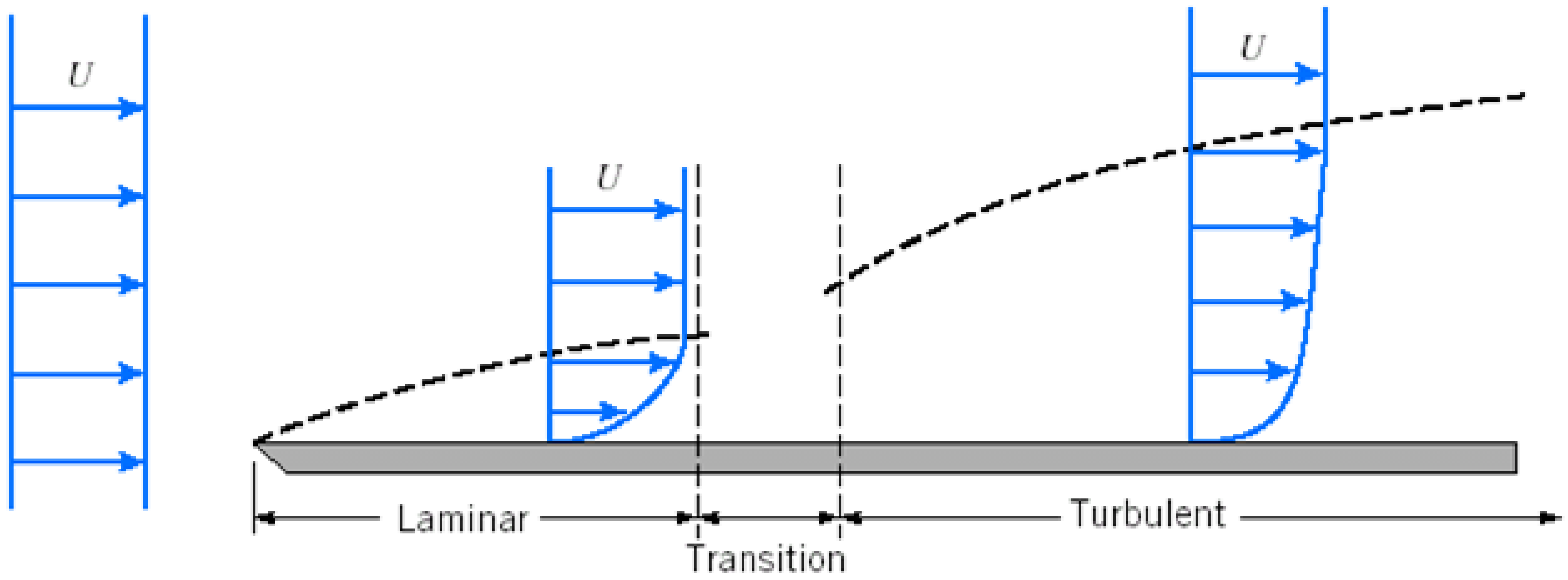
CLO	Course Learning Outcome
CLO10	Understand the Concept of boundary layer flows and control of flow separation.
CLO11	Determine the flows over streamlined and bluff bodies to predict the drag and lift forces.
CLO12	Understand the thickness factor with respect to Displacement, momentum and energy thickness.

The Boundary-Layer Concept



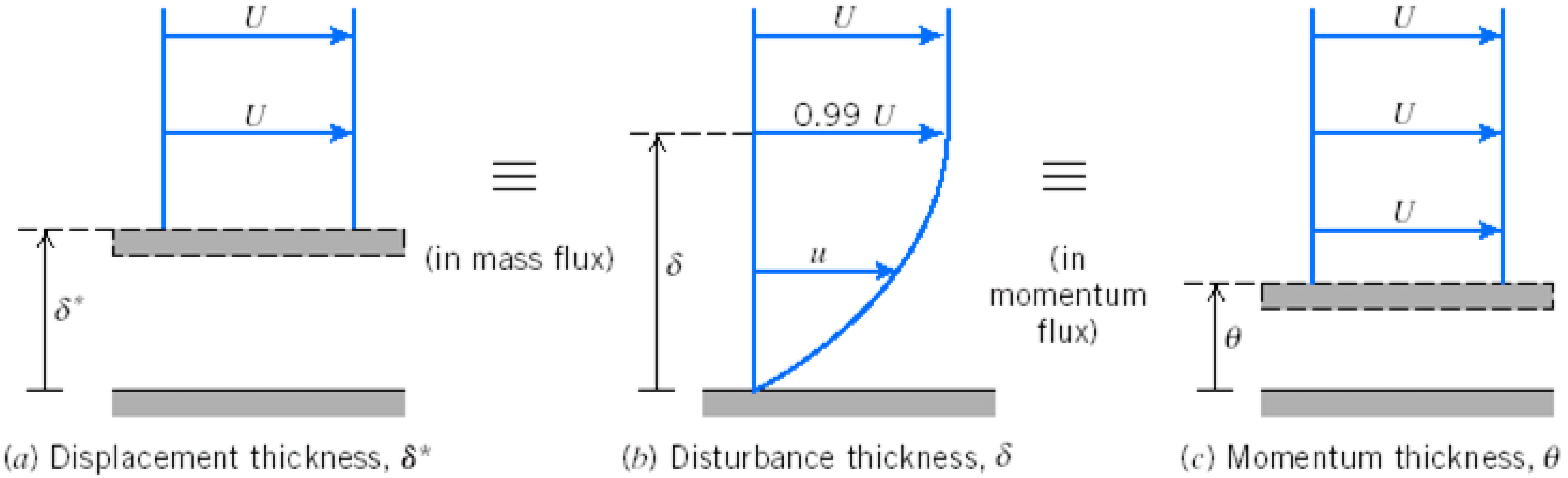
Details of Viscous flow Around an Airfoil.

The Boundary-Layer Concept



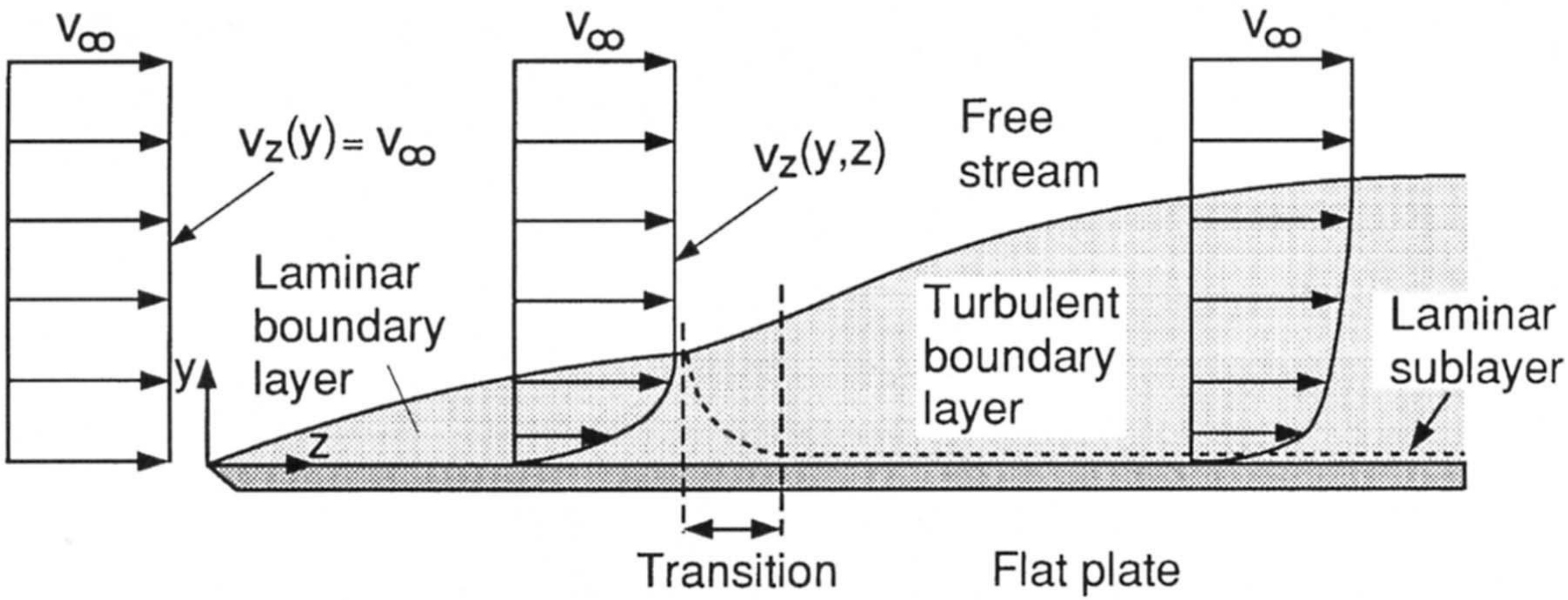
Boundary Layer on a flat Plate(Vertical thickness exaggerated greatly)

Boundary Layer Thicknesses



Boundary-Layer thickness Definitions

Boundary Layer Characteristics



Momentum boundary Layer over a flat plate: Laminar-to-Turbulent Transition

$$\frac{\partial v_z}{\partial y} = 0$$

Boundary Layer Thicknesses

- Disturbance Thickness, δ

✓ **Displacement Thickness, δ^***

$$\delta^* \approx \int_0^{\delta} \left(1 - \frac{u}{U}\right) dy$$

✓ **Momentum Thickness, θ**

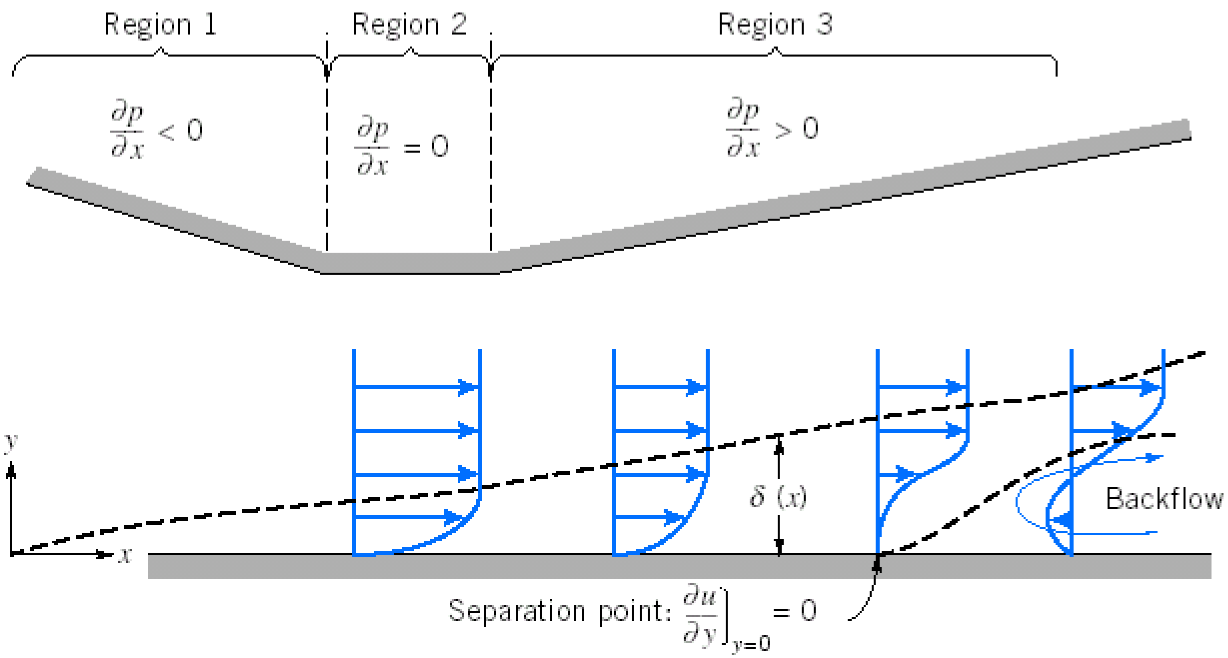
$$\theta \approx \int_0^{\delta} \frac{u}{U} \left(1 - \frac{u}{U}\right) dy$$

Energy thickness

- Energy thickness is basically defined as the distance, measured perpendicular to the boundary of the solid body, by which the boundary should be displaced to compensate for the reduction in kinetic energy of the flowing fluid on account of boundary layer formation.
- Energy thickness will be displayed by the symbol δ**.

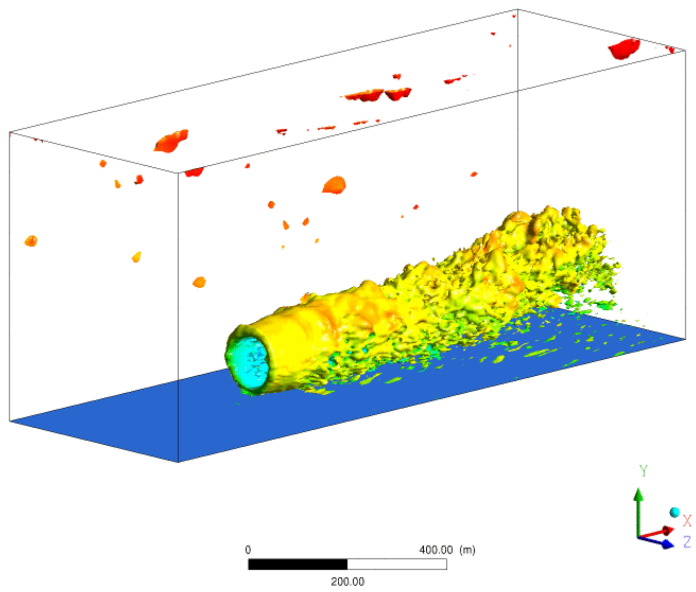
$$\delta^{**} = \int_0^{\delta} \frac{u}{U}\left[1 - \frac{u^2}{U^2}\right] dy.$$

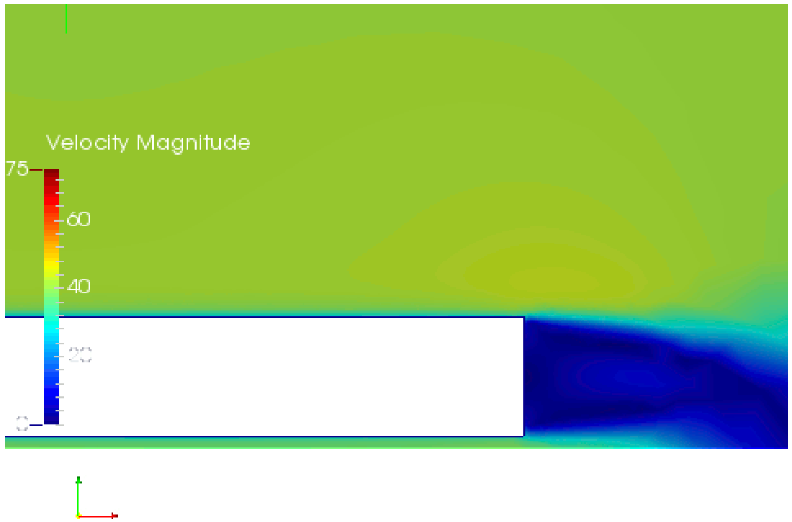
Pressure Gradients in Boundary-Layer Flow



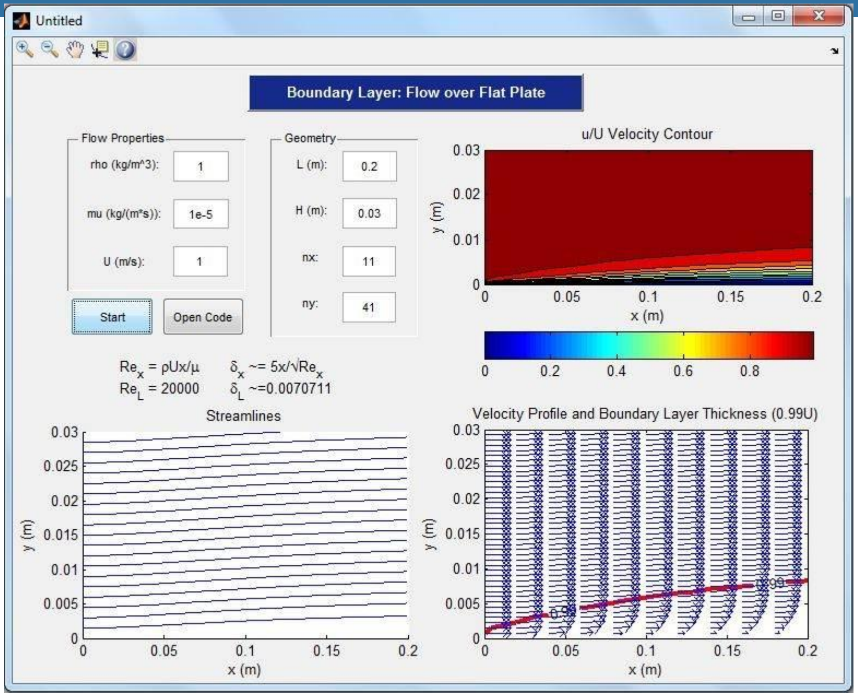
Boundary Layer flow with pressure gradient (Boundary layer thickness)

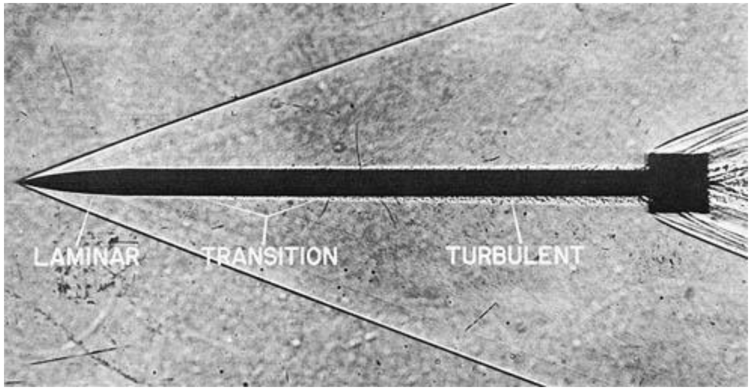
Boundary layer flow traversing

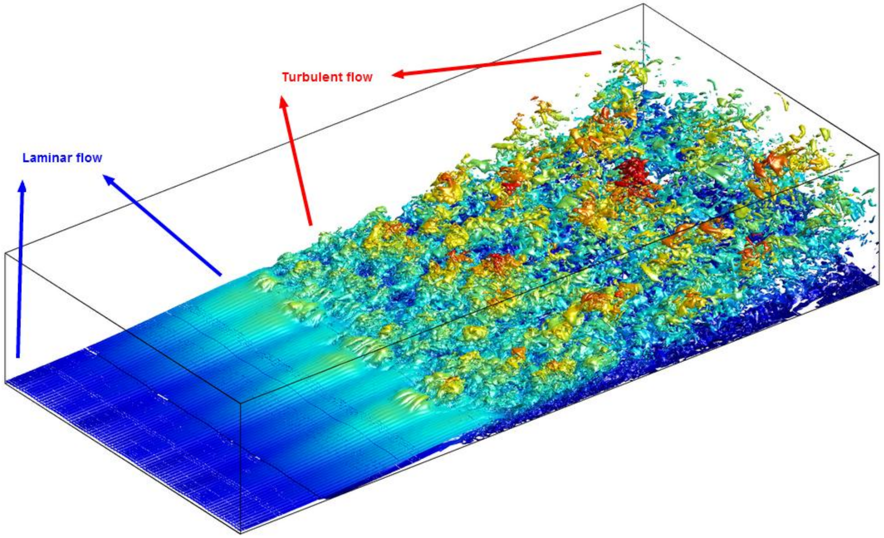




Boundary layer flow traversing







Methods of Preventing the Separation of Boundary Layer

- Suction of the slow moving fluid by a suction slot
- Supplying additional energy from the blower
- Providing a bypass in the slotted wing
- Rotating boundary in the direction of flow
- Providing small divergence in a diffuser
- Providing guide-blades in a bend
- Providing a trip-wire ring in the laminar region for the flow a sphere.

Lift force

$F_L = ½ C_L ρ A_P v^2$

F_L is lift force,

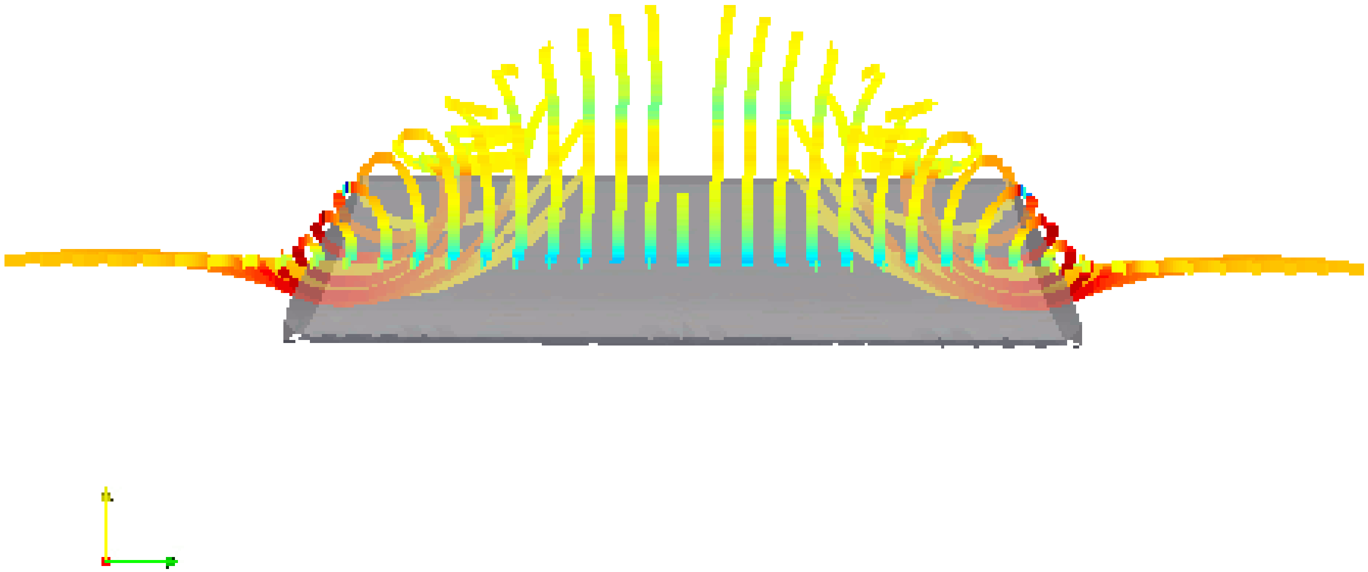
C_L is the coefficient of lift,

ρ is fluid density,

A_P is the projected area of the body or surface area orientated perpendicular to the fluid flow, and

v is relative velocity of the body with respect to the fluid.

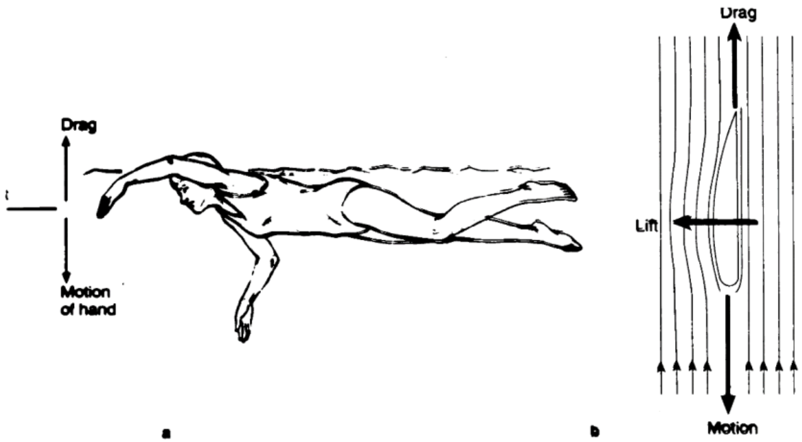
Note: The size, shape and orientation of the body (angle of attack) in the fluid are essential for generating lift force. The lift force increases with the square of the flow of velocity similar to drag force, but lift force increases are an advantage in sporting activities.



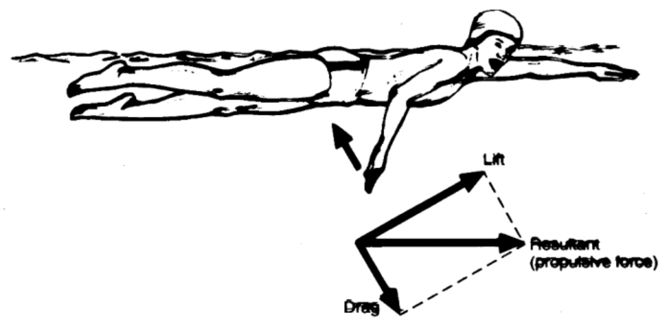
The lift/drag ratio

- The aim in sport is to maximize lift force while reducing drag force. The angle of attack of projected objects (a swimmer's hand) is constantly changing throughout the flight path, and therefore, the lift/drag ratio changes as well.

Forces acting on a human body



6.22. The downward motion of the crawl swimmer's hand produces propulsive lift.



6.23. In the final phase of the arm pull in the crawl stroke, the resultant of lift and drag is a propulsive force.

Drag

- Drag Coefficient

$$C_D \equiv \frac{F_D}{\frac{1}{2}\rho V^2 A}$$

with $$C_D = f(Re)$$

or $$C_D = f(Re, Fr, M)$$

Drag types

- Pure Friction Drag: Flat Plate Parallel to the Flow
- Pure Pressure Drag: Flat Plate Perpendicular to the Flow
- Friction and Pressure Drag: Flow over a Sphere and Cylinder
- Streamlining

Drag

- Flow over a Flat Plate Parallel to the Flow: Friction Drag

$$F_D = \int_{\text{plate surface}} \tau_w \, dA$$

Boundary Layer can be 100% laminar, partly laminar and partly turbulent, or essentially 100% turbulent; hence several different drag coefficients are available

Drag

- Flow over a Flat Plate Parallel to the Flow: Friction Drag (Continued)

Laminar BL:

$$C_D = \frac{1.33}{\sqrt{Re_L}}$$

Turbulent BL:

$$C_D = \frac{0.0742}{Re_L^{1/5}}$$

… plus others for transitional flow

Drag

- Flow over a Flat Plate Perpendicular to the Flow: Pressure Drag

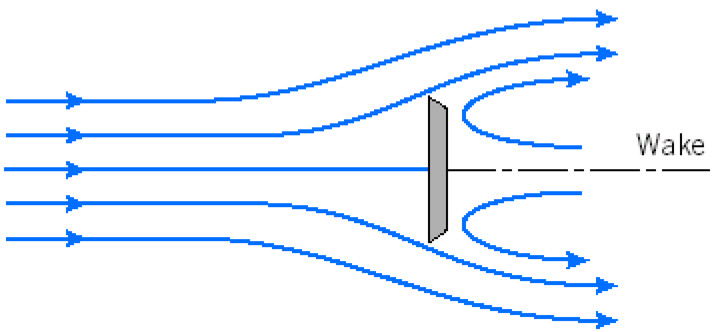
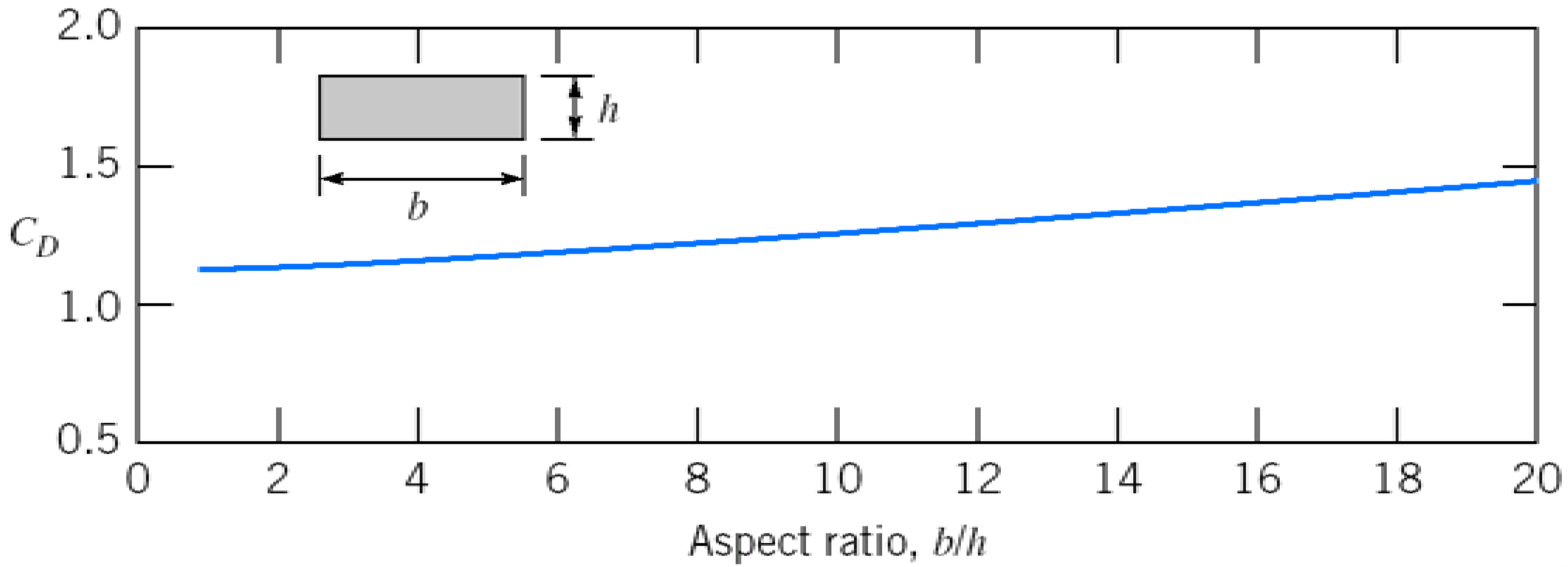


Fig. 9.9 Flow over a flat plate normal to the flow.

$$F_D = \int_{\text{surface}} p\, dA$$

Drag coefficients are usually obtained empirically

- Flow over a Flat Plate Perpendicular to the Flow: Pressure Drag (Continued)



Variation of drag coefficient with aspect ratio for a flat plate of finite width normal to the flow with $Re_h > 1000$ [16].

- Flow over a Sphere and Cylinder: Friction and Pressure Drag

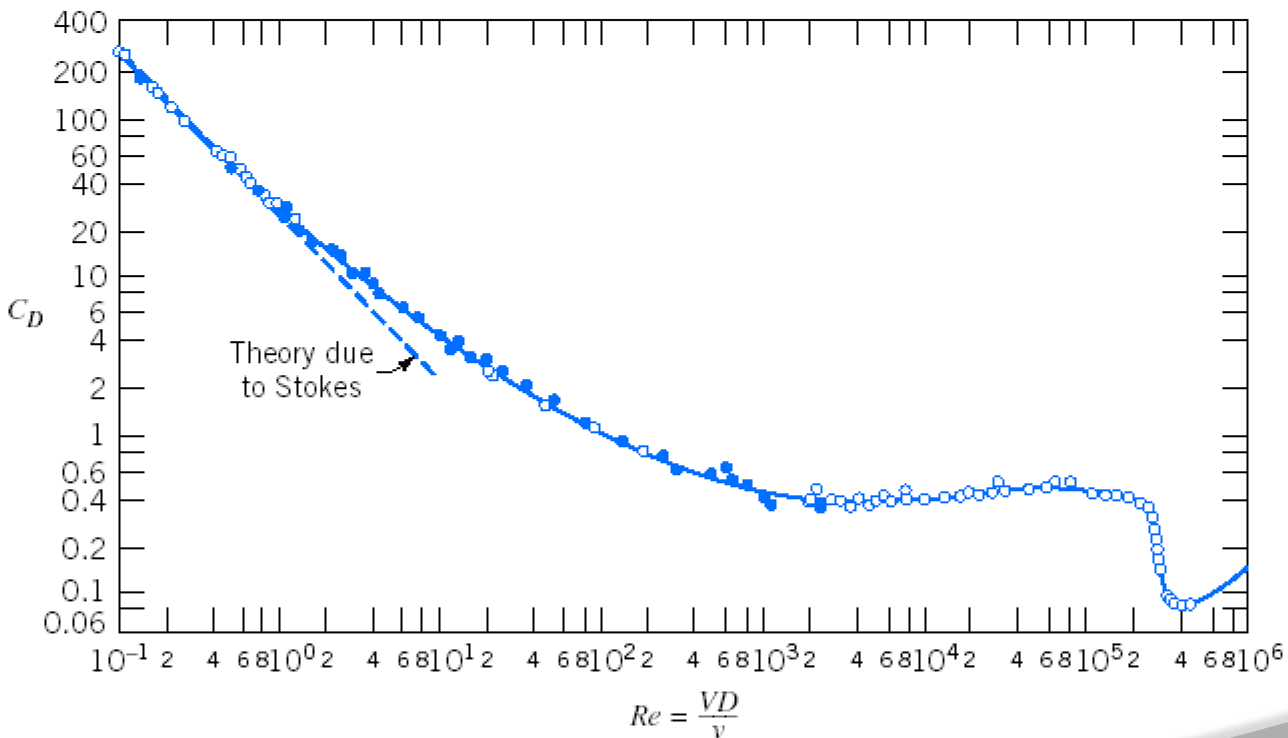
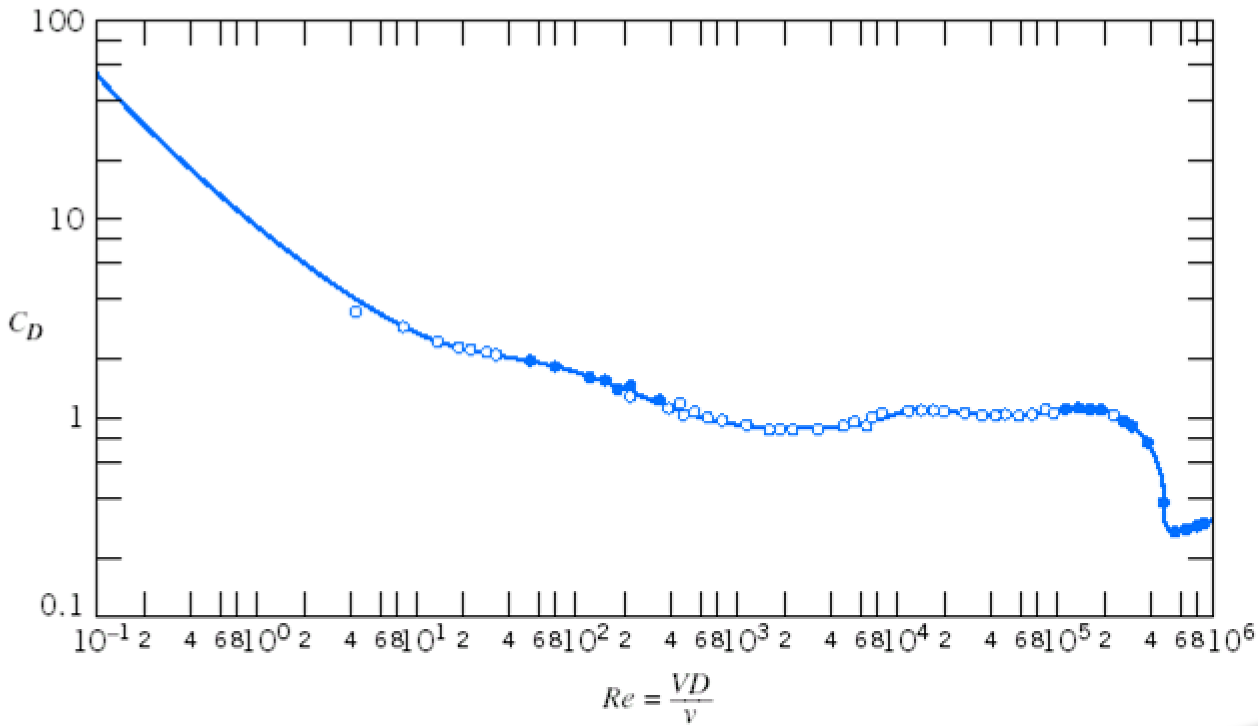


Fig. 9.11 Drag coefficient of a smooth sphere as a function of Reynolds number [3].

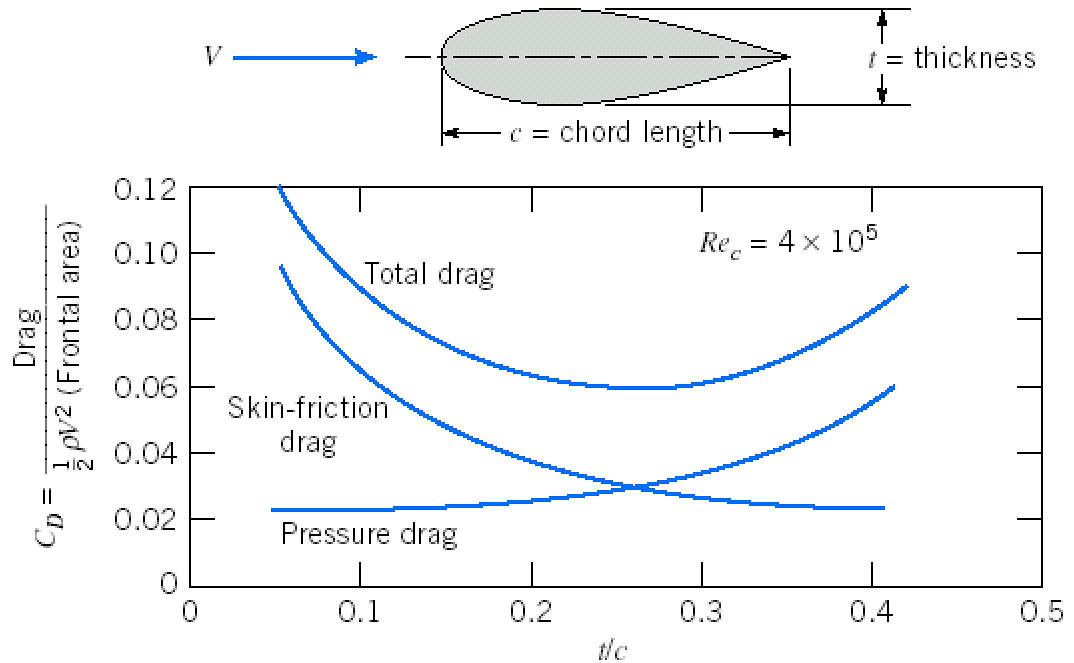
Drag

- Flow over a Sphere and Cylinder: Friction and Pressure Drag (Continued)



Streamlining(control of boundary layer separation)

- Used to Reduce Wake and hence Pressure Drag



Drag coefficient on a streamlined strut as a function of thickness ratio, showing contributions of skin friction and pressure to total drag [19].

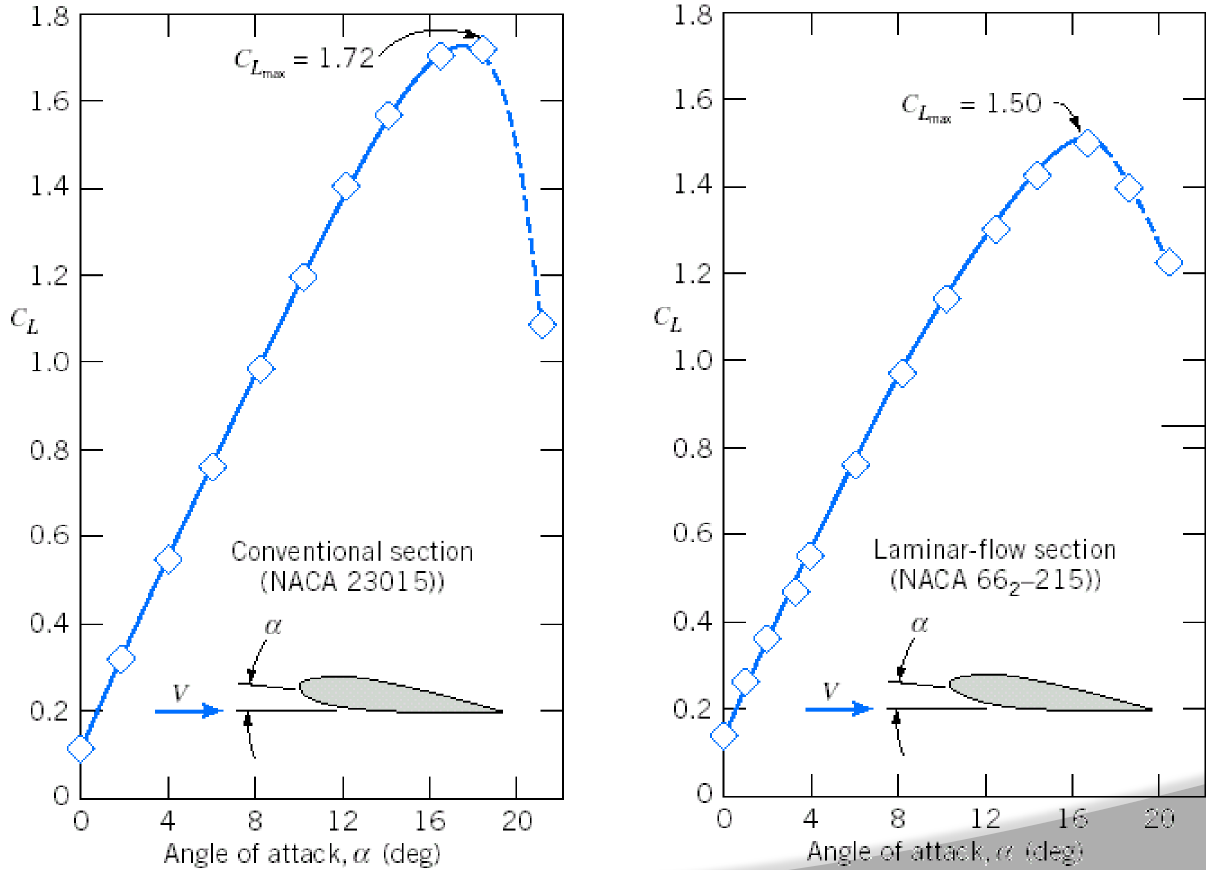
Lift

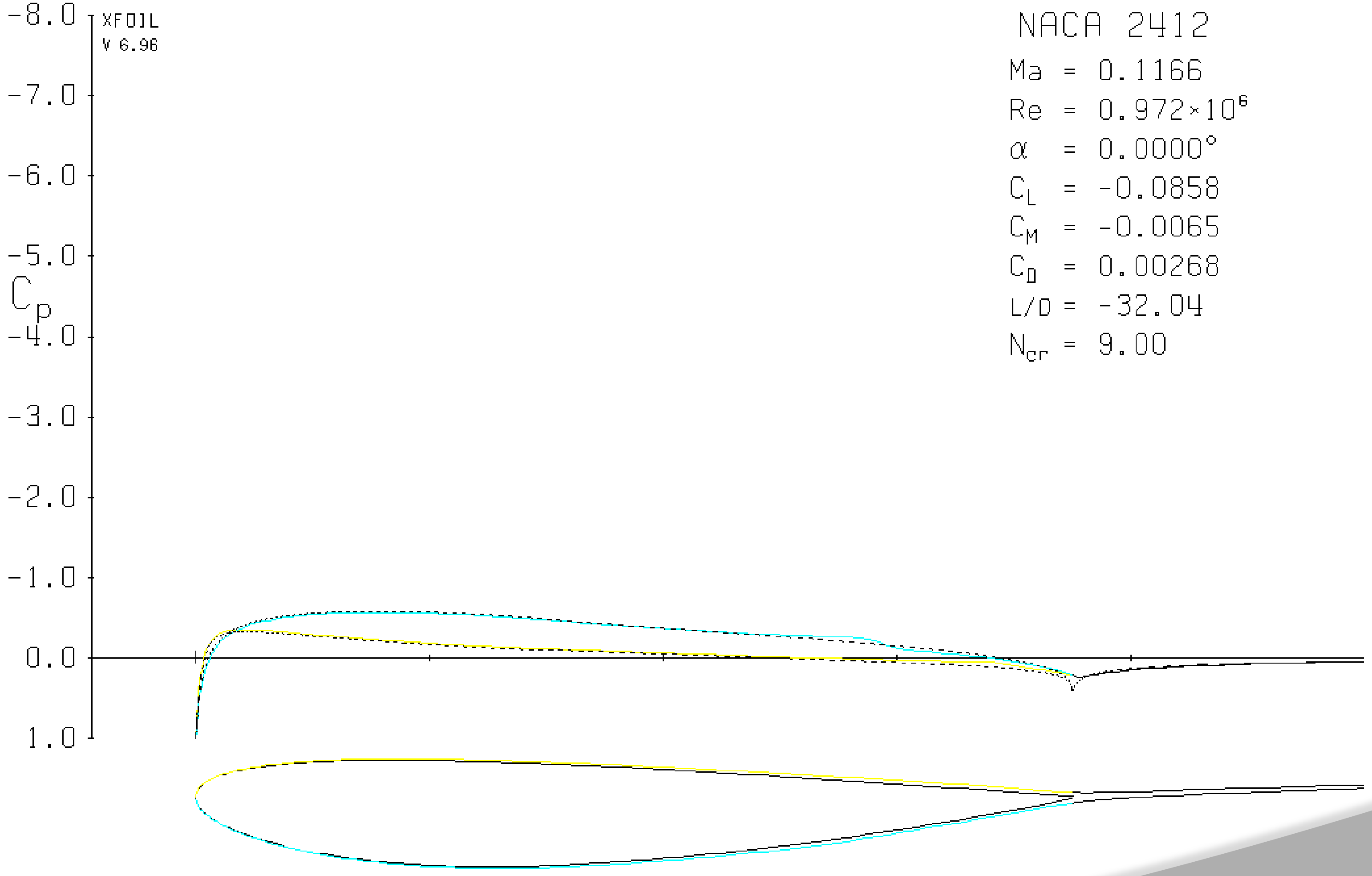
- Mostly applies to Airfoils

$$C_L \equiv \frac{F_L}{\frac{1}{2}\rho V^2 A_p}$$

Note: Based on planform area *A_p*

- Examples: NACA 23015; NACA 66_2-215





XFOIL
V 6.96
NACA 2412
Ma = 0.1166
Re = 0.972×10^6
α = 0.0000°
C_L = -0.0858
C_M = -0.0065
C_D = 0.00268
L/D = -32.04
N_cr = 9.00
C_p
-8.0
-7.0
-6.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0

Induced Drag

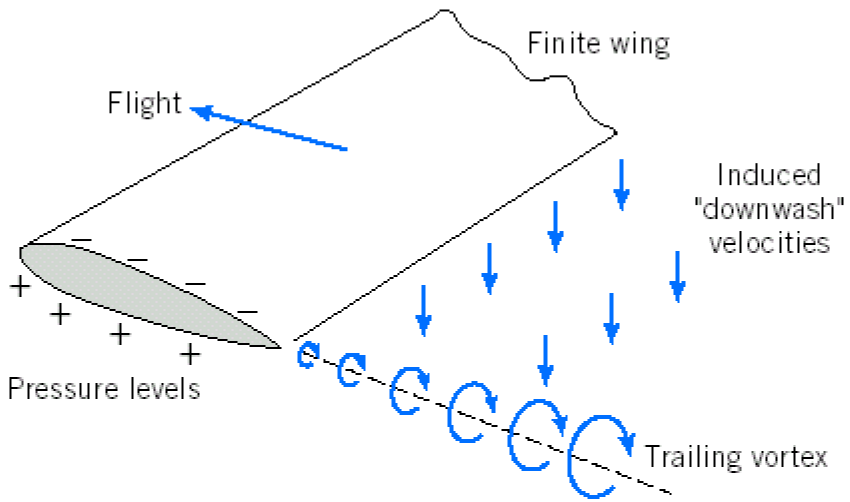
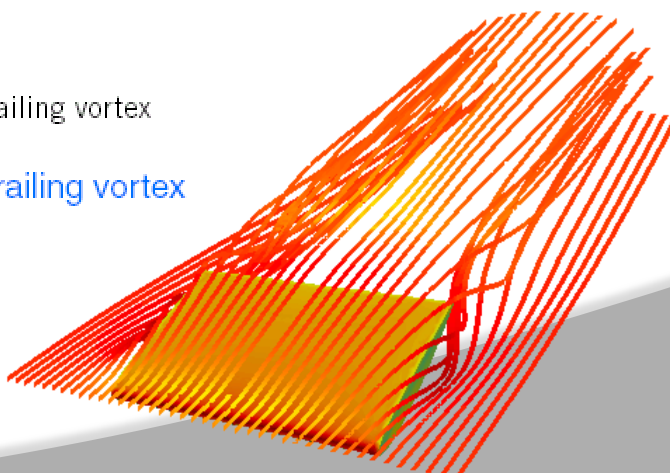


Fig. 9.20 Schematic representation of the trailing vortex system of a finite wing.



- Induced Drag (Continued)

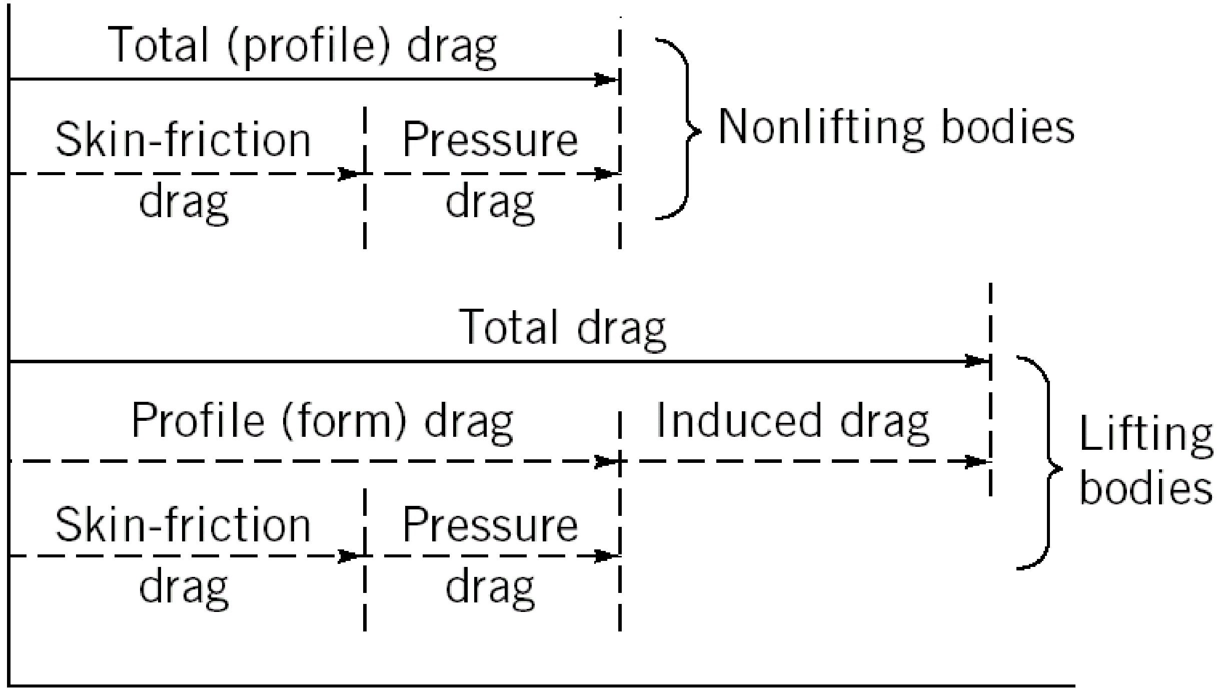
Reduction in Effective Angle of Attack:

$$\Delta\alpha \approx \frac{C_L}{\pi ar}$$

Finite Wing Drag Coefficient:

$$C_D = C_{D,\infty} + C_{D,i} = C_{D,\infty} + \frac{C_L^2}{\pi ar}$$

- Induced Drag (Continued)



Drag breakdown on nonlifting and lifting bodies.

1. A flat plate 1.5m x 1.5m moves at 50 km/hr in stationary air of density 1.15kg/m3. If the coefficients of drag and lift are 0.15 and 0.75 respectively, determine

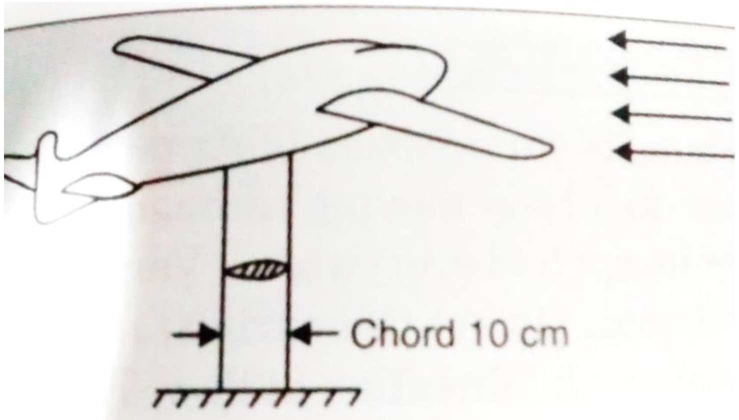
i. Lift force

ii. Drag force

iii. The resultant force and

iv. The power required to keep the plate in motion.

2. An aircraft model is mounted in a wind tunnel for drag determination. To decrease the drag contribution of the mounting system, the 1m long column is streamlined into an airfoil shape with a chord length of 10cm. At flow speed of 80m/s in the wind tunnel, estimate the error due to the drag on the mounting column, if the variation of C_D of the streamlined column with Re given in table.



C_D Vs Re for Mounting Column

Re	C_D
3×10^5	0.0045
6×10^5	0.0055
1×10^6	0.0060
3×10^6	0.0065

$$C_D = 0.072\, Re_L^{-1/5} - 1670/Re_L$$

Unit 5

Turbo Machinery

CLO	Course Learning Outcome
CLO13	Explain about the turbo machinery systems and working.
CLO14	Describe the concepts of turbo machinery in the field of aerospace engineering and concepts of internal flows through engines.
CLO15	Demonstrate the knowledge gained from the working of compressors, fans and pumps.

Syllabus

Introduction and classification of fluid machines: Turbo machinery analysis; The angular momentum principle; Euler turbo machine equation; Application to fluid systems, working principle overview of turbines, fans, pumps and compressors.

Introduction

- A fluid machine is a device which converts the energy stored by a fluid into mechanical energy or *vice versa*.
- The energy stored by a fluid mass appears in the form of potential, kinetic and intermolecular energy.
- The mechanical energy, on the other hand, is usually transmitted by a rotating shaft.
- Machines using liquid (mainly water, for almost all practical purposes) are termed as hydraulic machines.

CLASSIFICATIONS OF FLUID MACHINES

The fluid machines may be classified under different categories as follows:

- **Classification Based on Direction of Energy Conversion.**
- **Classification Based on Principle of Operation**
- **Classification Based on Fluid Used**

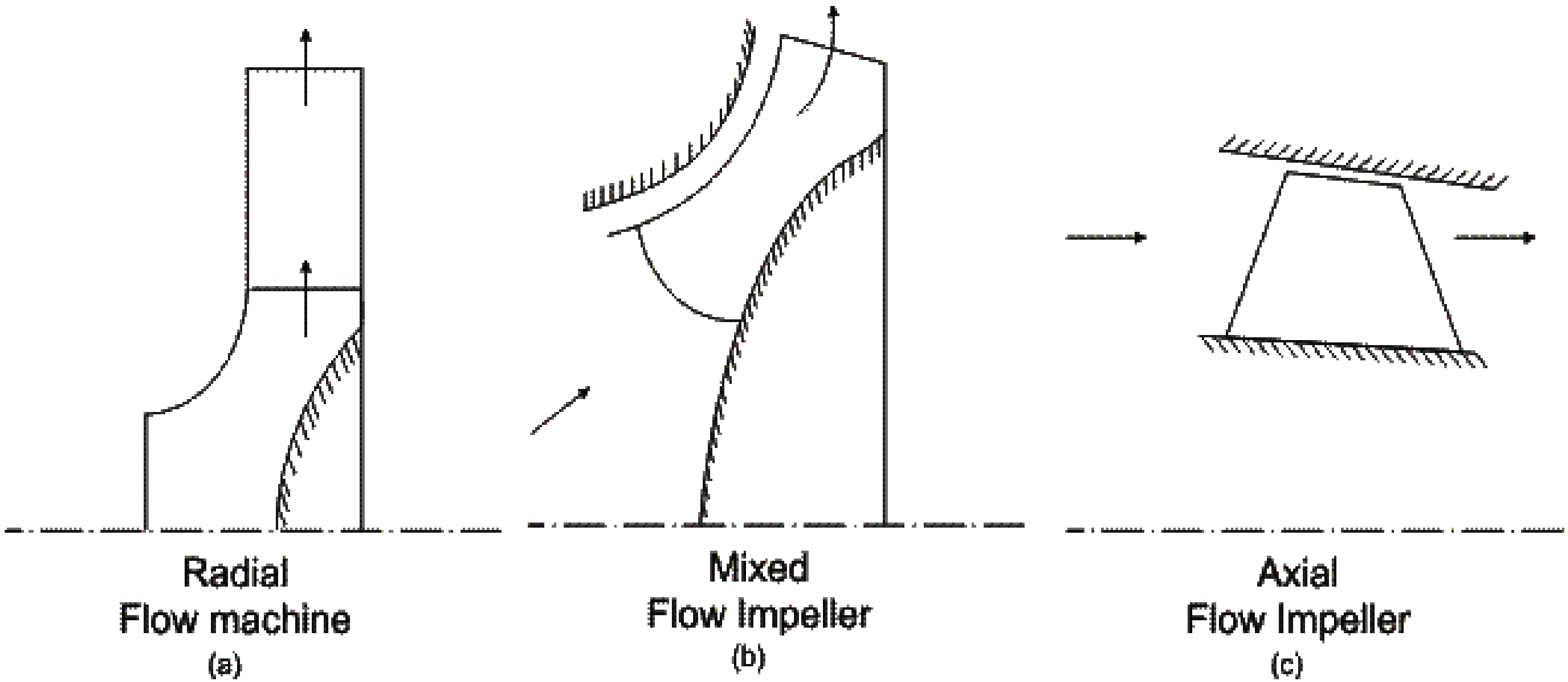
Classification Based on Direction of Energy Conversion

- The device in which the kinetic, potential or intermolecular energy held by the fluid is converted in the form of mechanical energy of a rotating member is known as a *turbine* .
- The machines, on the other hand, where the mechanical energy from moving parts is transferred to a fluid to increase its stored energy by increasing either its pressure or velocity are known as *pumps, compressors, fans or blowers* .

Classification Based on Principle of Operation

- The machines whose functioning depend essentially on the change of volume of a certain amount of fluid within the machine are known as *positive displacement machines*.
- The word positive displacement comes from the fact that there is a physical displacement of the boundary of a certain fluid mass as a closed system.
- The machines, functioning of which depend basically on the principle of fluid dynamics, are known as *rotodynamic machines*.

- For turbines, the work is done by the fluid on the rotor, while, in case of pump, compressor, fan or blower, the work is done by the rotor on the fluid element. Depending upon the main direction of fluid path in the rotor, the machine is termed *as radial flow or axial flow machine* .



schematic of different types of impellers

Classification Based on Fluid Used

- The fluid machines use either liquid or gas as the working fluid depending upon the purpose.
- The machine transferring mechanical energy of rotor to the energy of fluid is termed as a pump when it uses liquid, and is termed as a compressor or a fan or a blower, when it uses gas.
- The compressor is a machine where the main objective is to increase the static pressure of a gas.

ROTODYNAMIC MACHINES

- The important element of a rotodynamic machine, in general, is a rotor consisting of a number of vanes or blades. There always exists a relative motion between the rotor vanes and the fluid. The fluid has a component of velocity and hence of momentum in a direction tangential to the rotor. While flowing through the rotor, tangential velocity and hence the momentum changes.

- The rate at which this tangential momentum changes corresponds to a tangential force on the rotor. In a turbine, the tangential momentum of the fluid is reduced and therefore work is done by the fluid to the moving rotor.
- But in case of pumps and compressors there is an increase in the tangential momentum of the fluid and therefore work is absorbed by the fluid from the moving rotor.

Turbo machinery analysis

- The word turbo implies a spinning action is involved. In turbomachinery a blade or row of blades rotates and imparts or extracts energy to or from the fluid. Work is generated or extracted by means of enthalpy changes in the working fluid.
- In general, two kinds of turbomachines are encountered in practice.
- These are open and closed turbomachines. Open machines such as propellers, windmills, and unshrouded fans act on an infinite extent of fluid, whereas, closed machines operate on a finite quantity of fluid as it passes through a housing or casing.
- We will examine only turbomachines of the closed type.

Basic Equation of Energy Transfer in Rotodynamic Machines

- The basic equation of fluid dynamics relating to energy transfer is same for all roto-dynamic machines and is a simple form of "Newton 's Laws of Motion" applied to a fluid element traversing a rotor.
- Here we shall make use of the momentum theorem as applicable to a fluid element while flowing through fixed and moving vanes.

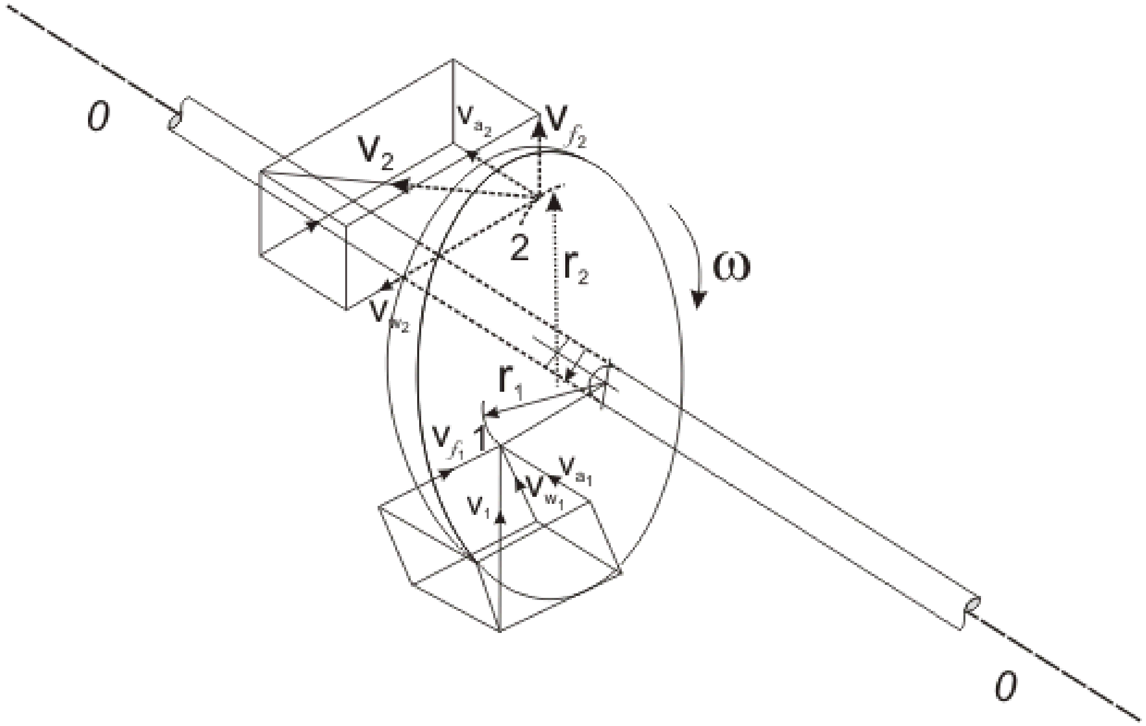
- Figure represents diagrammatically a rotor of a generalised fluid machine, with 0-0 the axis of rotation and ω the angular velocity.
- Fluid enters the rotor at 1, passes through the rotor by any path and is discharged at 2. The points 1 and 2 are at radii r_1 and r_2 from the centre of the rotor, and the directions of fluid velocities at 1 and 2 may be at any arbitrary angles.

- For the analysis of energy transfer due to fluid flow in this situation, we assume the following:

(a) The flow is steady, that is, the mass flow rate is constant across any section (no storage or depletion of fluid mass in the rotor).

(b) The heat and work interactions between the rotor and its surroundings take place at a constant rate.

(c) Velocity is uniform over any area normal to the flow. This means that the velocity vector at any point is representative of the total flow over a finite area. This condition also implies that there is no leakage loss and the entire fluid is undergoing the same process.



Components of flow velocity in a generalised fluid machine

- The velocity at any point may be resolved into three mutually perpendicular components as shown in Fig.
- The axial component of velocity Va is directed parallel to the axis of rotation, the radial component V_f is directed radially through the axis to rotation, while the tangential component V_w is directed at right angles to the radial direction and along the tangent to the rotor at that part.

- The change in magnitude of the axial velocity components through the rotor causes a change in the axial momentum.
- This change gives rise to an axial force, which must be taken by a thrust bearing to the stationary rotor casing.
- The change in magnitude of radial velocity causes a change in momentum in radial direction.
- However, for an axisymmetric flow, this does not result in any net radial force on the rotor. In case of a non uniform flow distribution over the periphery of the rotor in practice, a change in momentum in radial direction may result in a net radial force which is carried as a journal load.

- The tangential component V_w only has an effect on the angular motion of the rotor. In consideration of the entire fluid body within the rotor as a control volume, we can write from the moment of momentum theorem

$$T = m(V_{w_2} r_2 - V_{w_1} r_1)$$

- The rate of energy transfer to the fluid is then given by

$$E = T\omega = m(V_{w_2} r_2 \omega - V_{w_1} r_1 \omega) = m(V_{w_2} U_2 - V_{w_1} U_1)$$

This Equation is known as Euler's equation in relation to fluid machines.

- The Eq. can be written in terms of head gained '*H*' by the fluid as

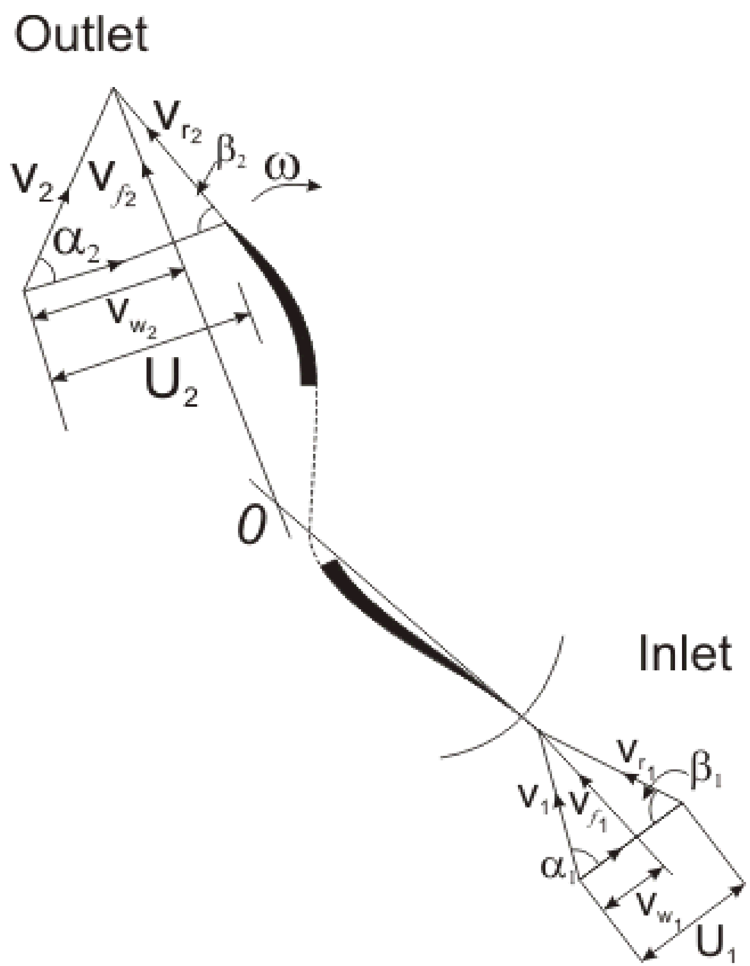
$$H = \frac{V_{w_2} U_2 - V_{w_1} U_1}{g}$$

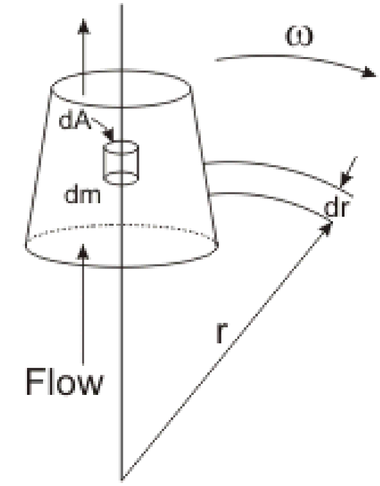
- In usual convention relating to fluid machines, the head delivered by the fluid to the rotor is considered to be positive and vice-versa. Therefore, the above Eq. written with a change in the sign of the right hand side in accordance with the sign convention as

$$H = \frac{V_{w_1} U_1 - V_{w_2} U_2}{g}$$

- ***Components of Energy Transfer*** It is worth mentioning in this context that either of the Eqs. (1.2) and (1.4) is applicable regardless of changes in density or components of velocity in other directions.
- Moreover, the shape of the path taken by the fluid in moving from inlet to outlet is of no consequence.
- The expression involves only the inlet and outlet conditions. A rotor, the moving part of a fluid machine, usually consists of a number of vanes or blades mounted on a circular disc.

- Figure 2a shows the velocity triangles at the inlet and outlet of a rotor. The inlet and outlet portions of a rotor vane are only shown as a representative of the whole rotor.


Outlet
V_{r_2}
β_2
ω
V_2
V_{f_2}
α_2
V_{w_2}
U_2
0
Inlet
V_{r_1}
β_1
V_1
V_{f_1}
α_1
V_{w_1}
U_1

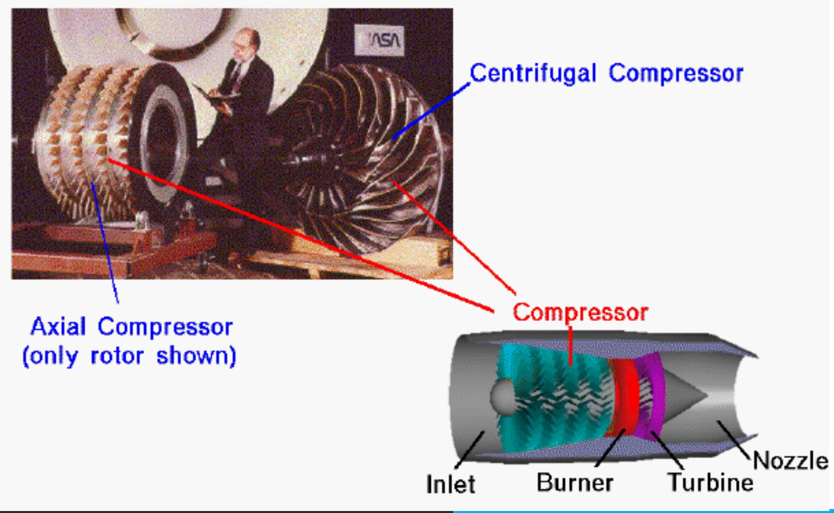

ω
dA
dm
dr
r
Flow

Application to fluid systems and working principle overview of turbines

Velocity Triangles

- In turbomachinery, a **velocity triangle** or a **velocity** diagram is a **triangle** representing the various components of velocities of the working fluid in a turbomachine.
- **Velocity triangles** may be drawn for both the inlet and outlet sections of any turbomachine.

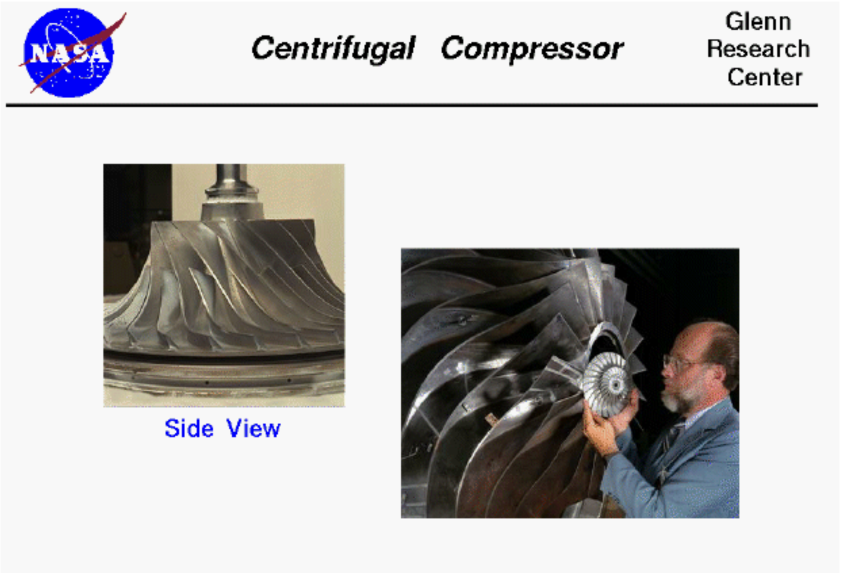
TWO PRIMARY TYPES OF COMPRESSORS

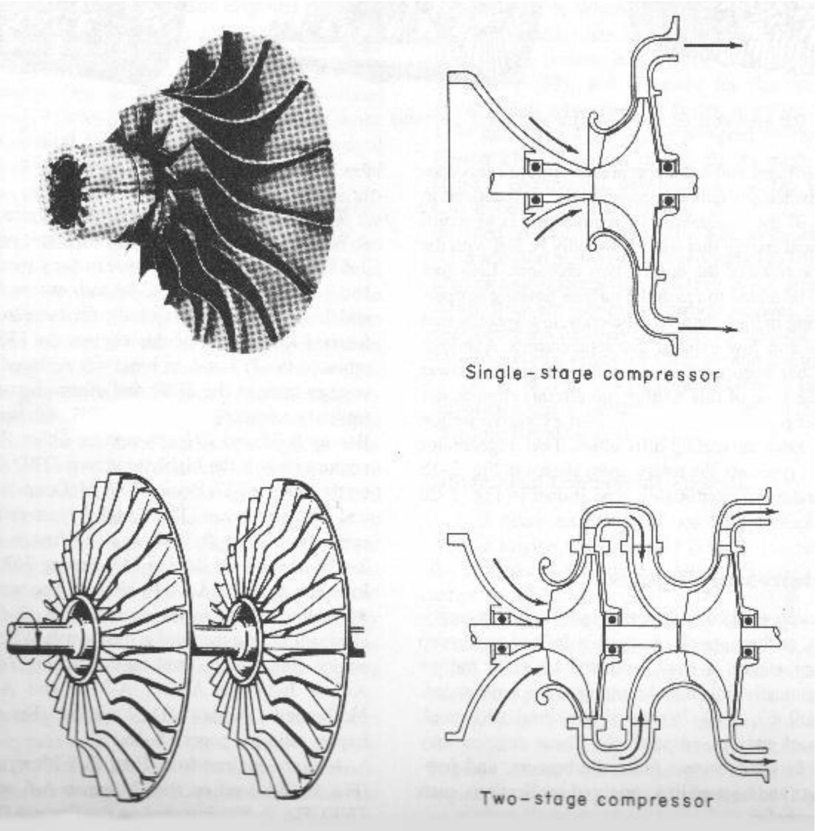


- **Axial Devices**
  - High mass flow
  - High efficiency
  - Stackable (multi-staging)
  - More parts
  - More complex

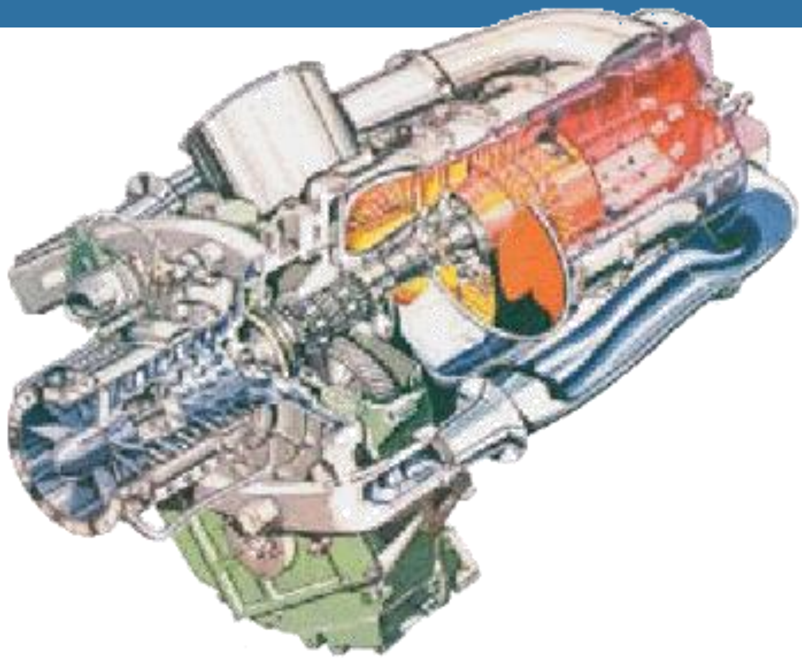
- **Radial (Centrifugal) Devices**
  - Can not handle as high mass flow
  - Less efficient than axial device
  - Short length
  - Robust
  - Less Parts

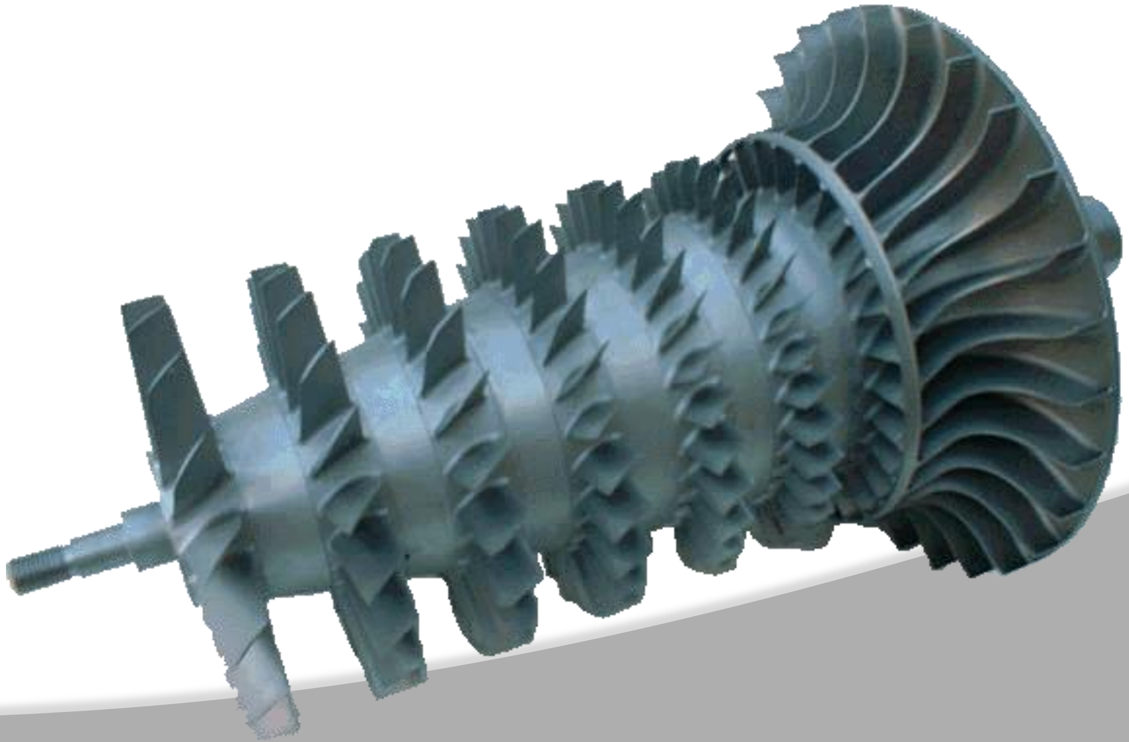
Centrifugal compressors



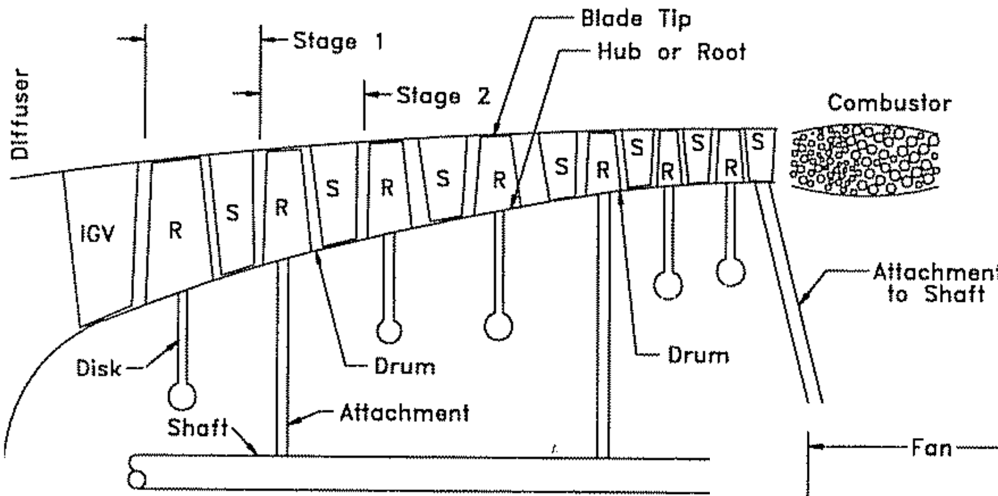


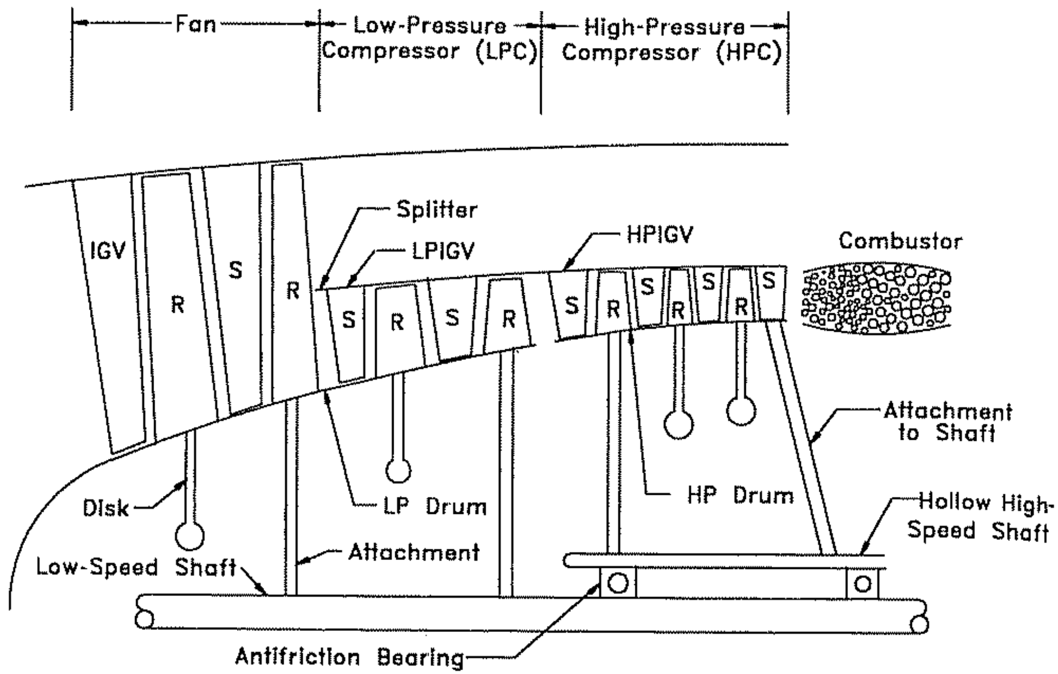
ALLISON 250: AXIAL + RADIAL DEVICE



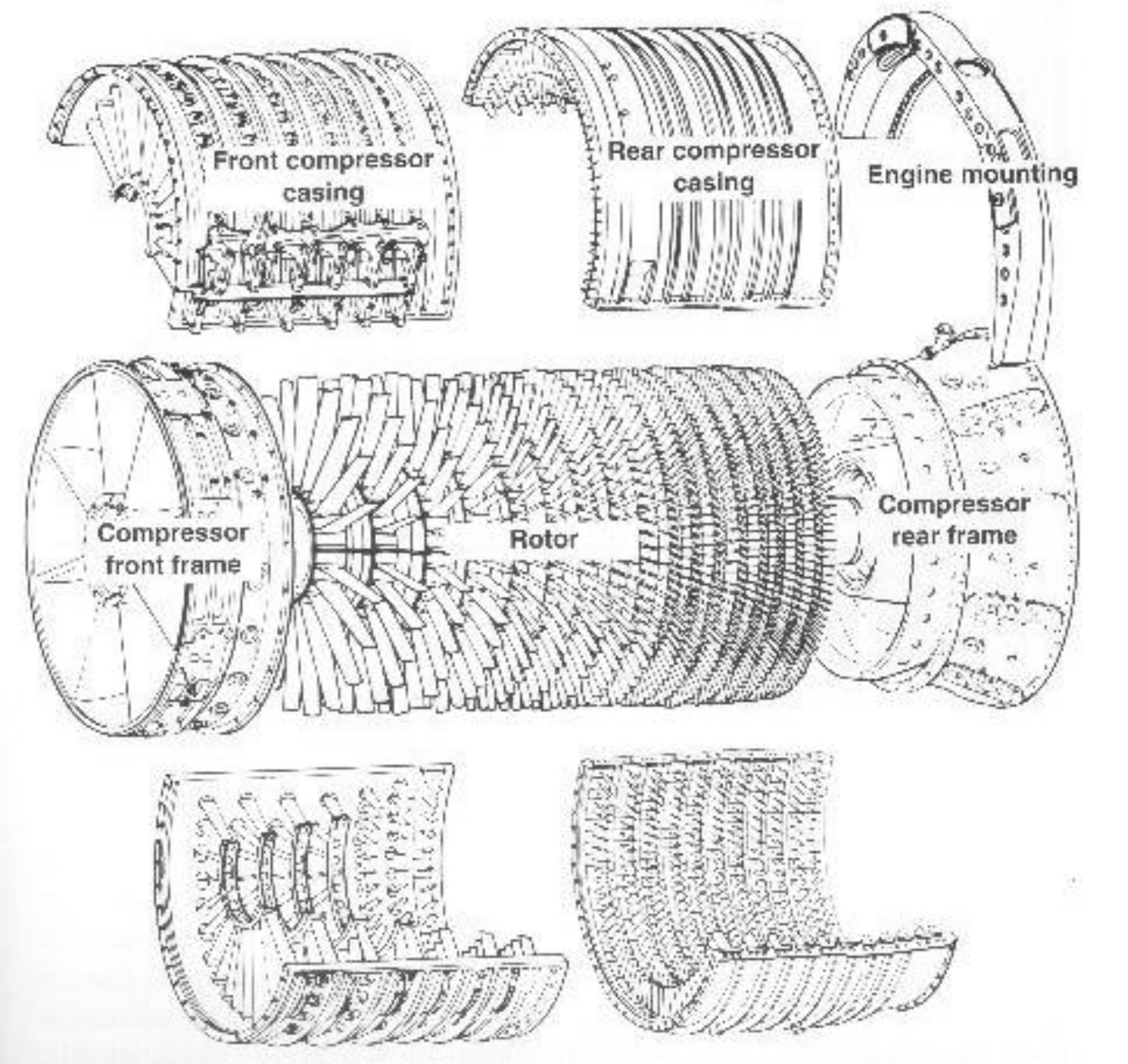


SCHEMATIC REPRESENTATION

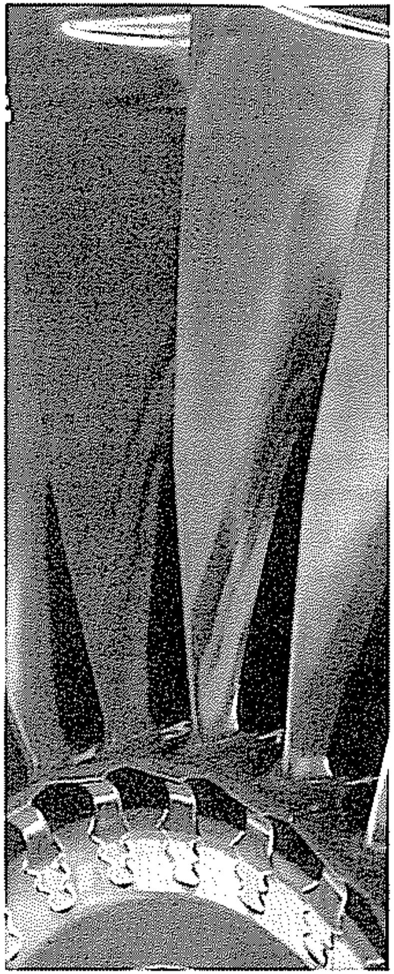




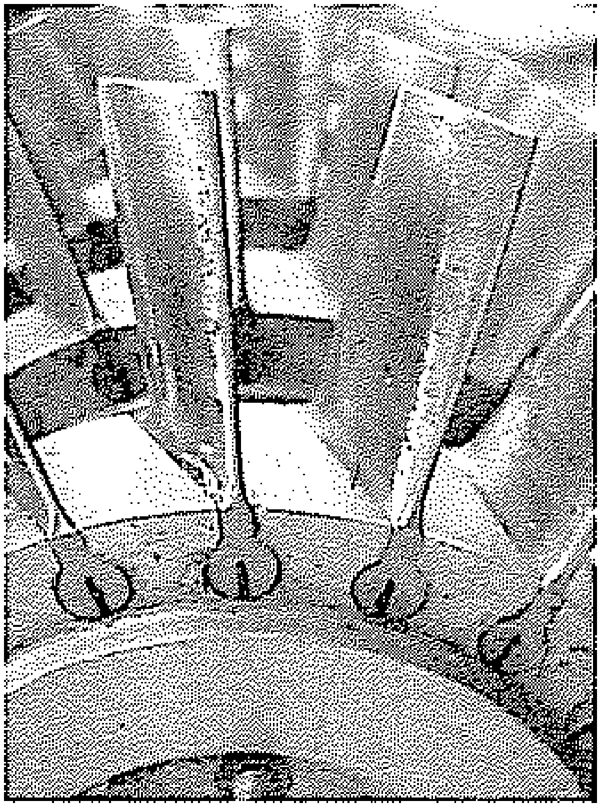
Axial compressor exploded view



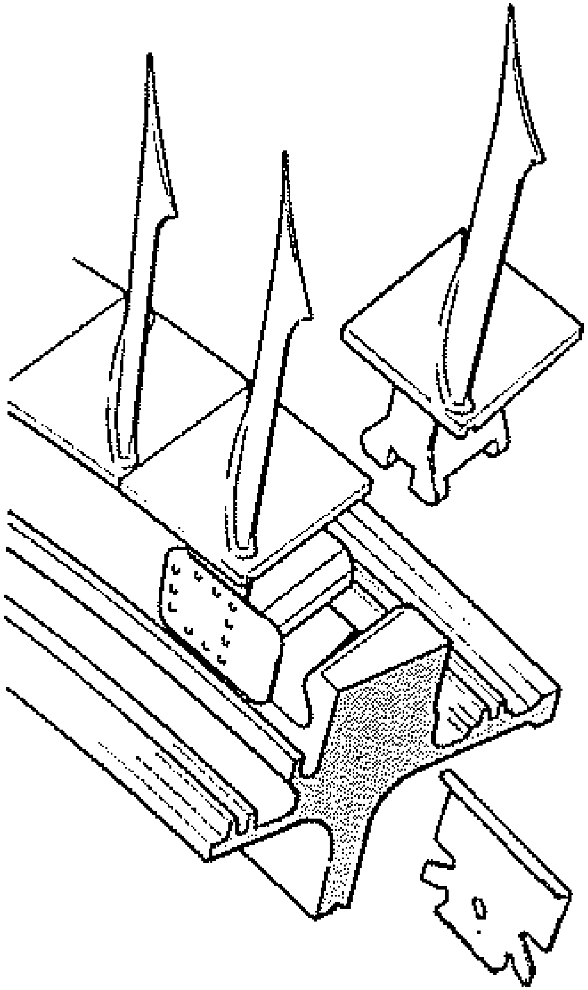
HOW BLADES ARE ATTACHED



(a) Fir Tree
(courtesy of Rolls-Royce)

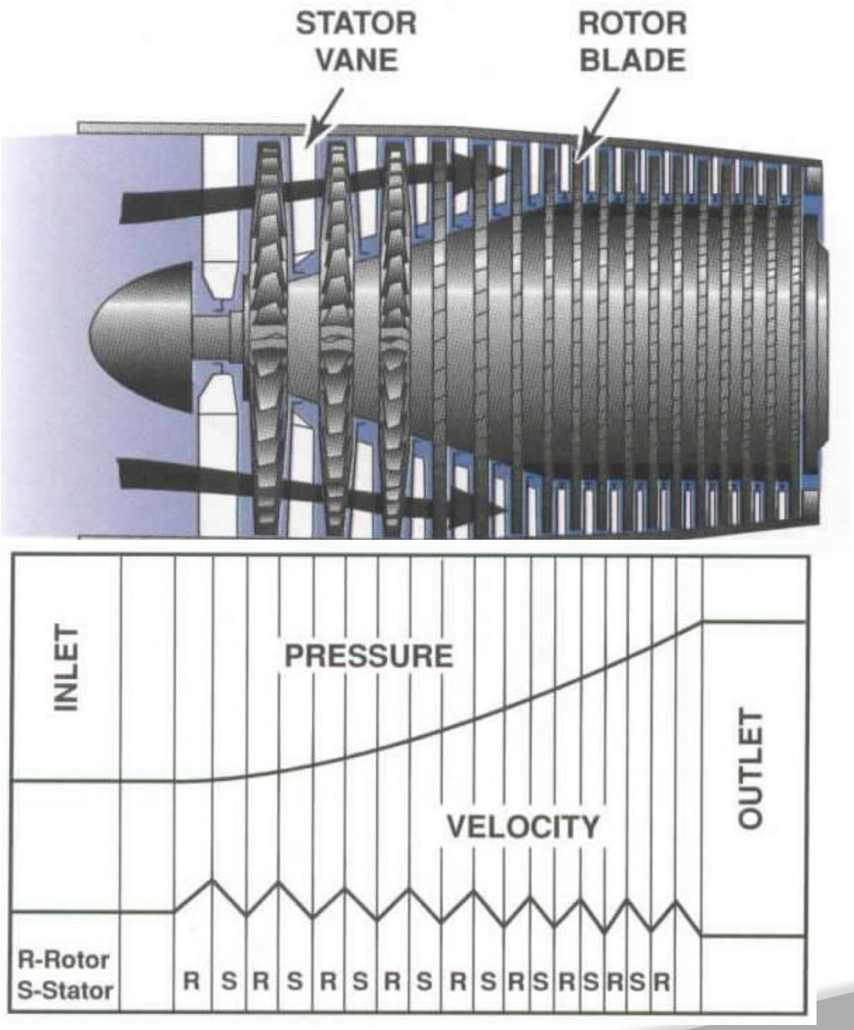


(b) Bulb of Westinghouse J30
(photo by R. Flack)



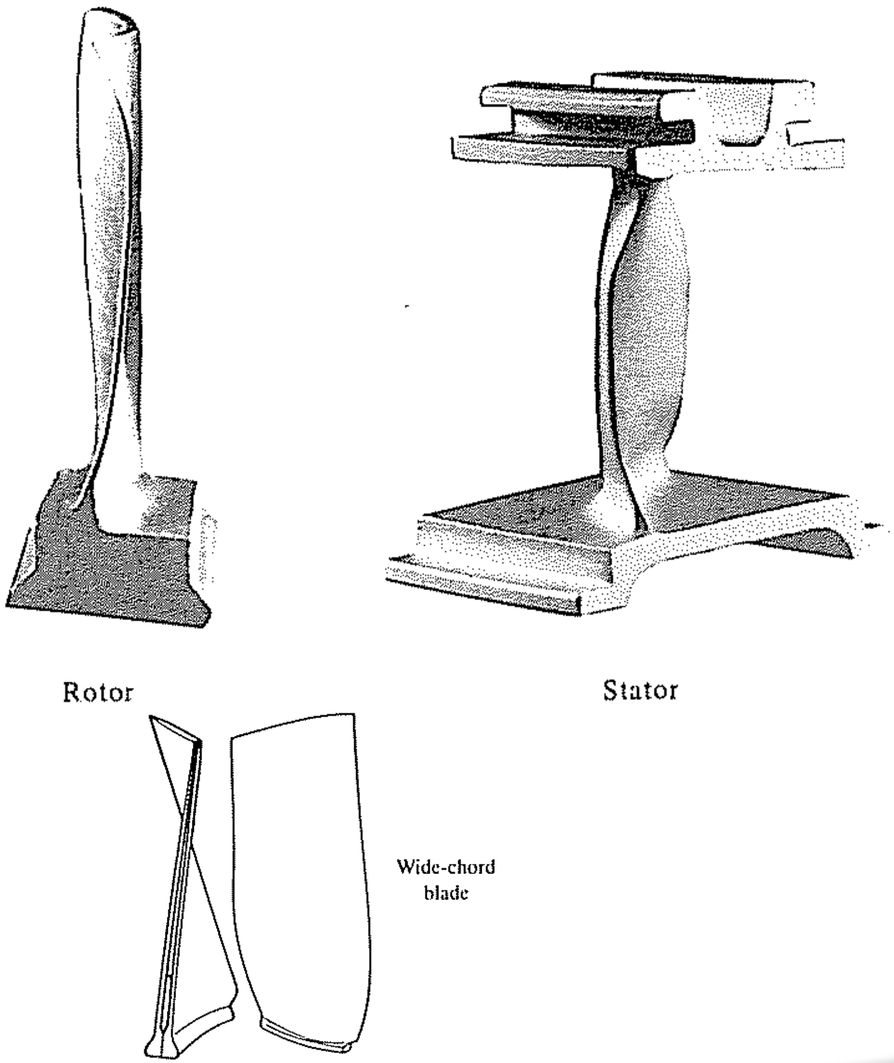
(c) "Loose"
(courtesy of Rolls-Royce)

Review: pressure distribution

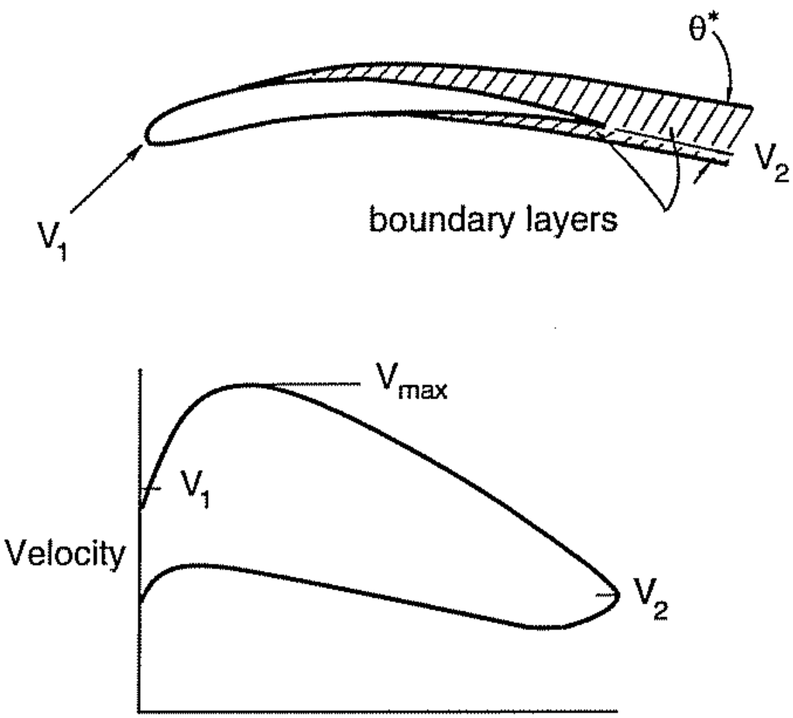


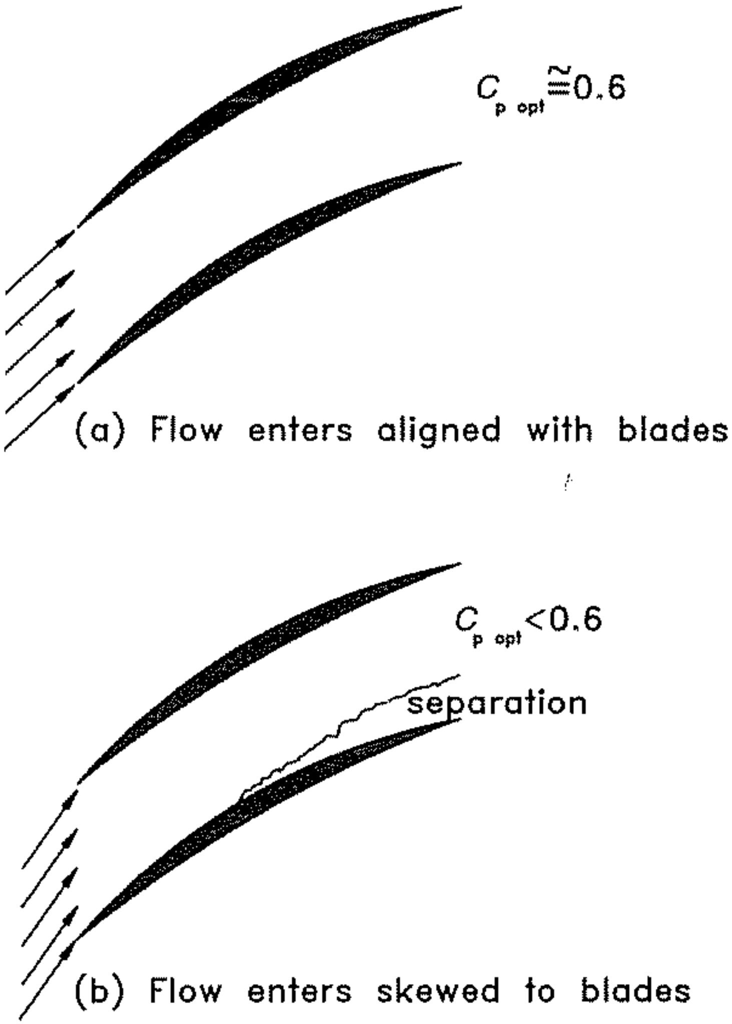
- **Rotor**
  - Adds swirl to flow
  - Adds kinetic energy to flow with ½rv^2
  - Increases total energy carried in flow by increasing angular momentum
- **Stator**
  - Removes swirl from flow
  - Not a moving blade → cannot add any net energy to flow
  - Converts kinetic energy associated with swirl to internal energy by raising static pressure of flow
  - GV adds no energy. Adds swirl in direction of rotor motion to lower Mach number of flow relative to rotor blades (improves aerodynamics)

examples of blade twist

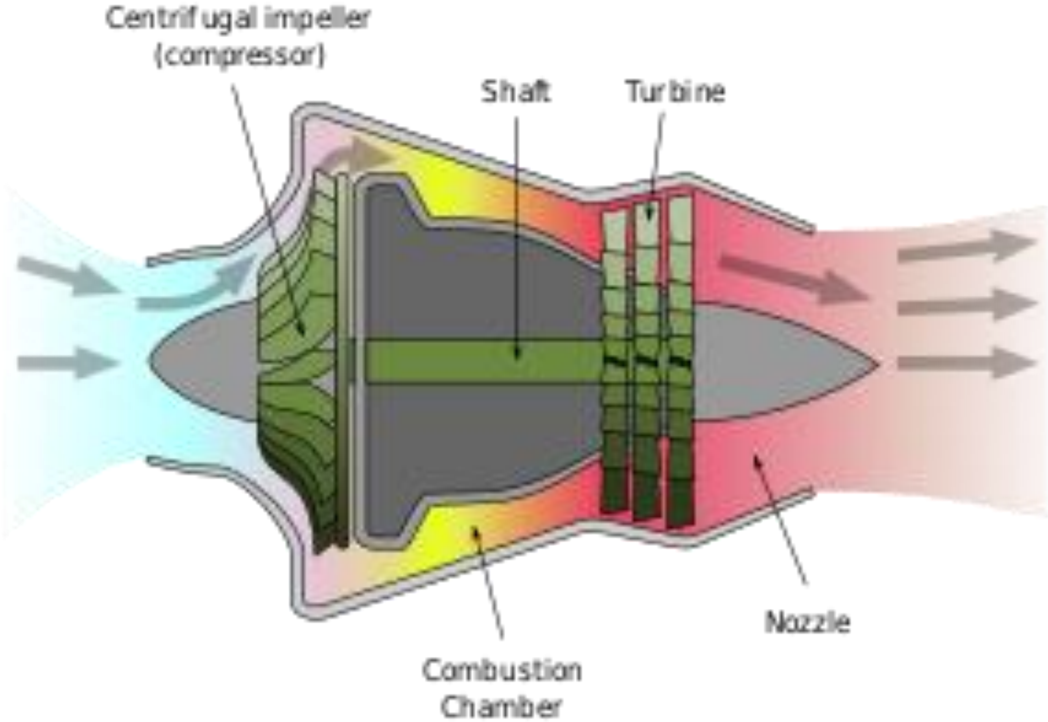


BOUNDARY LAYER LOSSES AND SEPARATION





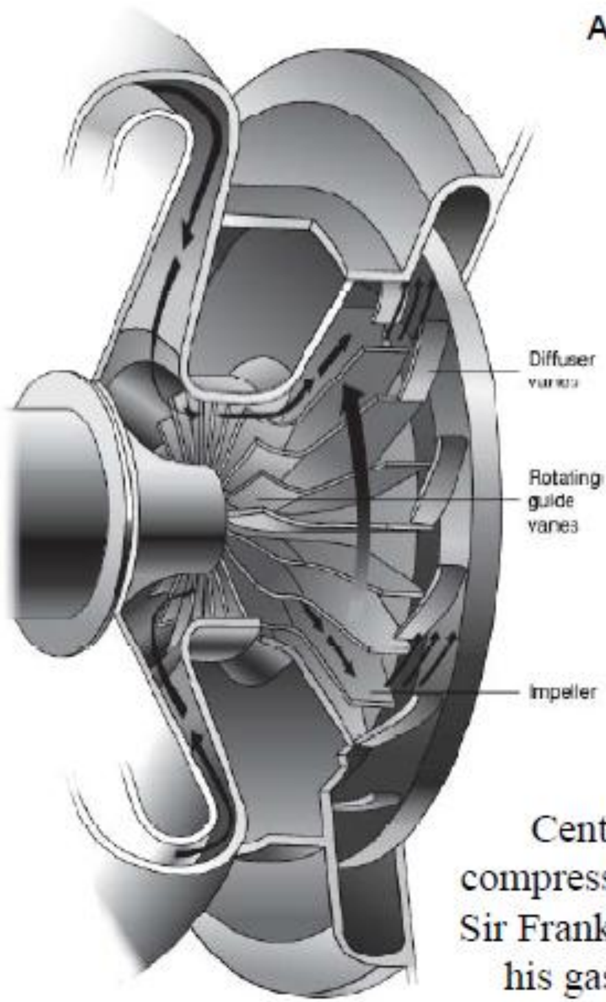
Centrifugal Compressor



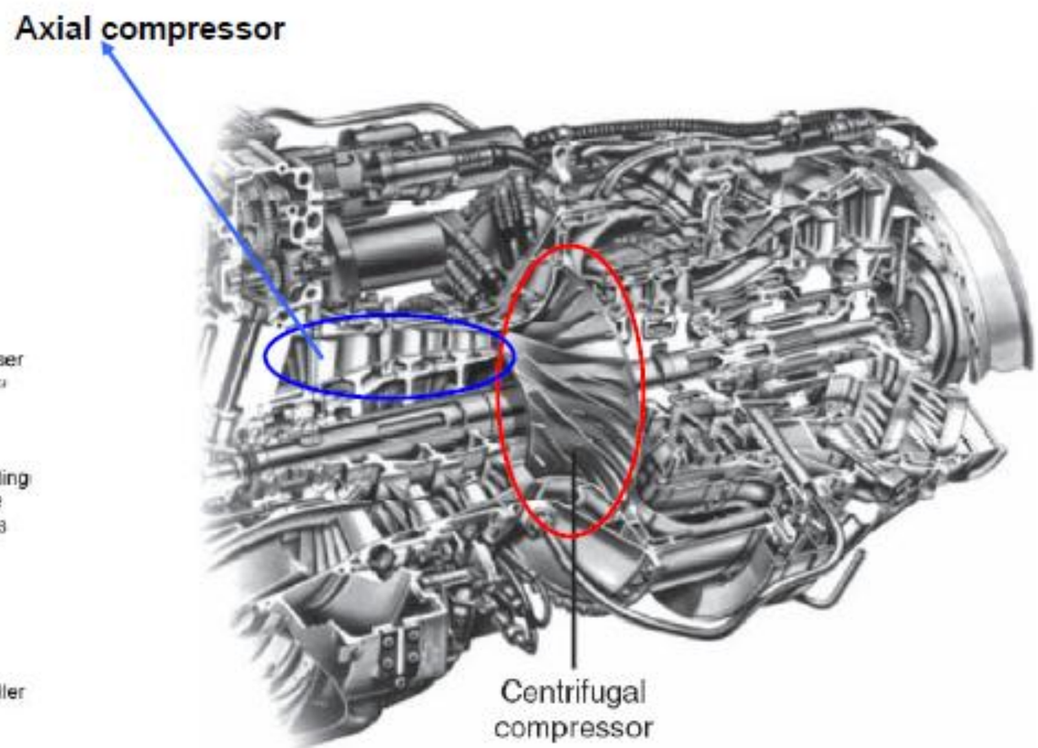
- Turbomachines employing centrifugal effects for increasing fluid pressure have been in use for more than a century.
- The earliest machines using this method were hydraulic pumps followed later by ventilating fans and blowers.
- A centrifugal compressor was incorporated in the Whittle turbojet engine.
- Axial flow compressors are more suitable for larger engines in terms of smaller frontal area (and drag) and 3-4% higher efficiency for the same duty than centrifugal compressors.

- But for very small compressors with low flow rates, the efficiency of axial compressors drops sharply, blading is small and difficult to make accurately, and the centrifugal compressor is again preferable .
- Many applications are found in small gas turbines for road vehicles and commercial helicopters as well as bigger applications, e.g., diesel engine turbochargers, chemical plant processes, factory workshop air supplies, large-scale air-conditioning plant, etc.

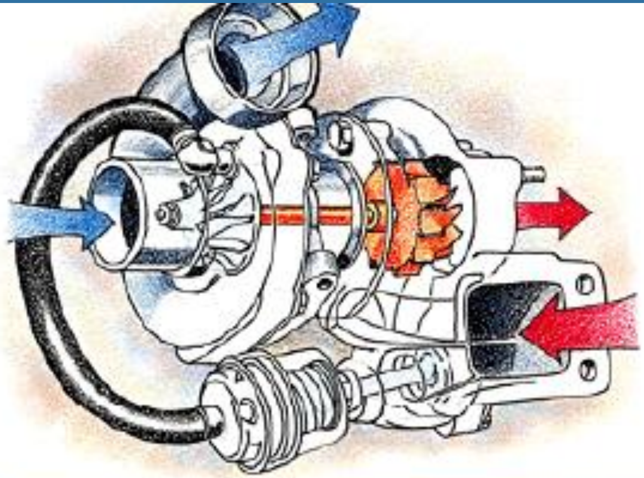
Applications of Centrifugal Compressor

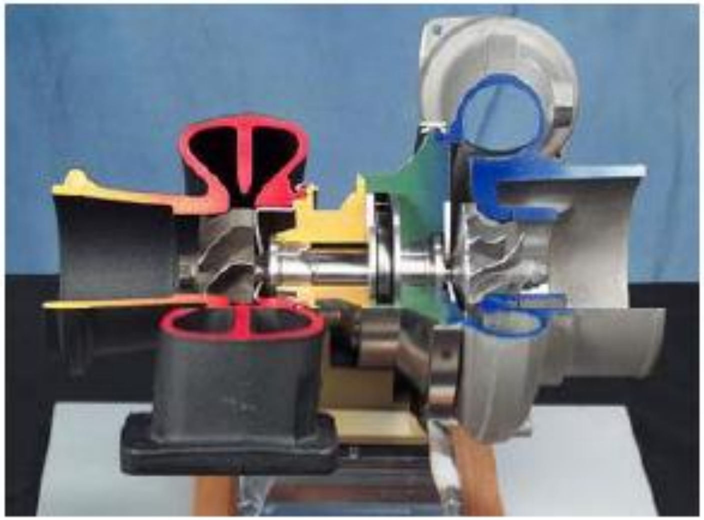


Centrifugal compressor used by Sir Frank Whittle in his gas turbine



The Turbomeca Centrifugal Compressor fitted to the RTM322 engine





Rolls Royce Goblin II engine using centrifugal compressor

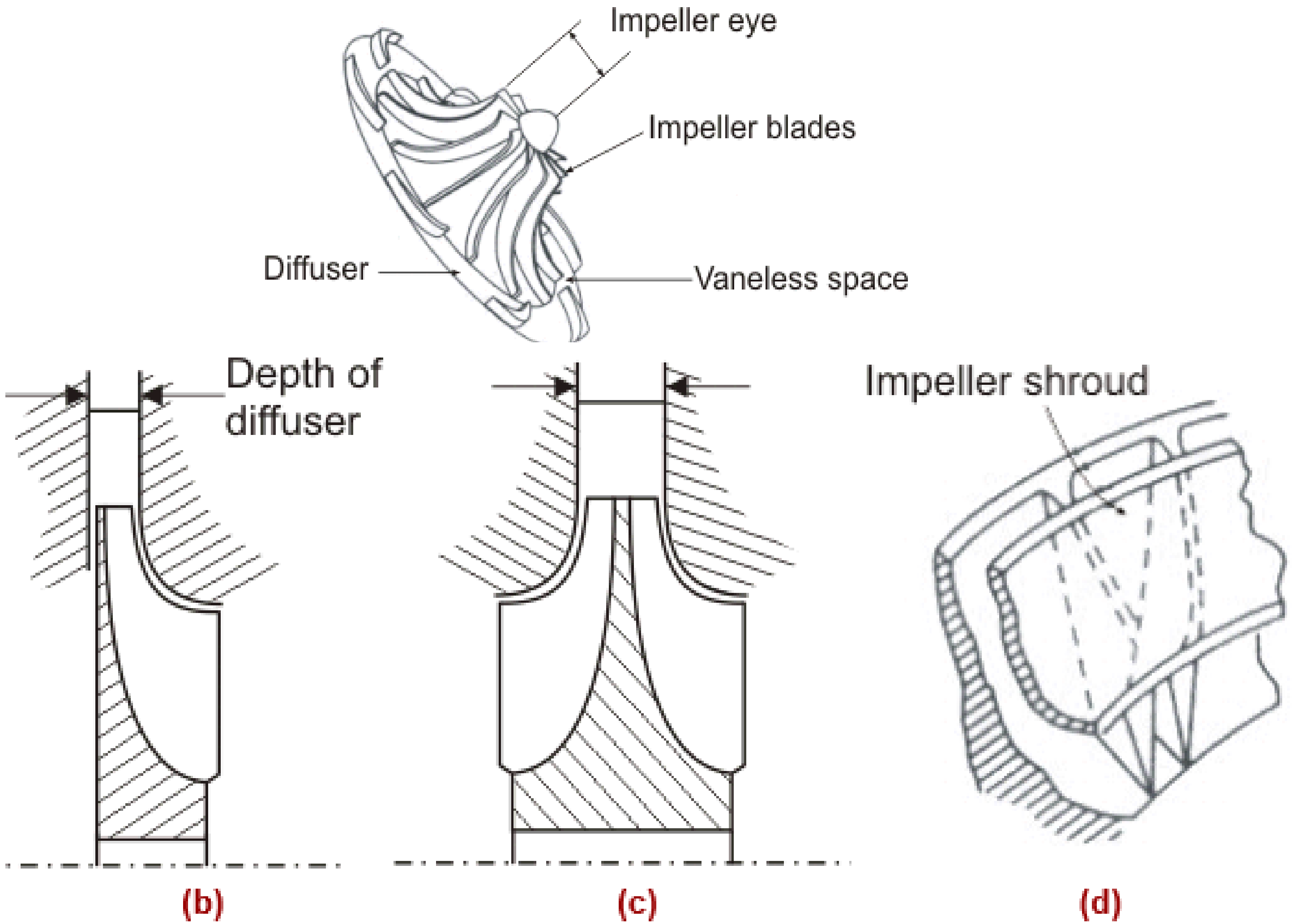
A centrifugal compressor essentially consists of three components.

- A **stationary casing**
- A **rotating impeller** as shown in fig (a) which imparts a high velocity to the air. The impeller may be single or double sided as show in Fig. (b) and (c), but the fundamental theory is same for both.
- A **diffuser** consisting of a number of fixed diverging passages in which the air is decelerated with a consequent rise in static pressure.

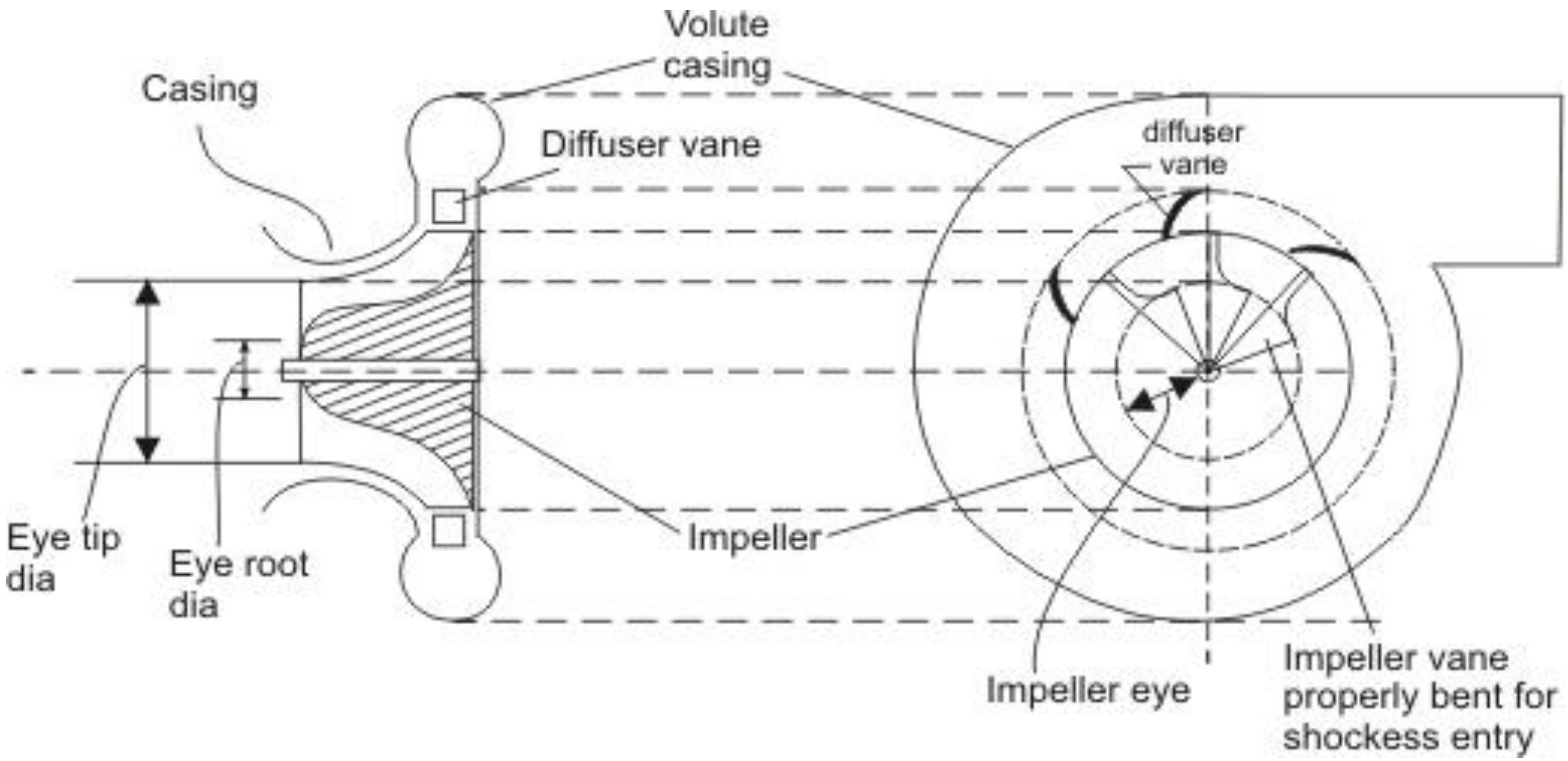
- **Principle of operation:** Air is sucked into the impeller eye and whirled outwards at high speed by the impeller disk. At any point in the flow of air through the impeller the centripetal acceleration is obtained by a pressure head so that the static pressure of the air increases from the eye to the tip of the impeller. The remainder of the static pressure rise is obtained in the diffuser, where the very high velocity of air leaving the impeller tip is reduced to almost the velocity with which the air enters the impeller eye.

- Usually, about half of the total pressure rise occurs in the impeller and the other half in the diffuser. Owing to the action of the vanes in carrying the air around with the impeller, there is a slightly higher static pressure on the forward side of the vane than on the trailing face. The air will thus tend to flow around the edge of the vanes in the clearing space between the impeller and the casing. This results in a loss of efficiency and the clearance must be kept as small as possible. Sometimes, a shroud attached to the blades as shown in Figure.(d) may eliminate such a loss, but it is avoided because of increased disc friction loss and of manufacturing difficulties.

- The straight and radial blades are usually employed to avoid any undesirable bending stress to be set up in the blades. The choice of radial blades also determines that the total pressure rise is divided equally between impeller and diffuser.



Schematic views of a centrifugal compressor

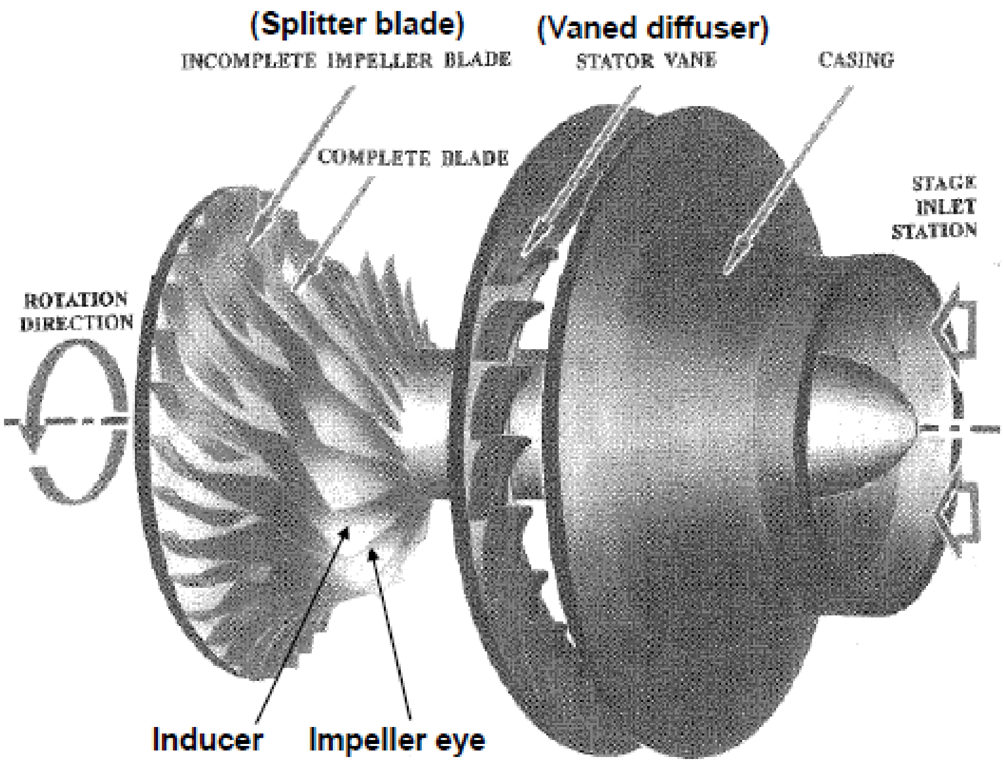


Single entry and single outlet centrifugal compresssor

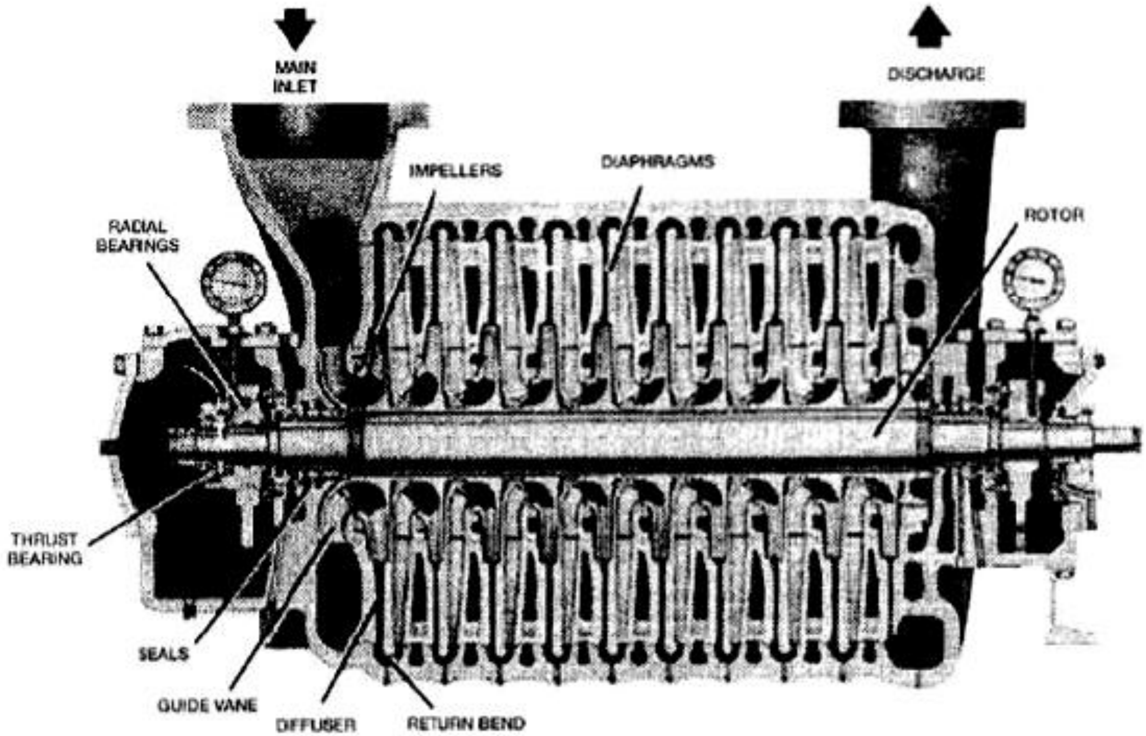
Before further discussions following points are worth mentioning for a centrifugal compresssor.

- (i) The pressure rise per stage is high and the volume flow rate tends to be low. The pressure rise per stage is generally limited to 4:1 for smooth operations.
- (ii) Blade geometry is relatively simple and small foreign material does not affect much on operational characteristics.
- (iii) Centrifugal impellers have lower efficiency compared to axial impellers and when used in aircraft engine it increases frontal area and thus drag. Multistaging is also difficult to achieve in case of centrifugal machines.

Single Stage Centrifugal Compressor



Multistage Centrifugal Compressor



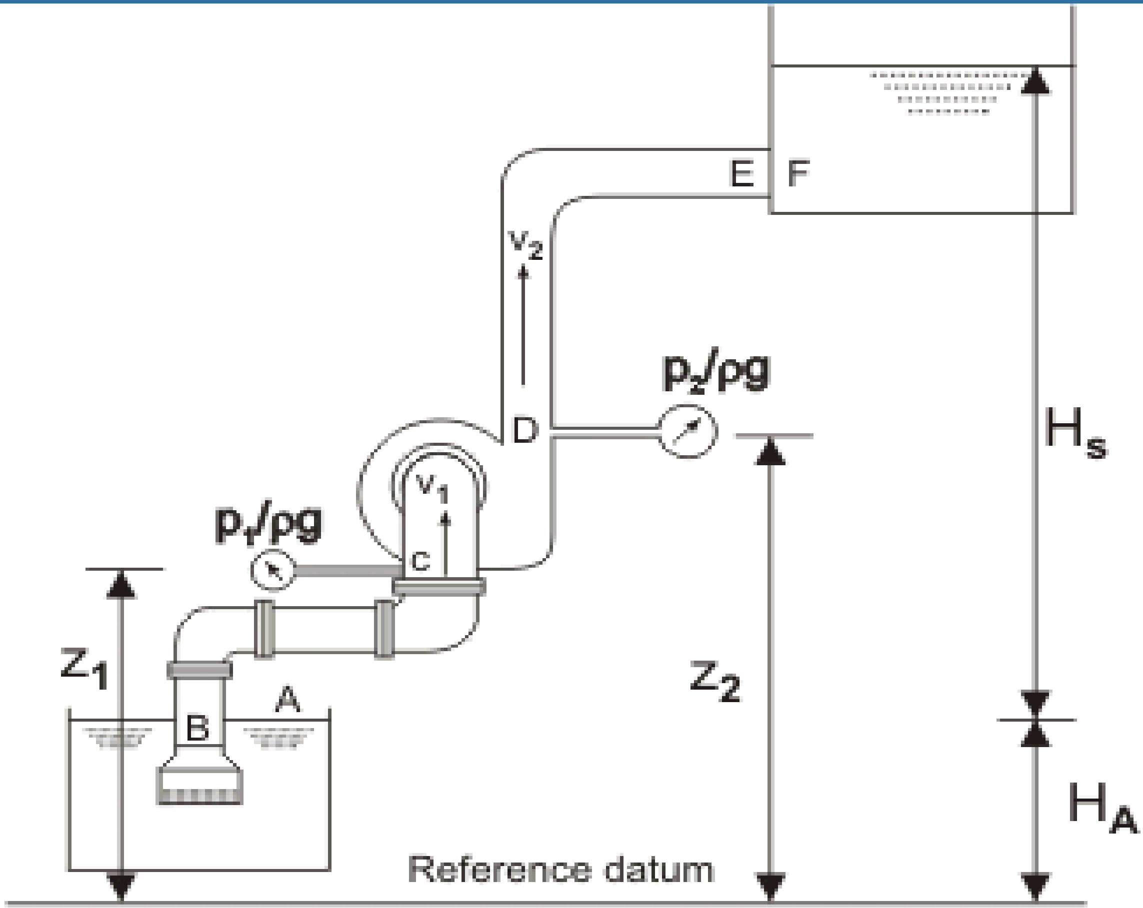
Dresser-Rand Company Multistage Centrifugal Compressor

Rotodynamic Pumps

- A rotodynamic pump is a device where mechanical energy is transferred from the rotor to the fluid by the principle of fluid motion through it. The energy of the fluid can be sensed from the pressure and velocity of the fluid at the delivery end of the pump. Therefore, it is essentially a turbine in reverse. Like turbines, pumps are classified according to the main direction of fluid path through them like (i) radial flow or centrifugal, (ii) axial flow and (iii) mixed flow types.

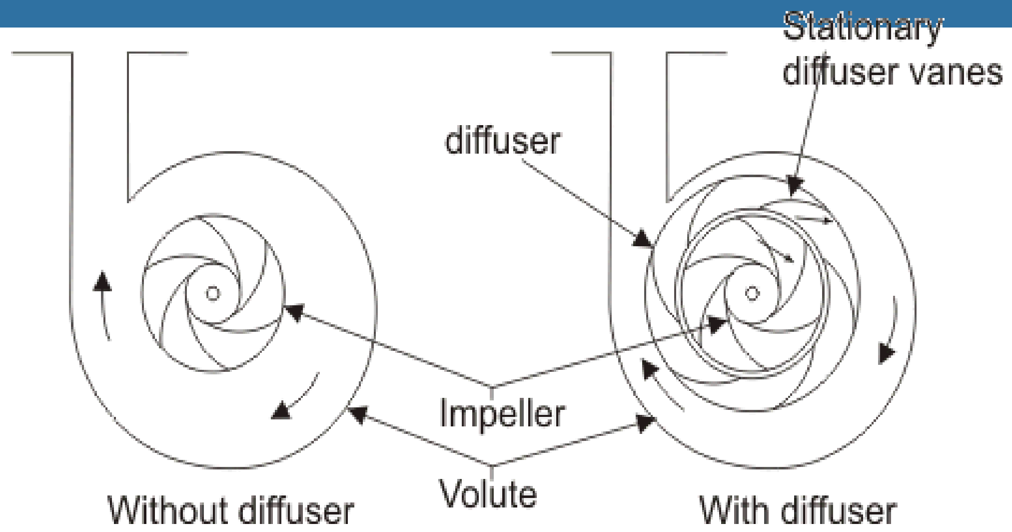
Centrifugal Pumps

- The pumps employing centrifugal effects for increasing fluid pressure have been in use for more than a century. The centrifugal pump, by its principle, is converse of the Francis turbine. The flow is radially outward, and the hence the fluid gains in centrifugal head while flowing through it. Because of certain inherent advantages, such as compactness, smooth and uniform flow, low initial cost and high efficiency even at low heads, centrifugal pumps are used in almost all pumping systems.



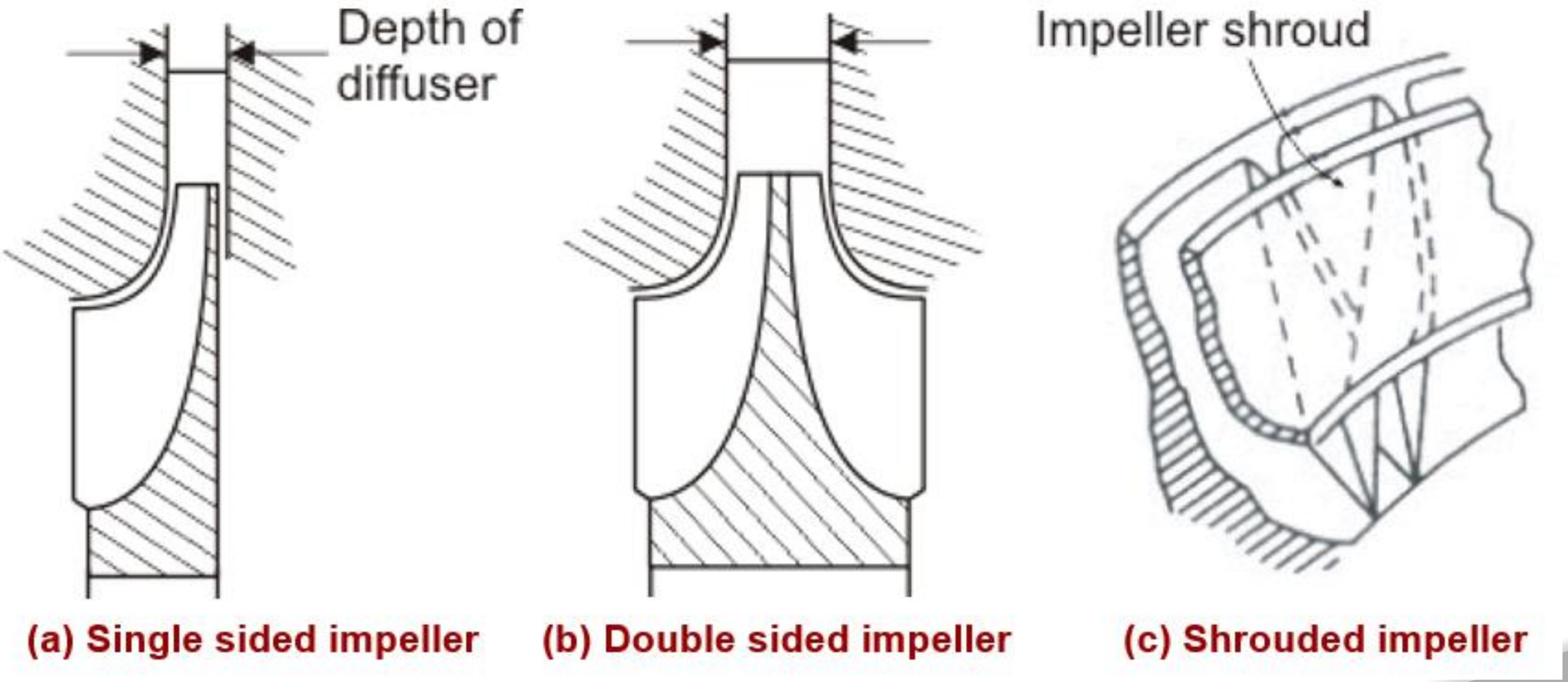
A general pumping system

$$H = [(p_2 - p_1)/\rho g] + [(V_2^2 - V_1^2)/2g] + [z_2 - z_1]$$



A centrifugal pump

The simplest from of a centrifugal pump is shown in Figure. It consists of three important parts: (i) the rotor, usually called as impeller, (ii) the volute casing and (iii) the diffuser ring. The impeller is a rotating solid disc with curved blades standing out vertically from the face of the disc. The impeller may be single sided or double-sided. A double sided impeller has a relatively small flow capacity.

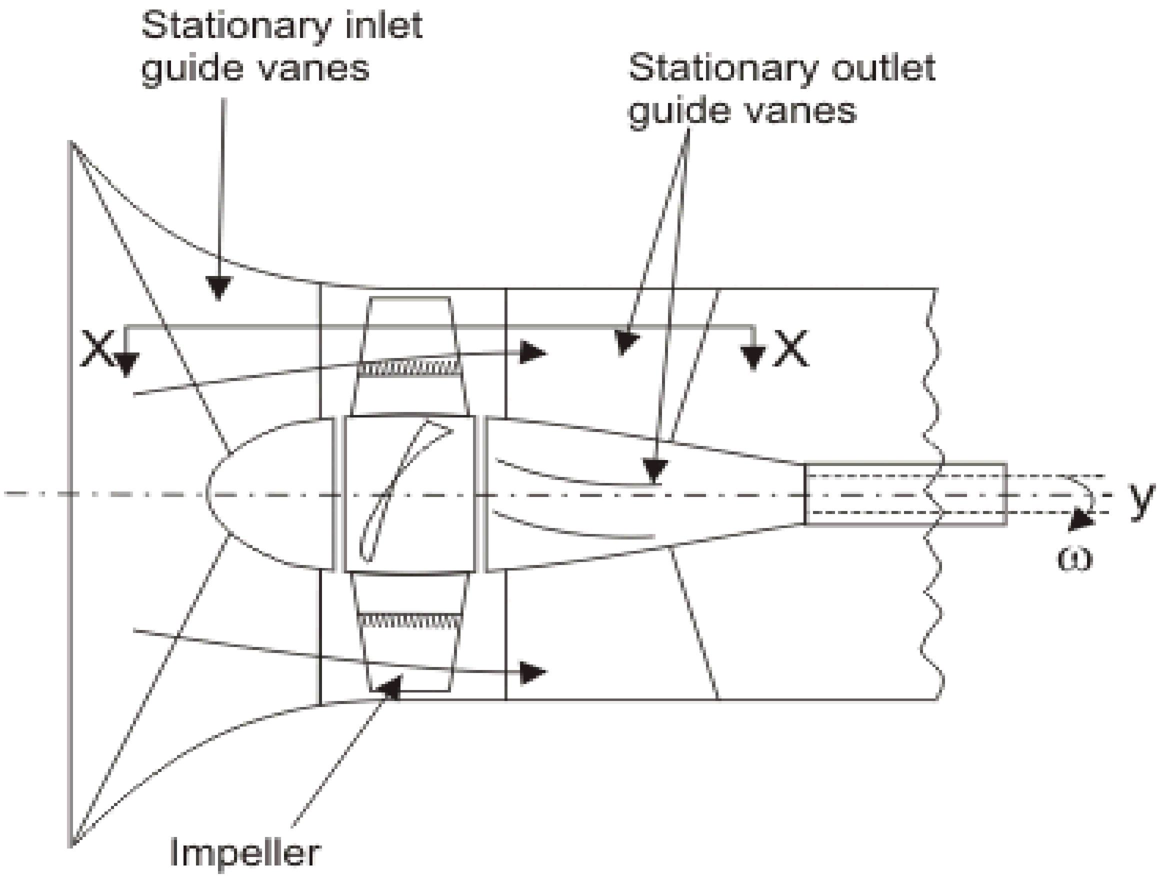


Types of impellers in a centrifugal pump

Axial Flow or Propeller Pump

- The axial flow or propeller pump is the converse of axial flow turbine and is very similar to it an appearance.
- The impeller consists of a central boss with a number of blades mounted on it.
- The impeller rotates within a cylindrical casing with fine clearance between the blade tips and the casing walls.
- Fluid particles, in course of their flow through the pump, do not change their radial locations.

- The inlet guide vanes are provided to properly direct the fluid to the rotor. The outlet guide vanes are provided to eliminate the whirling component of velocity at discharge.
- The usual number of impeller blades lies between 2 and 8, with a hub diameter to impeller diameter ratio of 0.3 to 0.6.

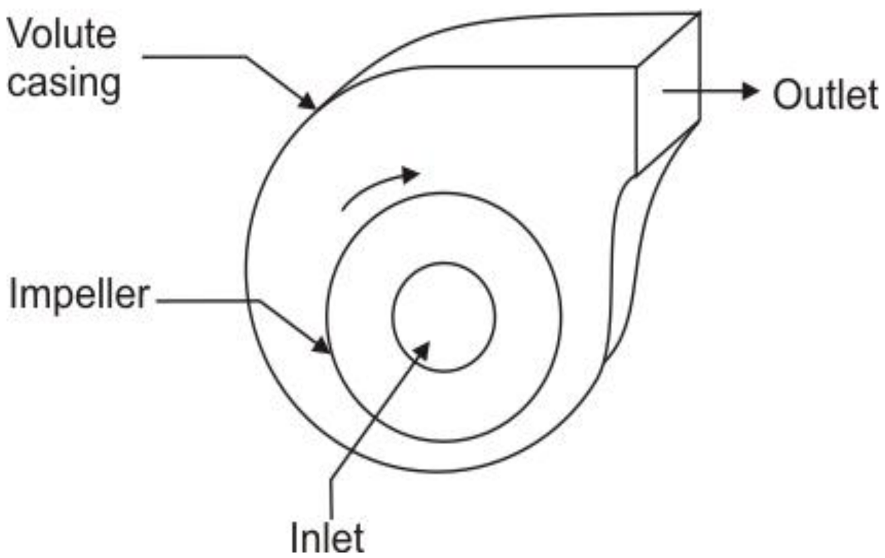


A propeller of an axial flow pump

Fans

- Fans and blowers are turbo-machines which deliver air at a desired high velocity (and accordingly at a high mass flow rate) but at a relatively low static pressure.
- The pressure rise across a fan is extremely low and is of the order of a few millimeters of water gauge.
- The upper limit of pressure rise is of the order of 250mm of water gauge. The rise in static pressure across a blower is relatively higher and is more than 1000 mm of water gauge that is required to overcome the pressure losses of the gas during its flow through various passages.

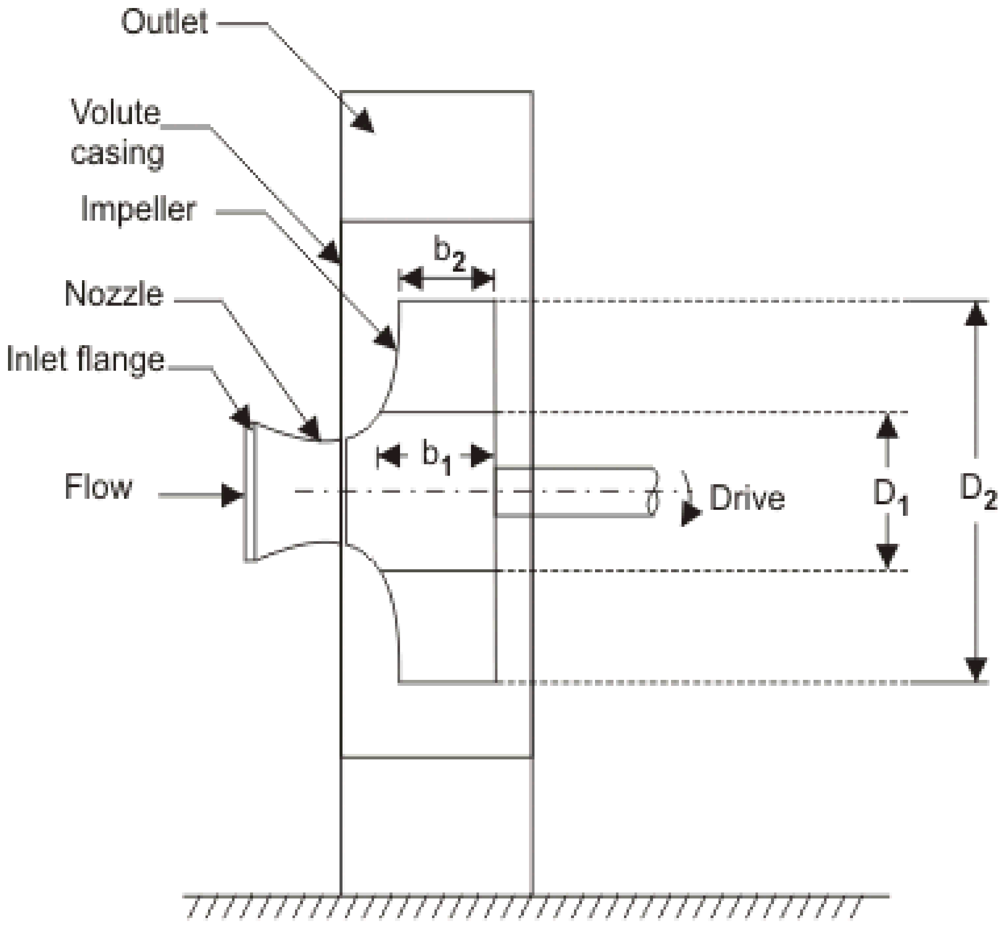
- A blower may be constructed in multistages for still higher discharge pressure.



A centrifugal fan or blower

- A large number of fans and blowers for relatively high pressure applications are of centrifugal type. The main components of a centrifugal blower are shown in Fig. 2.
- A blower consists of an impeller which has blades fixed between the inner and outer diameters. The impeller can be mounted either directly on the shaft extension of the prime mover or separately on a shaft supported between two additional bearings.
- Air or gas enters the impeller axially through the inlet nozzle which provides slight acceleration to the air before its entry to the impeller.

- The action of the impeller swings the gas from a smaller to a larger radius and delivers the gas at a high pressure and velocity to the casing. The flow from the impeller blades is collected by a spiral-shaped casing known as *volute casing* or *spiral casing* .
- The casing can further increase the static pressure of the air and it finally delivers the air to the exit of the blower.



Main components of a centrifugal blower

Thank You