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Fluid Mechanics and Machinery

Course Code: 23BTMEL201

B. Tech. - III Semester

Prepared by:

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Teaching and Evaluation Scheme

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Course Title: **Fluid Mechanics and Machinery**											
Semester	III	Teaching Scheme				Evaluation Scheme					
						Theory			Practical		
Term	Odd	Th	Tu	Pr	Credits	TAE	CAE	ESE	INT	EXT	
Course Category	PCC2	3 Hrs	-	2 Hrs	04	10	15	50	25	-	
Course Code	23BTMEL201 23BTMEP201										
Teaching Mode	Offline	5 Hrs.			Total	75			25		
Duration of ESE	3 Hrs.					100					

Course Objectives and Outcomes

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Course Objectives	1. To understand the basic fluid properties like density, specific gravity, viscosity, etc..
	2. To understand kinematics and dynamics of fluid flow.
	3. To study hydraulic losses in fluid flow system & various techniques of dimensional analysis.
	4. To study the working principles of hydraulic turbines and pumps& its performance characteristics.
Course Outcomes	Upon successful completion of this course, student shall be able to:
	CO 1. Understand the fluid properties and apply hydrostatic laws on submerged surfaces.
	CO 2. Evaluate the fluid flow kinematics and the basic principles of fluid dynamics.
	CO 3. Evaluate head losses for flow through pipe for given hydraulic systems and apply dimensional technique to fluid flow problems.
	CO 4. Evaluate the performance parameters of impulse and reaction turbines.
	CO 5. Design and evaluate performance characteristics of centrifugal and reciprocating pump.

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Mapping of Course Outcomes with Program Outcomes and Program Specific Outcomes:

Course Outcomes	Program Outcomes and Program Specific Outcomes														
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO 10	PO 11	PO12	PSO 1	PSO 2	PSO 3
CO1	3	3	3	2	-	-	-	2	-	2	-	3	3	3	3
CO2	3	3	3	2	-	-	-	2	-	3	-	3	3	3	3
CO3	3	3	3	3	-	-	-	2	-	2	-	3	3	3	3
CO4	3	3	3	3	-	-	-	2	-	3	-	3	3	3	3
CO5	3	3	3	3	-	-	-	2	-	2	-	3	3	3	3

Syllabus

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Unit	Contents
Unit 1	**Properties of Fluid:** Density, Specific gravity, Specific Weight, Specific Volume, Dynamic Viscosity, Kinematic Viscosity, Surface tension, Capillarity, Vapor Pressure. Fluid pressure, Pressure head, Pressure intensity, Concept of absolute, Vacuum, gauge and atmospheric pressure. Simple and differential manometers, Bourdon tube pressure gauge.
Unit 2	**Kinematics& Dynamics of fluid flows:** Types of fluid flows, Kinematics of fluid flow, Continuity equation, Bernoulli's theorem, Venturimeter – Construction, principle of working, Coefficient of discharge & derivation for discharge through venturimeter. Orifice meter – Construction, principle of working & derivation for discharge through Orifice meter, Pitot tube –Construction & Principle of Working.
Unit 3	**Flow through Pipes:** Darcy's equation for frictional losses, Major & Minor losses in pipes, Hydraulic gradient line and total energy line. Pipe in series and parallel. **Dimensional Analysis:** Fundamental dimensions, dimensional Homogeneity, Rayleigh's method and Buckingham's method.

Syllabus

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Unit	Contents
Unit 4	**Hydraulic Turbines:** Impact of Jet, Theory of impulse & reaction turbines, Principle, Constructional features, performance characteristics, analysis and governing.
Unit 5	**Hydraulic Pumps:** Classification of pumps. Working principle, construction and performance characteristics of Centrifugal and Reciprocating Pumps.

Study Material

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Text Books	1.	A Textbook of Fluid Mechanics and Hydraulic Machines, Dr. R. K. Bansal, 9th Edition, Laxmi Publications, New Delhi, 2017.
	2.	Fluid Mechanics and Fluid Power Engineering, Dr. D.S. Kumar, 8th Edition, S. K.Kataria & Sons, New Delhi, 2013.
	3.	A Text book of Fluid Mechanics and Hydraulic Machines, R.K. Rajput, S. Chand, 4th edition 2013.
E -Books	1.	Fluid Mechanics and Machinery, C.P.Kothandaraman & R. Rudramoorthy, 2nd Edition, New Age International, 2007.
	2.	Hydraulic Machines, K. Subramanya, 1st Edition, Tata McGraw Hill Publication Co., New Delhi, 2013.
Reference Books	1.	Hydraulics and Fluid Mechanics Including Hydraulics Machines, Dr. P.N. Modi & S.M. Seth, 18th Edition, Standard Book House, New Delhi, 2011.
	2.	Fluid Mechanics, F. M. White, 6th Edition, McGraw Hill Publications, 2011
	3.	Hydraulic Machines (including Fluidics), Dr. Jagdish Lal , 6th Edition, Metropolitan Book Co., New Delhi, 2016.

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Unit 1

Properties of Fluid:

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- Introduction to Fluid Mechanics
- Types of Fluid
- Applications of Fluid
- Properties of Fluid
- Pressure Measurement

Introduction

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- Intermolecular cohesive forces are large in solids, smaller in liquids & extremely small in gases & on account of this fact, solids posses compact & rigid form, liquid molecules can move freely within the liquid mass & molecules of gases have greater freedom of movement.
- Another difference between the solids & fluids is in their relative abilities to resists the external forces.
- A solid can resist tensile, compressive & shear stresses up to a certain limit.
- A fluid has no tensile strength & it can resist the compressive forces only when it is kept in a container. When it is subjected to a shearing force, a fluid deforms continuously as long as this shear force is applied.

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Distinction between solid & Fluid

- A substance exists in three primary phases: solid, liquid, and gas. A substance in the liquid or gas phase is referred to as a **fluid.**
- Distinction between a solid and a fluid is made on the basis of the substance's ability to resist an applied shear (or tangential) stress that tends to change its shape.
- A solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of shear stress, no matter how small.
- In solids, stress is proportional to strain, but in fluids stress is proportional to strain rate.

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Definition

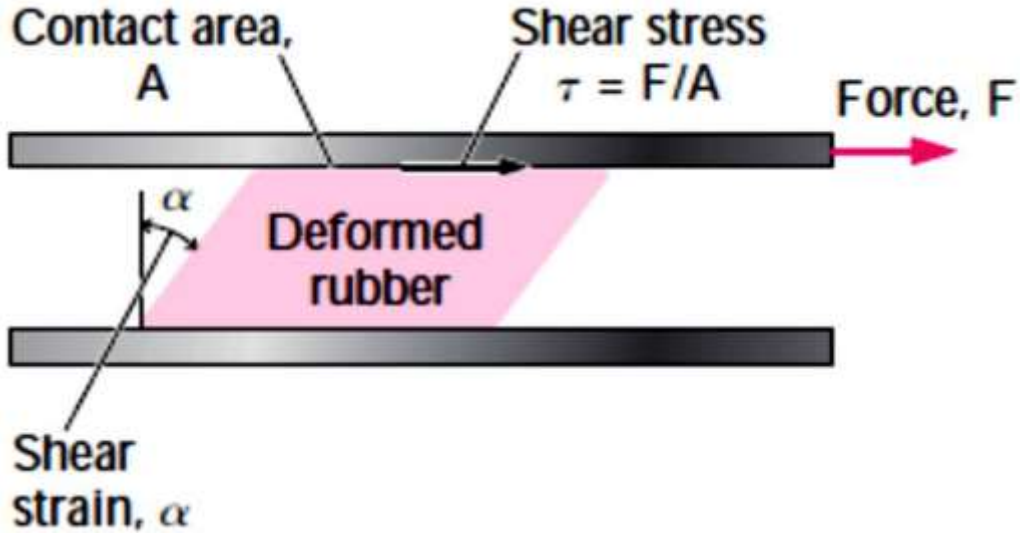
- **Fluid Mechanics:** It is that branch of science which deals with the behavior of the fluids at rest as well as in motion.
- **Fluid mechanics is divided in to three branches:**

- **Fluid Statics:** It is the study of mechanics of fluids at rest.
- **Fluid Kinematics:** It is the study of fluids in motion when the forces are not considered. It deals with velocities & acceleration without considering the forces.
- **Fluid Dynamics:** It is the study of fluids in motion when the forces are considered.

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What is a Fluid?

- **It is defined as a substance which is capable of flowing & it deforms continuously when it is subjected to tangential or shear stress.**



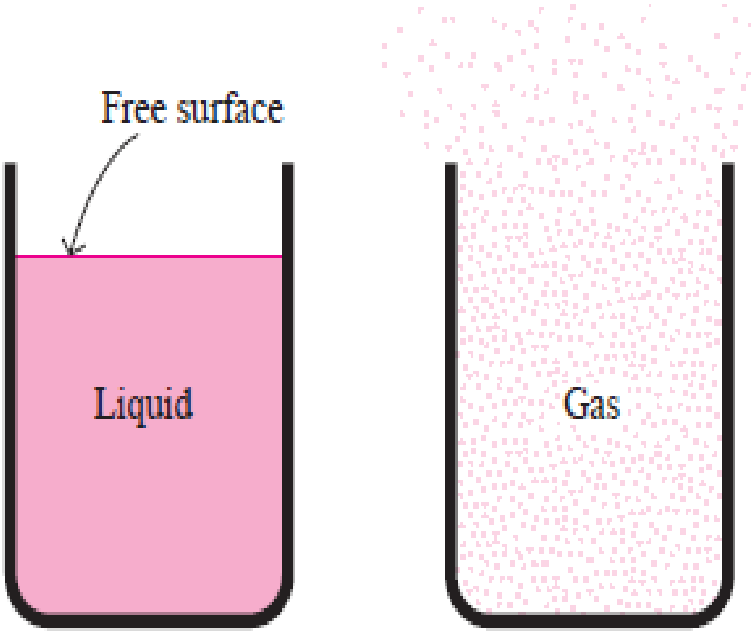
Figure

Deformation of a rubber eraser placed between two parallel plates under the influence of a shear force.

Difference between Liquid & Gases

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- In a liquid, molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules.
- As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational field.
- A gas, on the other hand, expands until it encounters the walls of the container and fills the entire available space.
- This is because the gas molecules are widely spaced, and the cohesive forces between them are very small.
- Unlike liquids, gases cannot form a free surface.



Differences between liquid and gases

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Liquid	Gases
Difficult to compress and often regarded as incompressible	Easily to compress – changes of volume is large, cannot normally be neglected and are related to temperature
Occupies a fixed volume and will take the shape of the container	No fixed volume, it changes volume to expand to fill the containing vessels
A free surface is formed if the volume of container is greater than the liquid.	Completely fill the vessel so that no free surface is formed.

Types of Fluids

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1. Ideal Fluid: A fluid, which is incompressible and is having no viscosity, is known as an ideal fluid.Ideal fluid does not exists , it is only an imaginary fluid. The fluid which exists in nature have some viscosity.

2. Real fluid: A fluid, which possesses viscosity, is known as real fluid. All the fluids which exists in nature are real fluids.

3. Newtonian Fluid: A real fluid, in which the shear stress is directly, proportional to the rate of shear strain (or velocity gradient), is known as a Newtonian fluid.

4. Non-Newtonian fluid: A real fluid, in which shear stress is not proportional to the rate of shear strain (or velocity gradient), known as a Non-Newtonian fluid.

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Types of Fluids

5. **Ideal Plastic Fluid.**

A fluid, in which shear stress is more than the yield value and shear stress is proportional to the rate of shear strain (or velocity gradient), is known as ideal plastic fluid.

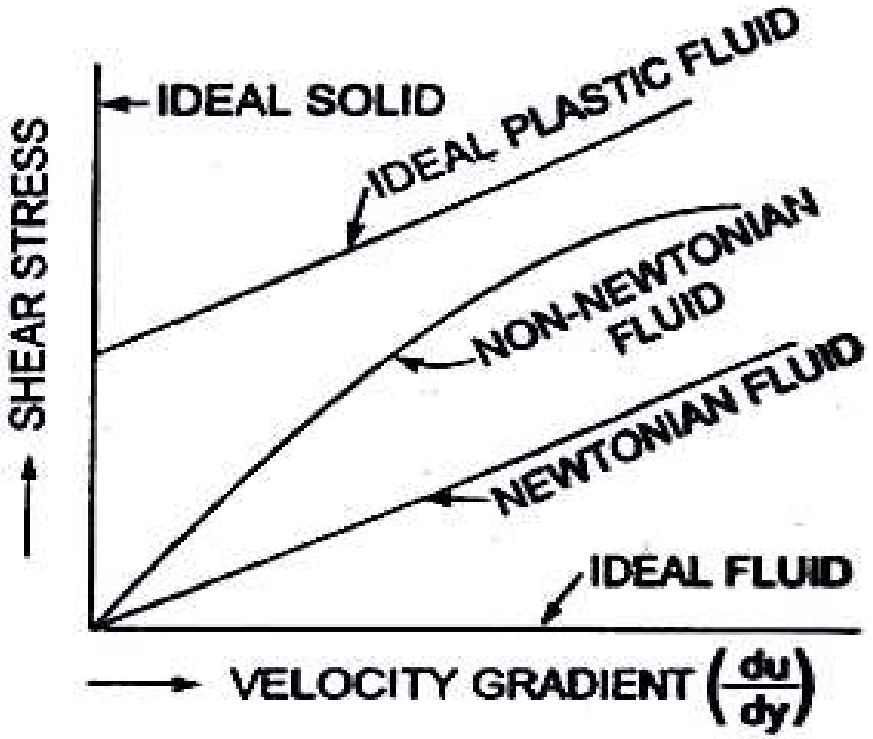


Fig. 1.2 *Types of fluids.*

Application areas of Fluid Mechanics

- Mechanics of fluids is extremely important in many areas of engineering and science. Examples are:
- **Biomechanics**
  - Blood flow through arteries and veins
  - Airflow in the lungs
  - Flow of cerebral fluid
- **Households**
  - Piping systems for cold water, natural gas, and sewage
  - Piping and ducting network of heating and air- conditioning systems
  - refrigerator, vacuum cleaner, dish washer, washing machine, water meter, natural gas meter, air conditioner, radiator, etc.
- **Meteorology and Ocean Engineering**
  - Movements of air currents and water currents

Application areas of Fluid Mechanics

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- **Mechanical Engineering**
  - Design of pumps, turbines, air-conditioning equipment, pollution-control equipment, etc.
  - Design and analysis of aircraft, boats, submarines, rockets, jet engines, wind turbines, biomedical devices, the cooling of electronic components, and the transportation of water, crude oil, and natural gas.
- **Civil Engineering**
  - Transport of river sediments
  - Pollution of air and water
  - Design of piping systems
  - Flood control systems
- **Chemical Engineering**
  - Design of chemical processing equipment

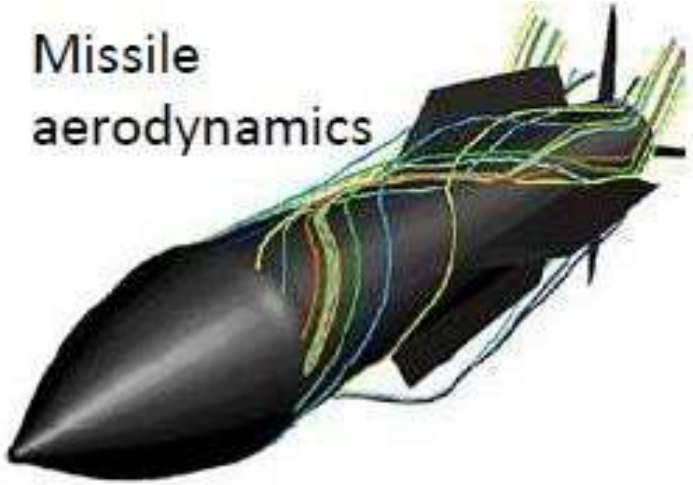
Application areas of Fluid Mechanics

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- **Turbomachines:** Pump, turbine, fan, blower, propeller, etc.
- **Military:** Missile, aircraft, ship, underwater vehicle, dispersion of chemical agents, etc.
- **Automobile:** IC engine, air conditioning, fuel flow, external aerodynamics, etc.
- **Medicine:** Heart assist device, artificial heart valve, Lab-on-a- Chip device, glucose monitor, controlled drug delivery, etc.
- **Electronics:** Convective cooling of generated heat.
- **Energy:** Combuster, burner, boiler, gas, hydro and wind turbine, etc.
- **Oil and Gas:** Pipeline, pump, valve, offshore rig, oil spill cleanup, etc.
- Almost everything in our world is either in contact with a fluid or is itself a fluid.

Application areas of Fluid Mechanics

- The number of fluid engineering applications is enormous: breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, jets, and sprinklers, to name a few.
- When you think about it, almost everything on this planet either is a fluid or moves within or near a fluid.

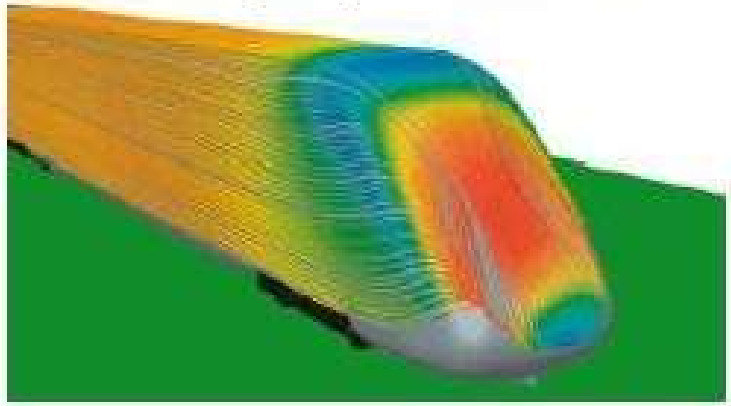




Application areas of Fluid Mechanics

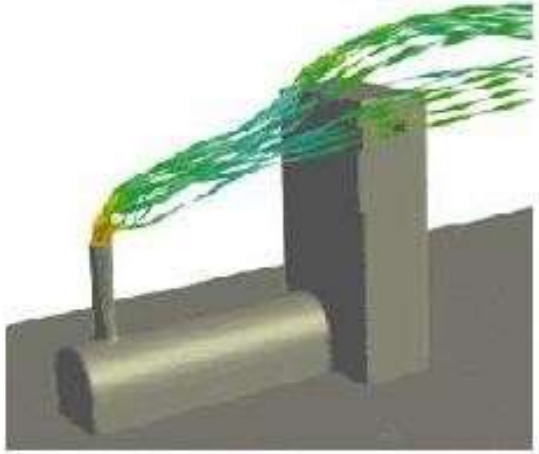
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High speed train



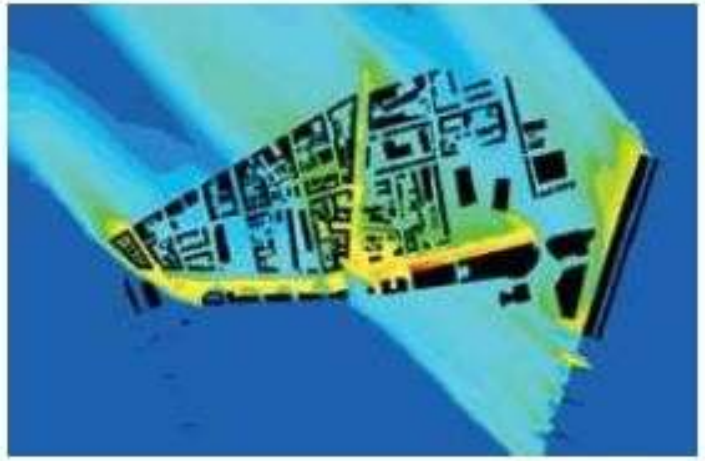


Wind turbines

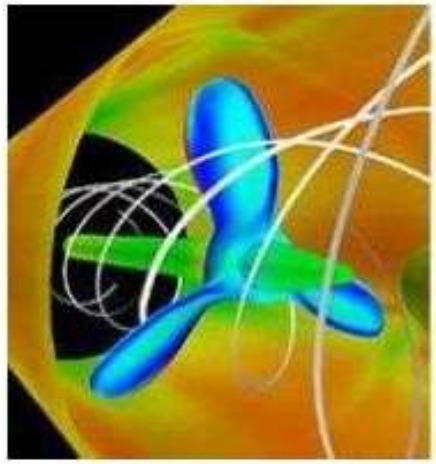


Smoke from a stack

Pollutant dispersion over a city



Application areas of Fluid Mechanics



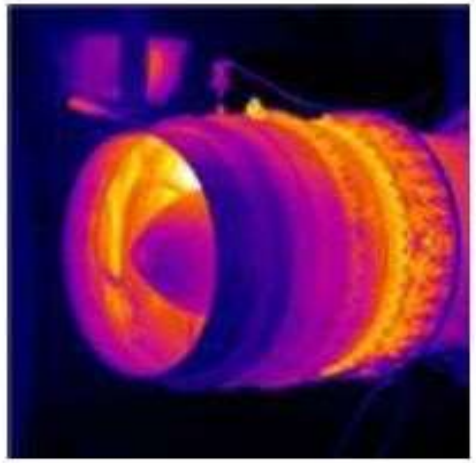
Propeller

Fan

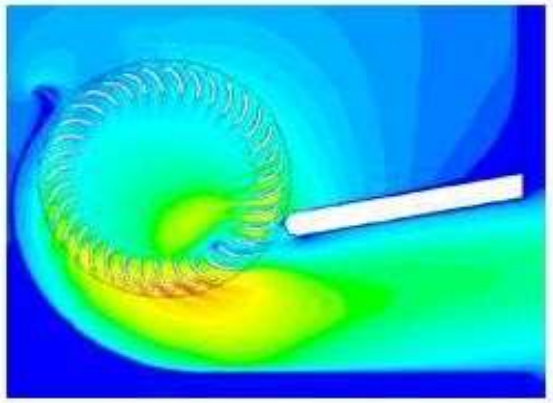


Centrifugal Pump





Jet Engine
Propulsion

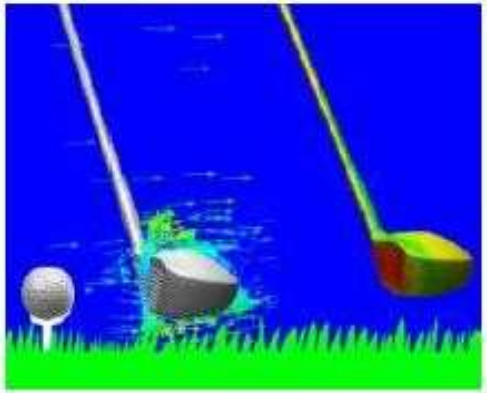


Crossflow fan

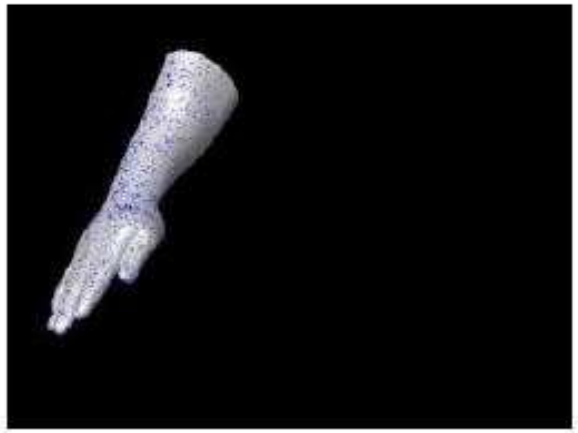
Application areas of Fluid Mechanics



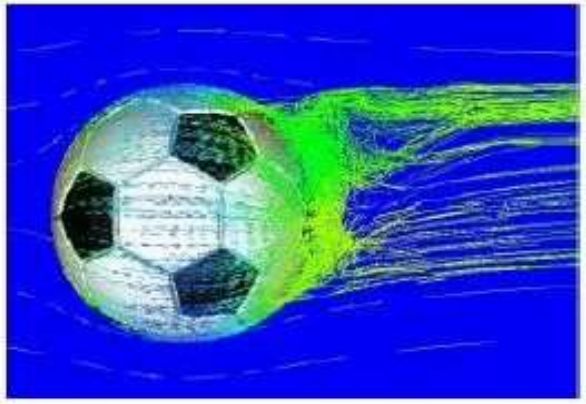
Ski Jumping



Golf



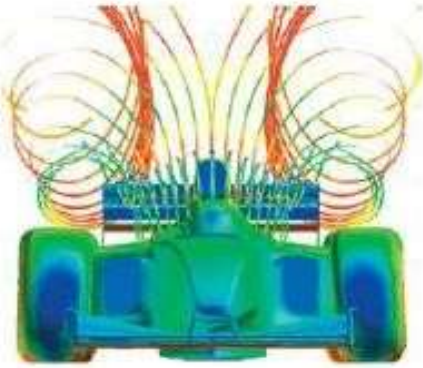
Swimming



Football



Cycling



Indy Car Racing

Properties of Fluids

Density or Mass Density

- Density or mass density of a fluid is defined as the ratio of the mass of a fluid to its volume. Thus mass per unit volume of a fluid is called density. It is denoted by the symbol ρ (rho).The unit of mass density in SI unit is kg per cubic meter, i.e., kg/m^3.
- As the temperature of a fluid increases, spacing between the molecules increases, so fewer molecules exist in a given volume of fluid. So, density decreases with increasing in temperature. By application of pressure, a large number of molecules can be forced into a given volume. So, ρ will increase with increasing pressure.
- Mathematically, mass density is written as.

$$\rho = \frac{\text{Mass of fluid}}{\text{Volume of fluid}}$$

- The mass density of water at 4^0c is $1000\ kg/m^3$.

Properties of Fluids

Specific weight or Weight Density

- Specific weight or weight density of a fluid is the ratio of weight of a fluid to its volume.
- Thus weight per unit volume of a fluid is called weight density and it is denoted by the symbol w or ϒ (gamma).
- Mathematically,

$$w = \frac{\text{Weight of fluid}}{\text{Volume of fluid}} = \frac{\text{(Mass of fluid) x Acceleration due to gravity}}{\text{Volume of fluid}}$$

- **Specific wt. of water at 4^0c is 9810 N/m^3**

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Properties of Fluids

Specific Volume

- Specific volume of a fluid is defined as the volume of a fluid occupied by a unit mass or volume per unit mass of a fluid is called specific volume.
- Mathematically, it is expressed as

$$\text{Specific volume} = \frac{\text{Volume of fluid}}{\text{Mass of fluid}} = \frac{1}{\frac{\text{Mass of fluid}}{\text{Volume}}} = \frac{1}{\rho}$$

- Thus, specific volume is the reciprocal of mass density. It is expressed as m^3/kg.
- It is commonly applied to gases.

Properties of Fluids

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Specific Gravity.

- Specific gravity is defined as the ratio of the weight density (or density) of a fluid to the weight density (or density) of a standard fluid.
- For liquids, the standard fluid is taken water and for gases, the standard fluid is taken air. Specific gravity is also called relative density. It is dimensionless quantity and is denoted by the symbol *S*.

$$S(\text{for liquids}) = \frac{\text{Weight density (density) of liquid}}{\text{Weight density (density) of water}}$$

$$S(\text{for gases}) = \frac{\text{Weight density (density) of gas}}{\text{Weight density (density) of air}}$$

$$\text{Thus weight density of a liquid} = S \times \text{Weight density of water}$$

$$= S \times 1000 \times 9.81 \text{N/m}^3$$

$$\text{Thus density of a liquid} = S \times \text{Density of water}$$

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Properties of Fluids

Specific Gravity.

- If the specific gravity of a fluid is known, then the density of the fluid will be equal to specific gravity of fluid multiplied by the density of water.
- For example the specific gravity of mercury is 13.6, hence density of mercury = 13.6 x 1000 = 13600 kg/m^3.

Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

Properties of Fluids

Example 1.
Calculate the specific weight, density and specific gravity of one liter of a liquid which weighs 7 N.

Solution. Given :

$$\text{Volume} = 1 \text{ litre} = \frac{1}{1000}\text{ m}^3 \quad \left(\because \ 1 \text{ litre} = \frac{1}{1000}\text{ m}^3 \text{ or } 1 \text{ litre} = 1000 \text{ cm}^3\right)$$

$$\text{Weight} = 7 \text{ N}$$

(*i*) Specific weight (w) $= \dfrac{\text{Weight}}{\text{Volume}} = \dfrac{7\text{ N}}{\left(\frac{1}{1000}\right)\text{m}^3} = 7000 \text{ N/m}^3$. Ans.

(*ii*) Density (ρ) $= \dfrac{w}{g} = \dfrac{7000}{9.81} \text{ kg/m}^3 = 713.5 \text{ kg/m}^3$. Ans.

(*iii*) Specific gravity $= \dfrac{\text{Density of liquid}}{\text{Density of water}} = \dfrac{713.5}{1000}$ $\{\because$ Density of water $= 1000 \text{ kg/m}^3\}$

$= 0.7135$. Ans.

Example 2. *Calculate the density, specific weight and weight of one litre of petrol of specific gravity = 0.7*

Solution. Given : Volume = 1 litre = $1 \times 1000\ cm^3 = \frac{1000}{10^6}\ m^3 = 0.001\ m^3$

Sp. gravity $S = 0.7$

(i) Density (ρ)

Density (ρ) $= S \times 1000\ kg/m^3 = 0.7 \times 1000 = \mathbf{700\ kg/m^3}$. **Ans.**

(ii) Specific weight (w)

$w = \rho \times g = 700 \times 9.81\ N/m^3 = \mathbf{6867\ N/m^3}$. **Ans.**

(iii) Weight (W)

We know that specific weight $= \frac{\text{Weight}}{\text{Volume}}$

or $w = \frac{W}{0.001}$ or $6867 = \frac{W}{0.001}$

$\therefore$ $W = 6867 \times 0.001 = \mathbf{6.867\ N}$. **Ans.**

Properties of Fluids

Viscosity

- Viscosity is defined as that property of a fluid by virtue of which it offers resistance to the movement of one layer of fluid over another adjacent layer of the fluid.
- When two layers of a fluid, a distance *'dy' apart move one* over the other at different velocities say u and u+ *du as shown in Fig. 1.1 , the viscosity together with* relative velocity causes a shear stress acting between the fluid laye

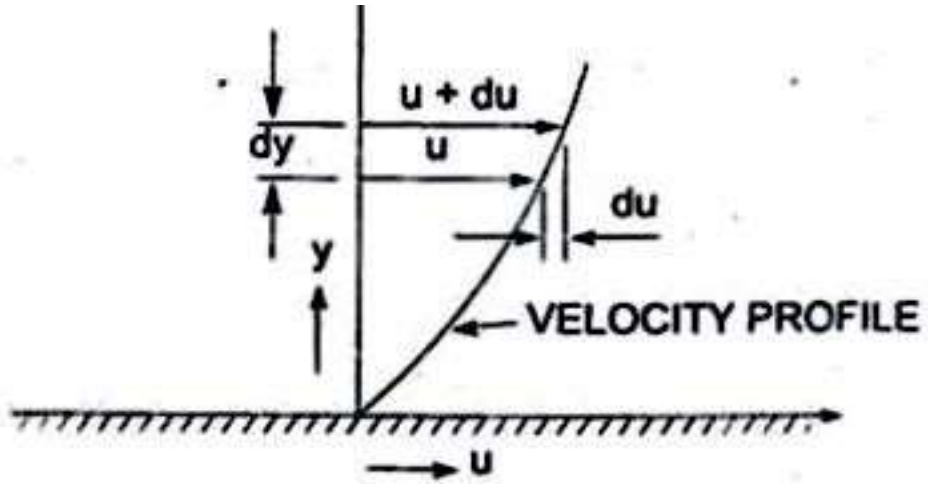


Fig. 1.1 *Velocity variation near a solid boundary.*

Properties of Fluids

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Viscosity

- The top layer causes a shear stress on the adjacent lower layer while the lower layer causes a shear stress on the adjacent top layer.
- This shear stress is proportional to the rate of change of velocity with respect to *y. It is denoted by symbol* τ called Tau.
- Mathematically, $$\tau \propto \frac{du}{dy}$$
- or $$\tau = \mu \frac{du}{dy}$$

The above equation is known as Newton's Law of Viscosity.

- **It states that the shear stress (τ) on a fluid element layer is directly proportional to the rate of shear strain. The constant of proportionality is called the co-efficient viscosity. Mathematically, it is expressed as given by above equation.**

Properties of Fluids

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- where μ (called mu) *is the constant of proportionality and is known as the coefficient of dynamic viscosity* or coefficient of viscosity.
- $\frac{du}{dy}$ *represents the rate of shear strain or rate of shear deformation or velocity gradient.*
- *From previous equation, we have*

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

- Thus viscosity or dynamic viscosity is defined as the shear stress required to produce unit rate of shear strain or angular deformation

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Properties of Fluids

Unit of Viscosity.

- The unit of viscosity is obtained by putting the dimension of the quantities in previous equation

$$\mu = \frac{\text{Shear stress}}{\dfrac{\text{Change of velocity}}{\text{Change of distance}}} = \frac{\text{Force/Area}}{\left(\dfrac{\text{Length}}{\text{Time}}\right) \times \dfrac{1}{\text{Length}}}$$

$$= \frac{\text{Force/(length)}^2}{\dfrac{1}{\text{Time}}} = \frac{\text{Force} \times \text{Time}}{(\text{Length})^2}$$

$$\text{SI unit of viscosity} = \frac{\text{Newton second}}{m^2} = \frac{Ns}{m^2}$$

Dynamic viscosity or viscosity is also expressed in Poise. 1 Poise= 0.1 N-s/m^2

Properties of Fluids

Kinematic Viscosity.

- It is defined as the ratio between the dynamic viscosity and density of fluid.lt is denoted by the Greek symbol (ν) called 'nu' . Thus, mathematically,

$$\nu = \frac{\text{Viscosity}}{\text{Density}} = \frac{\mu}{\rho}$$

- The SI unit of kinematic viscosity is m^2/s.
- It is also measured in stokes.
- 1 stoke= cm^2/s
- 1centistoke=0.01 stoke
- This is defined as kinematic viscosity, so called because force is not involved, the only dimensions being length & time as kinematics.

Effect of temperature on viscosity of Liquids & Gaseous

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- The viscosity of liquids decreases with the increase of temperature while the viscosity of gases increases with increase of temperature.
- In liquids, the viscosity is primarily due to force of cohesion between molecules & as the temp. increases, the force of cohesion diminishes, so viscosity decreases.
- On the other hand in gases, the viscosity is due to molecular momentum exchange between fluid layers & as the temperature increases, interchange of molecules between the layers of different velocities increases. Thus a rapidly moving molecule shifting in to a slower moving layer tends to speed up the latter & a slower moving molecule entering a faster moving layer tends to slow down the faster moving layer. This sets up a shear stresses or produces a friction force between adjacent layers. Thus, increased molecular activity at higher temperatures increases the viscosity of gases.

Example :

If the velocity distribution over a plate is given by

$$u = \frac{2}{3}y - y^2$$

in which u is velocity in metre per second at a distance y metre above the plate, determine the shear stress at y = 0 and y= 0.15 m. Take dynamic viscosity of fluid as 8.63 poises.

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Solution. Given : $u = \frac{2}{3}y - y^2 \quad \therefore \quad \frac{du}{dy} = \frac{2}{3} - 2y$

$$\left(\frac{du}{dy}\right)_{\text{at } y=0} \text{ or } \left(\frac{du}{dy}\right)_{y=0} = \frac{2}{3} - 2(0) = \frac{2}{3} = 0.667$$

Also $$\left(\frac{du}{dy}\right)_{\text{at } y=0.15} \text{ or } \left(\frac{du}{dy}\right)_{y=0.15} = \frac{2}{3} - 2 \times .15 = .667 - .30 = 0.367$$

Value of $\mu = 8.63$ poise $= \frac{8.63}{10}$ SI units $= 0.863$ N s/m^2

Now shear stress is given by equation (1.2) as $\tau = \mu \frac{du}{dy}$.

(*i*) Shear stress at $y = 0$ is given by

$$\tau_0 = \mu \left(\frac{du}{dy}\right)_{y=0} = 0.863 \times 0.667 = \mathbf{0.5756\ N/m^2.\ Ans.}$$

(*ii*) Shear stress at $y = 0.15$ m is given by

$$(\tau)_{y=0.15} = \mu \left(\frac{du}{dy}\right)_{y=0.15} = 0.863 \times 0.367 = \mathbf{0.3167\ N/m^2.\ Ans.}$$

Example :

Calculate the dynamic viscosity of an oil, which is used for lubrication between a square plate of size 0.8 m x 0.8 m and an inclined plane with angle of inclination 30° as shown in Fig. The weight of the square plate is 300 N and it slides down the inclined plane with a uniform velocity of 0.3 m/s. The thickness of oil film is 1.5 mm.

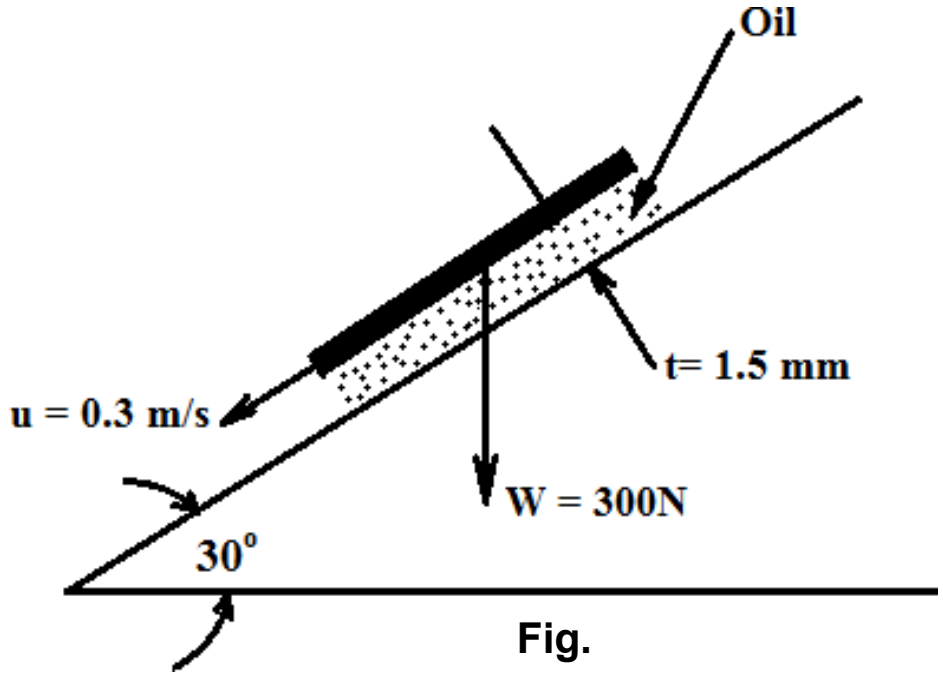


Fig.

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Solution. Given :

Area of plate, $A = 0.8 \times 0.8 = 0.64 \text{ m}^2$

Angle of plane, $\theta = 30°$

Weight of plate, $W = 300 \text{ N}$

Velocity of plate, $u = 0.3 \text{ m/s}$

Thickness of oil film, $t = dy = 1.5 \text{ mm} = 1.5 \times 10^{-3} \text{ m}$

Let the viscosity of fluid between plate and inclined plane is μ.

Component of weight W, along the plane $= W \cos 60° = 300 \cos 60° = 150 \text{ N}$

Thus the shear force, F, on the bottom surface of the plate = 150 N

and shear stress, $$\tau = \frac{F}{\text{Area}} = \frac{150}{0.64} \text{ N/m}^2$$

Now using equation (1.2), we have

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

where du = change of velocity $= u - 0 = u = 0.3 \text{ m/s}$

$$dy = t = 1.5 \times 10^{-3} \text{ m}$$

$$\therefore \quad \frac{150}{0.64} = \mu \frac{0.3}{1.5 \times 10^{-3}}$$

$$\therefore \quad \mu = \frac{150 \times 1.5 \times 10^{-3}}{0.64 \times 0.3} = 1.17 \text{ N s/m}^2 = 1.17 \times 10 = \mathbf{11.7 \text{ poise. Ans.}}$$

Example :

The space between two square flat parallel plates is filled with oil. Each side of the plate is 60 cm. The thickness of the oil film is 12.5 mm. The upper plate, which moves at 2.5 metre per sec requires a force of 98.1 N to maintain the speed.
Determine : ·
i.the dynamic viscosity of the oil, and
ii.the kinematic viscosity of the oil if the specific gravity of the oil is 0.95.

Solution. Given:
Each side of a square plate = 60 cm = 0.6 m
Area A= 0.6 x 0.6 = 0.36 m^2
Thickness of oil film dy = 12.5 mm = 12.5 x 10^{-3} m
Velocity of upper plate u = 2.5 m/s

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$\therefore$ Change of velocity between plates, $du = 2.5$ m/sec

Force required on upper plate, $F = 98.1$ N

$\therefore$ Shear stress, $$\tau = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} = \frac{98.1\,\text{N}}{0.36\,\text{m}^2}$$

(*i*) Let μ = Dynamic viscosity of oil

Using equation (1.2), $$\tau = \mu \frac{du}{dy} \text{ or } \frac{98.1}{0.36} = \mu \times \frac{2.5}{12.5 \times 10^{-3}}$$

$\therefore$ $$\mu = \frac{98.1}{0.36} \times \frac{12.5 \times 10^{-3}}{2.5} = 1.3635 \frac{\text{Ns}}{\text{m}^2}$$ **Ans.**

(*ii*) Sp. gr. of oil, $S = 0.95$

Let ν = kinematic viscosity of oil

Using equation (1.1 A),

Mass density of oil, $$\rho = S \times 1000 = 0.95 \times 1000 = 950 \text{ kg/m}^3$$

Using the relation, $\nu = \frac{\mu}{\rho}$, we get $\nu = \frac{1.3635\left(\frac{\text{Ns}}{\text{m}^2}\right)}{950} = .001435 \text{ m}^2/\text{sec}$ **Ans.**

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Compressibility and Bulk Modulus

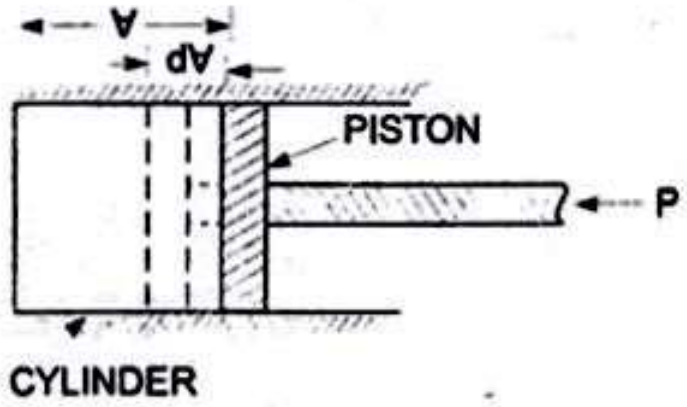
- Compressibility is the reciprocal of the bulk modulus of elasticity, K which is defined as the ratio of compressive stress to volumetric strain.
- Consider a cylinder fitted with a piston as shown in the Fig.
- Let V= *Volume of a gas enclosed in the cylinder*

  p =*Pressure of gas when volume is V*
- Let the pressure is increased *to* $p+dp$, *the volume of gas* decreases from V *to* $V-dV$.
- Then increase in pressure = dp
- Decrease in volume = dV
- Volumetric strain = - dV/V

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Compressibility and Bulk Modulus

- - ve sign means the volume decreases with increase of pressure.



$$\therefore \text{Bulk modules} \quad K = \frac{\text{Increase of pressure}}{\text{Volumetric strain}}$$

$$= \frac{dp}{\frac{-dV}{V}} = -\frac{dp}{dV}V$$

- Compressibility is given by = 1/K

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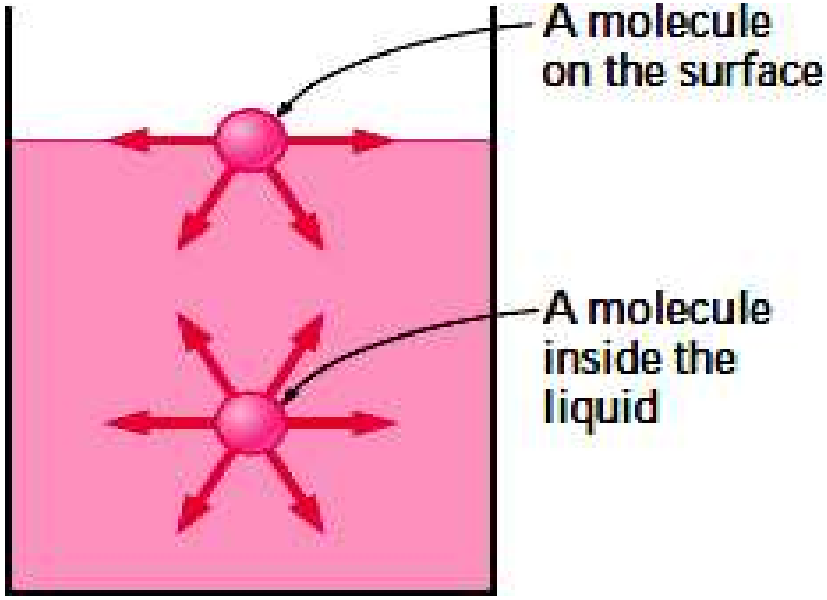
Surface Tension and Capillarity

- Due to molecular attraction, liquids possess certain properties such as cohesion & adhesion.
- Cohesion means intermolecular attraction between molecules of the same liquid. That means it is the tendency of the liquid to remain as one assemblage of particles.
- Adhesion means attraction between the molecules of the liquid & the molecules of a solid boundary surface in contact with the liquid.
- Surface tension is due to cohesion between liquid particles at the surface.
- Whereas, Capillarity is due to both cohesion & adhesion.

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Surface Tension and Capillarity

- A liquid molecule on the interior of the liquid body has other molecules on all sides of it so that the forces of attraction are in equilibrium & the molecule is equally attracted on all sides by the molecules surrounding it.
- On the other hand, a liquid molecule at the surface of the liquid does not have any liquid molecule above it &consequently there is a net downward force on the molecule due to attraction of the molecule below it.
- The surface molecules are pulled inward towards the bulk of liquid.



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Surface Tension and Capillarity

- Surface tension is defined as the tensile force acting on the surface of a liquid in contact with a gas or on the surface between two immiscible liquids such that the contact surface behaves like a membrane under tension.

- Surface tension is created due to the unbalanced cohesive forces acting on the liquid molecules at the fluid surface.

- Molecules in the interior of the fluid mass are surrounded by molecules that are attracted to each other equally.

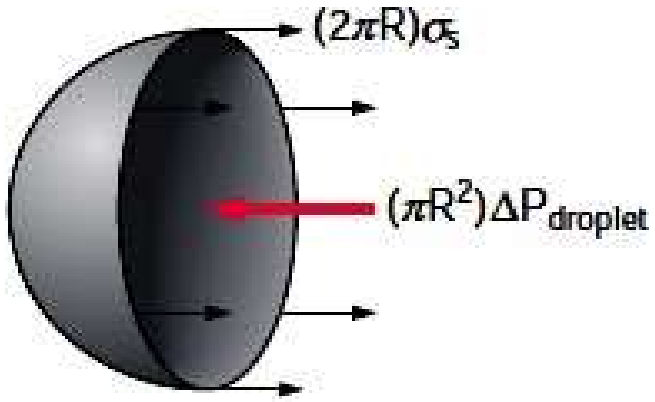
- However, molecules along the surface are subjected to a net force toward the interior.

Surface Tension and Capillarity

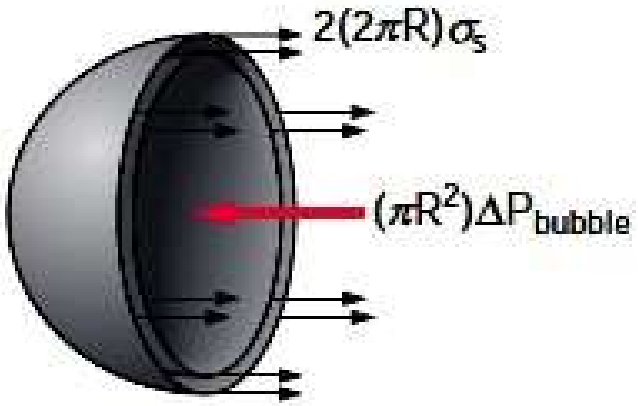
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Surface Tension on liquid Droplet and Bubble

- Consider a small spherical droplet of a liquid of radius *'R'. On the entire surface of the droplet, the tensile force due to surface tension will be acting.*
- Let σ = surface tension of the liquid
- ΔP= Pressure intensity inside the droplet (in excess of the outside pressure intensity)
- *R= Radius of droplet.*
- Let the droplet is cut into two halves. The forces acting on one half (say left half) will be



(a) Half a droplet



(b) Half a bubble

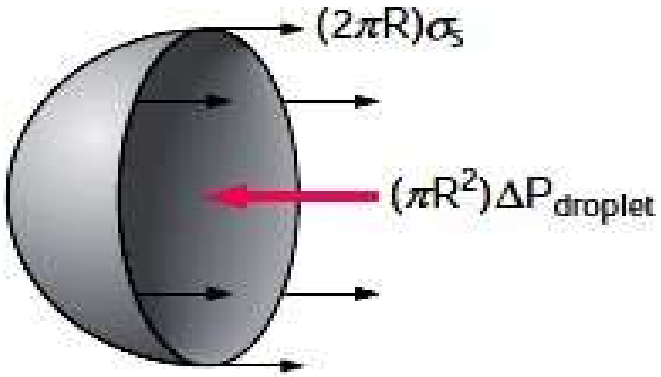
Surface Tension and Capillarity

- (i) tensile force due to surface tension acting around the circumference of the cut portion as shown and this is equal to

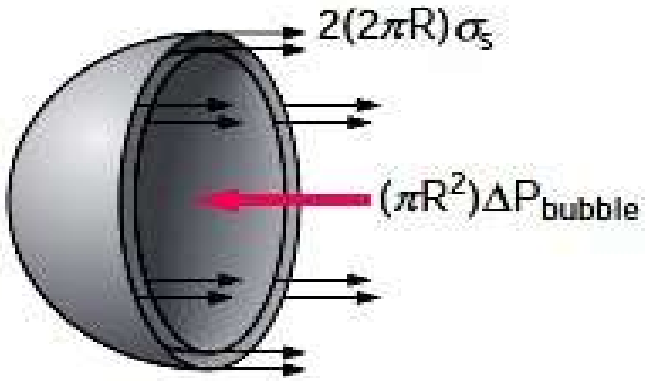
  $= \sigma \times$ Circumference

  $= \sigma \times 2\pi R$

- (ii) pressure force on the area $(\pi/4)d^2$ and
- $= \Delta P \; x \; \pi R^2$ *as shown in Fig. a & b*



(a) Half a droplet



(b) Half a bubble

Fig.

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Surface Tension and Capillarity

- These two forces will be equal and opposite under equilibrium conditions, *i.e.*,

Droplet: $(2\pi R)\sigma_s = (\pi R^2)\Delta P_{droplet} \rightarrow \Delta P_{droplet} = P_i - P_o = \frac{2\sigma_s}{R}$

Bubble: $2(2\pi R)\sigma_s = (\pi R^2)\Delta P_{bubble} \rightarrow \Delta P_{bubble} = P_i - P_o = \frac{4\sigma_s}{R}$

- A hollow bubble like a soap bubble in air has two surfaces in contact with air, one inside and other outside. Thus two surfaces are subjected surface tension. So, surface tension force is doubled in case of hollow bubble.

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Surface Tension……. Example :

- Find the surface tension in a soap bubble of 40 mm diameter when the inside pressure is 2.5 N/m^2 above atmospheric pressure.

Solution. Given :

Dia. of bubble, $d = 40 \text{ mm} = 40 \times 10^{-3} \text{ m}$

Pressure in excess of outside, $p = 2.5 \text{ N/m}^2$

For a soap bubble, using equation (1.15), we get

$$p = \frac{8\sigma}{d} \quad \text{or} \quad 2.5 = \frac{8 \times \sigma}{40 \times 10^{-3}}$$

$$\sigma = \frac{2.5 \times 40 \times 10^{-3}}{8} \text{ N/m} = \mathbf{0.0125 \text{ N/m. Ans.}}$$

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Surface Tension……. Example :

- The pressure outside the droplet of water of diameter 0.04 mm is 10.32 N/cm^2 (atmospheric pressure). Calculate the pressure within the droplet if surface tension is given as 0.0725 N/m of water.

Solution. Given :

Dia. of droplet, $d = 0.04 \text{ mm} = .04 \times 10^{-3} \text{ m}$

Pressure outside the droplet $= 10.32 \text{ N/cm}^2 = 10.32 \times 10^4 \text{ N/m}^2$

Surface tension, $\sigma = 0.0725 \text{ N/m}$

The pressure inside the droplet, in excess of outside pressure is given by

$$\text{or} \qquad p = \frac{4\sigma}{d} = \frac{4 \times 0.0725}{.04 \times 10^{-3}} = 7250 \text{ N/m}^2 = \frac{7250 \text{ N}}{10^4 \text{ cm}^2} = 0.725 \text{ N/cm}^2$$

$\therefore$ Pressure inside the droplet $= p +$ Pressure outside the droplet

$= 0.725 + 10.32 = \mathbf{11.045 \text{ N/cm}^2}$. **Ans.**

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Surface Tension and Capillarity

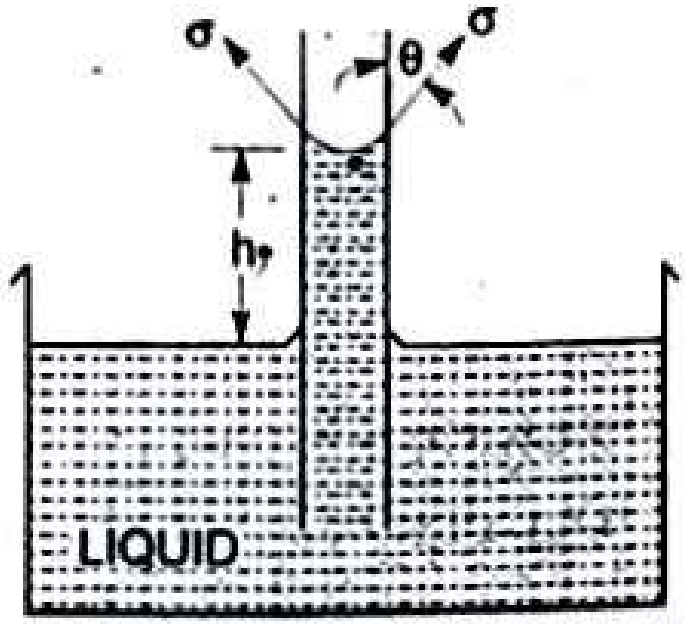
Capillarity

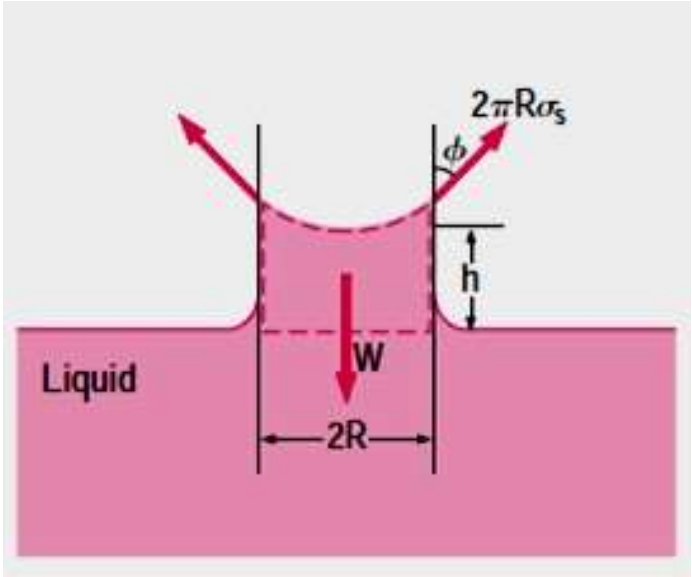
- Capillarity is defined as a phenomenon of rise or fall of a liquid surface in a small tube relative to the adjacent general level of liquid when the tube is held vertically in the liquid.
- The rise of liquid surface is known as capillary rise while the fall of the liquid surface is known as capillary depression.
- The attraction (adhesion) between the wall of the tube and liquid molecules is strong enough to overcome the mutual attraction (cohesion) of the molecules and pull them up the wall. Hence, the liquid is said to *wet the solid surface.*
- It is expressed in terms of cm or mm of liquid. Its value depends upon the specific weight of the liquid, diameter of the tube and surface tension of the liquid.

Surface Tension and Capillarity

Expression for Capillary Rise

- Consider a glass tube of small diameter ‘d’ opened at both ends and is inserted in a liquid, say water.
- The liquid will rise in the tube above the level of the liquid.
- Let h = the height of the liquid in the tube . Under a state of equilibrium, the weight of the liquid of height h is balanced by the force at the surface of the liquid in the tube. But the force at the surface of the liquid in the tube is due to surface tension.





Expression for Capillary Rise…

- Let σ = Surface tension of liquid

  θ = Angle of contact between the liquid and glass tube

- The weight of the liquid of height h in the tube

  = (Area of the tube x h) x ρ x g

$$= \frac{\pi}{4} d^2 \times h \times \rho \times g$$

where ρ = Density of liquid

Vertical component of the surface tensile force

$$= (\sigma \times \text{Circumference}) \times \cos\theta$$

$$= \sigma \times \pi d \times \cos\theta$$

For equilibrium, equating (1.17) and (1.18), we get

$$\frac{\pi}{4} d^2 \times h \times \rho \times g = \sigma \times \pi d \times \cos\theta$$

or

$$h = \frac{\sigma \times \pi d \times \cos\theta}{\frac{\pi}{4} d^2 \times \rho \times g} = \frac{4\sigma\cos\theta}{\rho \times g \times d}$$

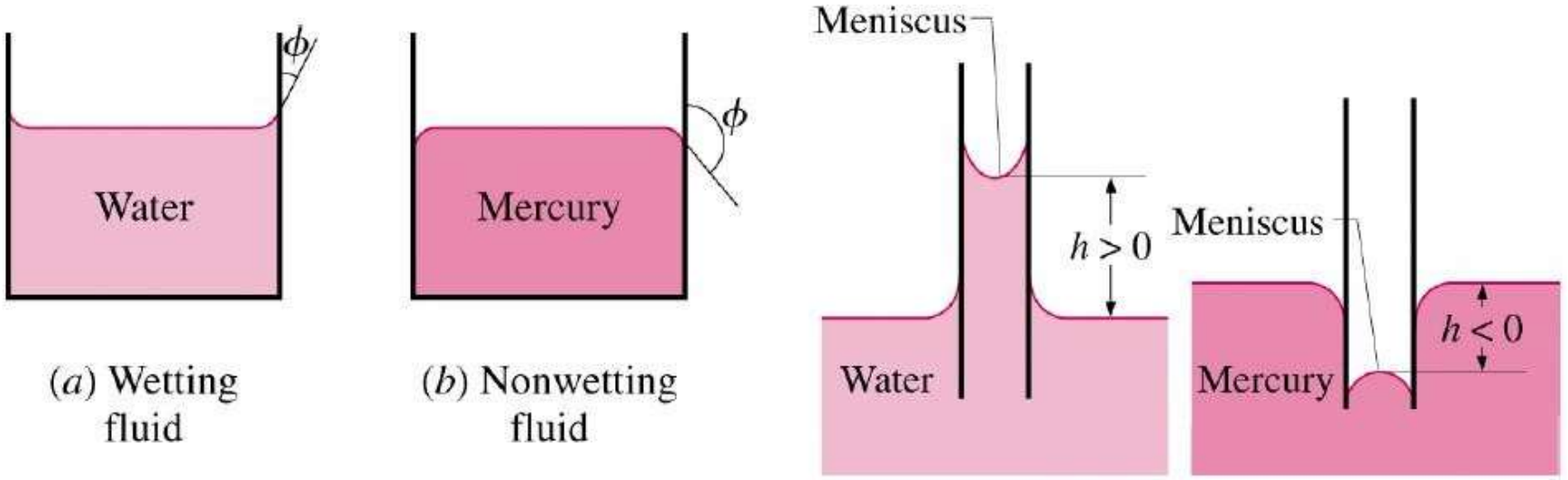
Expression for Capillary Rise…

- The value of θ between water and clean glass tube is approximately equal to zero and hence cos θ is equal to unity. Then rise of water is given by

$$h = \frac{4\sigma}{\rho \times g \times d}$$

- Contact angle depends on both the liquid and the solid.
- If θ is less than 90°, the liquid is said to "wet" the solid. However, if θ is greater than 90°, the liquid is repelled by the solid, and tries not to "wet" it.
- For example, water wets glass, but not wax. Mercury on the other hand does not wet glass.

Capillarity



(a) Wetting fluid

(b) Nonwetting fluid

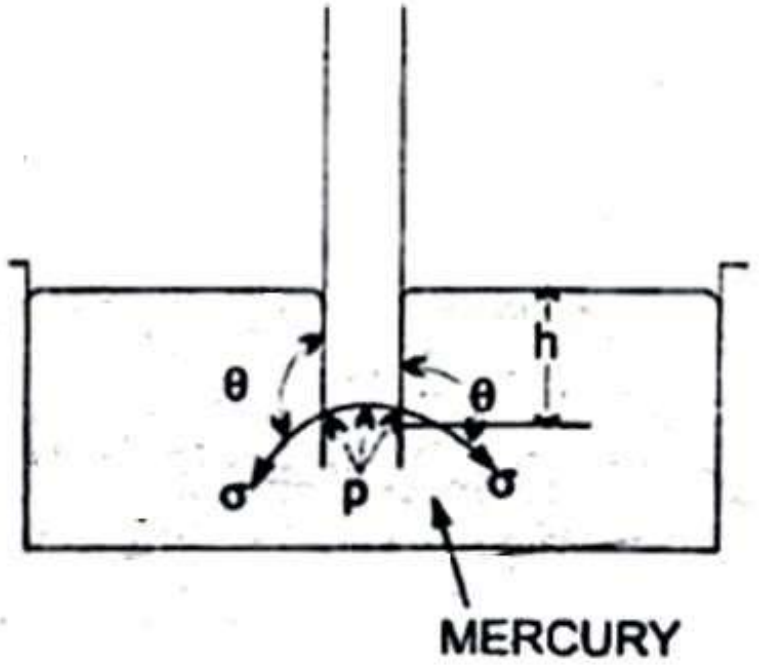
Expression for Capillary Fall

- lf the glass tube is dipped in mercury, the revel of mercury in the tube will be lower than the general level of the outside liquid as shown above.

Capillarity

Expression for Capillary Fall

- Let *h = Height of depression in tube.*
- Then in equilibrium, two forces arc acting on the mercury inside the tube.
- First one is due to surface tension acting in the downward direction and is equal to σ x *πd x cos θ.*
- Second force is due to hydrostatic force acting upward and is equal to intensity of pressure at a depth *'h' x Area*



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Capillarity

Expression for Capillary Fall

$$= p \times \frac{\pi}{4} d^2 = \rho g \times h \times \frac{\pi}{4} d^2 \{\because p = \rho g h\}$$

Equating the two, we get

$$\sigma \times \pi d \times \cos\theta = \rho g h \times \frac{\pi}{4} d^2$$

$$h = \frac{4\sigma \cos\theta}{\rho g d}$$

Value of θ for mercury and glass tube is 128^{o}

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Capillarity…Example :

- Calculate the capillary rise in a glass tube of 2.5 mm diameter when immersed vertically in (a) water and (b) mercury. Take surface tensions $\sigma = 0.0725$ N/m for water and $\sigma = 0.52$ N/m for mercury in contact with air. The specific gravity for mercury is given as 13.6 and angle of contact = 130^{o}.

Solution. Given :

Dia. of tube,	$d = 2.5 \text{ mm} = 2.5 \times 10^{-3}$ m
Surface tenstion, σ for water	= 0.0725 N/m
σ for mercury	= 0.52 N/m
Sp. gr. of mercury	= 13.6

Capillarity...Example

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$\therefore$ **Density** $= 13.6 \times 1000 \text{ kg/m}^3$.

(*a*) Capillary rise for water ($\theta = 0$)

Using equation (1.20), we get $h = \dfrac{4\sigma}{\rho \times g \times d} = \dfrac{4 \times 0.0725}{1000 \times 9.81 \times 2.5 \times 10^{-3}}$

$= .0118 \text{ m} =$ **1.18 cm. Ans.**

(*b*) For mercury

Angle of constant between mercury and glass tube, $\theta = 130°$

Using equation (1.21), we get $h = \dfrac{4\sigma \cos\theta}{\rho \times g \times d} = \dfrac{4 \times 0.52 \times \cos 130°}{13.6 \times 1000 \times 9.81 \times 2.5 \times 10^{-3}}$

$= -.004 \text{ m} =$ **– 0.4 cm. Ans.**

The negative sign indicates the capillary depression.

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Capillarity…Example :

- Find out the minimum size of glass tube that can be used to measure water level if the capillary rise in the tube is to be restricted to 2 mm. Consider surface tension of water in contact with air as 0.073575 N/m.

Solution. Given :

Capillary rise, $h = 2.0 \text{ mm} = 2.0 \times 10^{-3} \text{ m}$

Surface tension, $\sigma = 0.073575 \text{ N/m}$

Let dia. of tube $= d$

The angle θ for water $= 0$

The density for water, $\rho = 1000 \text{ kg/m}^3$

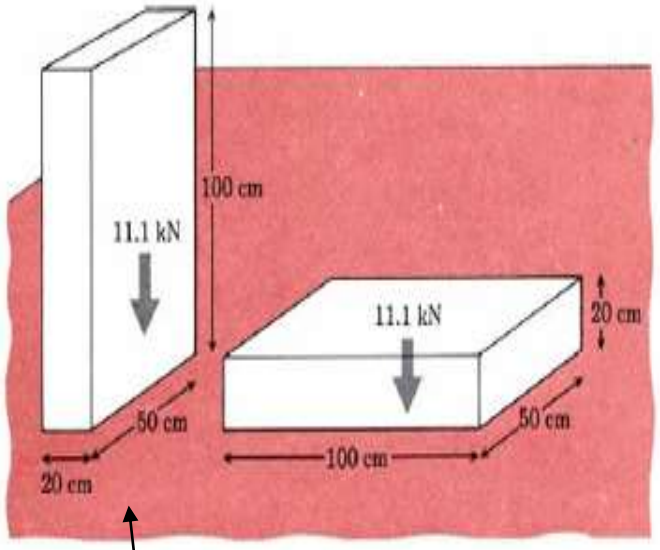
$$h = \frac{4\sigma}{\rho \times g \times d} \text{ or } 2.0 \times 10^{-3} = \frac{4 \times 0.073575}{1000 \times 9.81 \times d}$$

$$\therefore \quad d = \frac{4 \times 0.073575}{1000 \times 9.81 \times 2 \times 10^{-3}} = 0.015 \text{ m} = \mathbf{1.5 \text{ cm. Ans.}}$$

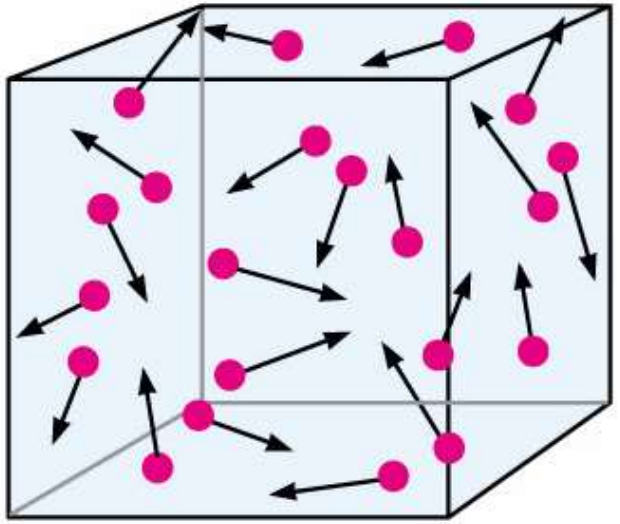
Thus minimum diameter of the tube should be 1.5 cm.

Pressure

- **Pressure is the normal force exerted by a fluid per unit area.**



Greater pressure!
(same force, less area)

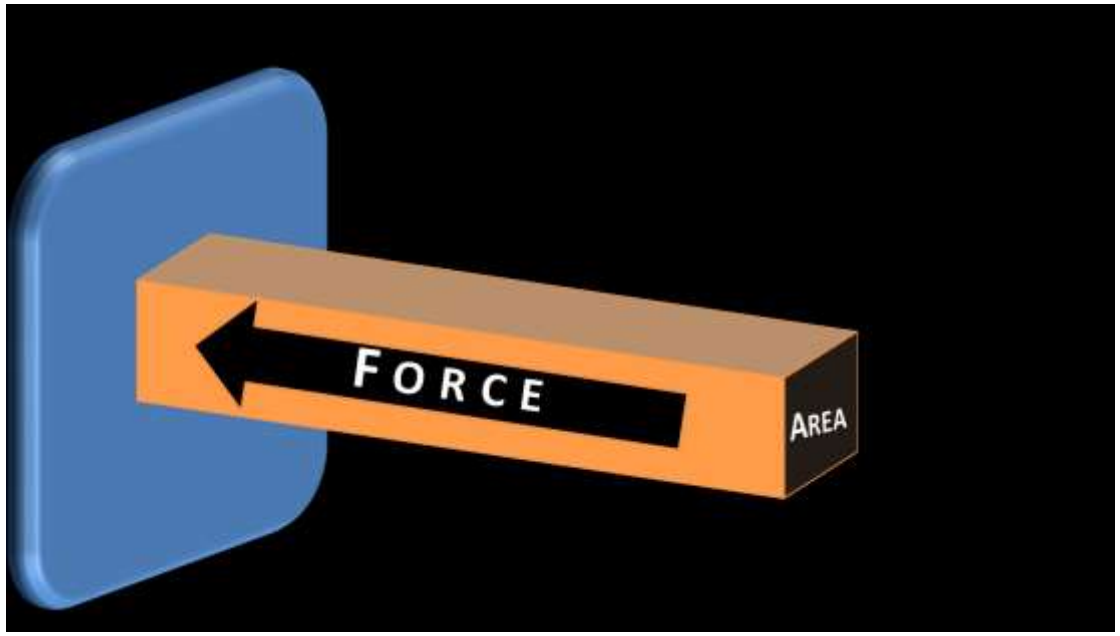


Exerts a pressure on the sides and through the fluid



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Pressure



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

- **Units of pressure** are N/m^2 or Pascals (Pa) – 1 N/m^2 = 1 Pa

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Introduction

- When the fluids at rest (there is no relative motion between adjacent layers),there will be no shearing stresses in the fluid, and the only forces that develop on the surfaces of the particles will be due to the pressure.

- The fluid property responsible for those forces is **pressure**, which is a normal force exerted by a fluid per unit area.

- Thus, our principal concern is to investigate pressure and its variation throughout a fluid and the effect of pressure on submerged surfaces.

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Pressure

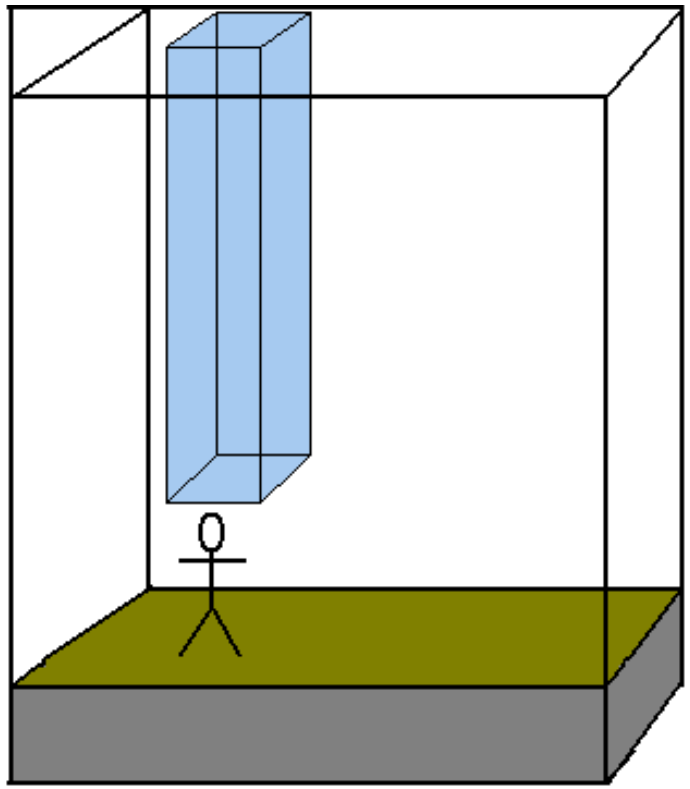
- **Pressure** is defined as a normal force exerted by a fluid per unit area.

- Since pressure is defined as force per unit area, it has the unit of newton per square meter (N/m^2), which is called a **pascal (Pa).** That is,

$$1\ Pa = 1\ N/m^2$$

- The pressure unit pascal is too small for pressures encountered in practice. Therefore, its multiples kilopascal ($1\ kPa = 10^3\ Pa$) and megapascal ($1\ MPa = 10^6\ Pa$) are commonly used.

Atmospheric Pressure



Pressure = Force per Unit Area

The atmospheric air exerts a normal pressure upon all surfaces with witch it is in contact & is known as Atmospheric Pressure. It is also called Barometric Pressure & varies with elevation above sea level.

Standard Atmospheric Pressure:

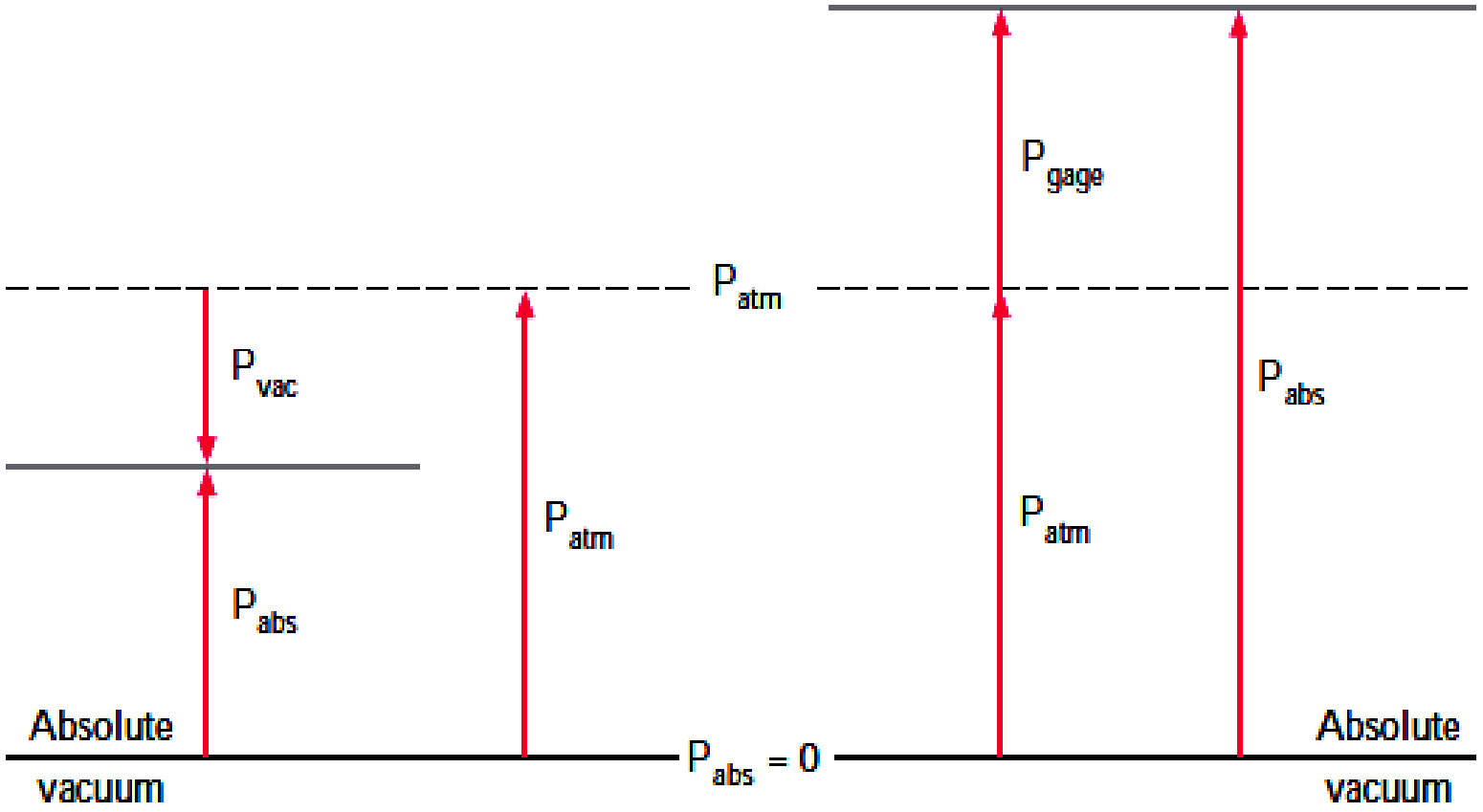
At sea level, the atmospheric pressure is 1.01325 bar

or 1.01325×10^5 Pa

or 760 mm of Hg

or 10.3 m of water.

Atmospheric, Absolute & Gauge Pressure



Pressure

- Other pressure units commonly used in practice, especially in Europe, are bar and standard atmosphere

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa}$$

$$1 \text{ atm} = 101{,}325 \text{ Pa} = 101.325 \text{ kPa} = 1.01325 \text{ bars}$$

- If the pressure is measured relative to absolute zero, it is called **absolute pressure,** and it is measured above absolute zero or complete vacuum.
- When pressure measured relative to atmospheric pressure as a base, it is called **gage pressure.** Most pressure-measuring devices, however, are calibrated to read zero in the atmosphere.
- If the pressure is below that of the atmosphere, it is designated as a **vacuum.**

Gauge Pressure





Gauge Pressure is the pressure difference from atmosphere. (e.g. Tyres)

$$P_{absolute} = P_{atmosphere} + P_{gauge}$$

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Pressure Head

- The vertical height of the free surface above any point in a fluid at rest is known as pressure head.
- The pressure head may be expressed as
- h=p /w
- where, h=height of the free liquid surface above the point & w=weight density of the fluid.
- When pressure is expressed in this fashion, it is commonly referred to as pressure head.

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Pascal's Law

- The pressure at a point in a fluid at rest has the same magnitude in all directions.
- In other words, when the certain pressure is applied at any point in a fluid at rest, the pressure is equally transmitted in all directions & to every other point in the fluid.
- Thus, Pascal's law states that the intensity of pressure is transmitted equally in all directions through a mass of fluid at rest.
- This important result is known as **Pascal's law**

Vapor pressure

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- All liquids have a tendency to evaporate or vaporize i.e. to change from liquid to gaseous state. Such vaporization occurs because of continuous escaping of the molecules through the free liquid surface. The vapor molecules exert a partial pressure in the space above the liquid known as vapor pressure.

- If the space above the liquid is confined, the ejected vapor molecules get accumulated in the space between the free liquid surface & top of the vessel. This accumulated vapor of the liquid exerts a partial pressure on the liquid surface which is known as vapor pressure of the liquid.

- As molecular activity increases with temperature, vapor pressure of the liquid also increases with temperature.

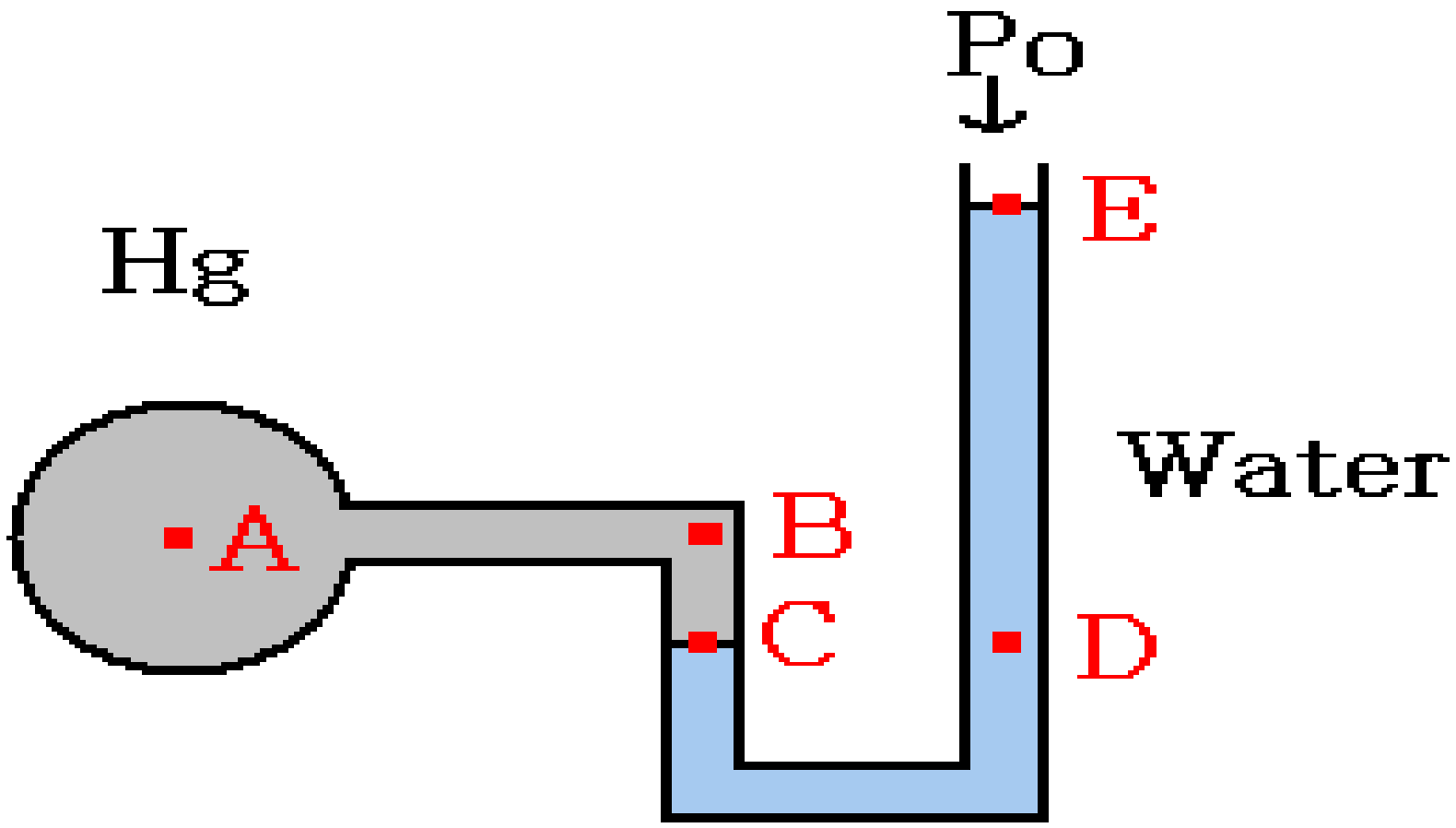
- Mercury has a very low vapor pressure & hence it is an excellent fluid to be used in a barometer.

The Manometer

- **Manometers** are those pressure measuring devices which are based on the principle of balancing the column of liquid (whose pressure is to be found) by the same or another column of liquid & used to measure small and moderate pressure differences.
- Manometers are classified as (i) Simple Manometers (ii) Differential Manometers.
- **Simple manometers** are those which measures pressure at a point in a fluid contained in a pipe.
- **Differential manometers** measure the difference of pressure between any two points in a fluid contained in a pipe.
- Simple manometer mainly consists of a glass or plastic U-tube containing one or more fluids such as mercury, water, alcohol, or oil & having one of its ends connected to the gage point where the pressure is to be measured & other remains open to atmosphere.

U-Tube Manometer

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Differential Manometer

- Manometers are particularly well-suited to measure pressure drops across a horizontal flow section between two specified points due to the presence of a device such as a valve or heat exchanger or any resistance to flow.
- This is done by connecting the two legs of the manometer to these two points, as shown in the Fig.
- The working fluid can be either a gas or a liquid whose density is ρ_1. The density of the manometer fluid is ρ_2, and the differential fluid height is *h*.

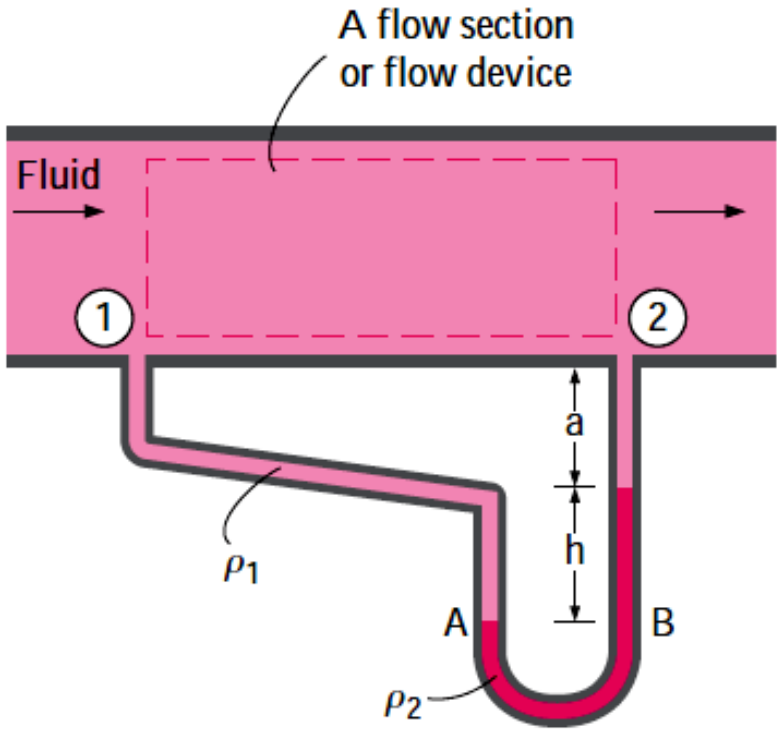


Fig. Measuring the pressure drop across a flow section or a flow device by a differential manometer.

Pressure by Elastic Transducers

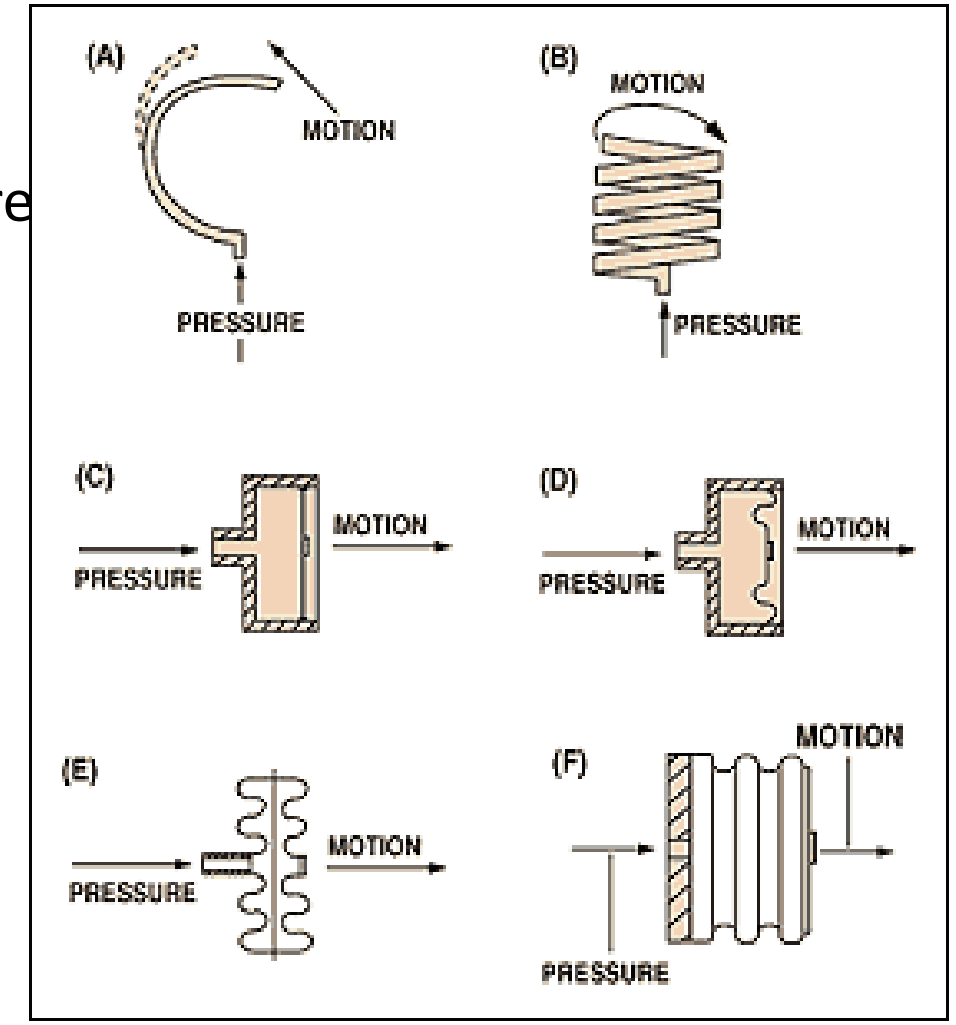
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- Bourdon
- Bellows
- Diaphragm

Uses flexible element as sensor. As pressure changes, the flexible element moved, and this motion is used to rotate a pointer in front of dail

Sensing Elements

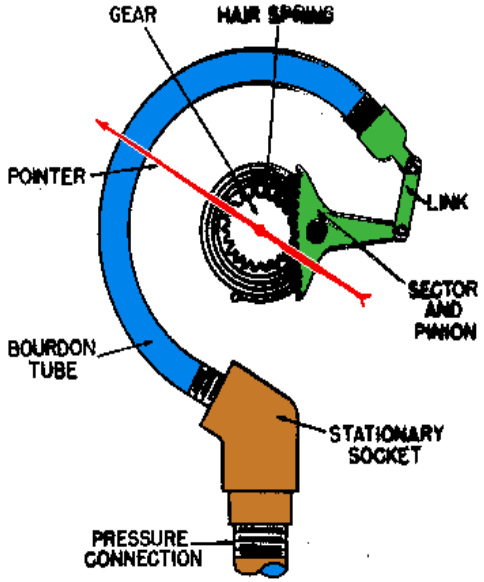
- The main types of sensing elements are Bourdon tubes, diaphragms, capsules, and bellows
- All except diaphragms provide a fairly large displacement that is useful in mechanical gauges and for electrical sensors that require a significant movement

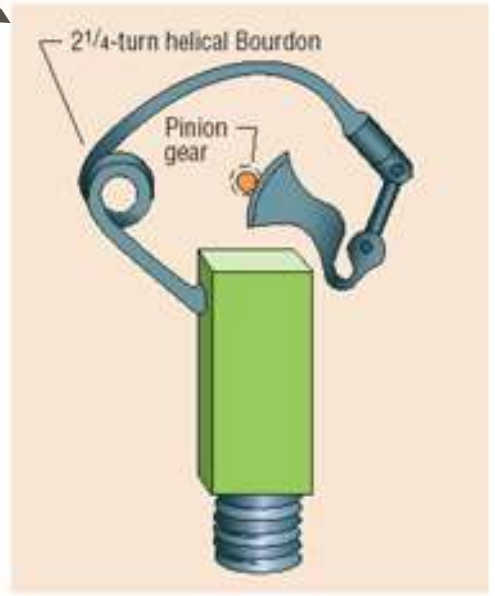


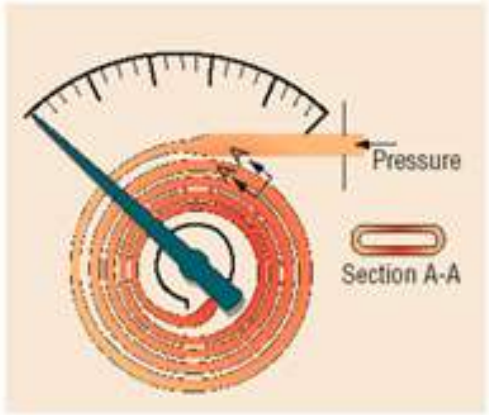
Bourdon Tube Pressure Gauge

Bourdon tubes are generally are of three types

1. **C-type**
2. Helical type
3. Spiral type

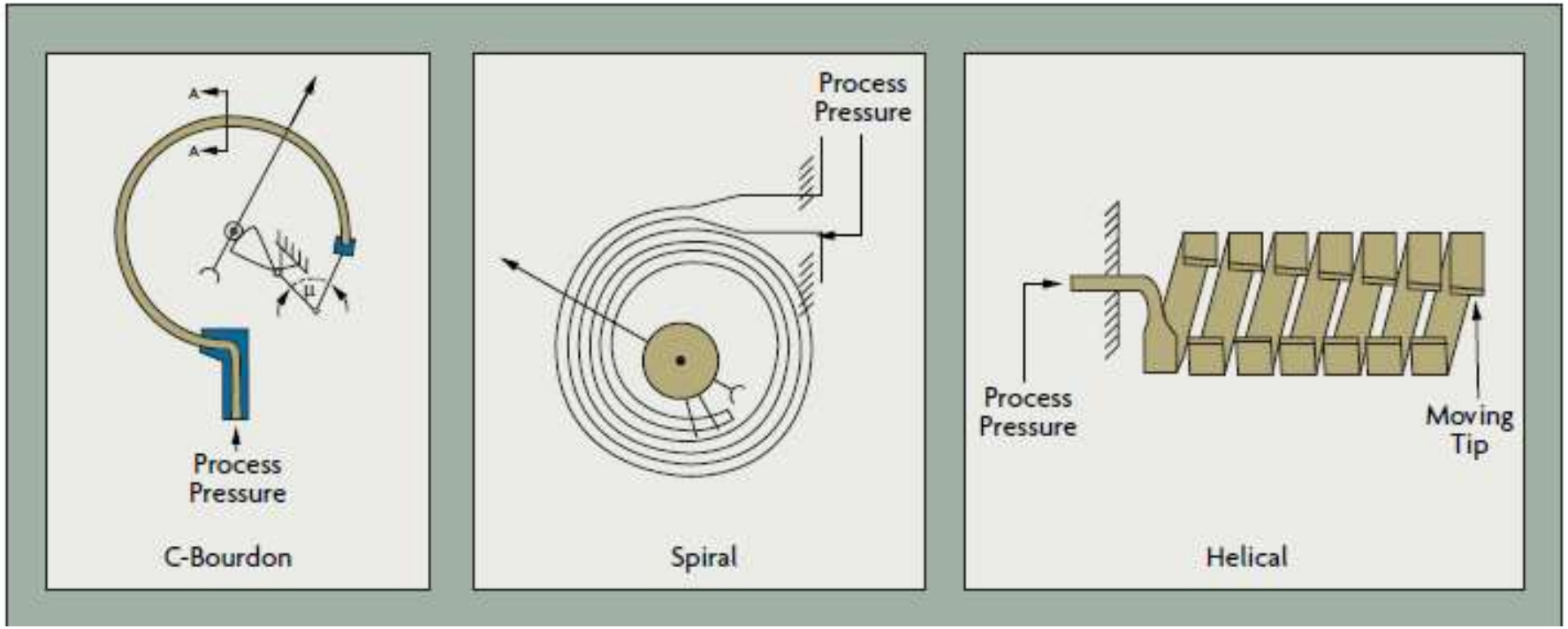


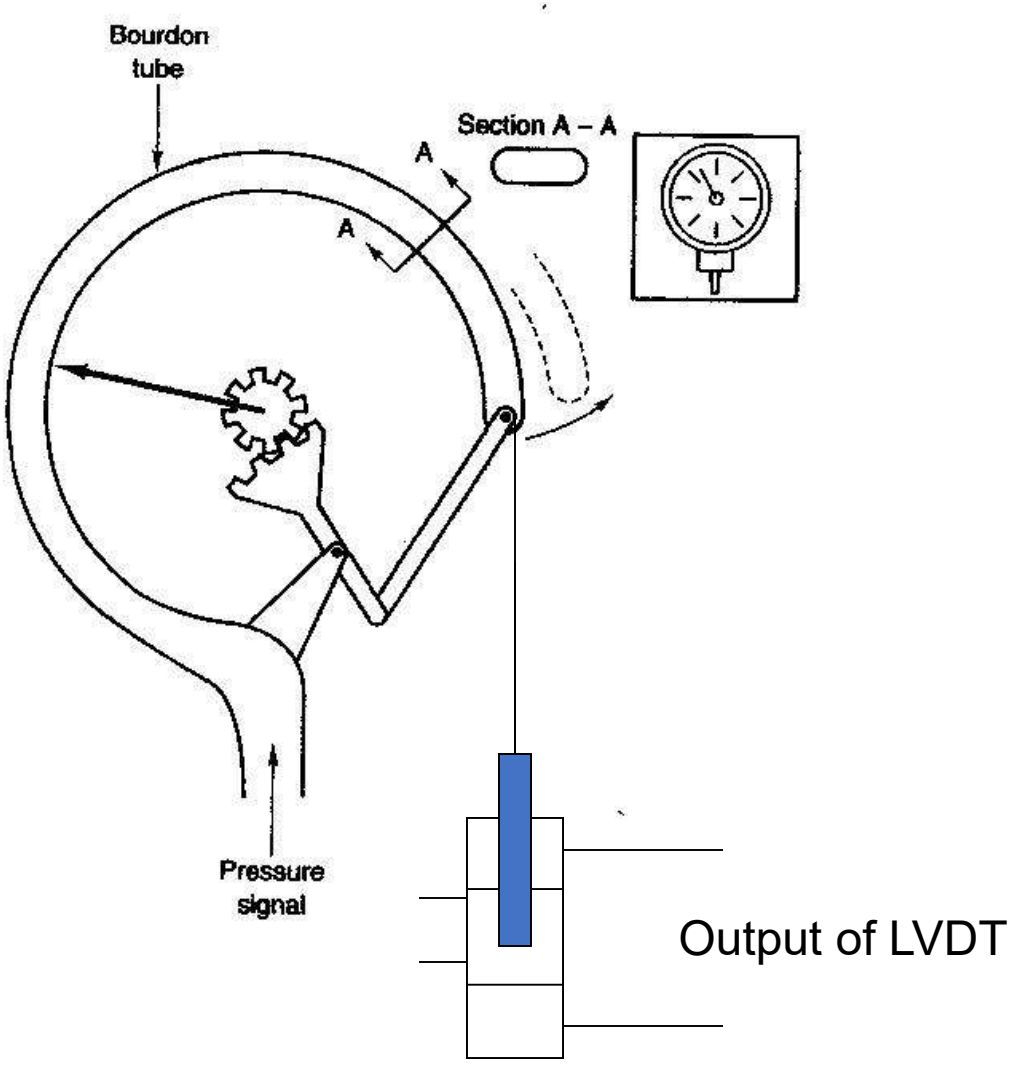




Bourdon Tube Pressure Gauge



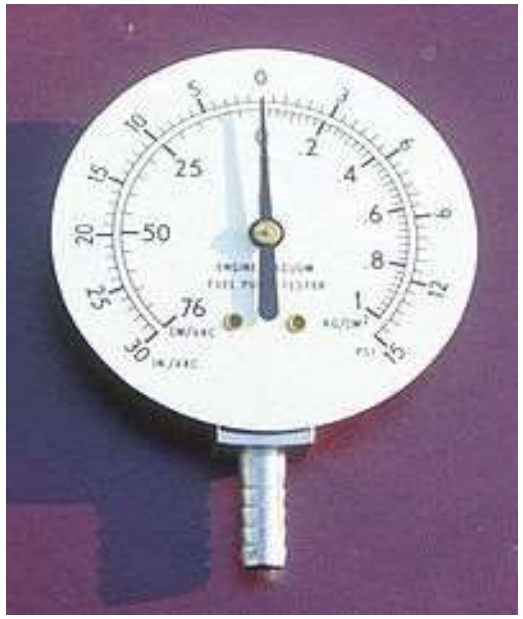


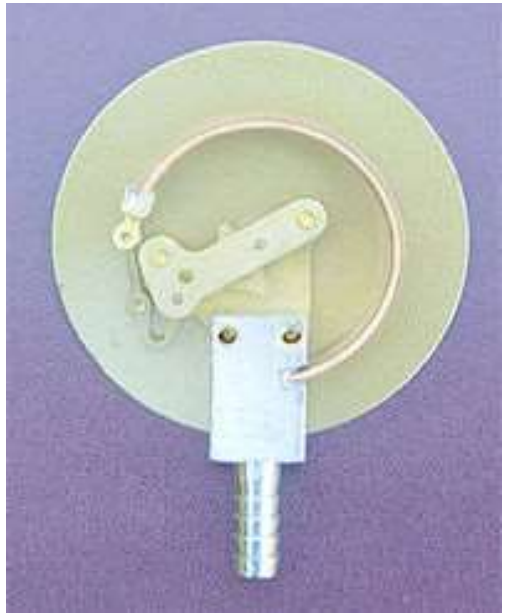

Bourdon tube
Section A – A
A
A
Pressure signal
Output of LVDT

Pressure Measurement

Bourdon gauge

A Bourdon gauge uses a coiled tube, which, as it expands due to pressure increase causes a rotation of an arm connected to the tube.







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Unit 2

Kinematics& Dynamics of fluid flows:

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- **Types of Fluid Flows**

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Classification of Fluid Flows

Steady versus Unsteady Flow

- A flow of fluid is said to be steady if the various characteristics such as velocity, pressure, density at any point doesn't change with time. Steady implies ***no change at a point with time*** ***or independent of time.***

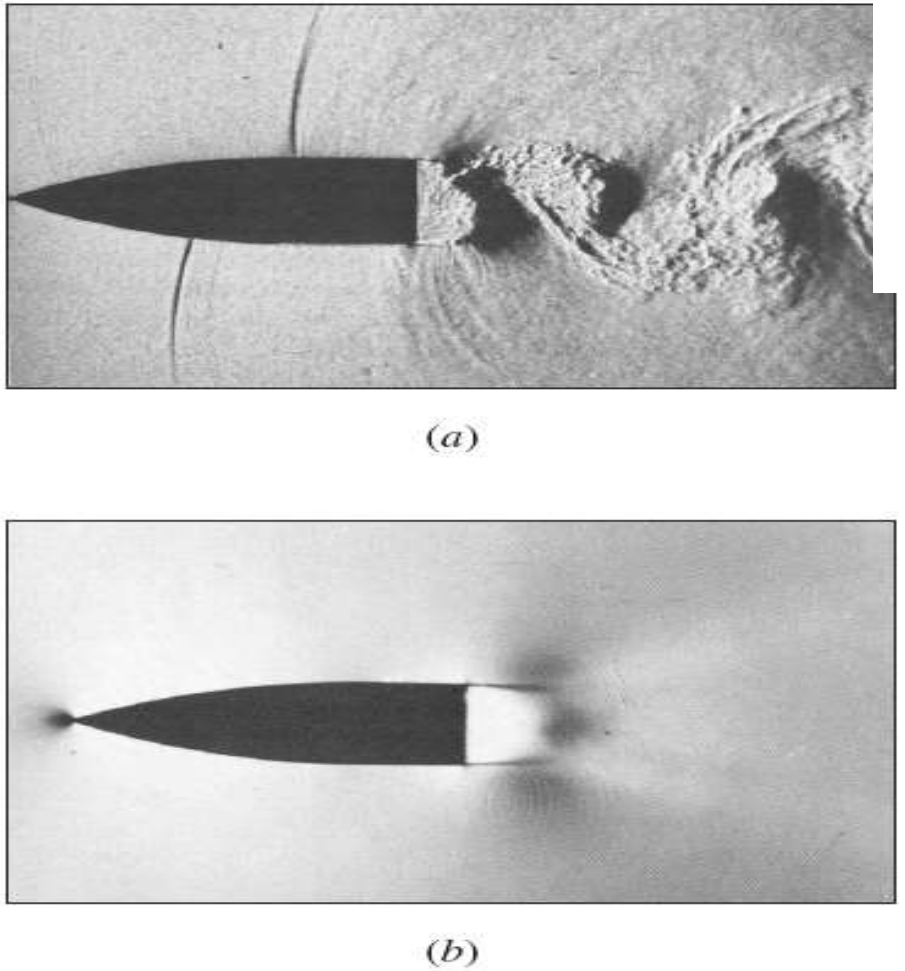
- ***For ex. Flow of water in a pipeline due to a centrifugal pump being run at uniform rotational speed.***

- The opposite of steady is **unsteady.**

- A flow of fluid is said to be **unsteady**, if any one or all the characteristics of fluid in motion change with time.

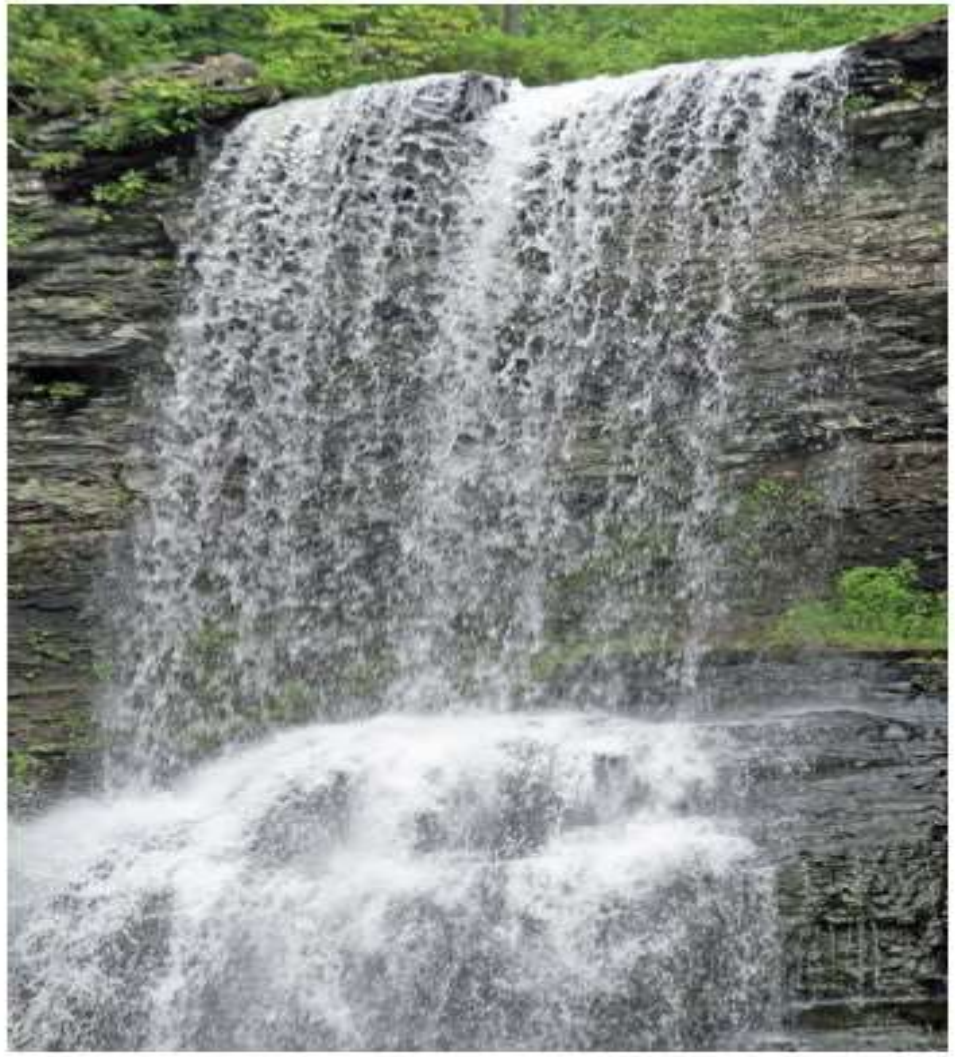
Steady versus Unsteady Flow

- The term **steady** implies *no change at a point with time*.
- The opposite of steady is **unsteady**.
- The term **uniform** implies *no change with location* over a specified region.
- The term **periodic** refers to the kind of unstea flow in which the flow oscillates about a stead mean.
- Many devices such as turbines, compressors, boilers, condensers, and heat exchangers operate for long periods of time under the same conditions, and they are classified as **steady-flow devices**.



Oscillating wake of a blunt-based airfoil at Mach number 0.6. Photo (*a*) is an instantaneous image, while photo (*b*) is a long-exposure (time-averaged) image.

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(a)



(b)

Comparison of (*a) instantaneous* snapshot of an unsteady flow, and (*b) long exposure picture of the* same flow.

Based on space criterion

❑ Uniform and non-uniform flow

Uniform flow: velocity is the same at any given point in the fluid.

$$\left(\partial v/\partial s\right)_{t_o} = 0$$

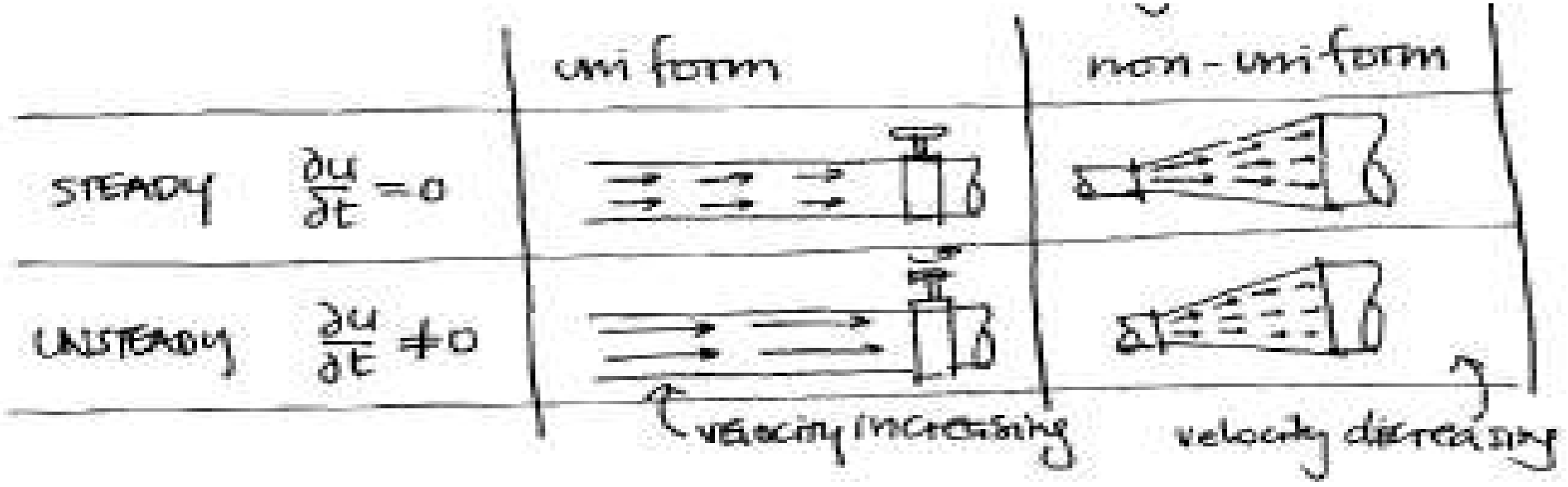
When the velocity of fluid doesn't change both in magnitude & direction from point to point in the fluid for any given instant of time, the flow is said to be uniform.

Non-uniform flow: If the velocity of flow of fluid changes from point to point in the fluid at any instant, the flow is said to be non-uniform flow.

$$\left(\partial v/\partial s\right)_{t_o} \neq 0$$

Examples

- ✓ The flow through a long uniform pipe diameter at a constant rate is steady uniform flow.
- ✓ The flow through a long uniform pipe diameter at a varying rate is unsteady uniform flow.
- ✓ The flow through a diverging pipe diameter at a constant rate is a steady non-uniform flow.
- ✓ The flow through a diverging pipe diameter at a varying rate is an unsteady non-uniform flow.

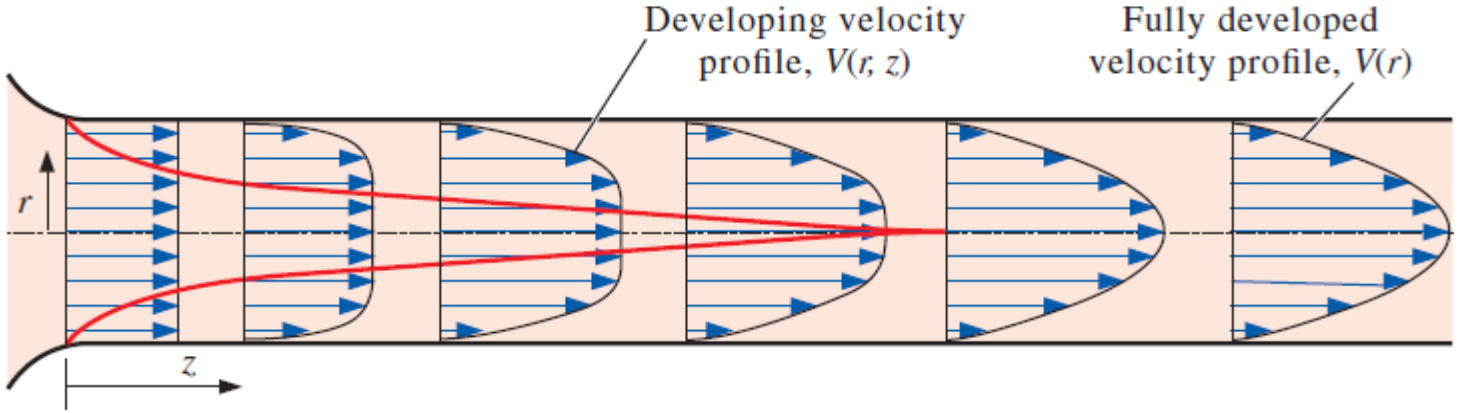


One-, Two-, and Three-Dimensional Flows

- A flow field is best characterized by its velocity distribution.
- A flow is said to be one-, two-, or three-dimensional if the flow velocity varies in one, two, or three dimensions, respectively.
- However, the variation of velocity in certain directions can be small relative to the variation in other directions and can be ignored.



Flow over a car antenna is approximately two-dimensional except near the top and bottom of the antenna.



The development of the velocity profile in a circular pipe. $V = V(r, z)$ and thus the flow is two-dimensional in the entrance region, and becomes one-dimensional downstream when the velocity profile fully develops and remains unchanged in the flow direction, $V = V(r)$.

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Internal(Pressure flow)versus External Flow(Pressure less flow)

- A fluid flow is classified as being internal or external, depending on whether the fluid is forced to flow in a confined channel or over a surface.
- The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe is **external flow. The** fluid motion is bounded on all the three sides & fourth side is exposed to atmosphere. The flow in open channels, the flow in rivers.
- The flow in a pipe or duct is **internal flow** if the fluid is completely bounded by solid surfaces. This flow is also called **pressure flow.**
- Water flow in a pipe, for example, is internal flow, and airflow over a ball or over an exposed pipe during a windy day is external flow .

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Compressible versus Incompressible Flow

- A flow is classified as being compressible or incompressible, depending on the level of variation of density during flow.
- Incompressibility is an approximation, and a flow is said to be **incompressible** if the density remains nearly constant throughout.
- Therefore, the volume of every portion of fluid remains unchanged over the course of its motion when the flow (or the fluid) is incompressible.
- The densities of liquids are essentially constant, and thus the flow of liquids is typically incompressible. Therefore, liquids are usually referred to as *incompressible substances*.

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❑ Rotational and Irrotational Flow

Rotational flow:

The flow is said to be rotational if the fluid particles while moving in the direction of flow rotates about their own mass centers.

Irrotational flow:

The flow is said to be Irrotational if the fluid particles while moving in the direction of flow don't rotate about their mass centers.
There is a small fluctuation in magnitude and direction of the velocity of the fluid particles

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❑ Laminar and turbulent flow

Laminar flow:

The fluid particles move along smooth well defined path or streamlines that are parallel, thus particles move in laminas or layers, smoothly gliding over each other.

Turbulent flow:

The fluid particles do not move in orderly manner and they occupy different relative positions in successive cross-sections.

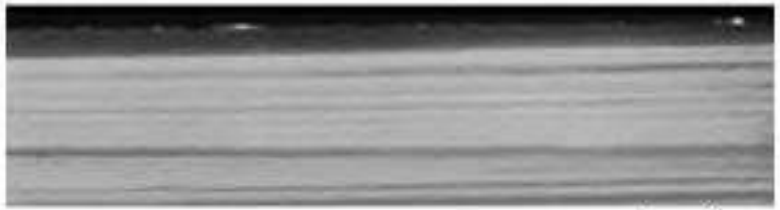
There is a small fluctuation in magnitude and direction of the velocity of the fluid particles

transitional flow

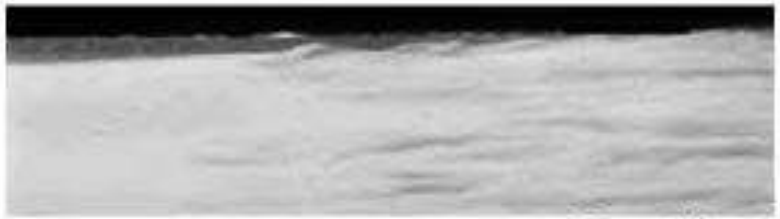
The flow occurs between laminar and turbulent flow

Laminar versus Turbulent Flow

- Some flows are smooth and orderly while others are rather chaotic.
- The highly ordered fluid motion characterized by smooth layers of fluid is called **laminar.**
- The flow of high-viscosity fluids such as oils at low velocities is typically laminar.
- The highly disordered fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations is called **turbulent .**



Laminar



Transitional

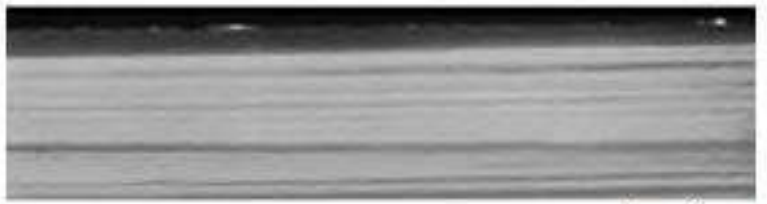


Turbulent

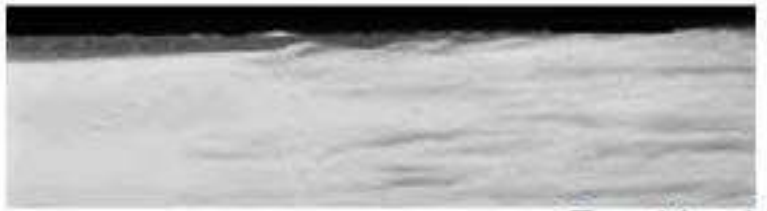
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Laminar versus Turbulent Flow

- The flow of low-viscosity fluids such as air at high velocities is typically turbulent.
- A flow that alternates between being laminar and turbulent is called **transitional.**



Laminar



Transitional



Turbulent

Reynolds Number

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In Reynolds experiment the flow conditions are affected by

- Diameter of pipe
- Average velocity
- Density of liquid
- Viscosity of the fluid

This four factors are combined in one way as Reynolds number

Reynolds number is obtained by the following equation

$$Re = \frac{\text{Inertial Forces}}{\text{Viscous Forces}} = \frac{\text{Mass X Acceleration of Liquid Flowing}}{\text{Shear Stress X Area}}$$

- Inertial forces are due to mass and the velocity of the fluid particles trying to diffuse the fluid particles
- viscous force if the frictional force due to the viscosity of the fluid which make the motion of the fluid in parallel.

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✶ At low velocities the inertial forces are less when compared to the frictional forces

Resulting flow will be viscous in nature.

(Laminar/Viscous Flow)

✶Other hand when inertial forces are predominant the fluid layers break up due to the increase in velocity hence Turbulent Flow takes place.

✶If Re < 2000 the flow I said to be laminar

✶If Re > 4000 the flow is said to be turbulent

✶If Re lies between 2000 to 4000 the flow change between laminar to turbulent

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Natural Flow & Forced Flow:

- A fluid flow is said to be natural or forced, depending on how the fluid motion is initiated.

- In **forced flow,** a fluid is forced to flow over a surface or in a pipe by external means such as a **pump or a fan**.

- In **natural flows,** any fluid motion is due to natural means such as the buoyancy effect, which manifests itself as the rise of the warmer (and thus lighter) fluid and the fall of cooler (and thus denser) fluid .

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Energy Head in Pipe Flow

Water flow in pipes may contain energy in three basic forms:

1- Kinetic energy,

2- potential energy,

3- pressure energy.

Continuity Equation: The continuity equation is based on the principle of conservation of mass. It states as follows:

If no fluid is added or removed from the pipe in any length then the mass passing across different sections shall be same.

Consider the control volume between two cross-sections of a pipe:

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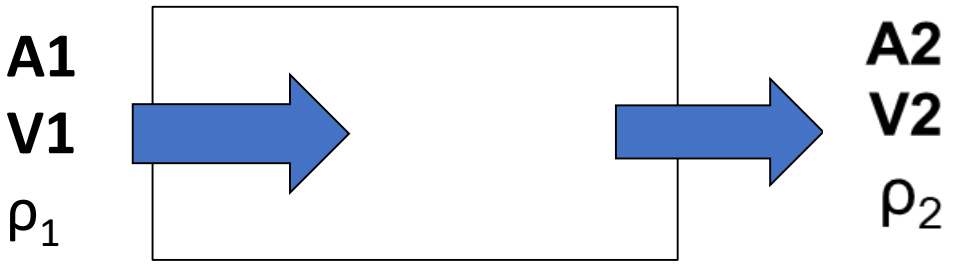
Control volume is defined as a fixed region in space upon which the attention is focused for study.

Let A_1= Area of section 1-1

V_1=Velocity of fluid at section 1-1

ρ_1= Density of fluid at section 1-1 &

A_2, V_2, ρ_2=Corresponding values at section2-2



The total quantity of fluid passing through the section1-1

$= A_1 V_1 \rho_1$

The total quantity of fluid passing through the section2-2

$= A_2 V_2 \rho_2$

From law of conservation of mass,

$$A_1 V_1 \rho_1 = A_2 V_2 \rho_2 \quad \text{----------(i)}$$

Above equation is continuity equation for compressible as well as incompressible fluid.

In case of incompressible fluid, $\rho_1 = \rho_2$

Therefore, equation (i) reduces to

$$A_1 V_1 = A_2 V_2$$

Bernoulli's Theorem

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Bernoulli's theorem may be stated as, "the sum of the kinetic energy (velocity head), the pressure energy (pressure head) & the potential energy (Elevation head) of an ideal, incompressible fluid is constant along a stream line" .

Total Energy or head = Kinetic head + Pressure head + Elevation head

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2$$

Where,

P_1, u_1, z_1 and P_2, u_2, z_2 are the pressure, velocity & elevation at section 1-1 & 2-2 respectively.

Applications of Bernoulli's Theorem

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1. Venturimeter
2. Orifice meter
3. Pitot tube

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Measurement of Fluid flow rate or Discharge

FLOW RATE AND VELOCITY MEASUREMENT



Venturimeter

- A Venturimeter is a device used for measuring the rate of a flow of a fluid flowing through a pipe. It consists of three parts:
- (1) A short converging part, (2) Throat, and (3) Diverging part.
- It is based on the Principle of Bernoulli's equation.
- Consider a Venturimeter fitted in a horizontal pipe through which a fluid is flowing (say water), as shown in the fig.

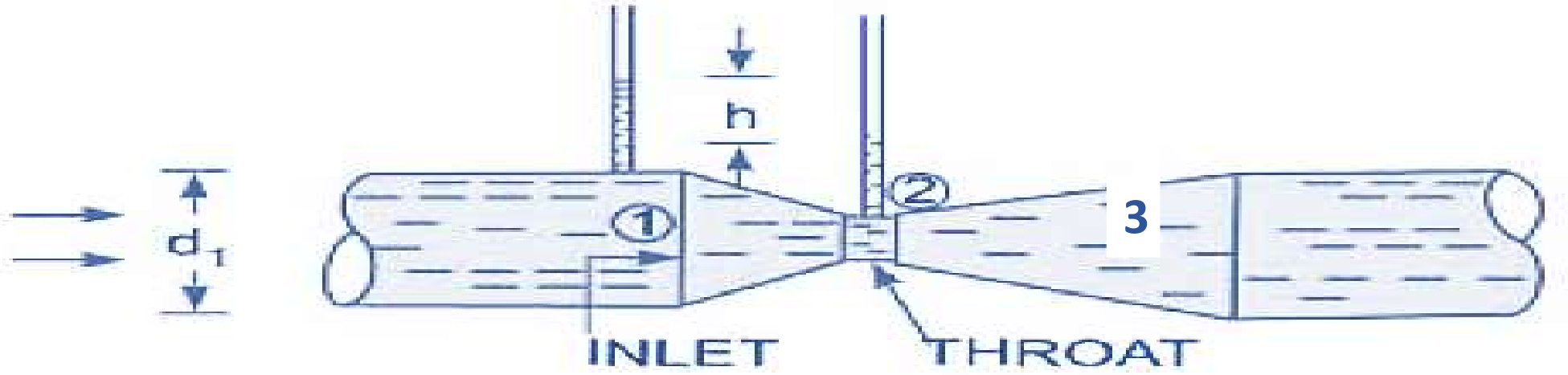


Fig. Venturimeter.

- $\frac{p_1}{w} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{w} + \frac{u_2^2}{2g} + z_2$
- As the pipe is horizontal, $z_1 = z_2$
- $\frac{p_1}{\rho g} + \frac{u_1^2}{2g} = \frac{p_2}{\rho g} + \frac{u_2^2}{2g}$
- Or
- $\frac{p_1 - p_2}{\rho g} = \frac{u_2^2}{2g} - \frac{u_1^2}{2g}$

$$\frac{p_1 - p_2}{\rho g} = \Delta h$$

Substituting this in the above equation, we get

$$\Delta h = \frac{u_2^2}{2g} - \frac{u_1^2}{2g} \qquad (a)$$

Now applying continuity equation at sections 1 and 2

$a_1 u_1 = a_2 u_2 \quad or \quad u_1 = \frac{a_2 u_2}{a_1}$ Substituting this value of u_1 in equation (a)

$$\Delta h = \frac{u_2^2}{2g} - \frac{\left(\frac{a_2 u_2}{a_1}\right)^2}{2g} = \frac{u_2^2}{2g}\left[1 - \frac{a_2^2}{a_1^2}\right] = \frac{u_2^2}{2g}\left[\frac{a_1^2 - a_2^2}{a_1^2}\right]$$

$$u_2^2 = 2g\Delta h \frac{a_1^2}{a_1^2 - a_2^2}$$

$$u_2 = \sqrt{2g\Delta h \frac{a_1^2}{a_1^2 - a_2^2}} = \frac{a_1}{\sqrt{a_1^2 - a_2^2}}\sqrt{2g\Delta h}$$

$$Q = a_2 u_2$$

$$Q = \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}}\sqrt{2g\Delta h}$$

The above Equation gives the discharge under ideal conditions and is called, theoretical discharge. Actual discharge will be less than theoretical discharge.

$$Q_{act} = C_d \times \frac{a_1 a_2}{\sqrt{a_1^2 - a_2^2}} \times \sqrt{2g\Delta h}$$

Where C_d = Co-efficient of venturimeter

Value of (Δh) given by differential U-tube manometer

Let the differential manometer contains a liquid which is heavier than the liquid flowing through the pipe. Let

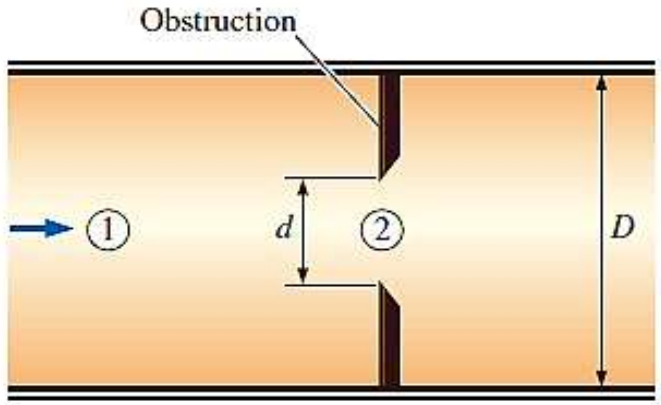
S_h = Sp. gravity of the heavier liquid

S_o = Sp. gravity of the liquid flowing through pipe

x = Difference of the heavier liquid column in U-tube, then

$$\Delta h = x\left(\frac{S_h}{S_o} - 1\right)$$

Orificemeter



Consider incompressible steady flow of a fluid in a horizontal pipe of diameter *D* that is constricted to a flow area of diameter *d*, as shown in Fig.

Mass balance: $Q = A_1 u_1 = A_2 u_2 \rightarrow$

$$u_1 = (A_2/A_1)u_1 = (d/D)^2\, u_2$$

Bernoulli equation ($z_1 = z_2$): $\frac{p_1}{\rho g} + \frac{u_1^2}{2g} = \frac{p_2}{\rho g} + \frac{u_2^2}{2g}$

Combining the above Eqs. and solving for velocity u_2 gives

$$u_2^2 = \left(\frac{p_1 - p_2}{\rho g} + \frac{u_1^2}{2g}\right) \times 2g$$

$$u_2^2 = \left(\frac{2(p_1 - p_2)}{\rho} + \left((d/D)^2\, u_2\right)^2\right)$$

$$u_2^2 = \left(\frac{2(p_1 - p_2)}{\rho} + (\beta^4\, u_2)^2\right)$$

Obstruction (with no loss):

$$u_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho(1 - \beta^4)}}$$

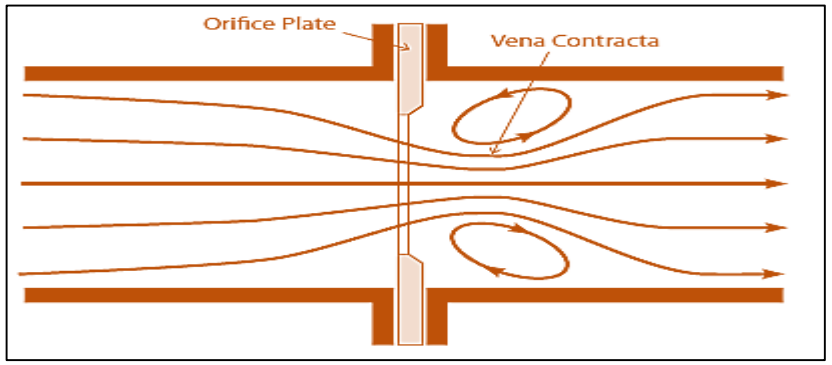
Where $\beta = d/D$ is the diameter ratio. Once u_2 is known, the flow rate can be determined from u_2

$$Q = A_2 u_2 = (\pi d^2/4)u_2.$$

Noting that the pressure drop between two points along the flow is measured easily by a differential pressure manometer,

The velocity in Eq. above is obtained by assuming no loss, and thus it is the maximum velocity that can occur at the constriction site. In reality, some pressure losses due to:

- frictional effects are inevitable, and thus the actual velocity is less.
- Also, the fluid stream continues to contract past the obstruction, and the vena contracta area is less than the flow area of the obstruction.



Both losses can be accounted for by incorporating a correction factor called the **discharge coefficient *Cd*** whose value (which is less than 1) is determined experimentally. Then the flow rate for obstruction flowmeters is expressed as

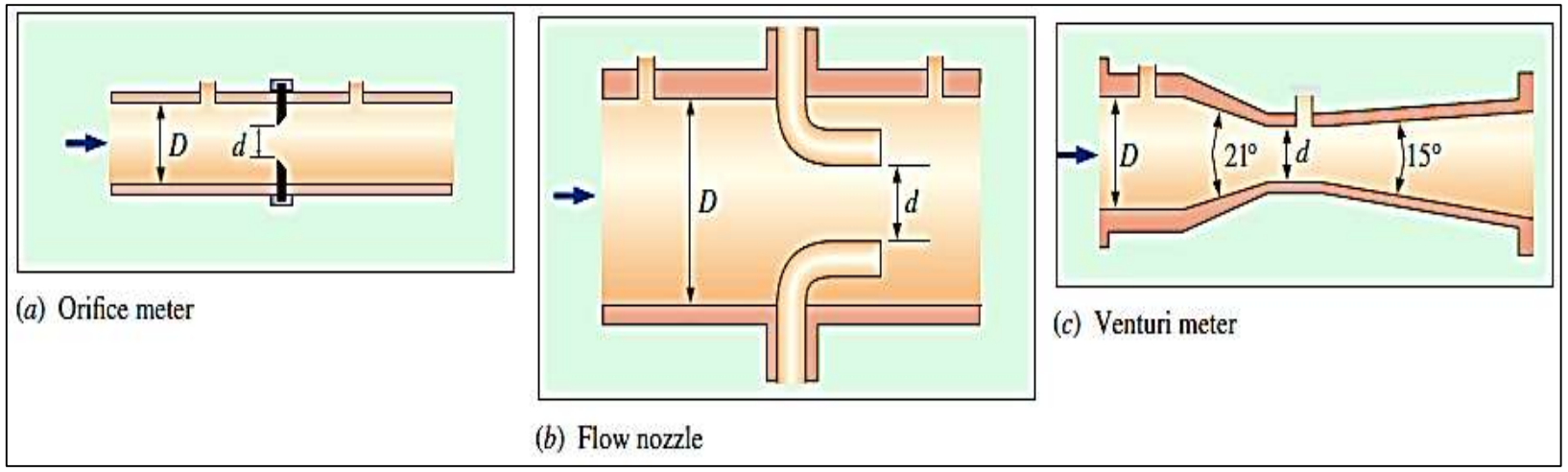
Obstruction flowmeters: $Q = A_2 \times Cd \times \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}}$

The value of *Cd* can be taken as 0.61 for orifices.

Owing to its streamlined design, the discharge coefficients of Venturi meters are very high, ranging between 0.95 and 0.99 in the absence of specific data, we can take *Cd* = 0.98 for Venturi meters.

Comparison

- The orifice meter has the simplest design and it occupies minimal space as it consists of a plate with a hole in the middle, but the sudden change in the flow area in orifice meters causes considerable swirl and thus significant head loss or permanent pressure loss.
- In nozzle meters, the plate is replaced by a nozzle, and thus the flow in the nozzle is streamlined. As a result, the vena contracta is practically eliminated and the head loss is smaller. However, flow nozzle meters are more expensive than orifice meters.
- The Venturi meter, is the most accurate flowmeter in this group, but it is also the most expensive. Its gradual contraction and expansion prevent flow separation and swirling, and it suffers only frictional losses on the inner wall surfaces. Venturi meters cause very low head losses, and thus, they should be preferred for applications that cannot allow large pressure drops.



(a) Orifice meter

(b) Flow nozzle

(c) Venturi meter

Pitot-tube

It is a device used for measuring the velocity at any point in a pipe or a channel.

It is based on the principle that if the velocity of flow at a point becomes zero, the pressure there is increased due to the conversion of the kinetic energy into pressure energy.

The pitot-tube consists of both a stagnation pressure tap and several circumferential static pressure taps and it measures both stagnation and static pressures (Fig)

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2$$

But $z_1 = z_2$ as points (1) and (2) are on the same line and $u_1 = 0$.

$\frac{p_1}{\rho g}$ = pressure head at (1) = h_1

$\frac{p_2}{\rho g}$ = pressure head at (2) = h_2

Substituting these values, we get

$$h_1 = h_2 + \frac{u_2^2}{2g}$$

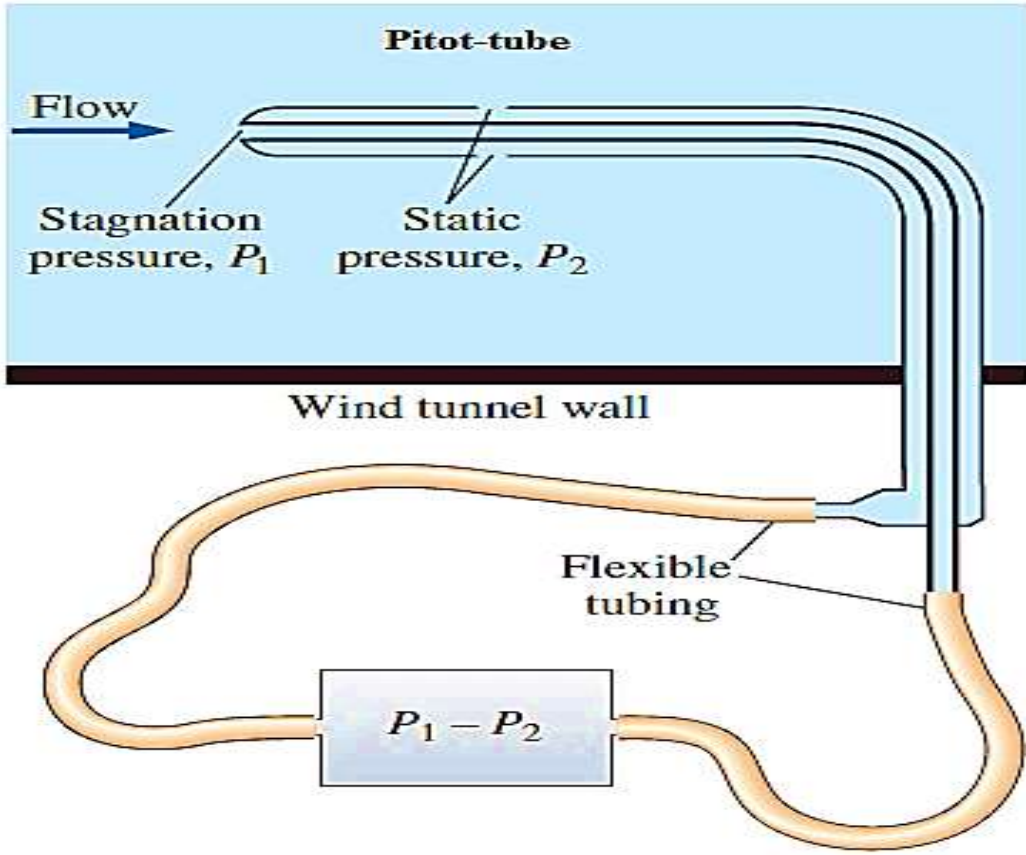
$$u_2 = \sqrt{2g\Delta h}$$

This is theoretical velocity. Actual velocity is given by

$$(u_2)_{act} = C_d\sqrt{2g\Delta h}$$

Where C_d is coefficient of pitot-tube

It is used to measure velocity in both liquids and gases.





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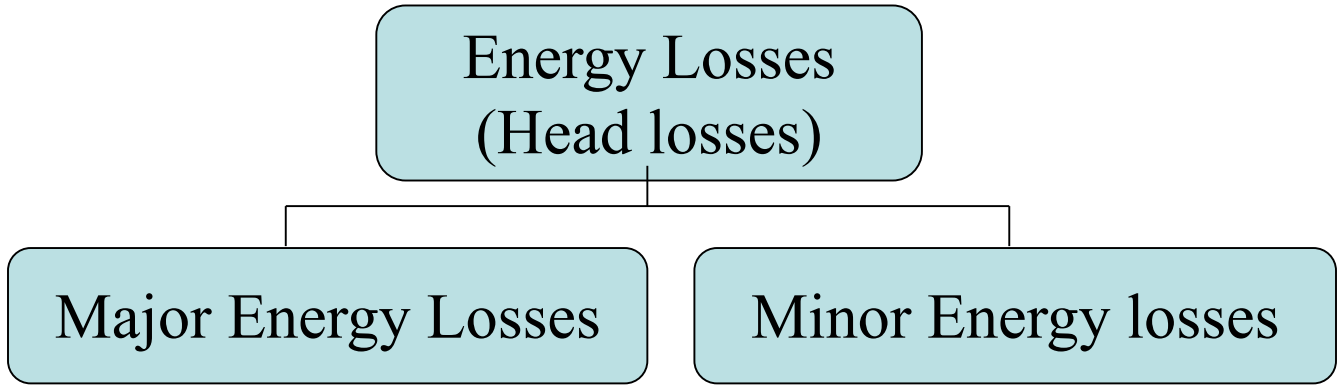
Unit 3

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Flow through Pipes &Dimensional Analysis

Energy Losses:

When a fluid is flowing through a pipe, the fluid experiences some resistance due to which some of energy (head) of fluid is lost.



Loss of head due to pipe friction and to viscous dissipation in flowing water

Loss due to the change of the velocity of the flowing fluid in the magnitude or in direction as it moves through fitting like Valves, Tees, Bends and Reducers.

Major losses

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- Several formulas have been developed in the past. Some of the important formulas have faithfully been used in various hydraulic engineering practices are:

1. Darcy-Weisbach formula

2. Chezy Formula

Darcy-Weisbach Equation

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$$h_L = \frac{4 f L V^2}{2 g D}$$

Where:

f is the friction factor or coefficient of friction

L is pipe length

D is pipe diameter

V is the velocity of flow

h_L is the loss of head due to friction

Minor losses

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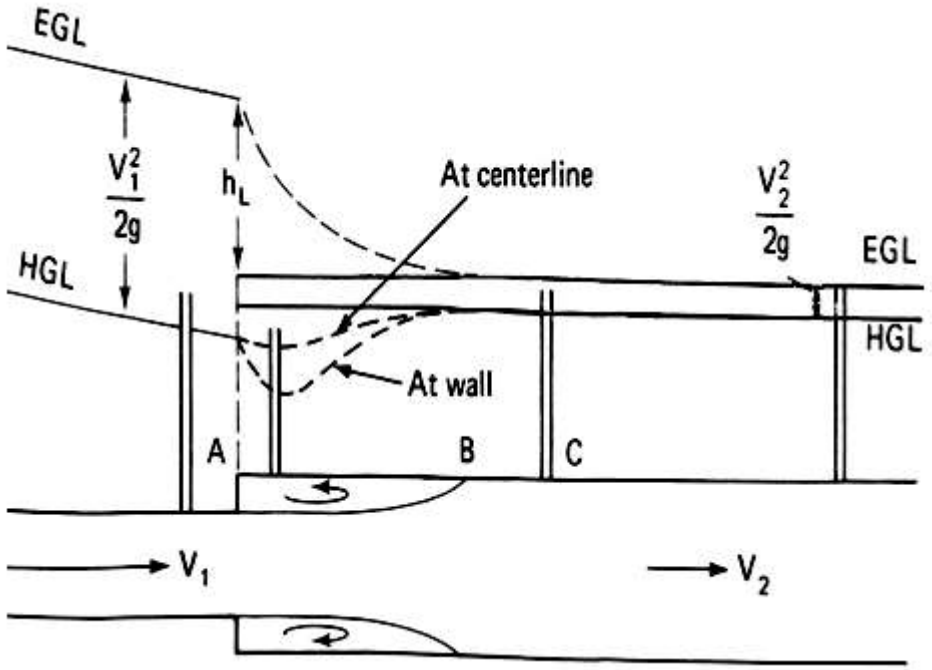
It is due to the change of the velocity of the flowing fluid in the magnitude or in direction [turbulence within bulk flow as it moves through and fitting]

- The minor loss of energy(or head) includes the following cases:
  - Loss of head due to sudden enlargement
  - Loss of head due to sudden contraction
  - Loss of head at the entrance to a pipe
  - Loss of head at the exit of a pipe
  - Loss of head due to an obstruction in the pipe
  - Loss of head due to bend in the pipe
  - Loss of head in various pipe fittings

Losses due to Enlargement

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A sudden Enlargement in a pipe

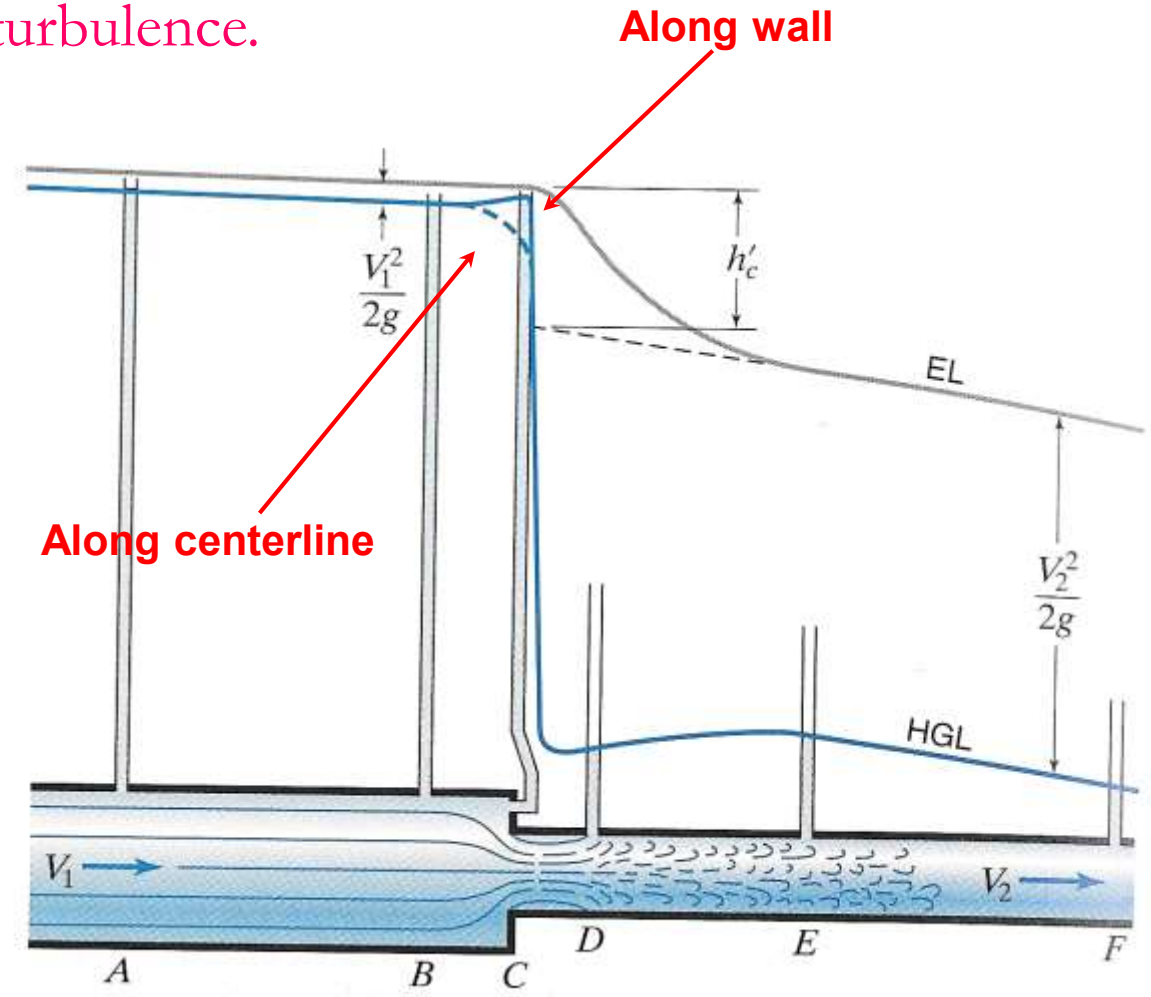


$$he = \frac{(V_1 - V_2)^2}{2g}$$

Losses due to contraction

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A sudden contraction in a pipe usually causes a marked drop in pressure in the pipe due to both the increase in velocity and the loss of energy to turbulence.

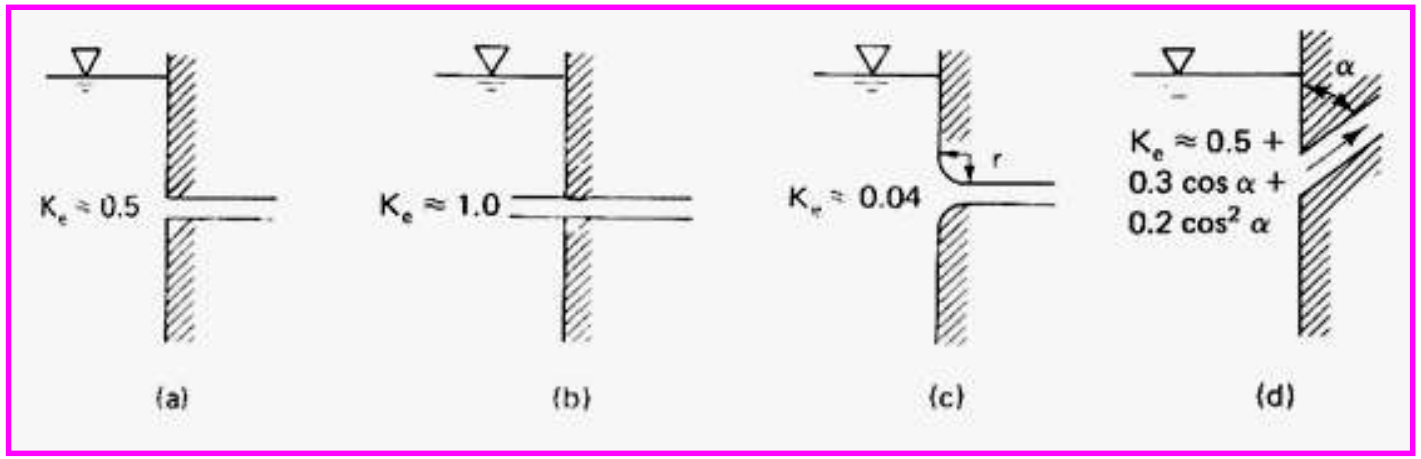


$$h_c = 0.5\frac{V_2^2}{2g}$$

Loss of head at the entrance to pipe

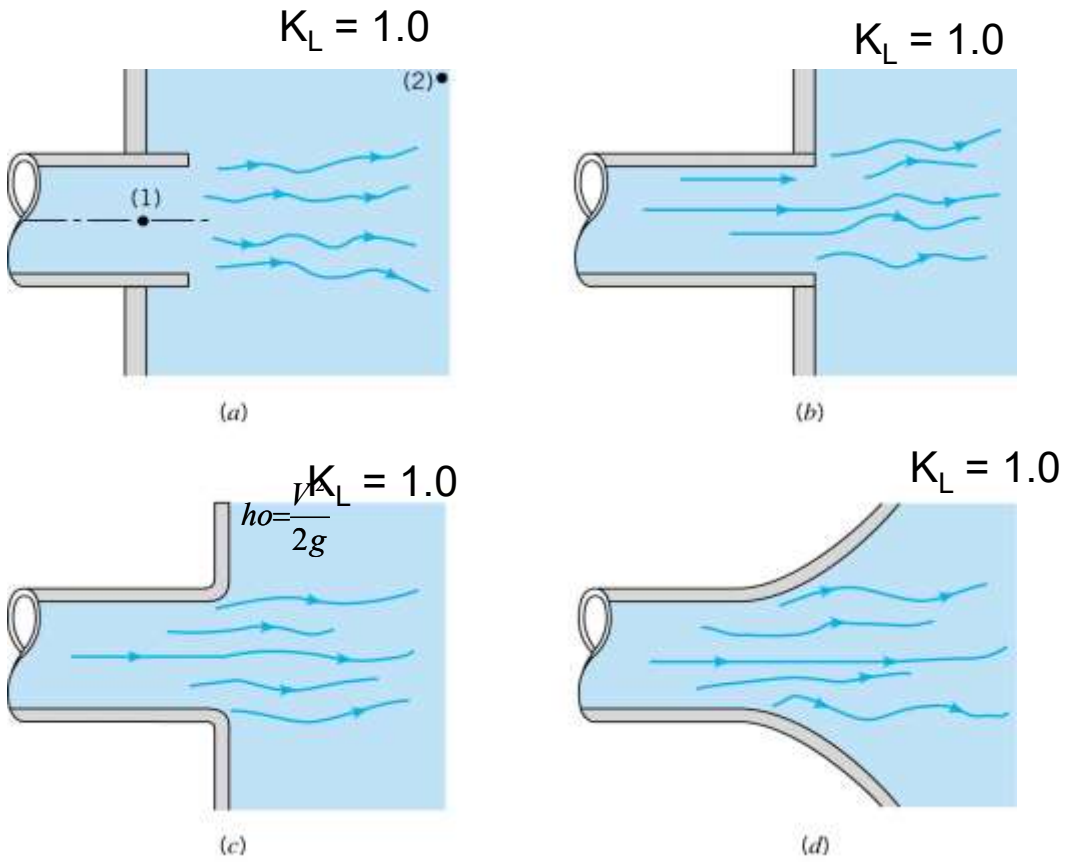
General formula for head loss at the entrance of a pipe is also expressed in term of velocity head of the pipe

$$h_i = 0.5\frac{V^2}{2g}$$



Head Loss at the Exit of a Pipe
(flow entering a tank)

$$ho = \frac{V^2}{2g}$$



The entire kinetic energy of the exiting fluid (velocity *V1*) is dissipated through viscous effects as the stream of fluid mixes with the fluid in the tank and eventually comes to rest ($V_2 = 0$).

Head Loss Due to Bends in Pipes

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$$h_b = k \frac{V^2}{2g}$$

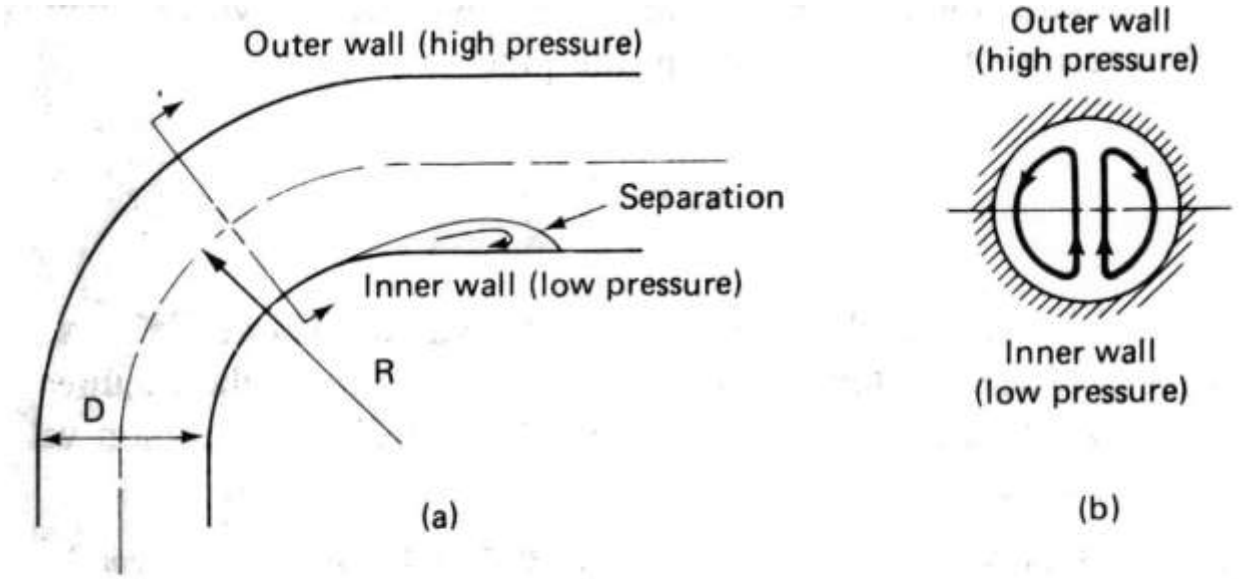


Figure Head loss at a bend: (a) flow separation in a bend; (b) secondary flow at a bend.

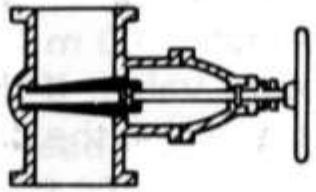
R/D	1	2	4	6	10	16	20
K_b	0.35	0.19	0.17	0.22	0.32	0.38	0.42

Loss of head due to an obstruction in the pipe or Head Loss due to Pipe Fittings (valves, elbows, bends, and tees)

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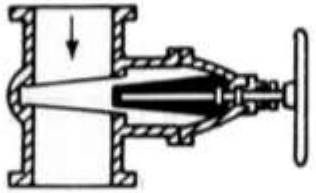
TABLE : Values of K_v for Certain Common Hydraulic Valves

A. Gate valves



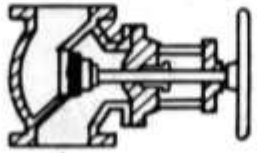
Closed

K_V = 0.15 (fully open)



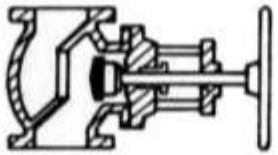
Open

B. Globe valves:



Closed

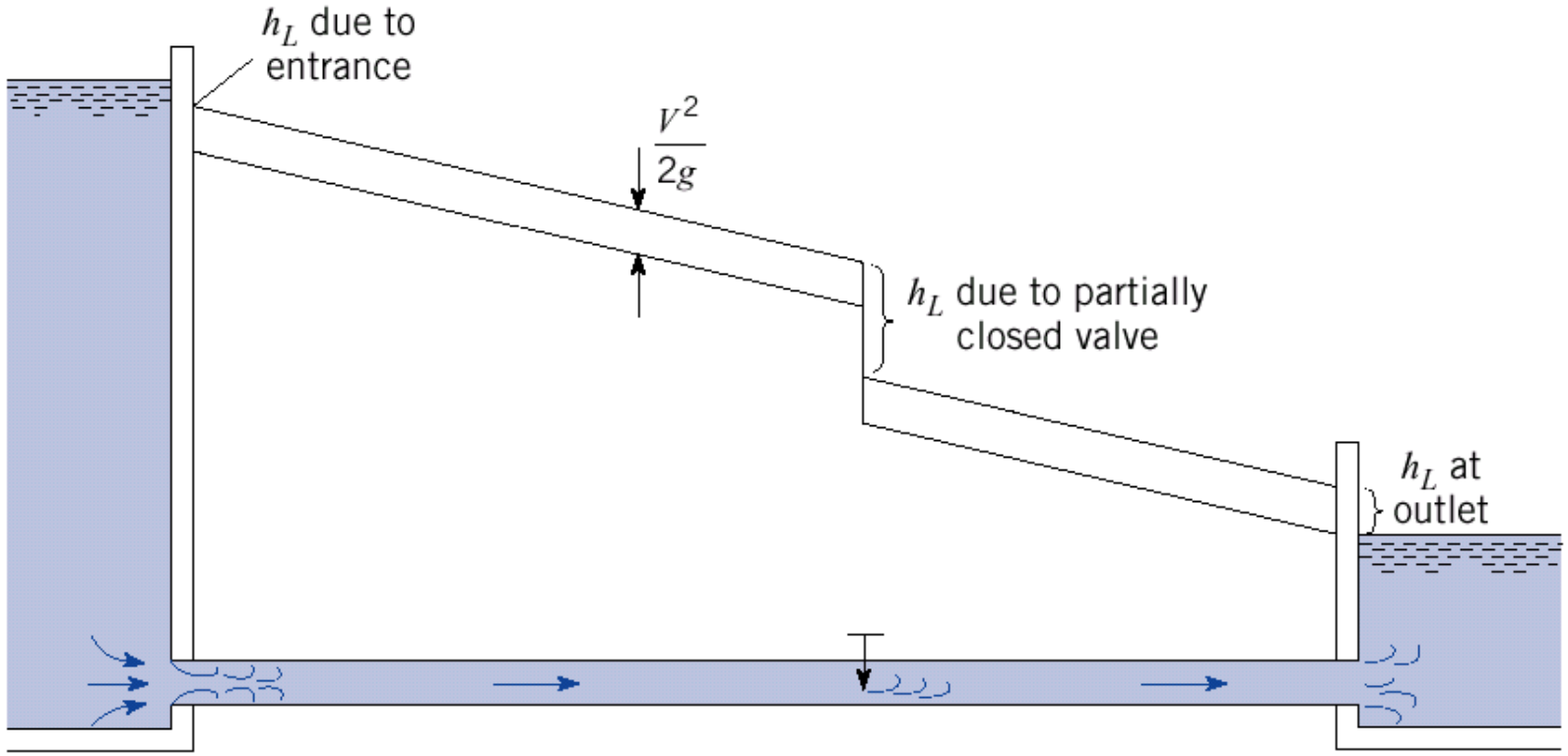
K_V = 10.0 (fully open)



Open

$$hb = K \frac{V^2}{2g}$$

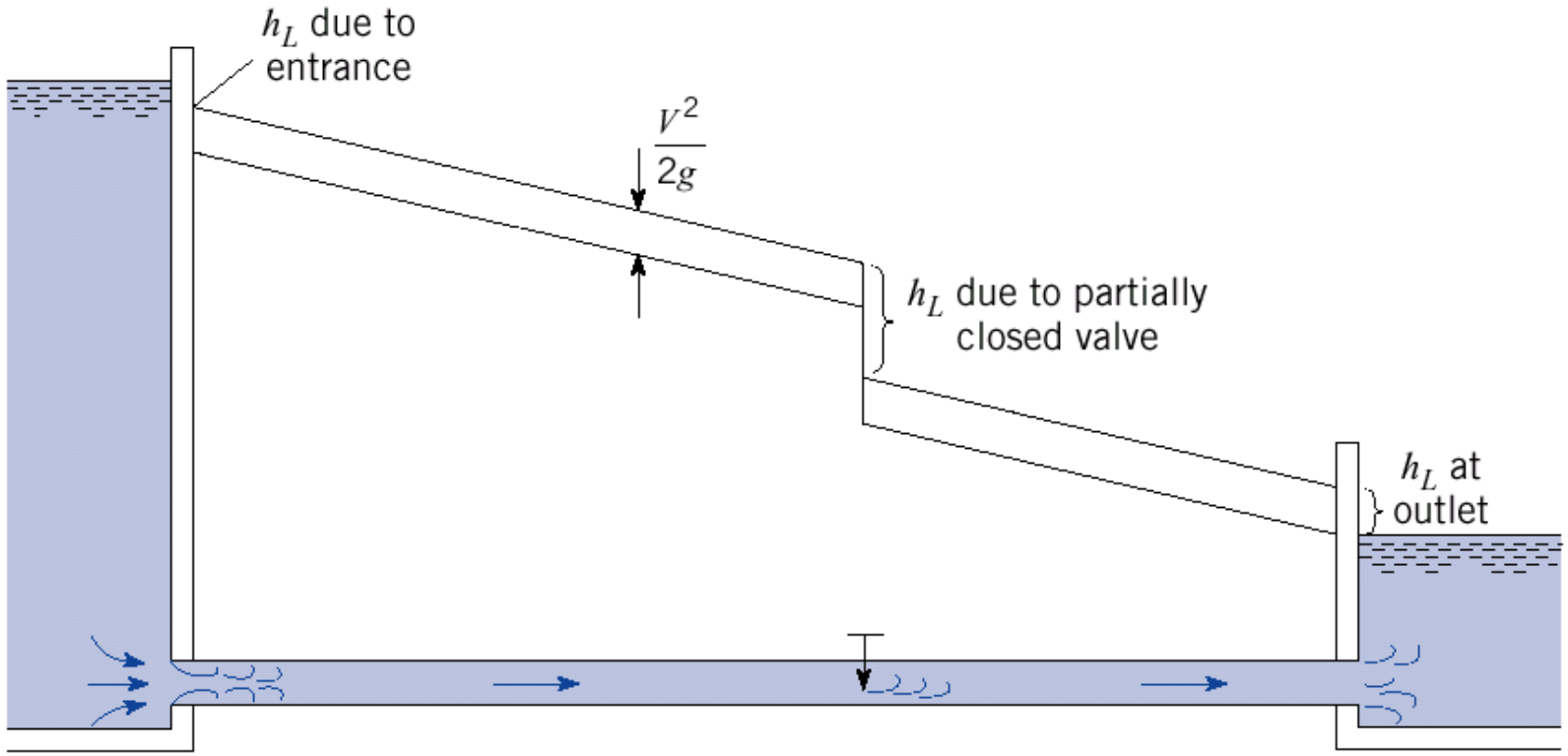
Total Energy Line (TEL)or Energy Gradient Line & Hydraulic Gradient Line (HGL)



Total energy line is the line represents the sum of pressure head, velocity head & elevation head.

Hydraulic Gradient Line is the line represents the sum of pressure head & elevation head.

Total Energy Line (TEL)or Energy Gradient Line & Hydraulic Gradient Line(HGL)



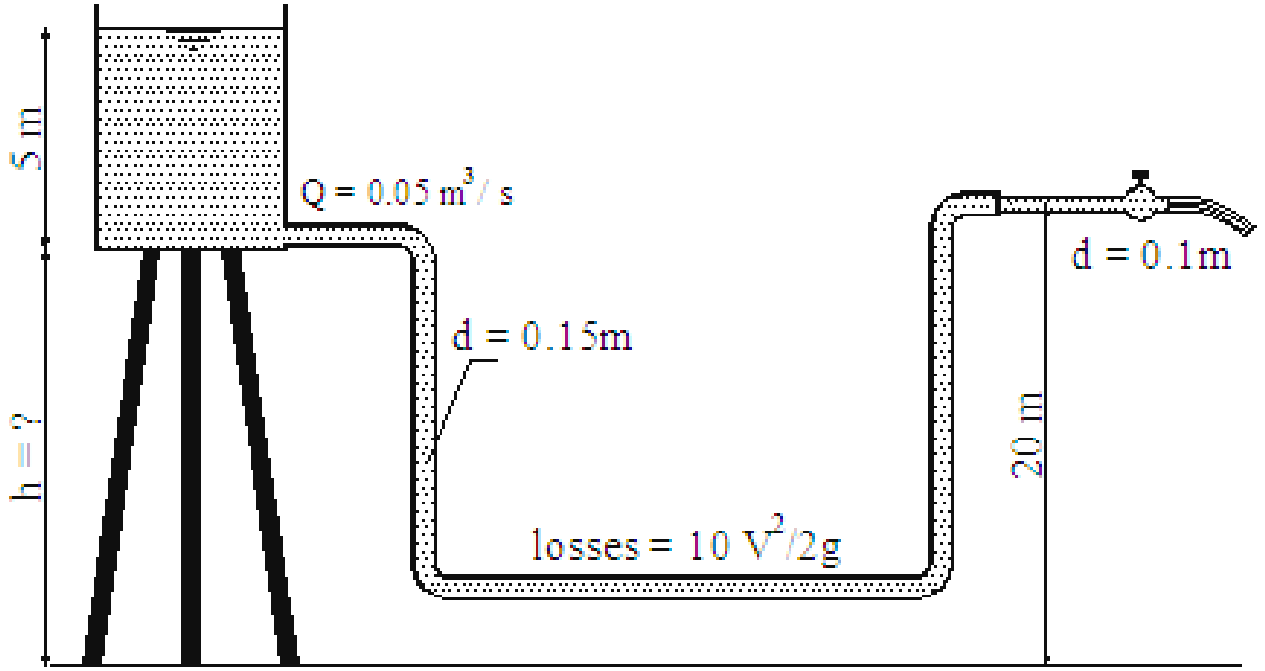
1. TEL always drops in the direction of flow because of loss of head.
2. HGL may rise or fall depending upon the pressure changes.
3. HGL is always below the TEL & vertical intercept between the two is equal to velocity head.
4. For a pipe of uniform cross-section the slope of HGL is equal to the slope of TEL.

Numerical on Pipes in Series & Parallel

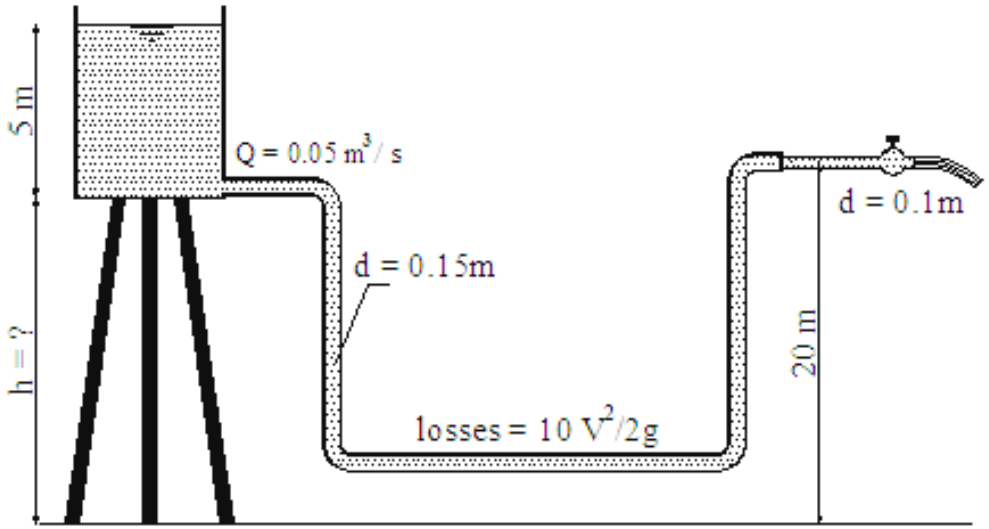
Example

In the figure shown:

Where the discharge through the system is 0.05 m3/s, the total losses through the pipe is 10 v2/2g where v is the velocity of water in 0.15 m diameter pipe, the water in the final outlet exposed to atmosphere.



Calculate the required height **(h =?)** below the tank



$$V = \frac{Q}{A} = \frac{0.05}{\frac{\pi}{4}(0.15)^2} = 2.83 m/s$$

$$V = \frac{Q}{A} = \frac{0.05}{\frac{\pi}{4}(0.10)^2} = 6.366 m/s$$

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

$$0 + 0 + (h + 5) = 0 + \frac{(6.366)^2}{2*9.81} + 20 + \frac{10(2.83)^2}{2*9.81}$$

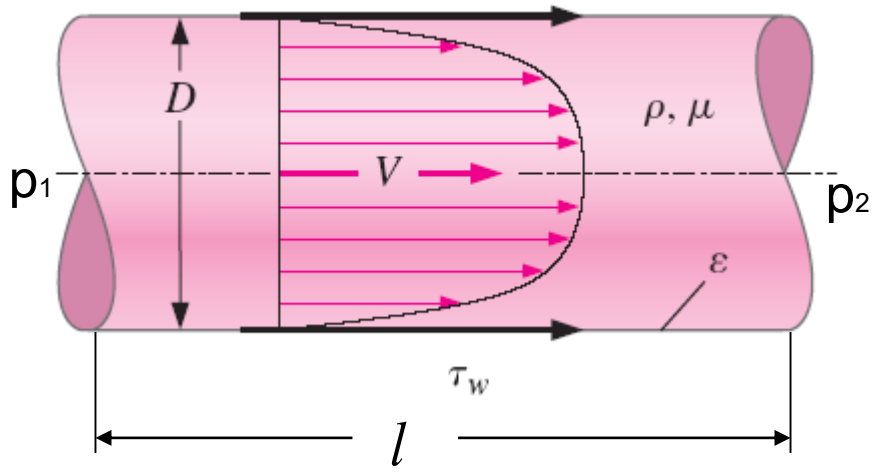
$$h = 21.147 m$$

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• DIMENTIONAL ANALYSIS

Determination of Pressure Difference by Dimensional Analysis

Many important chemical engineering problems cannot be solved completely by theoretical methods. For example, the pressure loss from friction losses (or the pressure difference $\Delta p = p_1 - p_2$ between two ends of a pipe) in a long, round, straight, smooth pipe a fluid is flowing depends on all these variables: pipe diameter d, pipe length l, fluid velocity v, fluid density ρ, and fluid viscosity μ.



The relationship may be written as: $\Delta p = f(D, l, v, \rho, \mu)$ (1)

The form of the function is unknown, but since any function can be expanded as a power series, the function can be regarded as the sum of a number of terms each consisting of products of powers of the variables. The simplest form of relations will be where the function consists simply of a single term, when:

$$\Delta p = \text{const}\, D^a l^b v^c \rho^d \mu^e \qquad (2)$$

The requirement of dimensional consistency is that the combined term on the right-hand side will have the same dimensions as that the on the left, i.e. it must have the dimensions of pressure.

Each of the variables in equation (2) can be expressed in terms of mass, length, and time. Thus, dimensionally:

$\Delta p = ML^{-1}T^{-2}$ $\quad v = LT^{-1}$

$D = L$ $\quad \rho = ML^{-3}$

$l = L$ $\quad \mu = ML^{-}T^{-1}$

i.e.:

$$ML^{-1}T^{-2} = L^a L^b (LT^{-1})^c (ML^{-3})^d (ML^{-1}T^{-1})^e$$

The conditions of dimensional consistency must be met for the fundamentals of M, L, and T and the indices of each of these variables can be equated. Thus:

In $\quad M \quad 1 = d + e$

$\quad L \quad -1 = a + b + c - 3d - e$

$\quad T \quad -2 = -c - e$

Thus three equations and five unknowns result and the equations may be solved in terms of any two unknowns. Solving in terms of b and e:

$$d = 1 - e \quad (\text{from the equation in M})$$

$$c = 2 - e \quad (\text{from the equation in T})$$

Substituting in the L equation:

$$-1 = a + b + (2 - e) - 3(1 - e) - e$$

$$0 = a + b + e$$

$$a = -b - e$$

Thus, substituting into equation (2): $\Delta p = \text{const}\, D^{-b-e} l^{b} v^{2-e} \rho^{1-e} \mu^{e} =$

$= \text{const}\, D^{-b} D^{-e} l^{b} v^{2} v^{-e} \rho \rho^{-e} \mu^{e} =$

$= \text{const}\left(D^{-1} l\right)^{b} \left(Dv\rho\mu^{-1}\right)^{-e} \left(v^{2}\rho\right)$

i.e. $$\frac{\Delta p}{\rho v^{2}} = \text{const}\left(\frac{l}{D}\right)^{b}\left(\frac{Dv\rho}{\mu}\right)^{-e}$$

Let: $$\text{const} = \frac{k}{2}$$

Thus: $$\frac{\Delta p}{\rho v^{2}} = \frac{k}{2}\left(\frac{l}{D}\right)^{b} Re^{-e} \longrightarrow \Delta p = \frac{k}{Re^{e}}\left(\frac{l}{D}\right)^{b}\frac{\rho v^{2}}{2}$$

b=1, and k and e have to determinate by experiments.

For laminar flow k=64 and e=1

For turbulent flow k=0,0791 and e=0,25.

$$\Delta p = \frac{k}{Re^{e}}\frac{l}{D}\frac{\rho v^{2}}{2} = 4f\frac{l}{D}\frac{\rho v^{2}}{2}$$

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Unit 4

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Hydraulic Turbines

Impact of Jets

- A jet of fluid emerging from a nozzle has some velocity and hence it possesses a certain amount of kinetic energy.
- If this jet strikes an obstruction placed in its path, it will exert a force on the obstruction.
- This impressed force is known as impact of the jet and it is designated as hydrodynamic force.

- Since a dynamic force is exerted by virtue of fluid motion, it always involves a change of momentum.
- Hence the impluse-momentum principle is applied to evaluate the hydrodynamic force exerted on a body by a fluid jet.



Impulse Momentum Principle

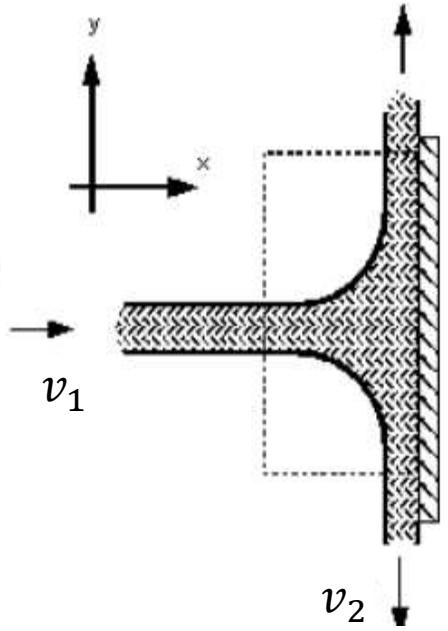
- From Newton's second law of motion "The rate of change of momentum is directly proportional to the applied force and takes place in the direction of force"

Hence

Force exerted by jet in the direction of motion = Rate of change of momentum in the same direction ..... (1)

- Let, 'm' be the mass of fluid in kg flowing with velocity 'v'

  And 'x' be the direction of motion of vane.



- Change of momentum $= m.dv$
- Hence, rate of change of momentum $= m.\frac{dv}{dt}$
- Force exerted in the direction of motion $= F_x$

Hence, From equation (1)

$$F_x = m.\frac{dv_x}{dt}$$

Where, dv_x is the change in velocity in x direction in time dt.

$$F_x = \frac{m}{t}(v_2 - v_1)_x \quad \text{.....(2)}$$

In the above equation suffix 'x' to the bracket indicates component of velocity in x direction.

Let Q be the discharge of fluid striking on the vane in m^3/sec.

and ρ be the density of fluid in kg/m^3

In equation 2, $\frac{m}{t}$ is the mass per unit time which is the mass flow rate ***ρQ*** **or** ***ρav***

Hence,

$$F_x = \rho Q(v_2 - v_1)_x$$

Basically above equation represents the force exerted by vane on jet which is opposite in direction of motion of jet but same in magnitude as per Newton's third law of motion.

$$-F_x = \rho Q(v_2 - v_1)_x$$

When a jet strikes on vane, velocity of fluid decreases. Hence the value of final velocity V_2 is less than V_1

So the right hand side of the equation also becomes negative.

So to make the quantity positive, multiplying above equation by – ve sign

$$F_x = \rho Q(v_1 - v_2)_x \quad \text{.....(3)}$$

Force exerted by jet

Case 1: Stationary Vanes

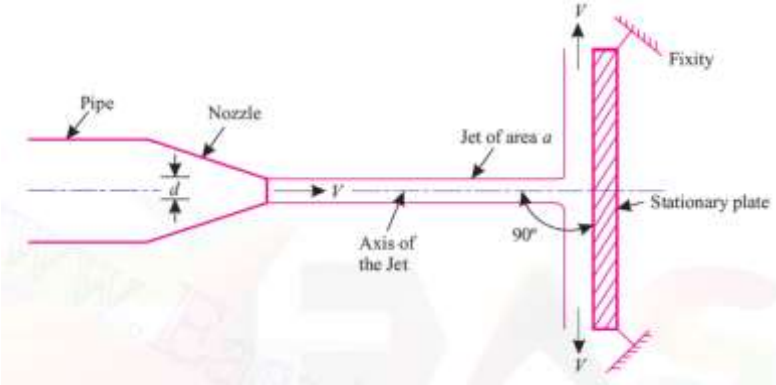
a) Flat plate held perpendicular to jet
b) Flat plate held inclined to jet
c) Curved plate
   I. If the vane is symmetrical
      - When jet strikes at the center of plate
      - When Jet strikes at one end tangentially
   II. If the vane is unsymmetrical and jet strikes tangentially

Case 2: Moving Vanes

a) Flat plate held perpendicular to jet
b) Flat plate held inclined to jet
c) Curved plate
   I. When jet strikes at the center of plate (symmetric)
      - Single vane
      - Series of vanes
   II. When Jet strikes at one end tangentially (Unsymmetrical)
      - Single vane
      - Series of vanes

Case 1: Stationary Vanes

a) Flat plate held perpendicular to jet



$F_x = \rho Q(v_1 - v_2)_x$

As, V_2 = 0 (Final velocity in x direction)

And ρQ = $\rho.a.v$

Also, $v_1 = v$ = velocity of jet issuing from nozzle

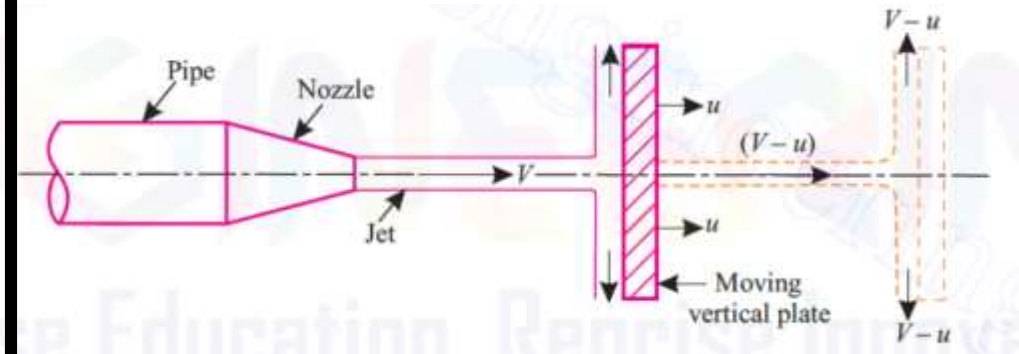
$F_x = \rho.\,a.\,v(v\ - 0)$

$$\boldsymbol{F_x = \rho.a.v^2}$$

Work done = 0

Case 2: Moving Vanes

a)Flat plate held perpendicular to jet



$F_x = \rho Q(v_1 - v_2)_x$

The relative velocity with which the jet strikes the plate is $(V - u)$.

$$\boldsymbol{F_x = \rho.a.(v-u)[(v-u)-0]}$$

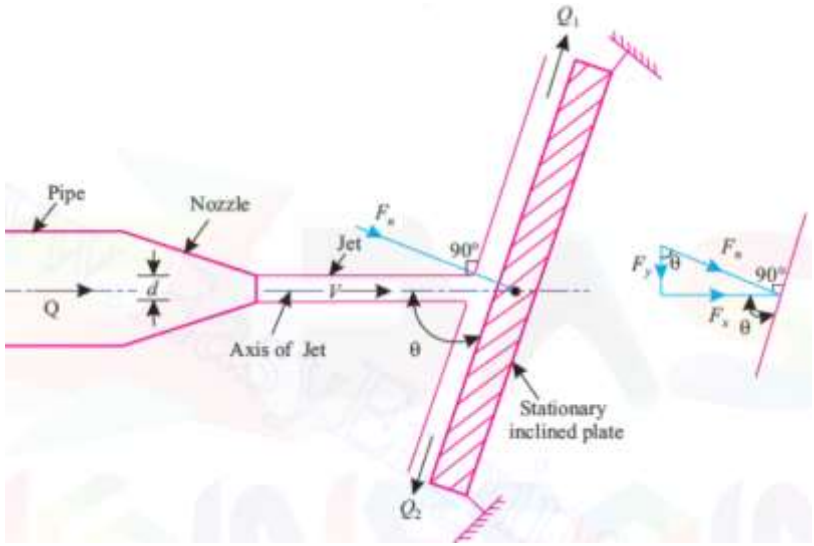
$$\boldsymbol{F_x = \rho.a.(v-u)^2}$$

Work done = Force × Displacement

Work done $= \boldsymbol{\rho.a.(v-u)^2 \times u}$

Case 1: Stationary Vanes

b) Flat plate held inclined to jet



$F_x = \rho Q(v_1 - v_2)_x$

The force exerted by the jet on the plate in the direction *normal* to the plate is

$$F_n = \rho.a.v[v.sin\theta\ - 0]$$

$$F_n = \rho.a.v^2 sin\theta$$

Hence, The force exerted in the direction of jet

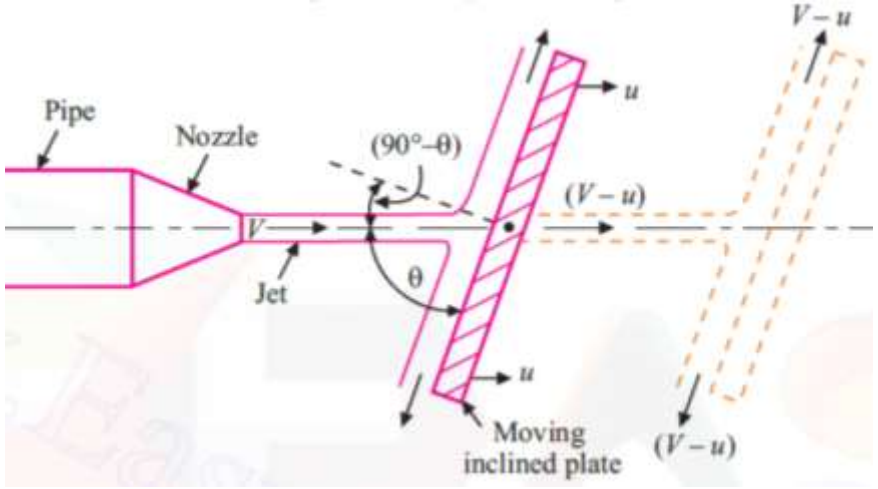
$$F_x = F_n \times sin\theta$$

$$\boldsymbol{F_x = \rho.a.v^2 sin^2\theta}$$

Work done $= 0$

Case 2: Moving Vanes

(b) Flat plate held inclined to jet



$F_x = \rho Q(v_1 - v_2)_x$

The force exerted by the jet on the plate in the direction *normal* to the plate is

$$F_n = \rho.a.(v-u)[(v-u)\ sin\theta\ - 0]$$

$$F_n = \rho.a.(v-u)^2 sin\theta$$

Hence, The force exerted in the direction of jet

$$F_x = F_n \times sin\theta$$

$$\boldsymbol{F_x = \rho.a.(v-u)^2 sin^2\theta}$$

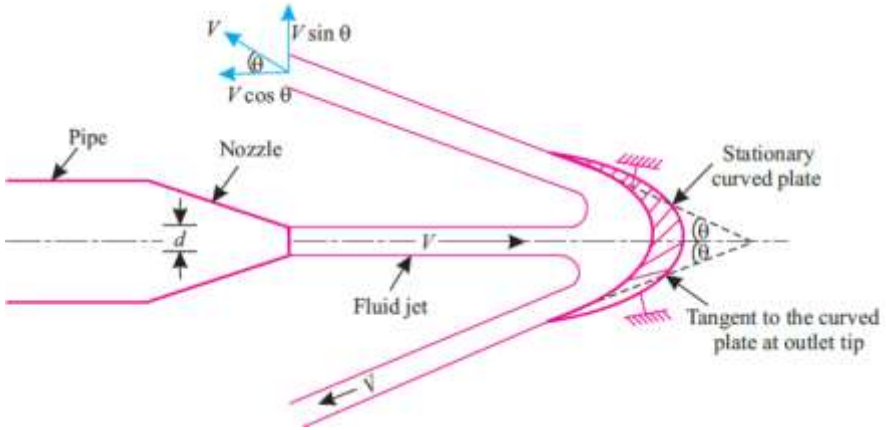
Work done $= \rho.a.(v-u)^2 sin^2\theta \times u$

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Case 1: Stationary Vanes

c) Curved plate (symmetric)

- When jet strikes at the center of plate



$F_x = \rho Q(v_1 - v_2)_x$

$$F_x = \rho.a.v[v - (-v\cos\theta)]$$

$$F_x = \rho.a.v[v + v\cos\theta]$$

$$F_x = \rho.a.v^2[1 + \cos\theta]$$

$$F_y = \rho.a.v[0 - v\,sin\,\theta]$$

$$F_y = -\rho.a.v^2\,sin\,\theta]$$

–ve sign indicates that force is acting in the *downward* direction.

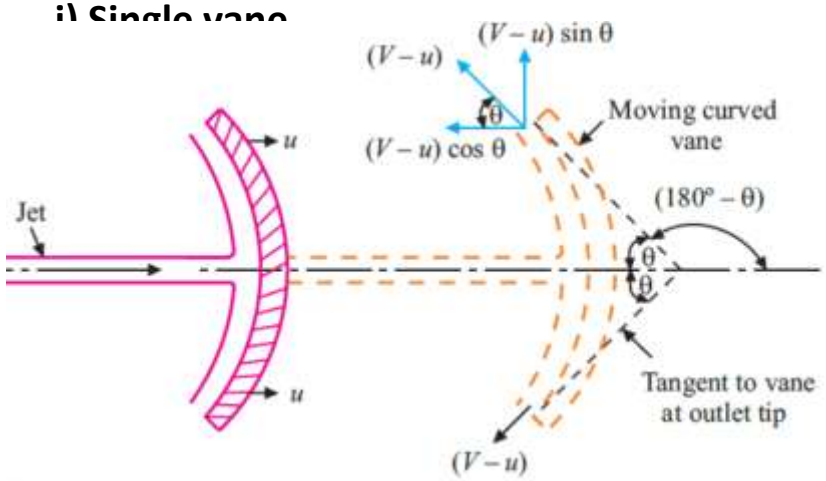
Work done = 0

Case 2: Moving Vanes

c) Curved plate (symmetric)

- When the vane is moving in the direction of jet

i) Single vane



$F_x = \rho Q(v_1 - v_2)_x$

$$F_x = \rho.a.(v-u)\{(v-u) - [-(v-u)\cos\theta]\}$$

$$F_x = \rho.a.(v-u)\{(v-u) + (v-u)\cos\theta\}$$

$$F_x = \rho.a.(v-u)^2(1 + cos\theta)$$

Work done $= [\rho.a.(v-u)^2(1 + cos\theta)] \times u$

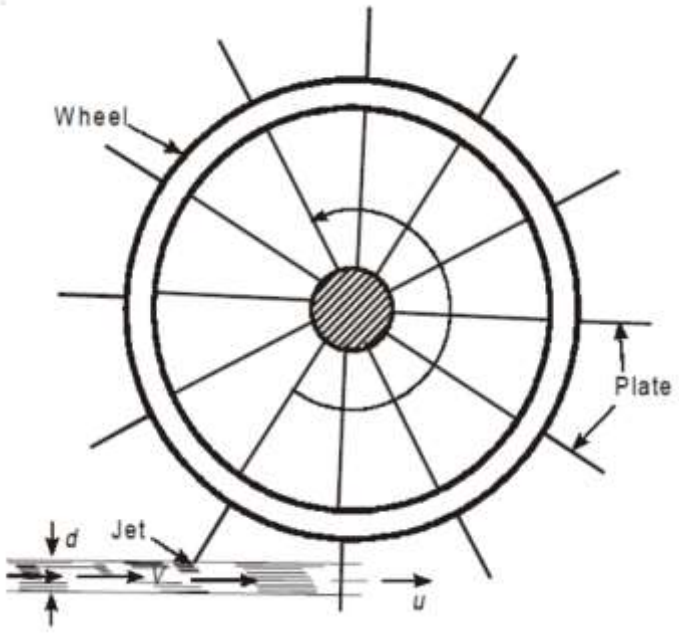
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Case 2: Moving Vanes

c) Curved plate

- When the vane is moving in the direction of jet

ii) Series of vanes



In this case since the vanes face the jet normally one after the other it is as if one vane is always in the vertical position to intercept the jet.

Therefore the mass of fluid striking the plates is $\rho . a . v$

$$F_x = \rho . a . v\{(v-u) - [-(v-u)\cos\theta]\}$$

$$F_x = \rho . a . v\{(v-u) + (v-u)\cos\theta\}$$

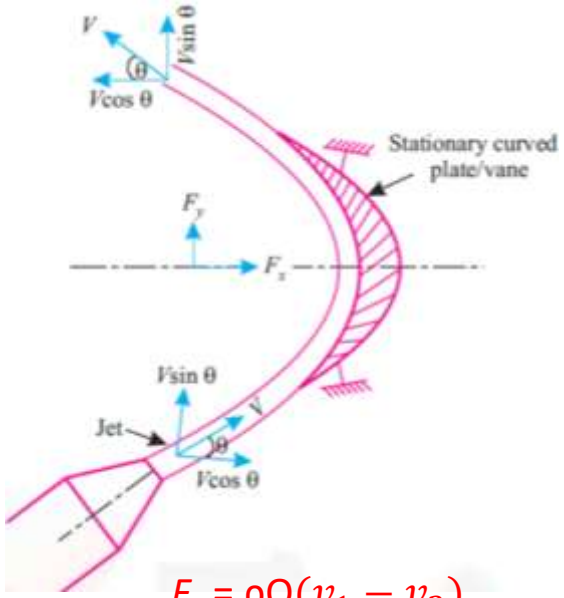
$$F_x = \rho . a . v\,(v-u)\,(1+cos\theta)$$

Work done $= [\rho . a . v\,(v-u)\,(1+cos\theta)] \times u$

Case 1: Stationary Vanes

c) Curved plate (symmetric)

- When Jet strikes at one end tangentially



$F_x = \rho Q(v_1 - v_2)_x$

$$F_x = \rho.a.v[v\,cos\theta\ -(-v\cos\theta)]$$

$$F_x = \rho.a.v[v\,cos\theta + v\,cos\,\theta]$$

$$F_x = \rho.a.v[2v\cos\theta]$$

$$F_x = 2\rho.a.v^2\cos\theta$$

$$F_y = \rho.a.v[vsin\theta\ - v\,sin\,\theta]$$

$$F_y = 0$$

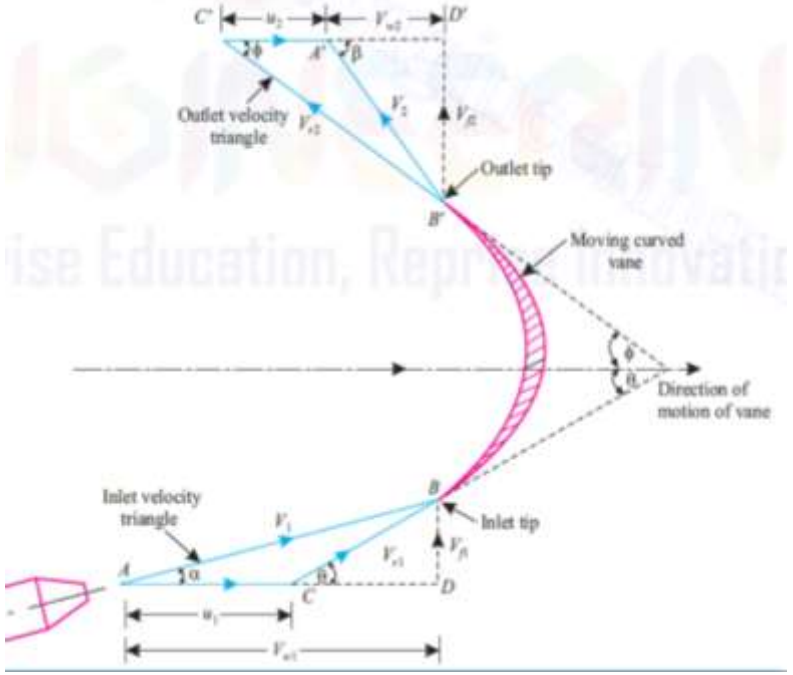
Work done = 0

Case 2: Moving Vanes

c) Curved plate (Unsymmetric)

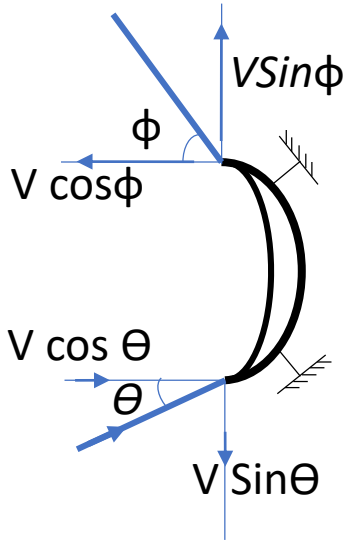
- When Jet strikes at one end tangentially

i) Single vane



Case 1: Stationary Vanes

c) Curved plate (unsymmetric)



$$V_{1x} = V\cos\theta;\ V_{1y} = V\sin\theta$$
$$V_{2x} = -V\cos\phi;\ V_{2y} = V\sin\phi$$

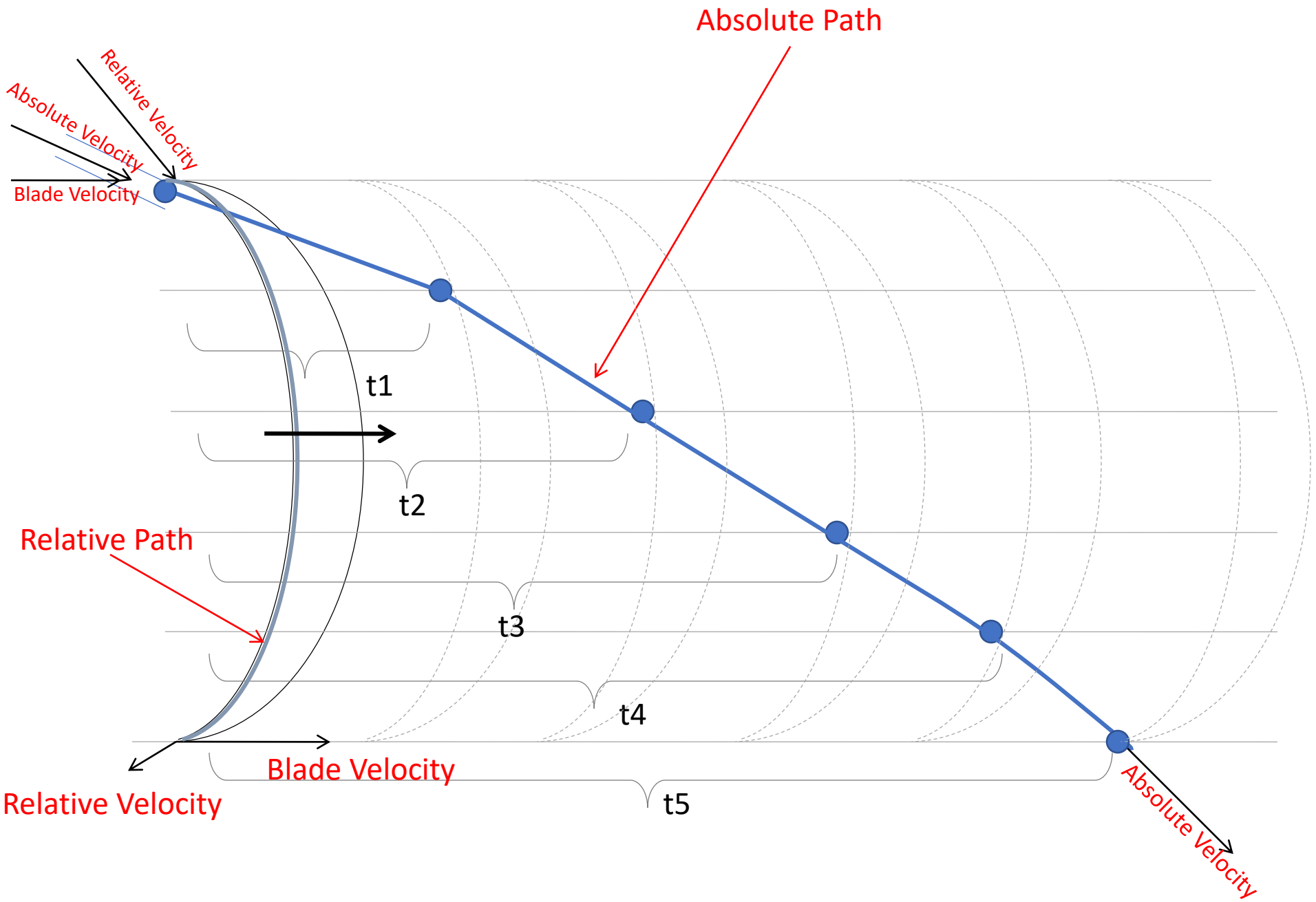
$$F_x = \rho aV(V_{1x} - V_{2x})$$
$$F_x = \rho aV[V\cos\theta - (-V\cos\phi)] = \rho aV(V\cos\theta + V\cos\phi)$$
$$F_x = \rho aV^2(\cos\theta + \cos\phi)$$
$$F_y = \rho aV(V_{1y} - V_{2y})$$
$$= \rho aV(V\sin\theta - V\sin\phi)$$
$$F_y = \rho aV^2(\sin\theta - \sin\phi)$$

Basics of velocity triangle diagram

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- Velocity triangle diagram consists of three velocity vectors namely
  - ✓absolute velocity,
  - ✓relative velocity
  - ✓Blade velocity
- Absolute velocity is tangential to absolute path,
- relative velocity is tangential to relative path,
- Blade velocity is tangential to path followed by blade

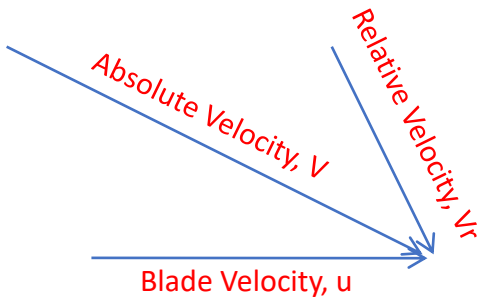
Let us consider a curved vane with jet striking tangentially at one end and leaving at another.


Absolute Path
Relative Velocity
Absolute Velocity
Blade Velocity
t1
t2
Relative Path
t3
t4
Blade Velocity
Relative Velocity
t5
Absolute Velocity

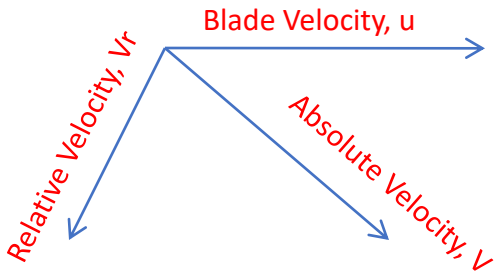
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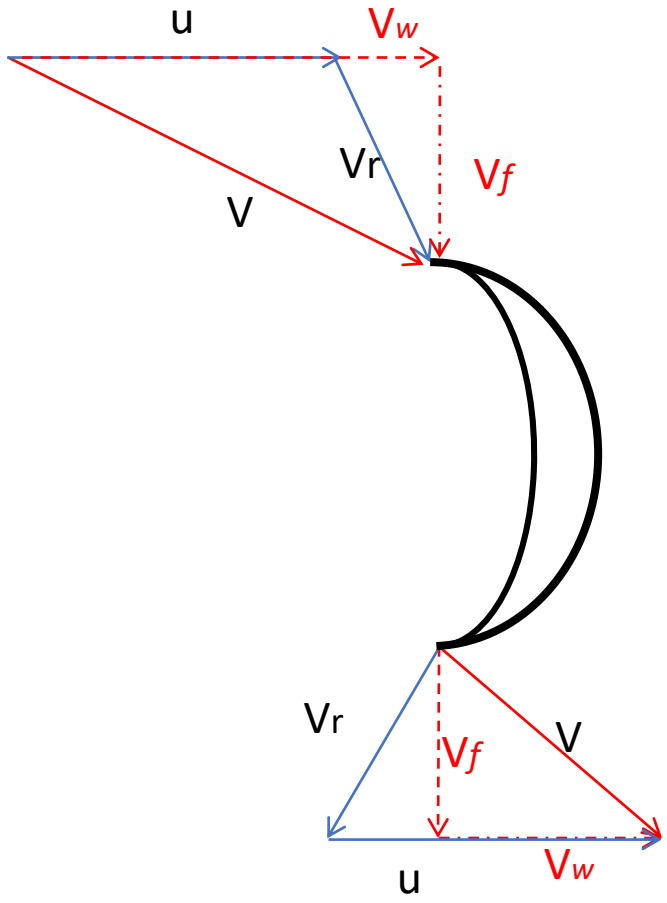
- Combining all three velocity components at inlet and outlet of blade

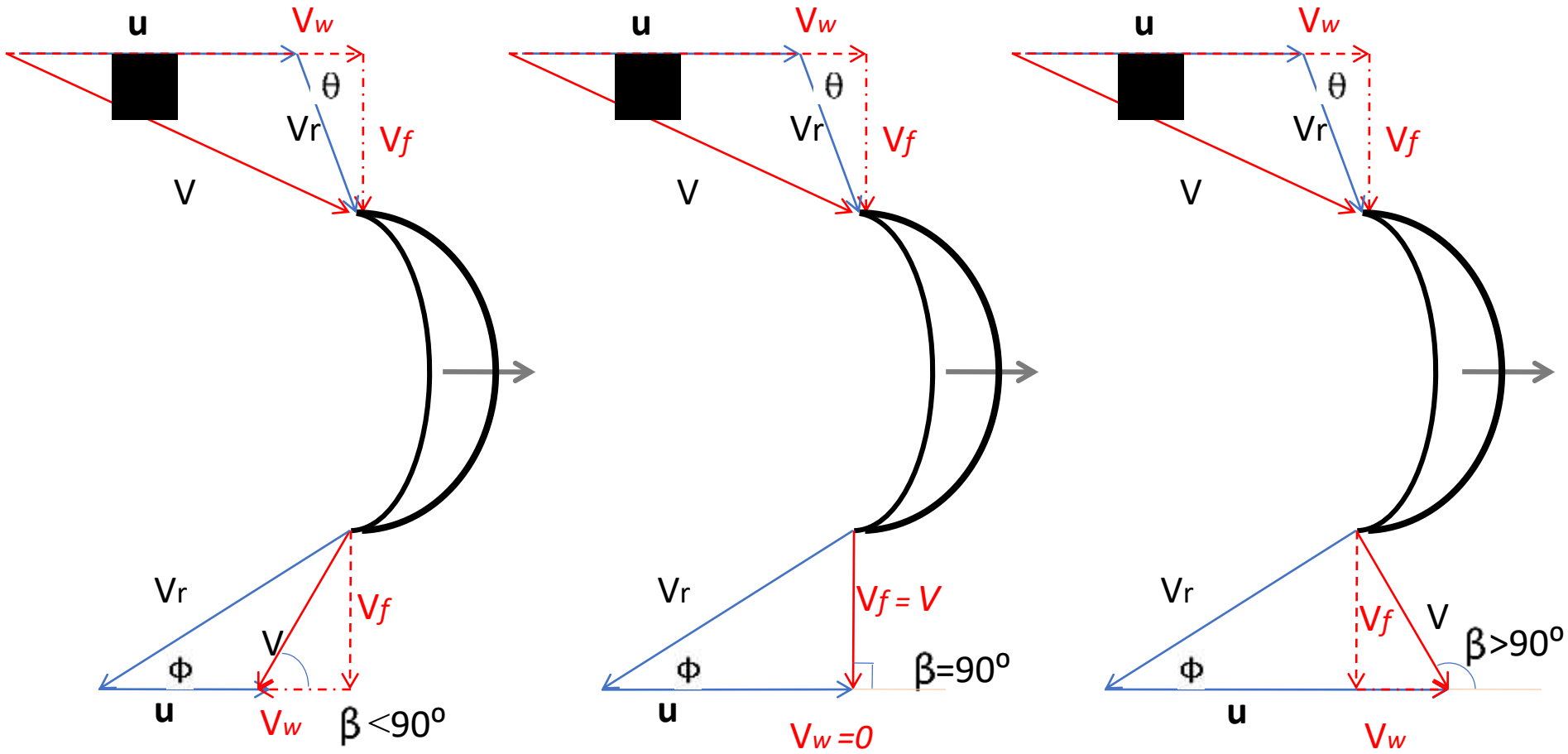
At Inlet from previous fig



At Outlet from previous fig







Slow Runner

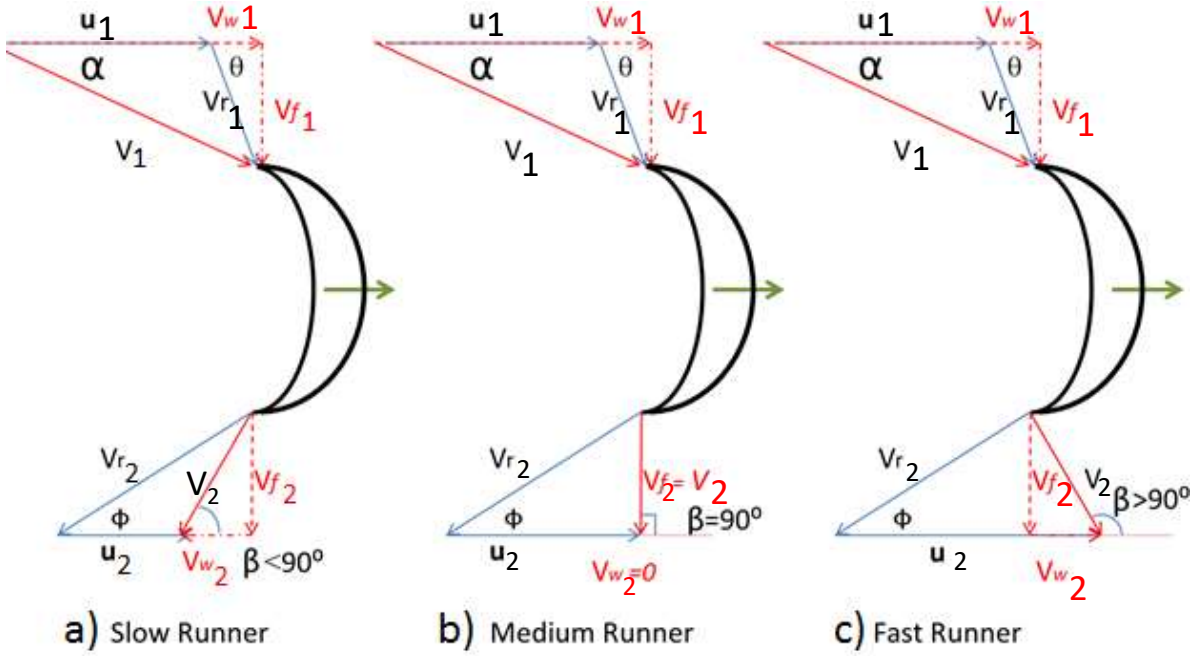
Medium Runner

Fast Runner

Where

1. V, u, Vr are absolute, blade, relative velocities resp.
2. Vf, Vw are flow and whirl velocities.
3. θ & ϕ are tip angles (Blade angles) at inlet and outlet resp.
4. α & β are angles made by abs velocity at inlet and outlet.

Jet striking tangentially at one end and leaving at another.



i) Single vane

$$F_x = \rho Q(v_1 - v_2)_x$$

In this case, The effective velocity with which the jet strikes the vane is the relative velocity. i.e. $v - u$ *or* V_r

The force exerted by the jet in the direction of motion is due to whirl velocity V_w

Hence the equation for force exerted becomes

- Let us consider the case of slow runner as shown in fig (a)

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$$= \rho a V_{r1}[V_{r1}\cos\theta - (-V_{r2}\cos\phi)]$$

$$V_{r1}\cos\theta = (V_{w1} - u_1), \text{ and } V_{r2}\cos\phi = (u_2 + V_{w2})$$

$$F_x = \rho a V_{r1}[(V_{w1} - u_1) - \{-(u_2 + V_{w2})\}]$$

$$= \rho a V_{r1}[V_{w1} - u_1 + u_2 + V_{w2}]$$

$$F_x = \rho a V_{r1}(V_{w1} + V_{w2}) \qquad (\because u_1 = u_2)$$

Hence $$F_x = \rho.a.v_{r1}\left(V_{w_1} + V_{w_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

- Now let us consider the case of medium runner as shown in fig (b)

  V_{w2} is zero.

Hence

$$F_x = \rho.a.v_{r1}\left(V_{w_1}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

- Now let us consider the case of fast runner as shown in fig (c)

  Vw2 is in the same direction as that of motion of vane

Hence $$F_x = \rho.a.v_{r1}\left(V_{w_1} - V_{w_2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Hence the generalized equation for force exerted becomes

$$F_x = \rho.a.v_{r1}\left(V_{w_1} \pm V_{w_2}\right) \quad \ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots(I)$$

Where, β

+ ve sign is to be used for slow runners (i.e. β < 90°)

– ve sign is to be used for fast runners (i.e. > 90°)

- Work done by the jet can be obtained by

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Work done on vane per sec = Force exerted by the jet on vane in the direction motion of vane × Distance travelled by the vane per sec

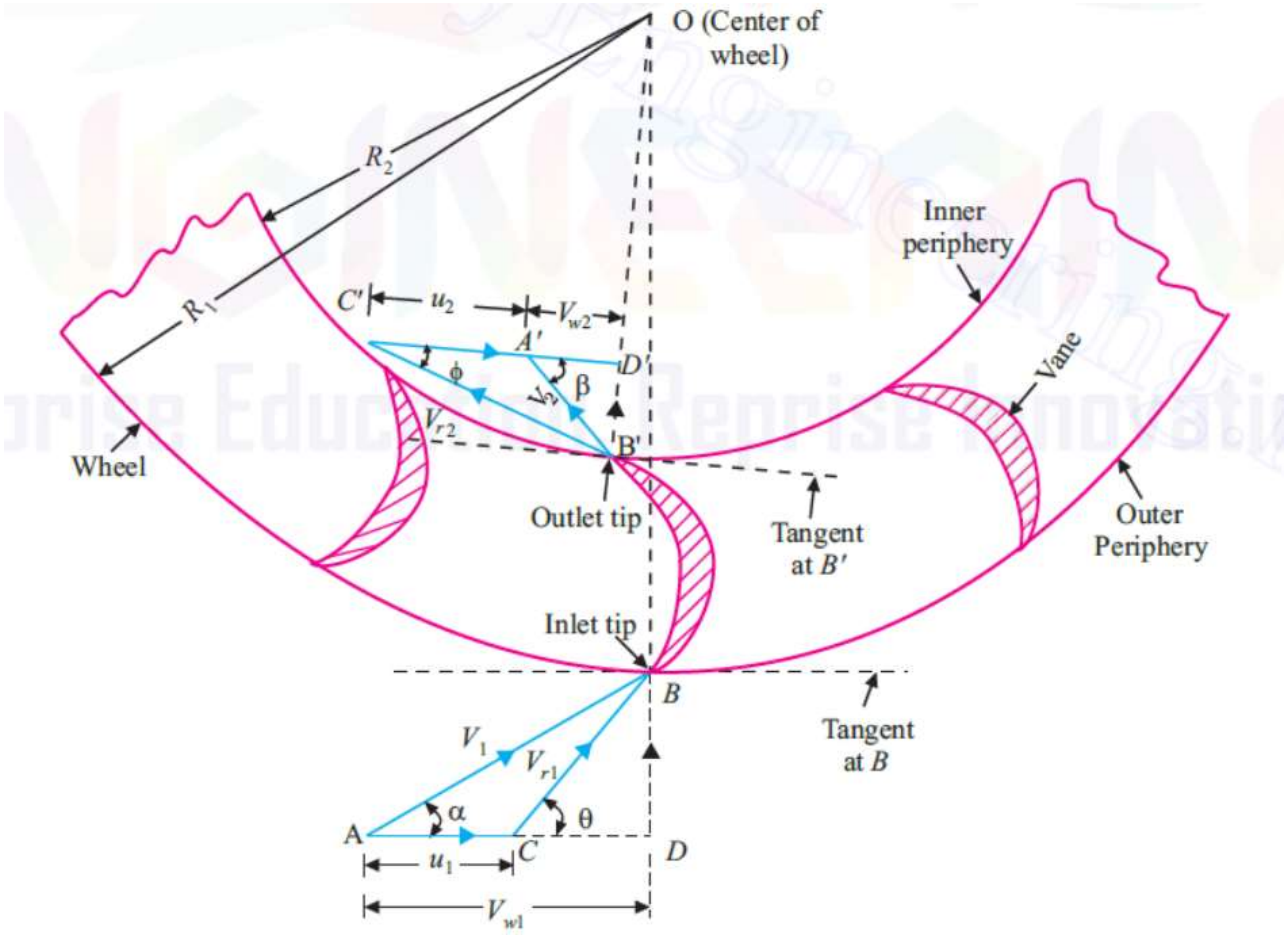
Hence,

$$\text{W.D.} = \rho.a.v_{rl}\left(V_{w_1} \pm V_{w_2}\right) \times u \quad \ldots\ldots\ldots\ldots\ldots \text{(II)} \quad \{\text{If } u_1 = u_2 = u\}$$

If $u_1 \neq u_2$, Then

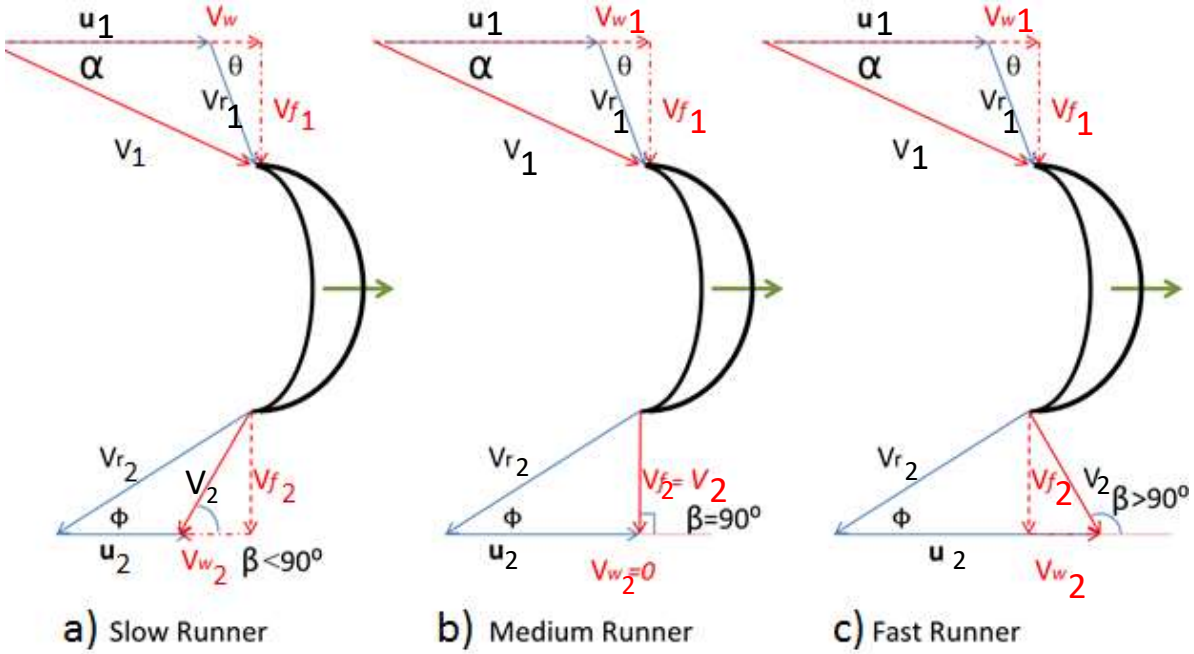
$$\text{W.D.} = \rho.a.v_{rl}\left(V_{w_1}u_1 \pm V_{w_2}u_2\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(III)}$$

ii) series of vanes



The mass of water striking per second (for a series of vanes)
= Mass of water issuing from the nozzle per second
=ρ.a.v1 = ρQ

Jet striking tangentially at one end and leaving at another.



In this case,

- Let us consider the case of slow runner as shown in fig (a)

V_{w2} is in the opposite direction of motion, Hence it is considered as – ve.

So, $$F_x = \rho Q\left[V_{w_1} - \left(-V_{w_2}\right)\right]$$

Hence $$F_x = \rho Q\left(V_{w_1} + V_{w_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

- Now let us consider the case of medium runner as shown in fig (b)

  V_{w2} is zero.

Hence

$$F_x = \rho Q\left(V_{w_1}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

- Now let us consider the case of fast runner as shown in fig (c)

  Vw2 is in the same direction as that of motion of vane

Hence $$F_x = \rho Q\left(V_{w_1} - V_{w_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Hence the generalized equation for force exerted becomes

$$F_x = \rho Q\left(V_{w_1} \pm V_{w_2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(I)$$

Where,

+ ve sign is to be used for slow runners (i.e. $\beta < 90°$)

– ve sign is to be used for fast runners (i.e. $\beta > 90°$)

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- Work done by the jet can be obtained by

Work done on vane per sec = Force exerted by the jet on vane in the direction motion of vane × Distance travelled by the vane per sec

Hence,

$$\text{W.D.} = \rho Q\left(V_{w_1} \pm V_{w_2}\right) \times u \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(II)}$$

If $u_1 = u_2 = u$,

like in the cases of Pelton turbine, Kaplan turbines, etc. above equation (eq. no. II) is valid.

If $u_1 \neq u_2$, like in the case of Francis turbine,

Then

$$\text{W.D.} = \rho Q\left(V_{w_1} u_1 \pm V_{w_2} u_2\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(III)}$$

Turbomachines

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- Device that exchanges energy using continuously flowing fluid and rotating blades.

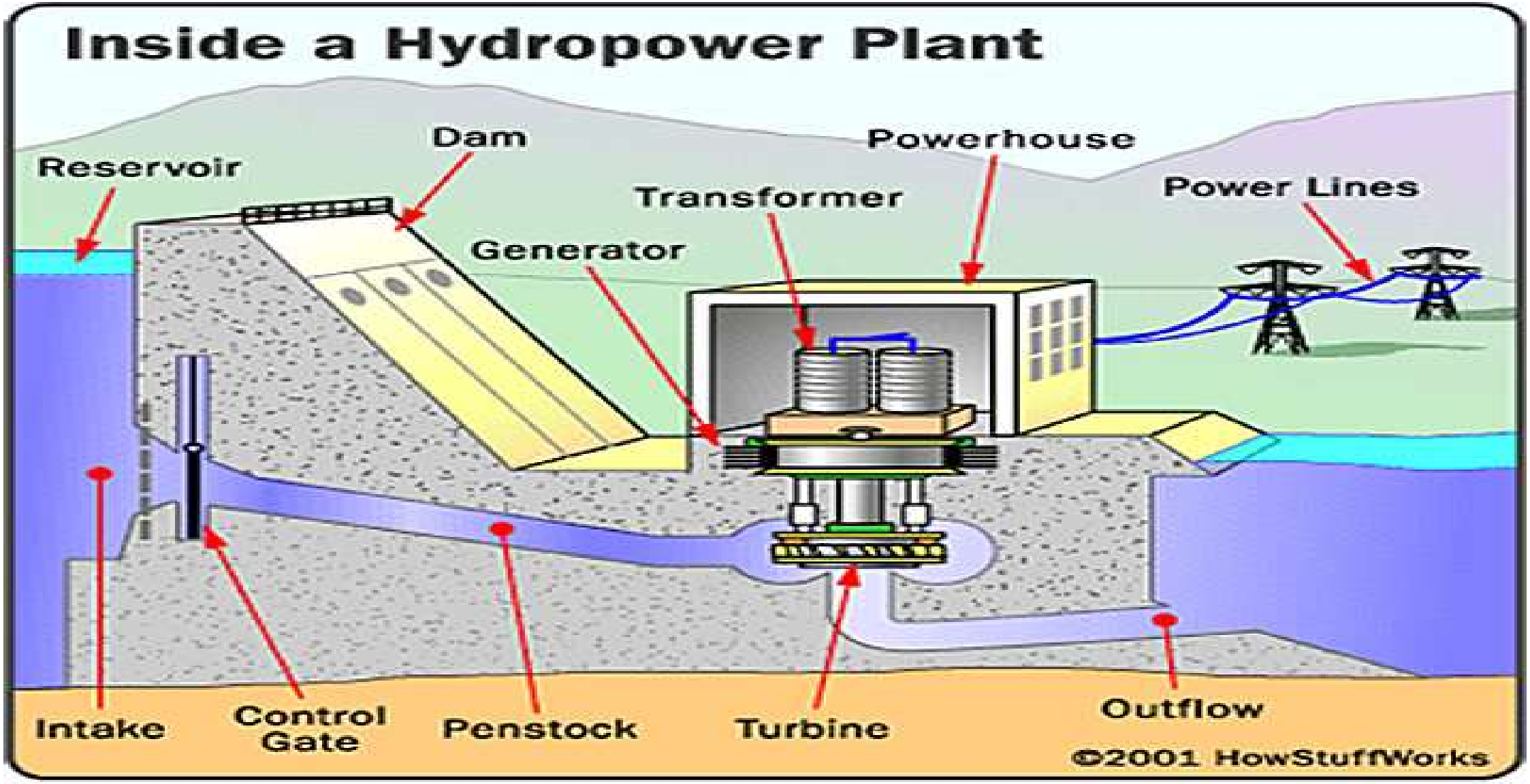
  Examples:
  - Wind / hydraulic / steam / gas turbines, etc.
    - Extracts energy from fluid and produces work
  - compressor, fan, blower, pump, etc.
    - Absorbs work and delivers energy to fluid.

Hydraulic Turbines

- Most of the electrical generators are powered by turbines.
- Steam and Gas turbines share in the electrical power generation is about 75%.
- About 20% of power is generated by hydraulic turbines.
- Rest of 5% only is by other means of generation.

Hydro Power Plant

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Hydraulic Power Plant

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- The main components of hydraulic power plant are
  - *The storage system*
    - The storage system consists of a reservoir with a dam structure and the water flow control in terms of sluices and gates etc.
    - The reservoir may be at a high level in the case of availability of such a location. In such cases the potential energy in the water will be large but the quantity of water available will be small.
  - *Conveying* system
    - The conveying system may consist of tunnels, channels and steel pipes called penstocks. Tunnels and channels are used for surface conveyance.
    - Penstocks are pressure pipes conveying the water from a higher level to a lower level under pressure.
  - *Hydraulic turbine with control system*
    - Nozzle or guide vanes are fitted at the end of penstock to control flow.
  - *Electrical generator*

Classification of Turbines

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Turbines can be classified on the basis of:

- Head and quantity of water available
- Hydraulic action of water
- Direction of flow of water in the runner
- Specific speed of turbines
- Disposition of the shaft of the runner

Classification of turbines

- Based on head and quantity of water

  According to head and quantity of water available, the turbines can be classified into

  a) High head turbines

  b) Medium head turbines

  c) Low head turbines

  a) High head turbines

  High head turbines are the turbines which work under the gross head more than 400m. The quantity of water needed in case of high head turbines is usually small. The Pelton turbines are the usual choice for high heads.

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Classification of turbines

- Based on head and quantity of water

b) Medium head turbines

The turbines that work under a head of 30m to 500m are called medium head turbines. It requires medium flow of water. Francis turbines are used for medium heads.

c) Low head turbines

Turbines which work under a head of less than 50m are called low head turbines. Owing to low head, large quantity of water is required. Kaplan turbines are used for low heads.

Figures of head given above overlaps each other , therefore it is difficult to classify plants based on head alone. therefore the basis used is specific speed.

Classification of turbines

- Based on hydraulic action of water

According to hydraulic action of water, turbines can be classified into

a) Impulse turbines

b) Reaction turbines

a) Impulse turbines

- Runner of a turbine rotates by the impact or impulse action of water.
- Pressure of water does not change while flowing through rotor.
- Pressure change occur only in nozzle and not in rotor.
- Jet impinges at atmospheric pressure.
- e.g. Pelton wheel.

b) Reaction turbines

- Pressure of water changes while flowing through rotor.
- Change in water velocity and reduction in pressure causes reaction on turbine blades
- Airtight casing fully filled with water under pressure
- e.g. Francis and Kaplan Turbine.

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Classification of turbines

- Based on direction of flow of water in the runner

  Depending upon the direction of flow through the runner, following types of turbines are there

  a) Tangential flow turbines

  b) Radial flow turbines

  c) Axial flow turbines

  d) Mixed flow turbines

  a) Tangential flow turbines

  When the flow is tangential to the wheel circle, it is a tangential flow turbine. A Pelton turbine is a Tangential flow turbine.

Classification of turbines

- Based on direction of flow of water in the runner

b) Radial flow turbines

In a radial flow, the path of the flow of water remains in the radial direction and in a plane normal to the runner shaft. No pure radial flow turbine is in use these days.

c) Axial flow turbines

When the path of flow water remains parallel to the axis of the shaft, it is an axial flow turbine. The Kaplan turbine is axial flow turbine

d) Mixed flow turbines

When there is gradual change of flow from radial to axial in the runner, the flow is called mixed flow. The Francis turbine is a mixed flow turbine.

Classification of turbines

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- Based on specific speed of turbine
  - This is better method of classification than classification based on head only.
  - Both head and discharge are accounted.
  - Turbines are classified as High, medium and low specific speed turbines.

Type of Turbine	Specific Speed
Pelton (Single jet OR per jet in multi jet turbine)	8-30
Francis	40-450
Kaplan	300-900

- Usually, Pelton turbines are setup with horizontal shafts, where as other types have vertical shafts.

Heads, Losses in Hydraulic Turbines

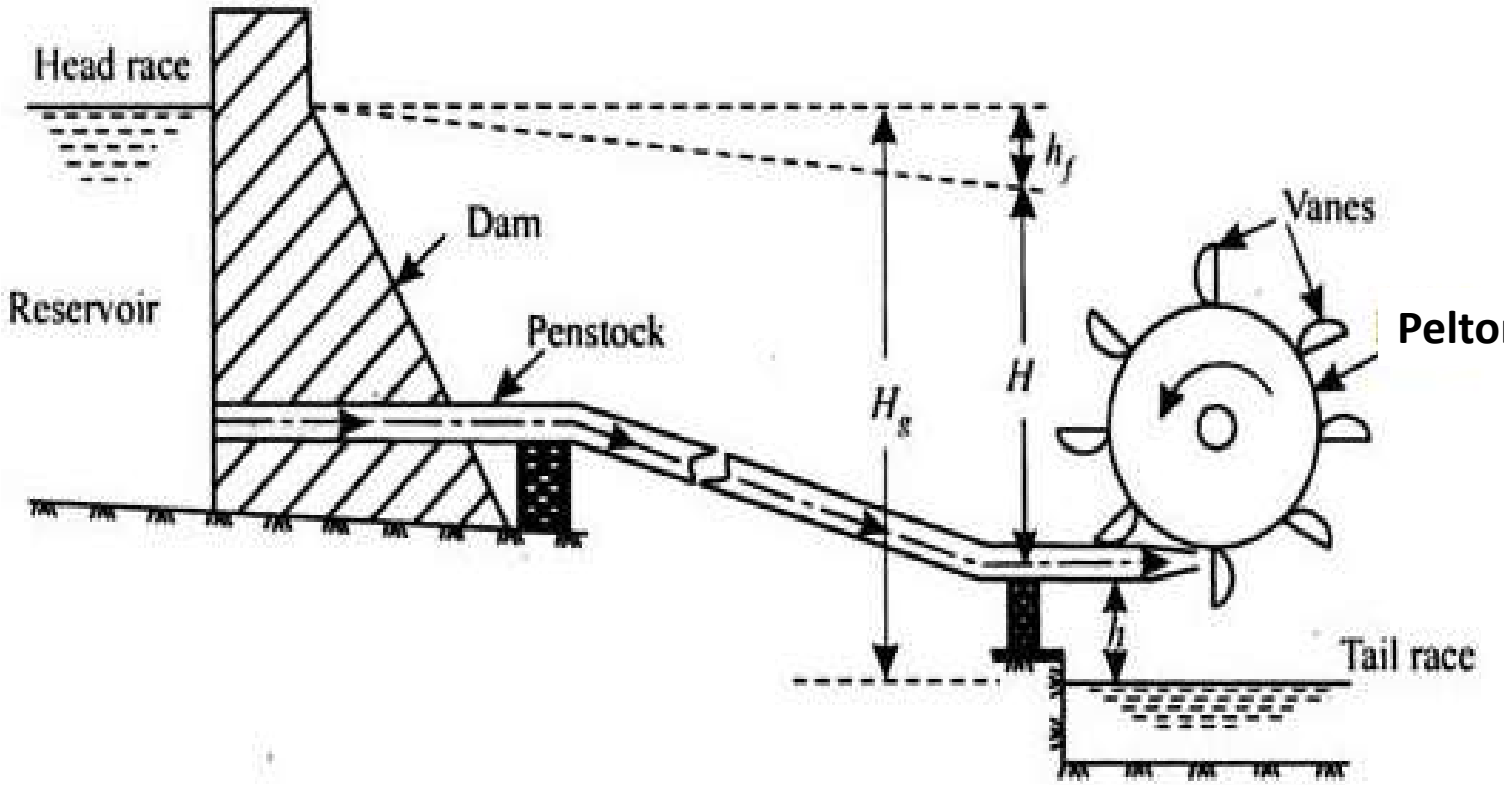
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- Heads

These are defined as below:

(a) Gross Head: Gross or total head is the difference between the headrace level and the tail race level when there is no flow.

(b) Net Head: Net head or the effective head is the head available at the turbine inlet. This is less than the gross head, by an amount, equal to the friction losses occurring in the flow passage, from the reservoir to the turbine inlet.


Head race
Dam
Reservoir
Penstock
h_f
H_g
H
Vanes
Pelton Wheel
h
Tail race

$$H = H_g - h_f - h$$

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1. Gross head. The gross (total) head is the difference between the water level at the reservoir (also known as the *head race*) and the water level at the tail race. It is denoted by H_g.

2. Net or effective head. The head available at the inlet of the turbine is known as net or effective head. It is denoted by H and is given by:

$$H = H_g - h_f - h$$

where, h_f = Total loss of head between the head race and entrance of the turbine

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- Losses

Various types of losses that occur in a power plant are given below:

(a) Head loss in the penstock: This is the friction loss in the pipe of a penstock.

(b) Head loss in the nozzle: In case of impulse turbines, there is head loss due to nozzle friction.

(c) Hydraulic losses: In case of impulse turbines, these losses occur due to blade friction, eddy formation and kinetic energy of the leaving water. In a reaction turbine, apart from above losses, losses due to friction in the draft tube and disc friction also occur.

(d) Leakage losses: In case of impulse turbines, whole of the water may not be striking the buckets and therefore some of the water power may go waste. In a reaction turbine, some of the water may be passing through the clearance between the casing and the runner without striking the blades and thus not doing any work. These losses are called leakage losses.

(e) Mechanical losses: The power produced by the runner is not available as useful work of the shaft because some power may be lost in bearing friction as mechanical losses.

f) Generator losses: Due to generator loss, power produced by the generator is still lesser than the power obtained at the shaft output.

Efficiencies

- Various types of efficiencies are defined as under:

(a) Hydraulic efficiency: It is the ratio of the power developed by the runner to the actual power supplied by water to the runner. It takes into account the hydraulic losses occurring in the turbine

η_h = Runner output / Water Power

= Runner output / (ρgQH)

Where, Q = Quantity of water actually striking the runner blades

H = Net head available at the turbine inlet

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(b) Volumetric efficiency: It is the ratio of the actual quantity of water striking the runner blades to the quantity supplied to the turbine. It takes into account the volumetric losses.

Let ΔQ = Quantity of water leaking or not striking the runner blades

$$\eta_v = Q / (Q + \Delta Q)$$

(c) Mechanical efficiency: The ratio of the shaft output to the runner output is called the mechanical efficiency and it accounts for the mechanical losses.

$$\eta_m = \text{Shaft output} / \text{Runner output}$$

(d) Overall efficiency: Ratio of shaft output to the net power available at the turbine inlet gives overall efficiency of the turbine

η_m = Shaft output / Net power available

$$\eta_o = \frac{Shaft.output}{\rho(Q+\Delta Q)gH}$$

$$\eta_o = \frac{Shaft.output}{Runner.output} \times \frac{Runner.output}{\rho gQH} \times \frac{Q}{(Q+\Delta Q)}$$

Thus all the three types of losses, mechanical, hydraulic and volumetric have been taken into account.

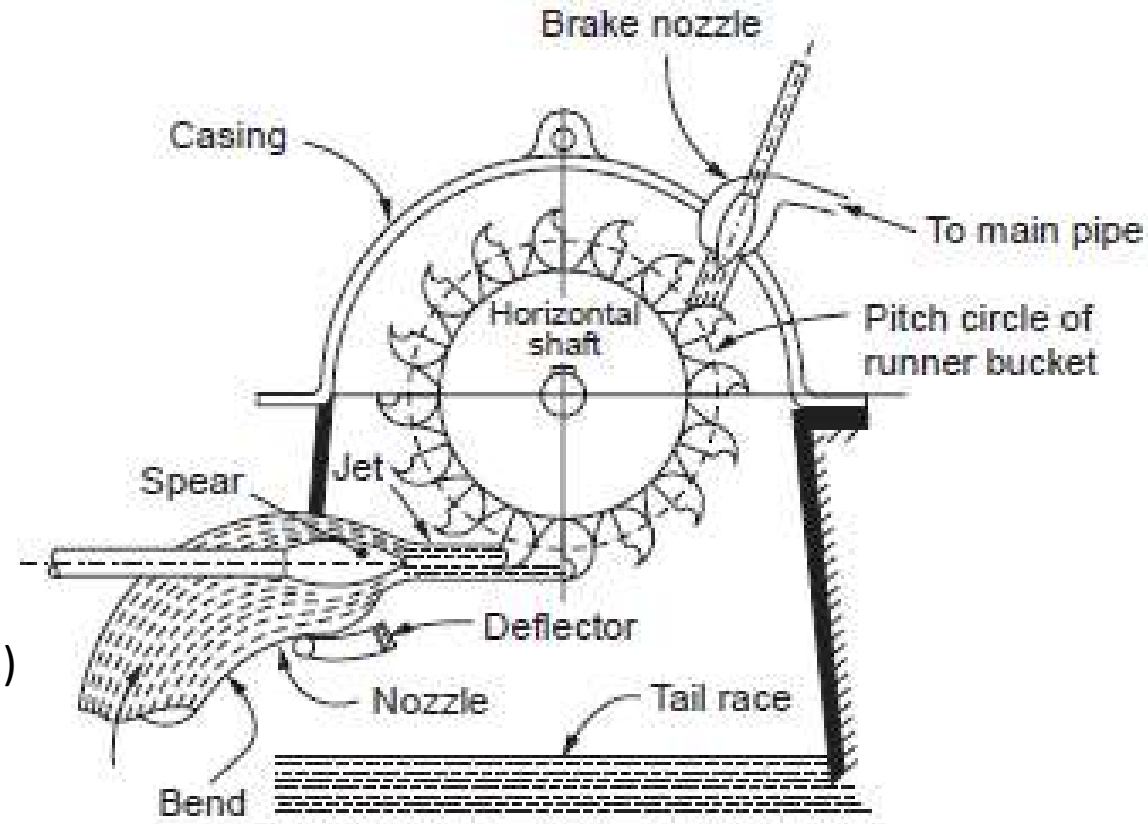
$$\eta_o = \eta_m \times \eta_h \times \eta_v$$

Pelton Turbine / Wheel

1. High head turbine, requires less quantity of water
2. Impulse turbine
3. Tangential flow turbine
4. Mostly installed with horizontal shaft
5. Low specific speed

In India installed at

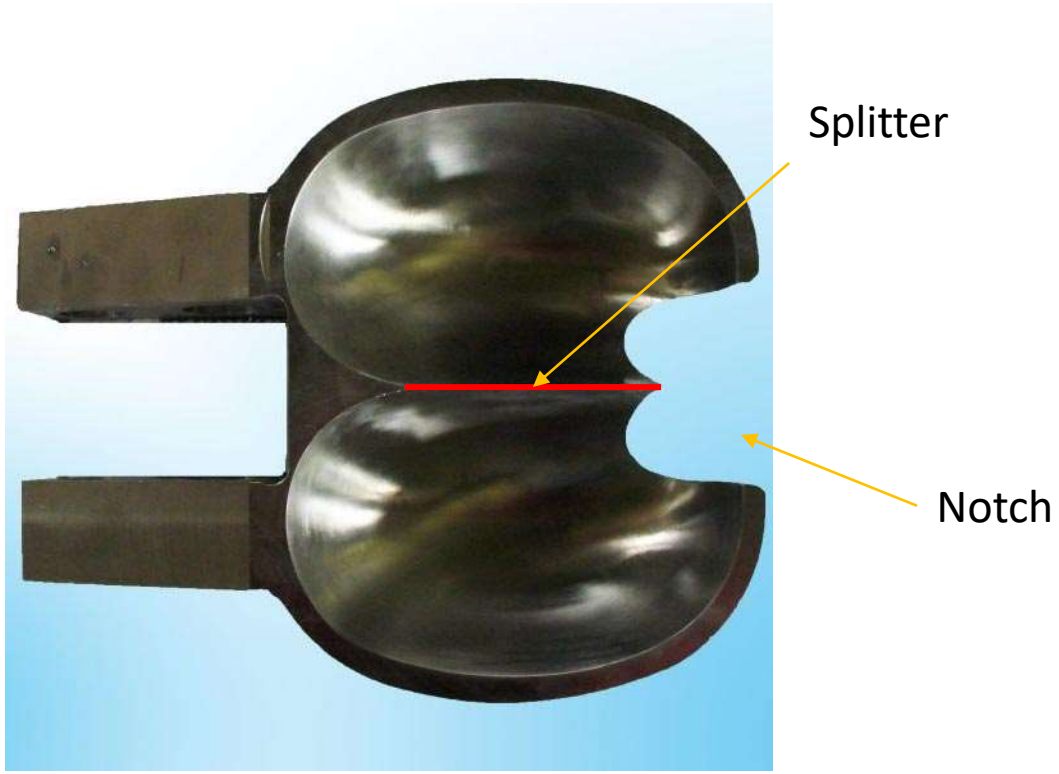
- Koyna hydroelectric plant
- Mahatma Gandhi hydroelectric plant, Sharavati river, (Karnataka)
- Mandi hydroelectric plant, Uhl river (Himachal P.)
- Pykara hydroelectric plant Pykara river (Tamilnadu)



L30



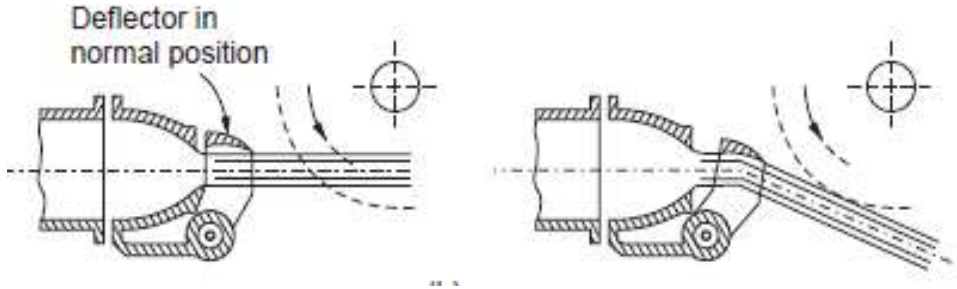




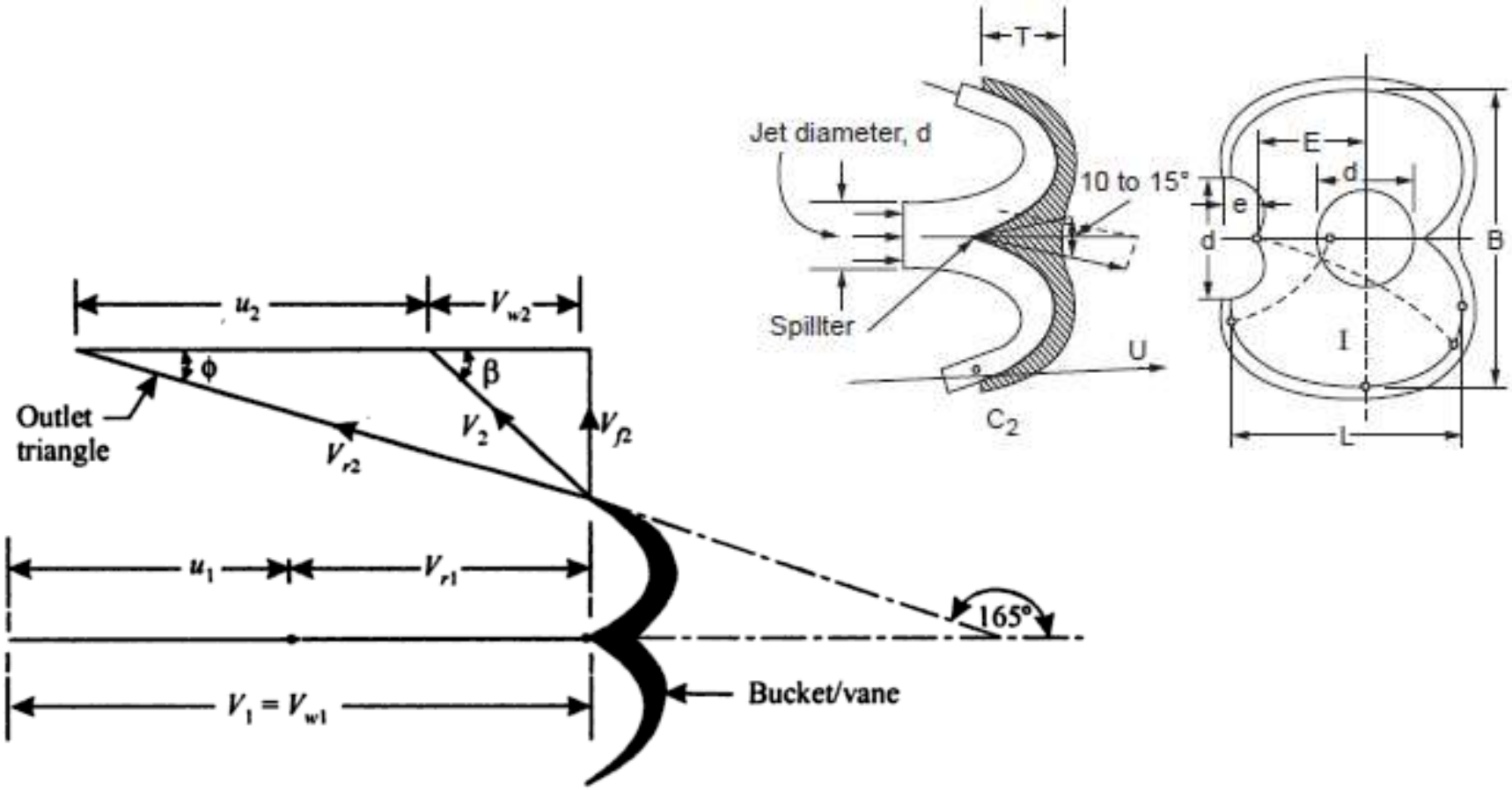
Double hemispherical shape blades

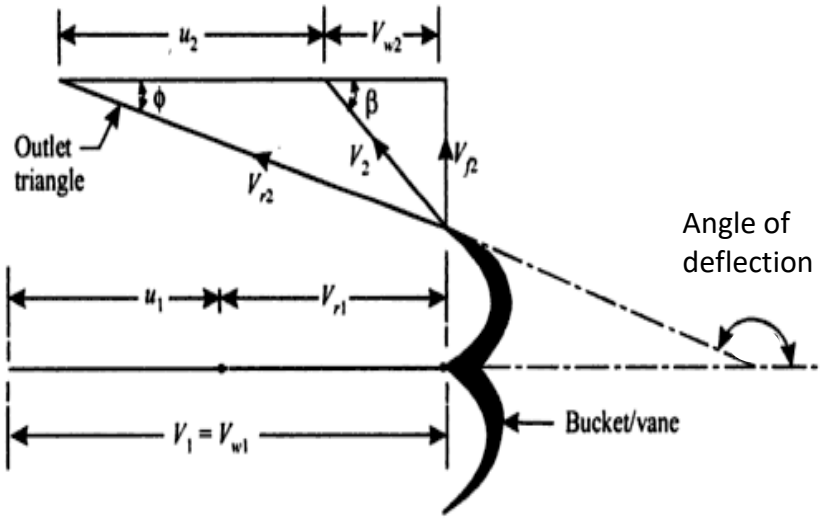
Main Components

- Penstock
  - Penstocks are pressure pipes conveying the water from a higher level to a lower level under pressure.
- Runner with buckets fixed on periphery.
  - Runner made of cast steel or forged steel and polished S.S. blades are bolted to disc.
  - Small units may be a single casting.
- The nozzle assembly with control spear and deflector.
  - To meet load fluctuation quantity of water flow should be changed.
  - A governor moves to and fro a suitably shaped spear placed inside the nozzle assembly in order to change the flow rate.
  - If water flow stopped suddenly, it will generate high pressure wave in the penstock and it may damage penstock.
  - To avoid this a deflector as shown in figure is used to suddenly play out and deflect the jet so that the jet bypasses the buckets.
- Brake nozzle.
- The casing.

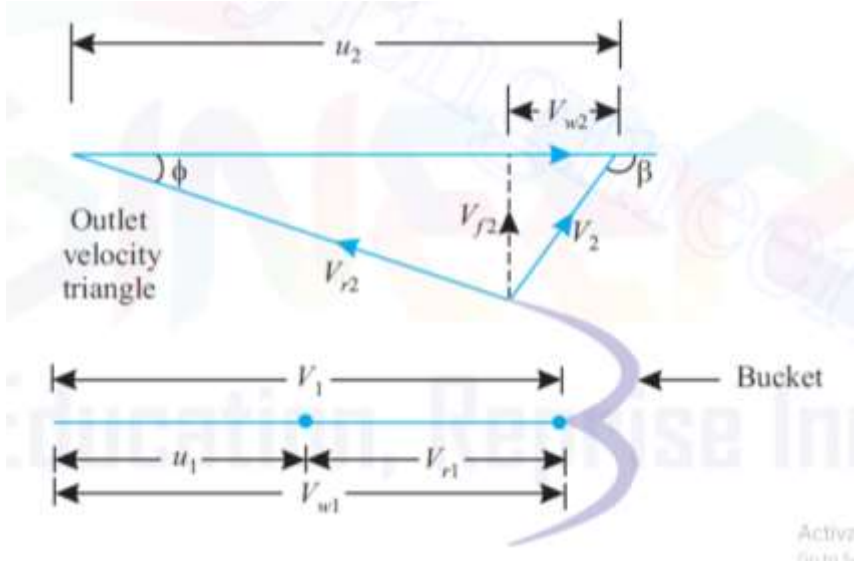


Velocity Diagram

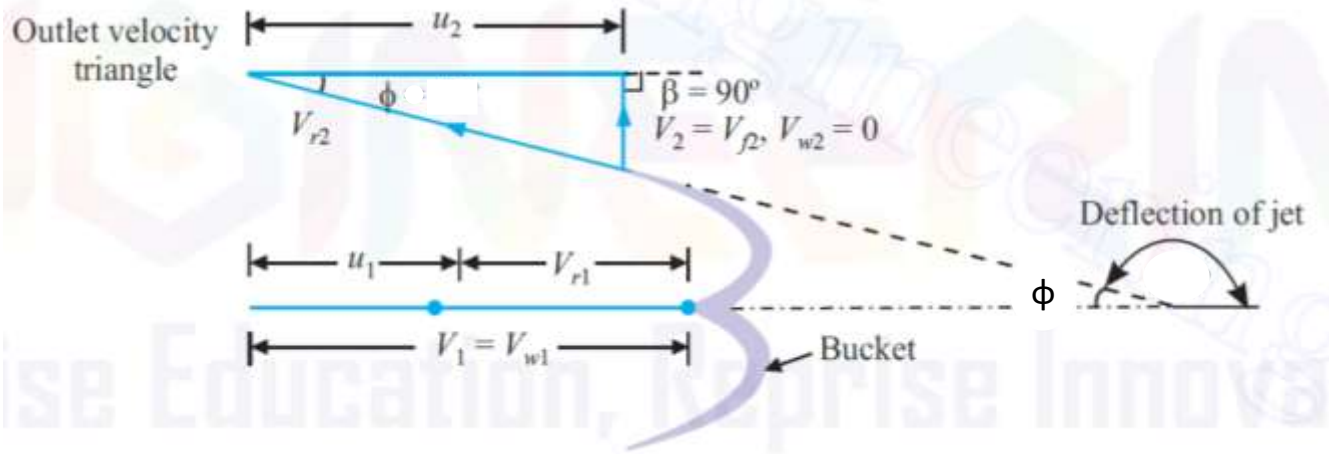




β< 90°
Vr2 cosϕ > u2



β> 90°
Vr2 cosϕ < u2



β= 90°

Work done and Efficiency

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- Inlet:

  The velocity triangle at inlet will be a straight line where

  $Vr1 = V1 - u1$

  $= V1 - u,$ $\quad Vw1 = V1$ (Since u1 = u2 = u)

  $\alpha = 0$ and $\theta = 0$

- Outlet :

  From velocity triangle at outlet, we have

  $Vr2 = KVr1,$

  where, K = blade friction co-efficient, slightly less than unity. Ideally when bucket surfaces perfectly smooth and energy losses due to impact at splitter are neglected.

- $Vw2 = Vr2 \cos \varphi - u2$

  $= Vr2 \cos \varphi - u$ (Since $u1 = u2 = u$)

- The force exerted by the jet of water in the direction of motion is given as:

$$\boldsymbol{F = \rho a V1\ (Vw1 \pm Vw2)}$$

- Now work done by the jet on runner per second (Runner Power)

$$\boldsymbol{F \times u = \rho a V1\ (Vw1 \pm Vw2) \times u}$$

Take + ve symbol when $\beta < 90°$

\- ve symbol when $\beta > 90°$

For, $\beta = 90°$, $Vw2 = 0$

$$\therefore \quad \text{Hydraulic efficiency, } \eta_h = \frac{\text{Work done per second}}{\text{K.E. of jet per second}} = \frac{\rho a V_1 (V_{w1} + V_{w2}) \times u}{\frac{1}{2}(\rho a V_1) \times V_1^2}$$

$$\text{or,} \qquad \eta_h = \frac{2 (V_{w1} + V_{w2}) \times u}{V_1^2}$$

Note, $\rho . g . Q . H = \frac{1}{2}(\rho a v 1) \times V 1^2$

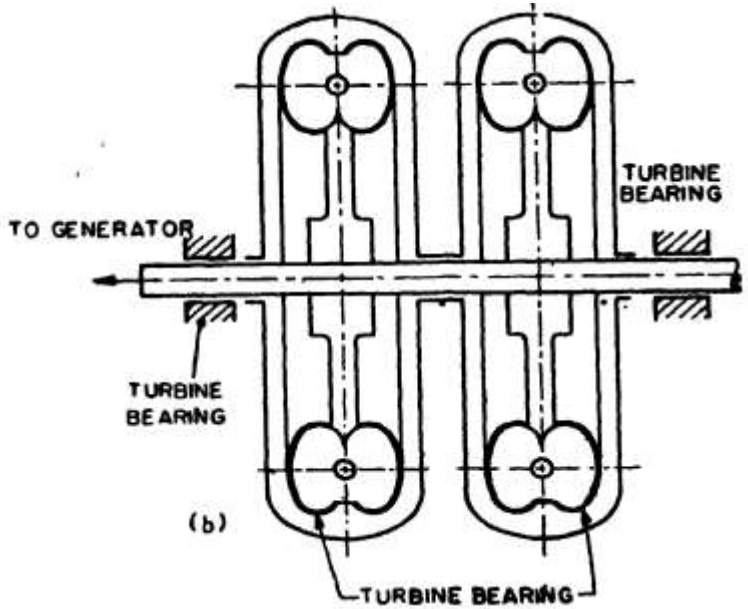
Mechanical Efficiency, $\eta_m = \dfrac{Shaft\ power}{Runner\ Power}$

$$\eta_m = \frac{S.P.}{\rho a V1\ (Vw1 + Vw2) \times u}$$

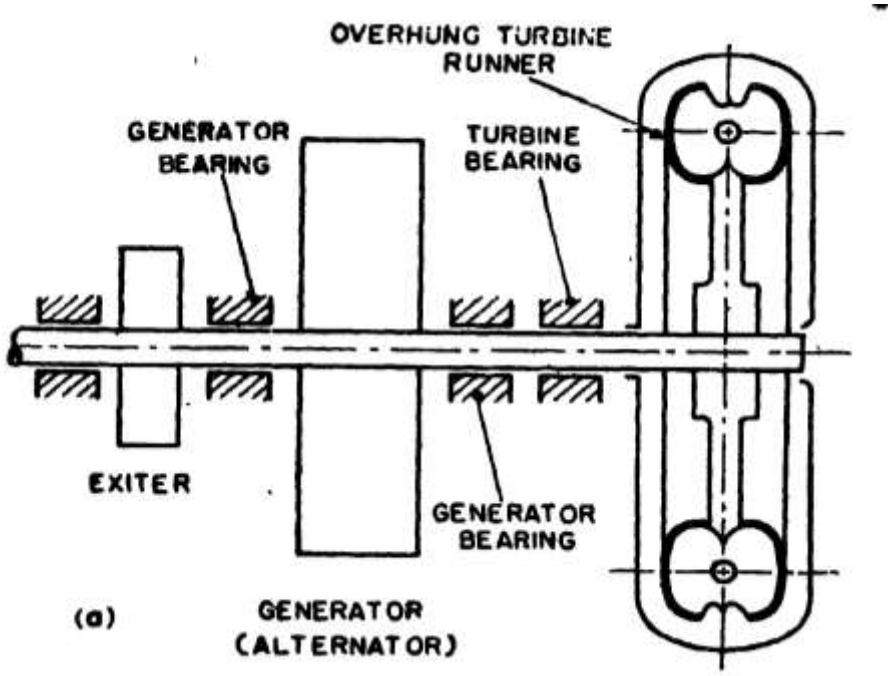
Overall Efficiency, $\eta_o = \dfrac{Shaft\ power}{Water\ Power}$

$$\eta_o = \frac{S.P.}{\rho . g . Q . H}$$

Arrangements of Runner



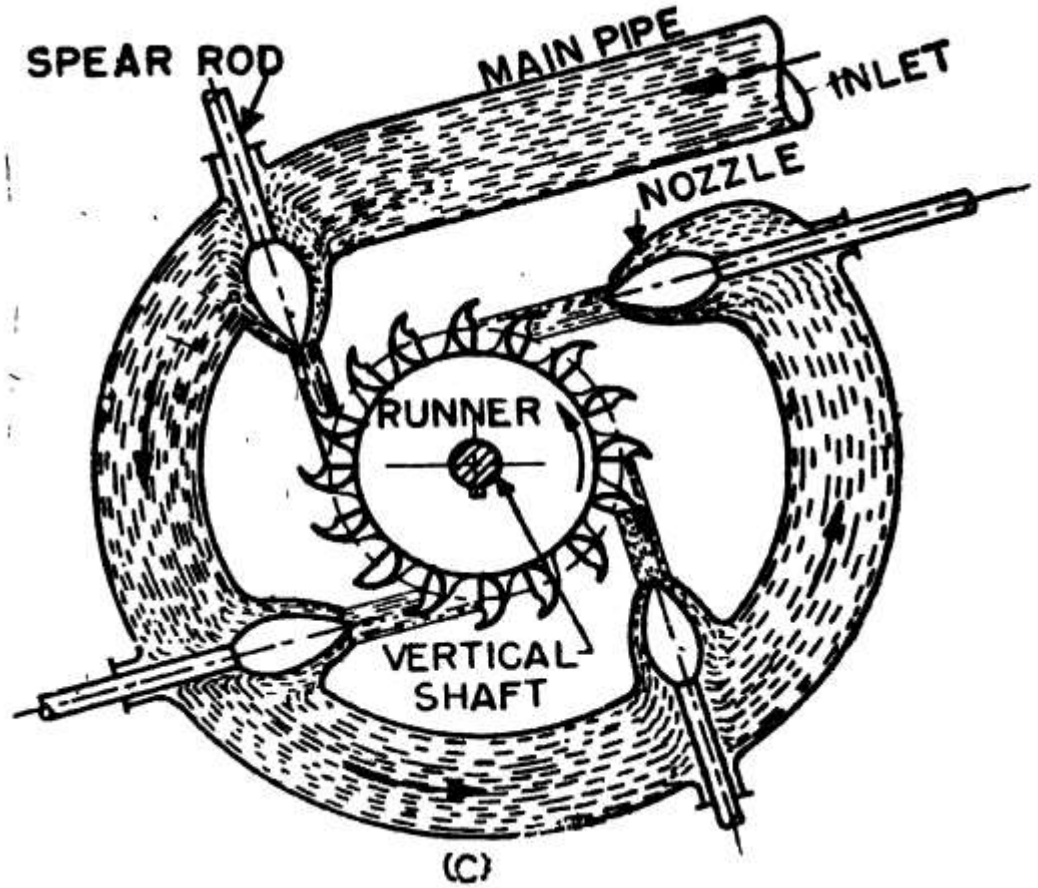
Double Runner



Single Overhung Runner

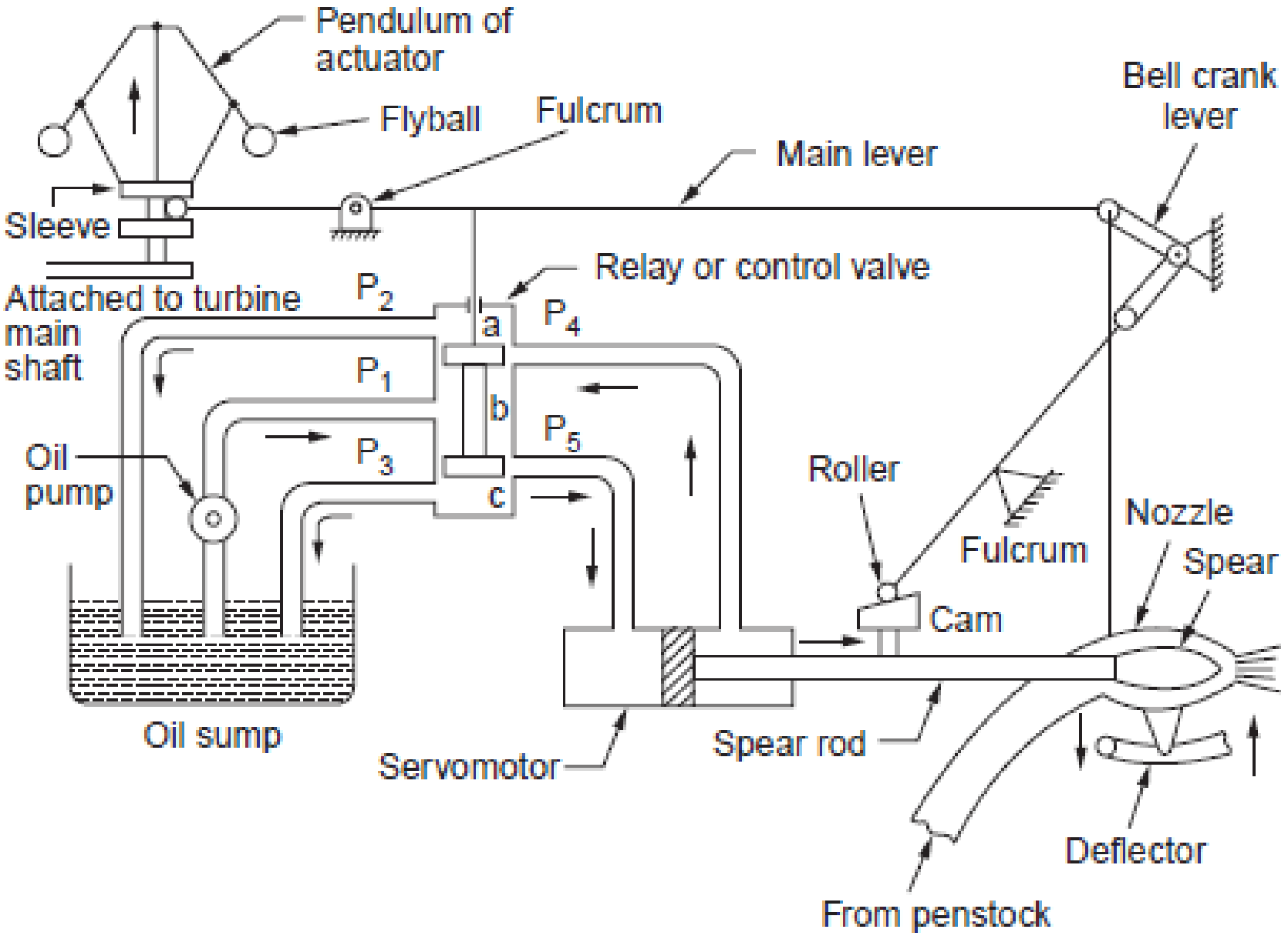
Arrangement of jets

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Four Jet Vertical Shaft Pelton Turbine

Governing of Pelton Turbine



Specific Speed

- The specific speed of a turbine is defined as the speed of a turbine which is identical in shape, geometrical dimensions, blade angles, gate opening, etc. which would develop unit power when working under a unit head.

$$N_s = \frac{N\sqrt{P}}{H^{5/4}}$$

Cavitation

- *The formation, growth, and collapse of vapour filled cavities or bubbles in a flowing liquid due to local fall in fluid pressure is called* **cavitation**.
- When the pressure at any point in a flow field equals the vapour pressure of the liquid at that temperature vapour cavities (bubbles of vapour) begin to appear. It is presumed that a vapour cavity is formed around a dust nuclei which is in the liquid (The vapour pressure values of water at 15° and 20° C are 1.74 m and 2.38 m of water column absolute).
- The cavities thus formed, due to motion of liquid, are carried to high pressure regions where the vapour condenses and they suddenly collapse.
- The adjoining liquid rushes with a very great velocity (and hence with very great force) to occupy the empty spaces thus created, causes series of violent, irregular, spherical shock waves. When these irregular implosions occur on the metallic surface, they produce noise and vibration.

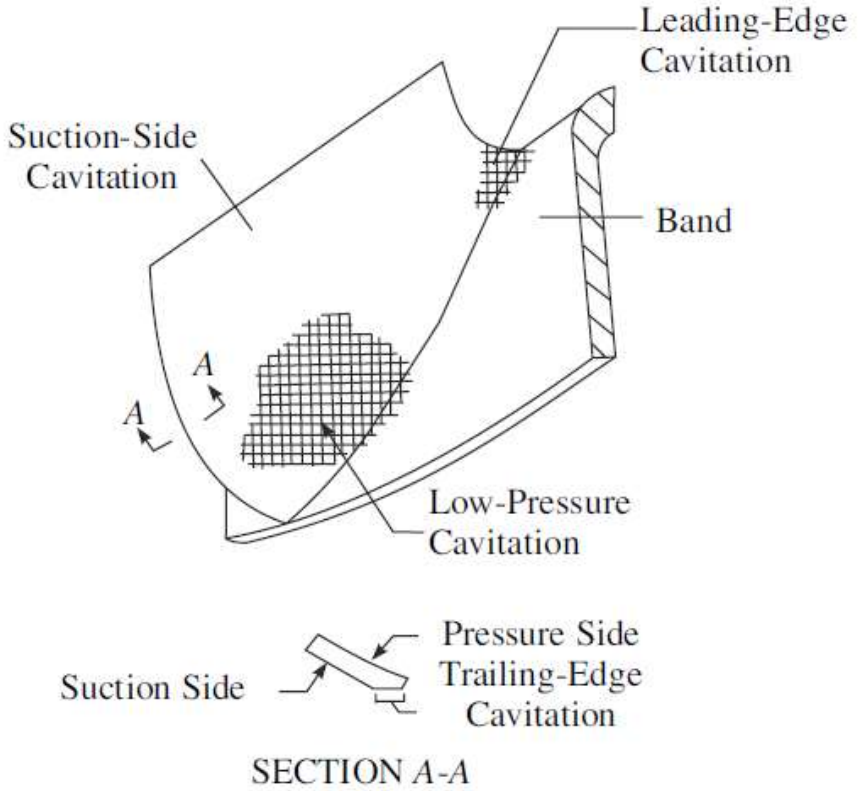
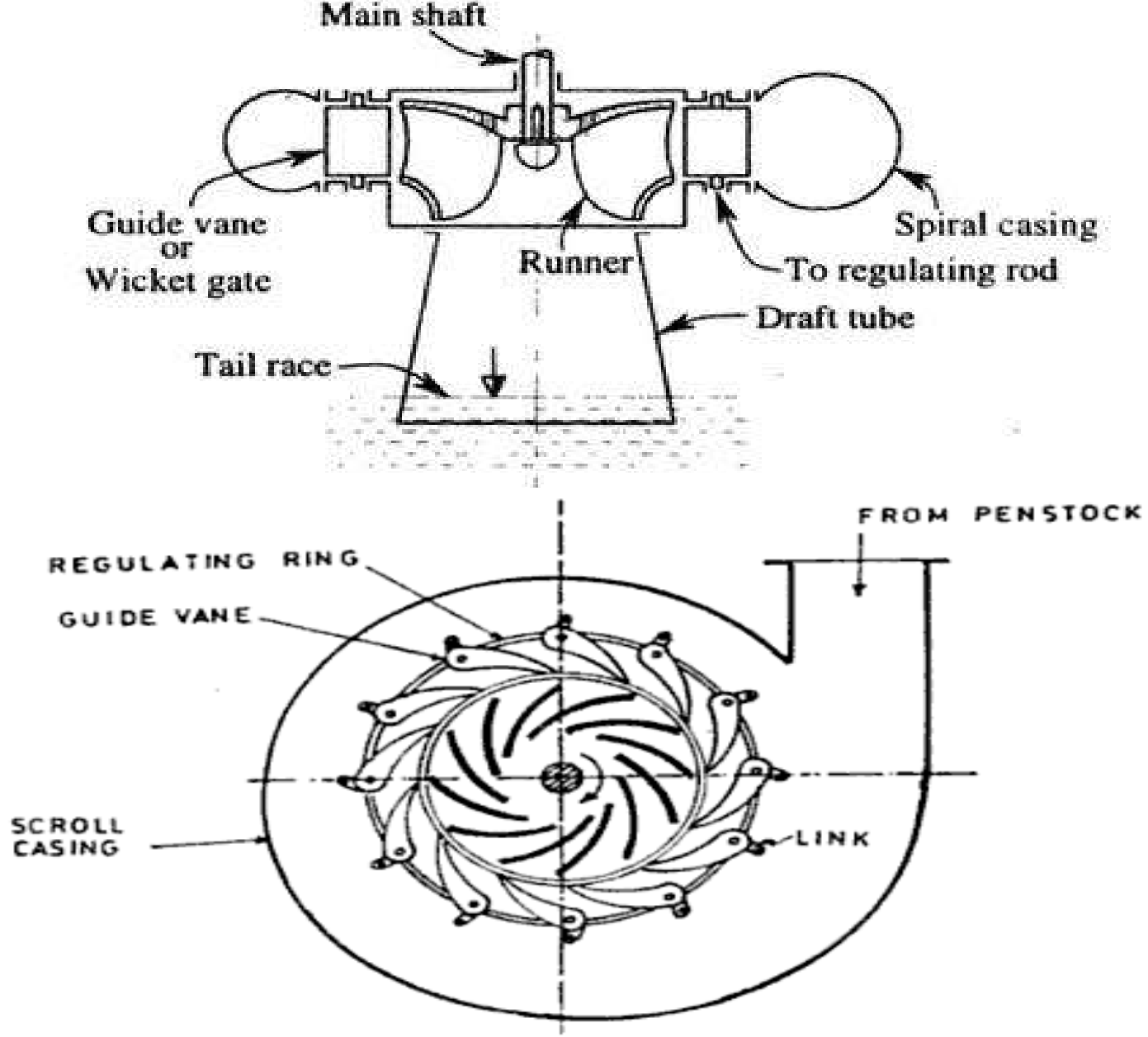


Fig. 2.30(b) *Areas of cavitation in a Francis runner (Ref. 2.2)*

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Francis Turbine



Sectional arrangement of Francis turbine.

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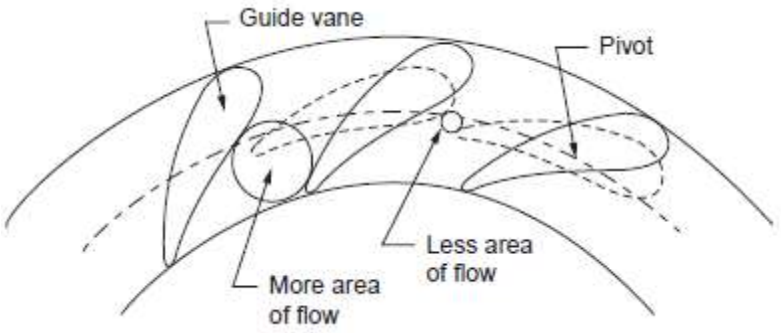
Characteristics

1. Medium head turbine, requires medium quantity of water
2. Reaction turbine
3. Mixed flow turbine
4. Mostly installed with vertical shaft
5. Medium specific speed

In India installed at

- Bhakra Dam Project, Sutlej River (Punjab)
- Cauvery hydroelectric plant, Cauvery river (Karnataka)
- Chambal hydroelectric plant, Chambal river (Rajasthan)
- Hirakud Dam, Hirakud river (Orissa)

- Main Components
  - **Spiral / Scroll Casing**
    - The spiral casing surrounds the runner completely
    - Its area of cross section decreases gradually around the circumference.
    - uniform distribution of water all along the circumference of the runner
  - **Guide Blades**
    - guiding the water at the proper direction
    - The blade passages act as a nozzle. Converts part of pressure energy in kinetic energy.
    - area of blade passage is changed to vary the flow rate of water according to the load as shown.



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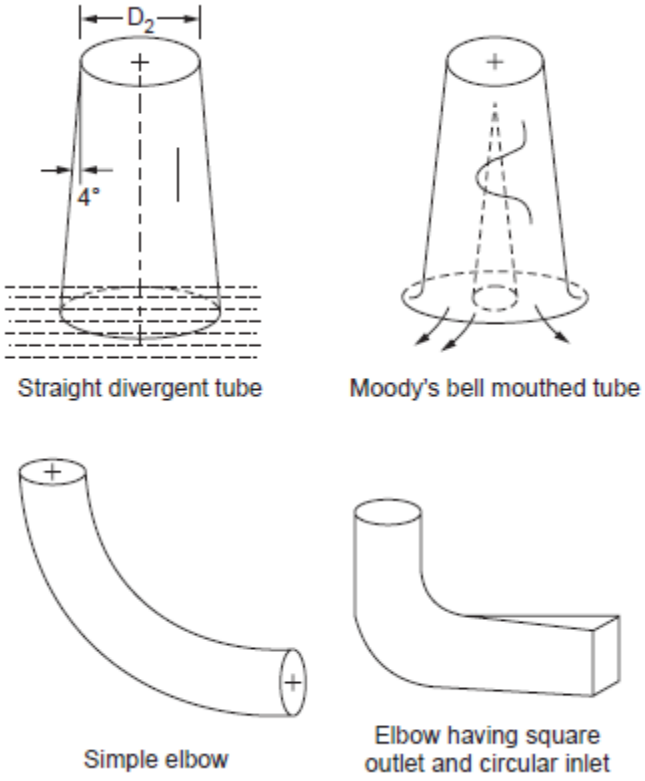
•The Runner

- •The runner is circular disc and has the blades fixed on one side
- •The runners change the direction and magnitude of the fluid velocity and in this process absorb the momentum from the fluid.

•Draft Tube

•Loss of head due to the installation at a higher level from the tailrace will be significant.

•This loss is reduced by connecting a fully flowing diverging tube from the turbine outlet to be immersed in the tailrace at the tube outlet.



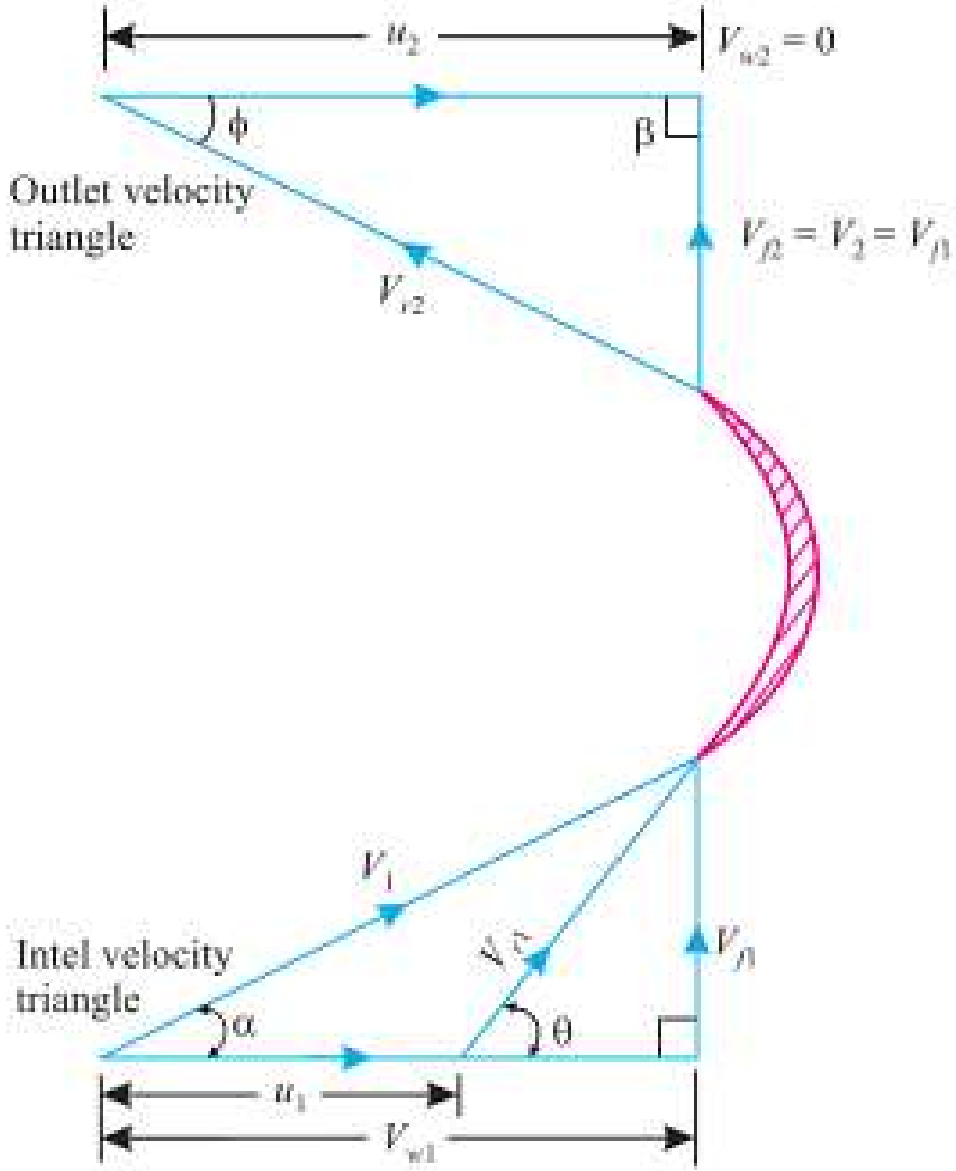
- because of the diverging section of the tube the kinetic energy is converted to pressure energy.
- pressure at the turbine outlet will be below atmospheric



Runner of Francis Turbine

Velocity Diagram

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$$\text{Work done} = \rho Q\,(V_{w1}\,u_1 \pm V_{w2}\,u_2)$$

$$= \frac{wQ}{g}\,(V_{w1}\,u_1 \pm V_{w2}\,u_2)$$

$$\text{Work done} = \frac{wQ}{g}\,(V_{w1}\,u_1)$$

As Vw2 = 0

Hydraulic efficiency, η_h :

If H is the net head, then input to the turbine = wQH.

$$\eta_h = \frac{\text{Power developed by the runner}}{\text{Power supplied to the turbine (water power)}} = \frac{\frac{wQ}{g}\,(V_{w1}\,u_1)}{wQH}$$

or, $$\eta_h = \frac{V_{w1}\,u_1}{gH} \quad ..$$

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1. Ratio of width to diameter $\left(\frac{B}{D}\right)$:

The ratio of width (B_1) to the diameter of the wheel (D_1) at inlet is represented by n. Thus,

$$n = \frac{B_1}{D_1}$$

The value of n varies from 0.10 to 0.45.

2. Flow ratio (K_f) :

Flow ratio is the *ratio of the velocity of flow at inlet to the theoretical jet velocity*. Thus,

$$\text{Flow ratio, } K_f = \frac{V_{f1}}{\sqrt{2gH}} \quad \ldots(2$$

The value of K_f varies from 0.15 to 0.30.

3. Speed ratio (K_u)

Speed ratio is the ratio of the peripheral speed at inlet to the theoretical jet velocity. Thus,

$$\text{Speed ratio, } K_u = \frac{u}{\sqrt{2gH}}$$

The value of K_u ranges from 0.6 to 0.9.

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total area at the outer periphery (*i.e.*, at the runner inlet),

$$A = (\pi D_1 - Z_{t1})\, B_1 = K_{t1} \pi D_1 B_1 \qquad ...(2.25)$$

where K_{t1} is known as *vane thickness factor/co-efficient*; its value is *always less than unity* (usually of the order of 0.95 or so).

$$\text{Discharge} = \text{Area of flow} \times \text{velocity of flow}$$

i.e.,

$$Q = K_{t1} \pi D_1 B_1 \times V_{f1} \qquad ...(2.26)$$

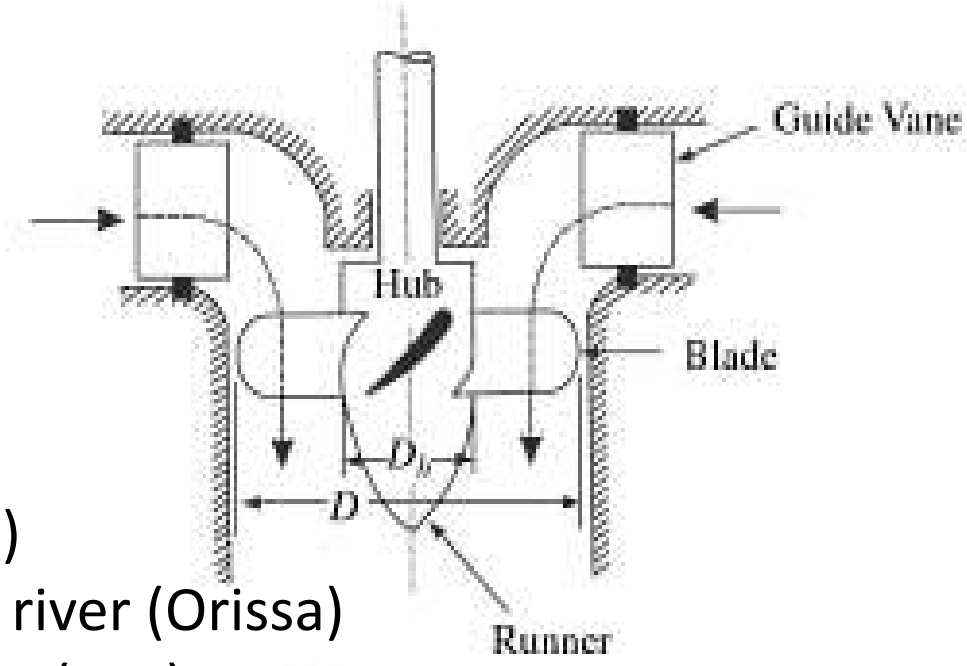
The velocity of flow at the exit (V_{f2}) is obtained as follows :

$$Q = K_{t1} \pi D_1 B_1 V_{f1} = K_{t2} \pi D_2 B_2 V_{f2}$$

Kaplan Turbine

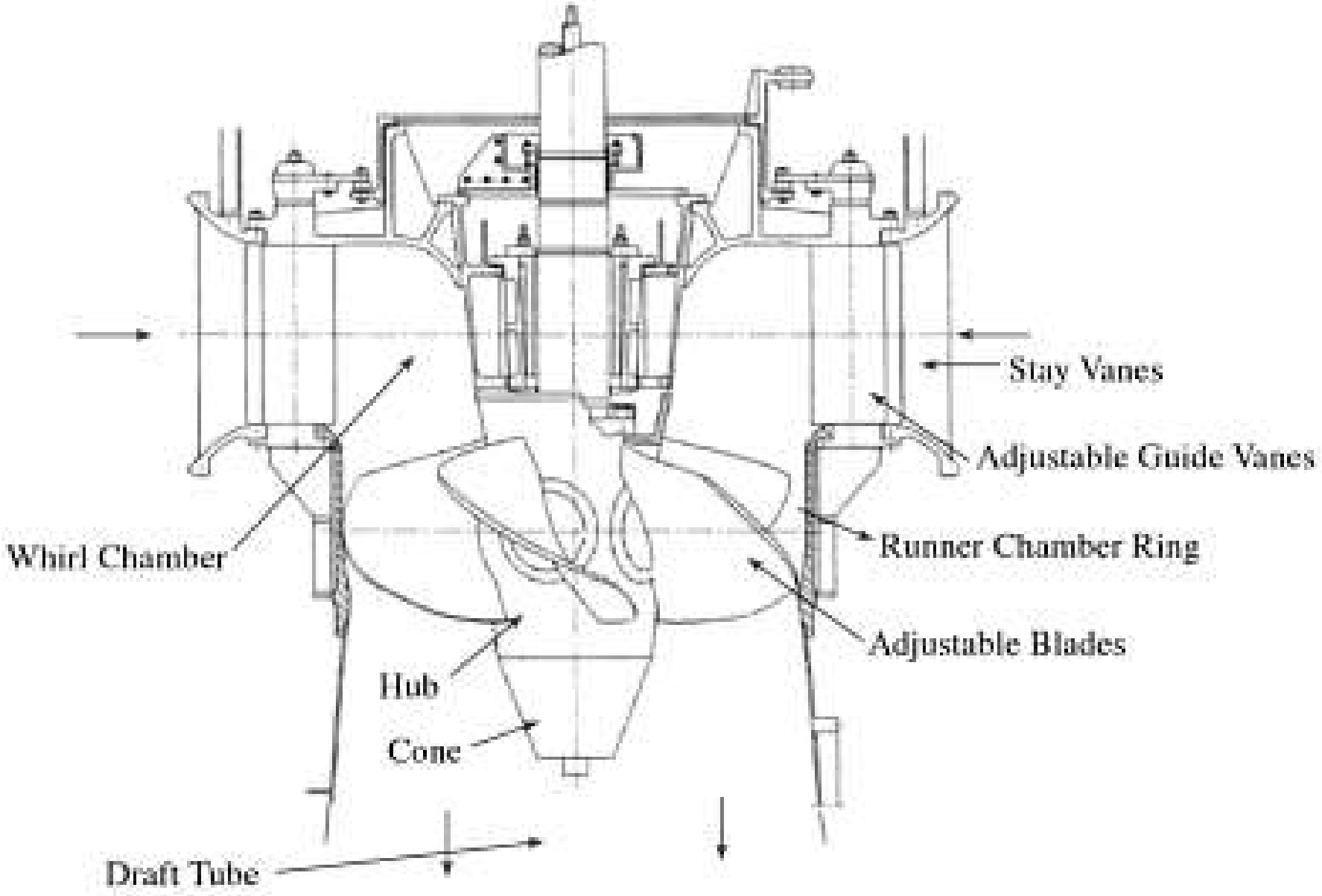
Characteristics

1. Low head turbine, requires large quantity of water
2. Reaction turbine
3. Axial flow turbine
4. Installed with vertical shaft
5. Large specific speed

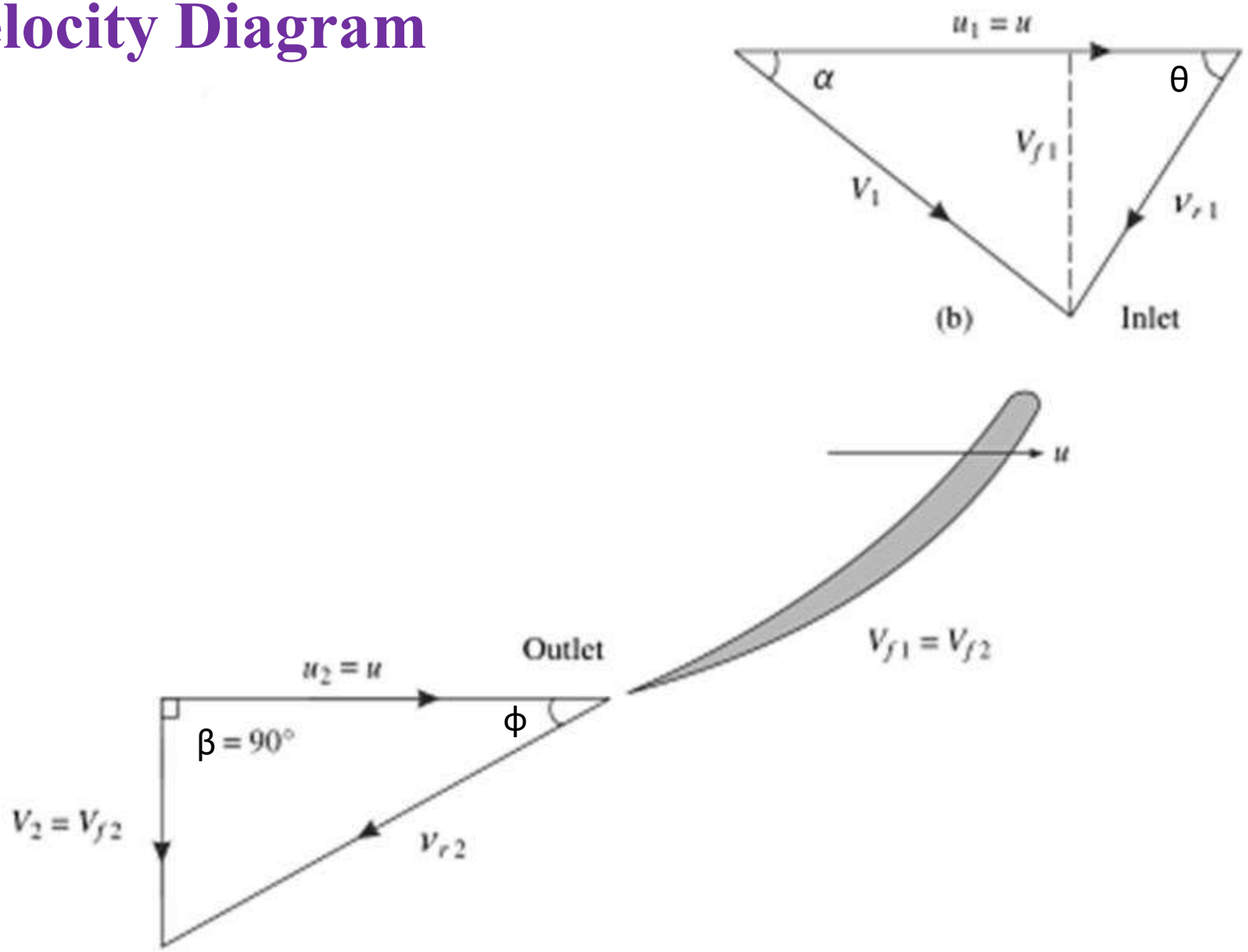


In India installed at

- Bhakra – Nangal Project (Punjab)
- Hirakud Dam Project, Mahanadi river (Orissa)
- Nizam Sagar Project, Nanjira river (A.P.)
- Radhanagari hydroelectric Scheme, Bhagvati river Kolhapur (M.S.)
- Tungabhadra hydroelectric Scheme, Tungabhadra river (Karnataka)


Stay Vanes
Adjustable Guide Vanes
Runner Chamber Ring
Whirl Chamber
Adjustable Blades
Hub
Cone
Draft Tube

Velocity Diagram



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1. In case of a propeller/Kaplan turbine, the ratio n is taken as $\frac{D_b}{D_0}$ $\left(\text{and not } \frac{B}{D}\right)$

where, D_0 = Outside diameter of the runner, and

D_b = Diameter of boss (or hub).

Discharge, Q = Area of flow × velocity of flow

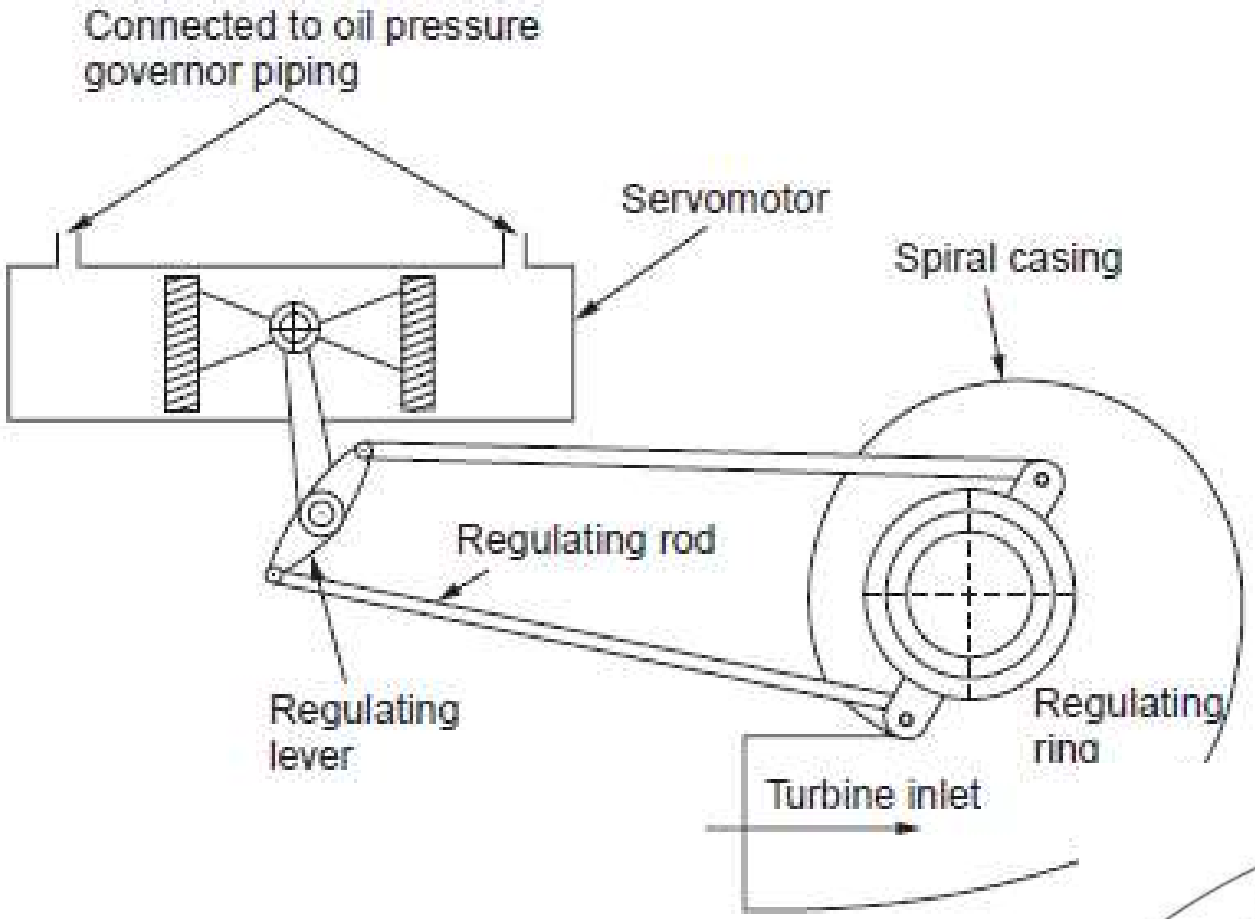
$$= \frac{\pi}{4}(D_0^2 - D_b^2) \times V_f$$

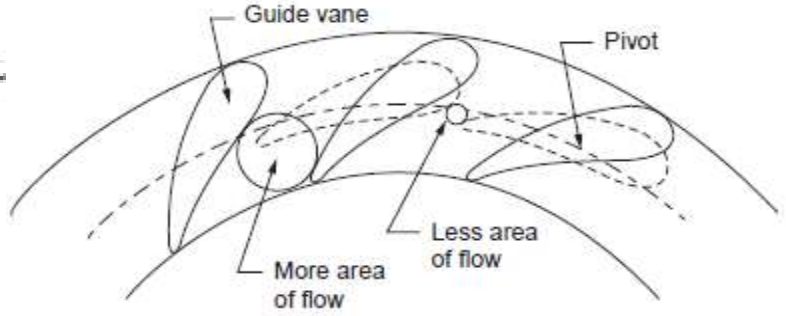
$$= \frac{\pi}{4}(D_0^2 - D_b^2) \times K_f \sqrt{2gH} \qquad \text{(where, } K_f = \text{flow ratio)}$$

$$Q = \frac{\pi}{4} D_0^2 (1 - n^2) \times K_f \sqrt{2gH}$$

$$\left(\because n = \frac{D_b}{D_0}, \quad \text{or,} \quad D_b = nD_0\right)$$

Governing of Reaction Turbine



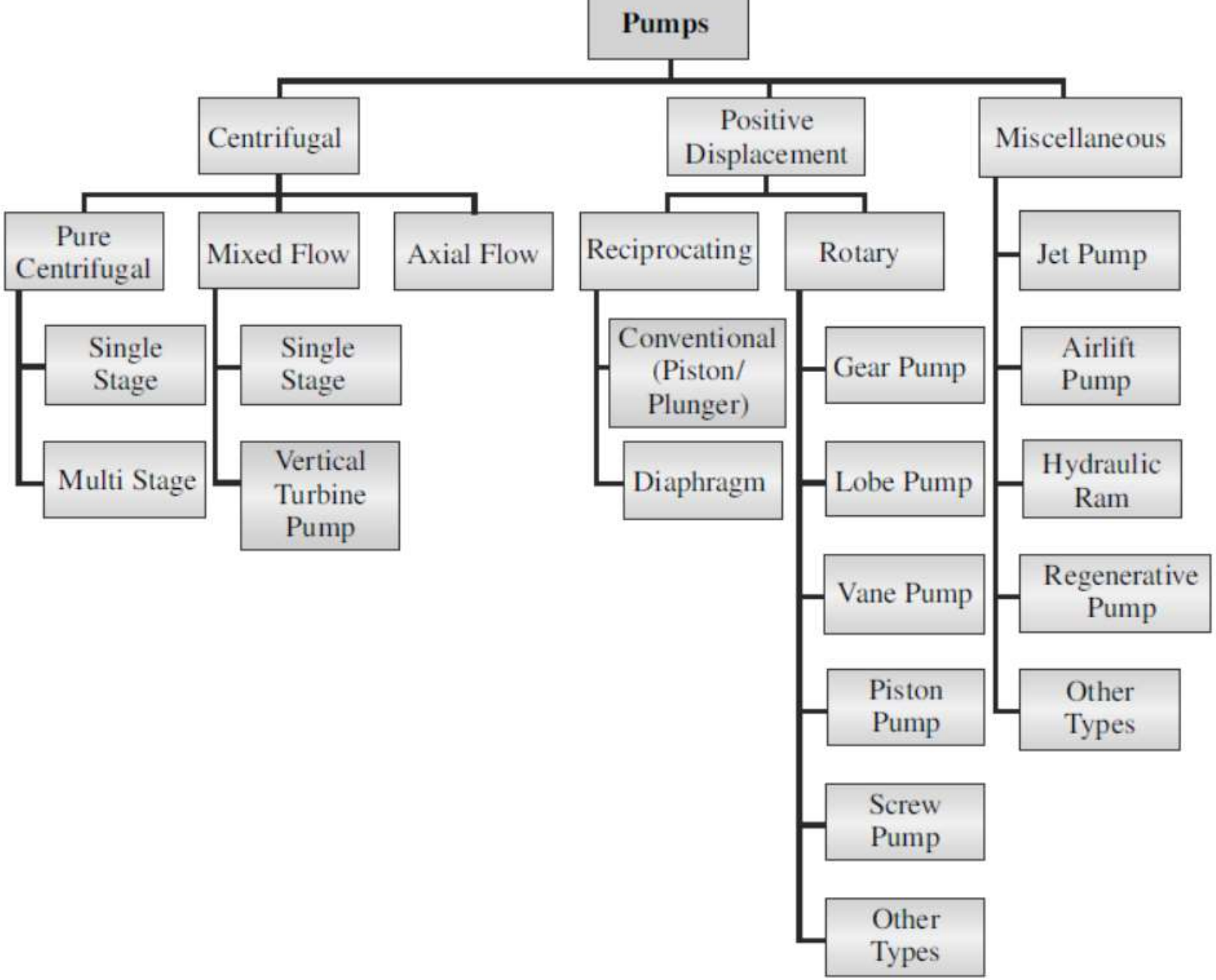


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Unit 5

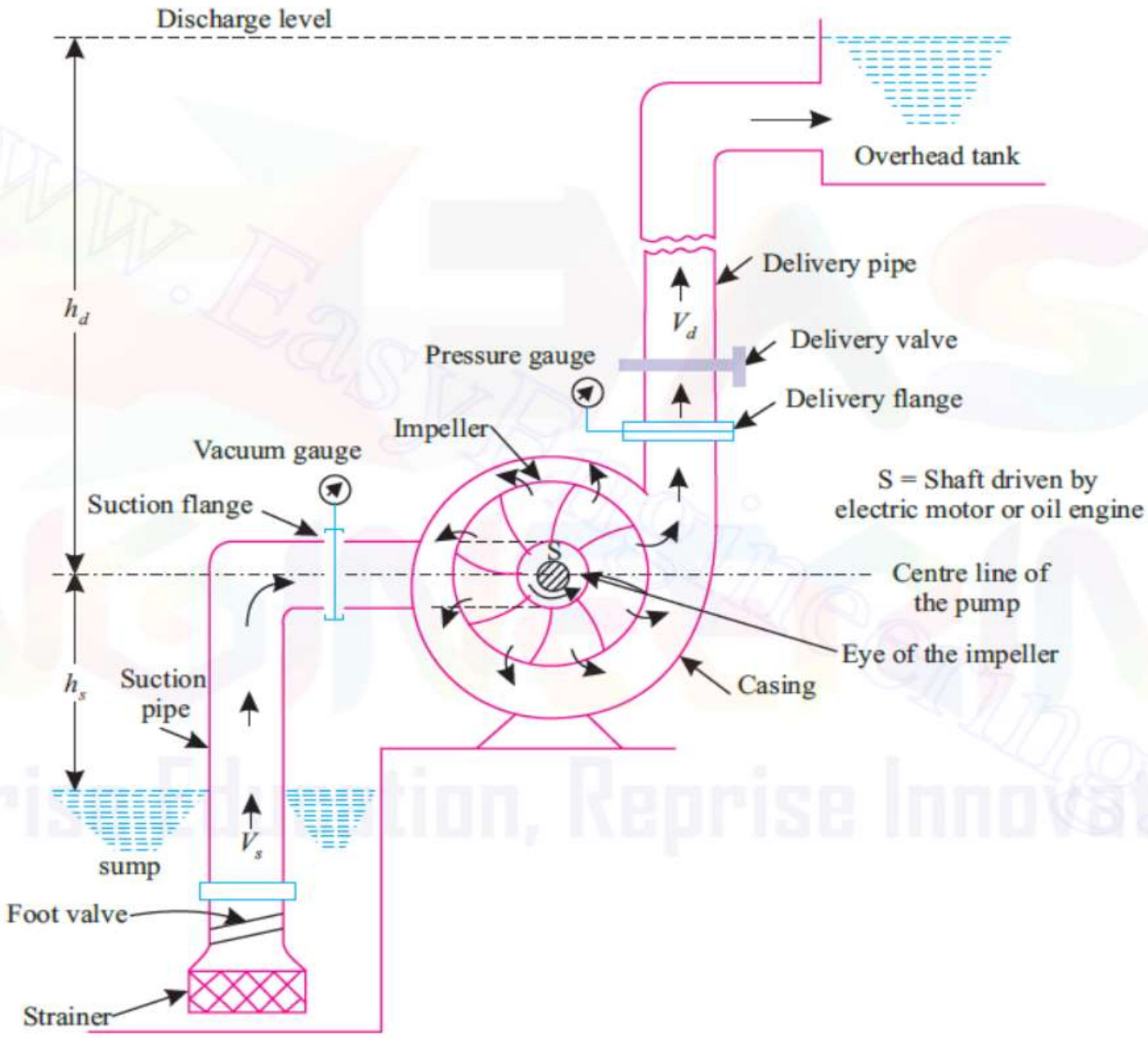
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Classification of Hydraulic Pumps

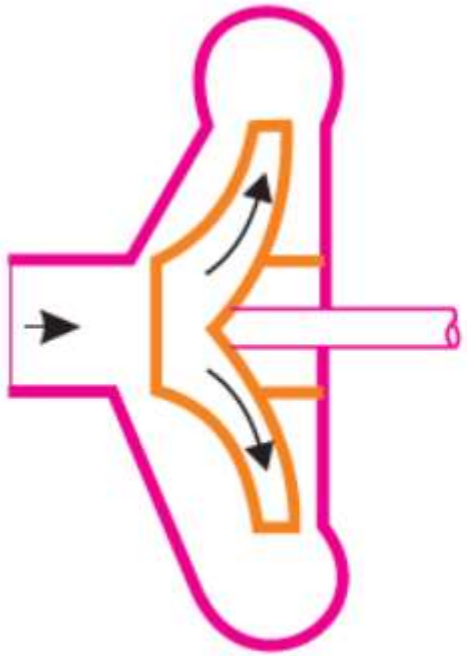

Pumps
Centrifugal
Positive Displacement
Miscellaneous
Pure Centrifugal
Mixed Flow
Axial Flow
Reciprocating
Rotary
Jet Pump
Single Stage
Single Stage
Conventional (Piston/ Plunger)
Gear Pump
Airlift Pump
Multi Stage
Vertical Turbine Pump
Diaphragm
Lobe Pump
Hydraulic Ram
Vane Pump
Regenerative Pump
Piston Pump
Other Types
Screw Pump
Other Types

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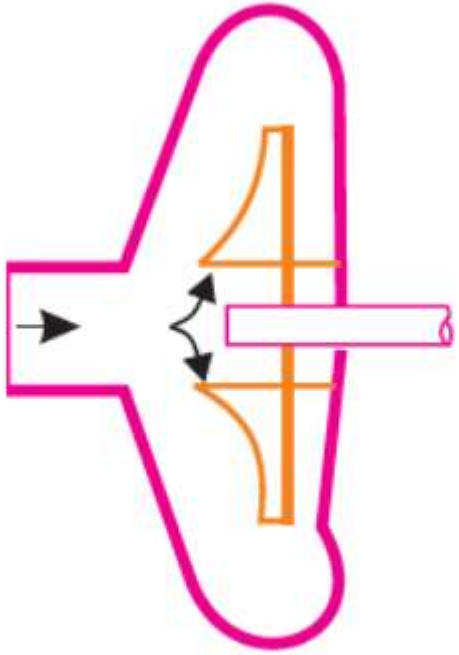
Centrifugal Pump


Discharge level
Overhead tank
Delivery pipe
V_d
h_d
Delivery valve
Pressure gauge
Delivery flange
Impeller
Vacuum gauge
S = Shaft driven by
electric motor or oil engine
Suction flange
S
Centre line of
the pump
Eye of the impeller
h_s
Suction
pipe
Casing
V_s
sump
Foot valve
Strainer

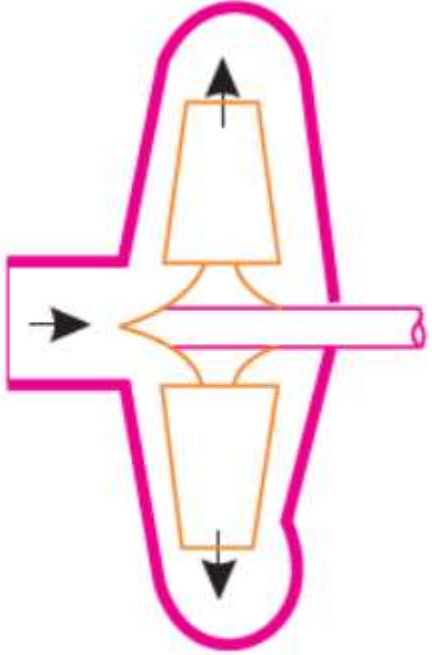
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(a)



(b)



(c)



(a) Shrouded Impeller



(b) Semi-enclosed Impeller



(c) Fully Open Impeller

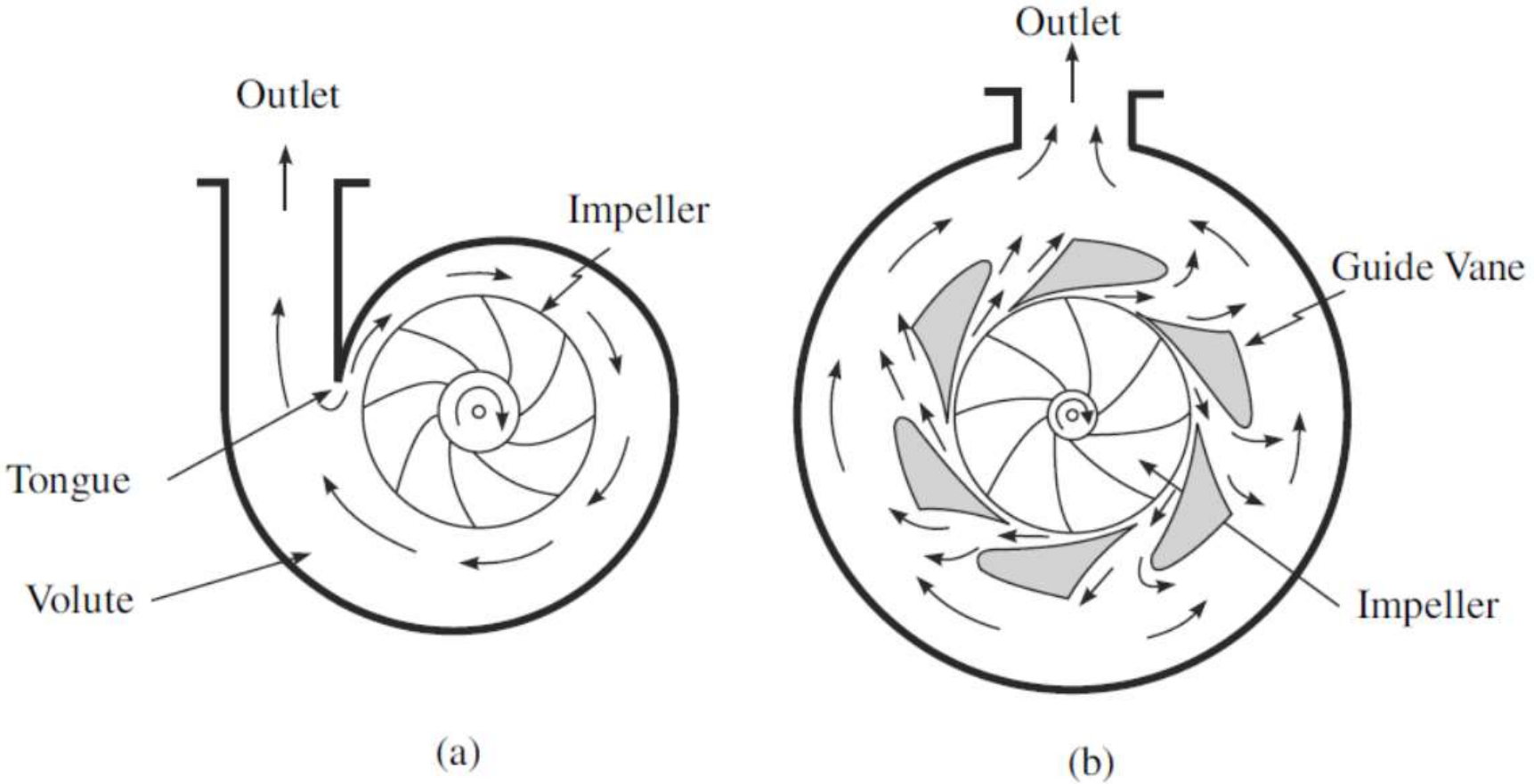


Fig. 5.4 *Types of centrifugal pumps: (a) Volute pump (b) Turbine pump / Diffuser pump*

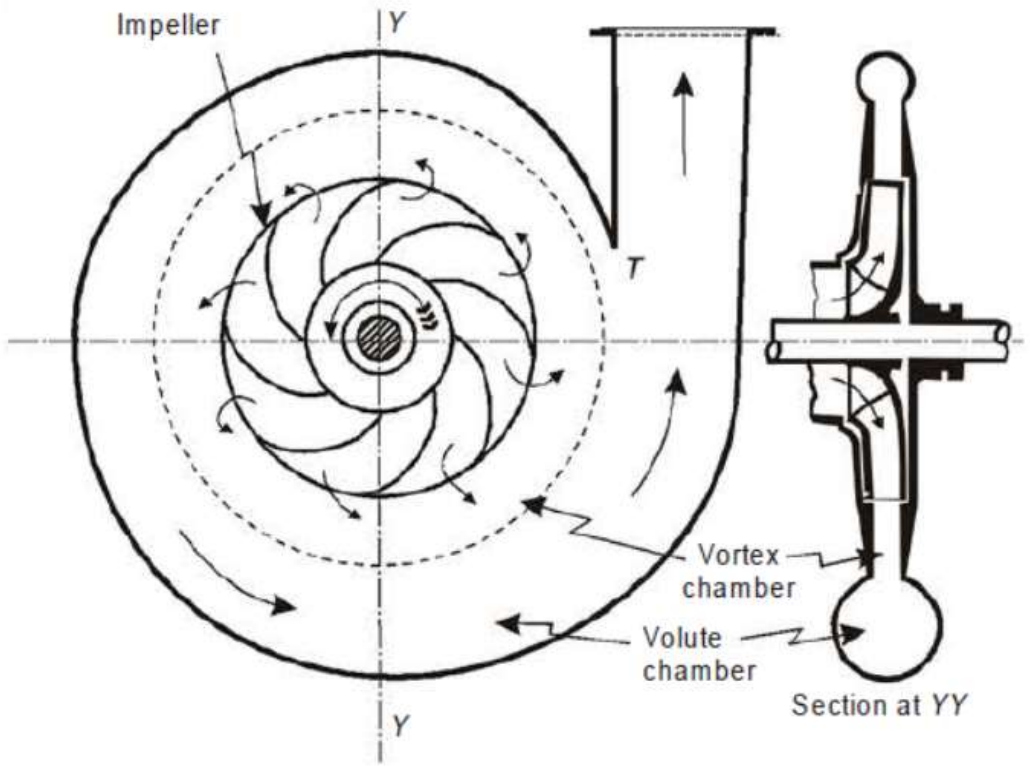
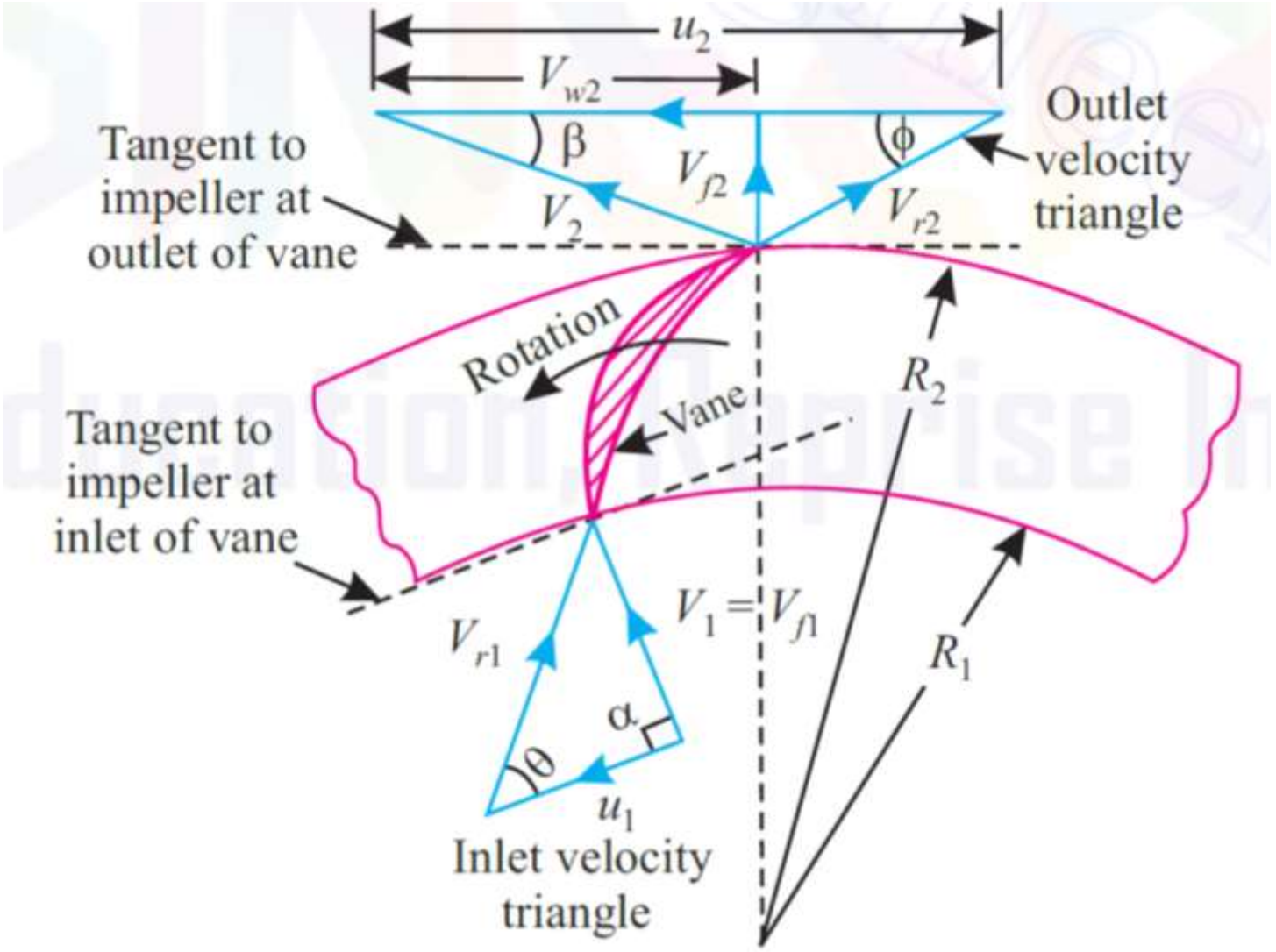


Figure 24.3 *Volute pump with vortex chamber*

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$$\text{Work done per second} = \frac{W}{g}(V_{w2}u_2 - V_{w1}u_1)$$

or, Work done per second per unit weight of liquid

$$= \frac{1}{g}(V_{w2}u_2 - V_{w1}u_1)$$

Work done per second per unit weight of liquid

$$= \frac{V_{w2}u_2}{g}$$

where W = Weight of water = $\rho \times g \times Q$

where Q = Volume of water

and Q = Area × Velocity of flow = $\pi D_1 B_1 \times V_{f_1}$

$= \pi D_2 B_2 \times V_{f_2}$

1 **Static Head (H_s).** The sum of suction head and delivery head is known as static head. This is represented by 'H_s' and is written as

$$H_s = h_s + h_d.$$

2 **. Manometric Head (H_m).** The manometric head is defined as the head against which a centrifugal pump has to work. It is denoted by 'H_m'. It is given by the following expressions :

(*a*) H_m = Head imparted by the impeller to the water – Loss of head in the pump

$$= \frac{V_{w_2} u_2}{g} - \text{Loss of head in impeller and casing}$$

$$= \frac{V_{w_2} u_2}{g} \text{ ...if loss of pump is zero}$$

(*b*) H_m = Total head at outlet of the pump – Total head at the inlet of the pump

$$= \left(\frac{p_2}{w} + \frac{V_2^2}{2g} + z_2\right) - \left(\frac{p_1}{w} + \frac{V_1^2}{2g} + z_1\right)$$

$\frac{p_2}{w}$ = Pressure head at outlet of pump = h_d,

$\frac{V_2^2}{2g}$ = Velocity head at outlet of the pump

= Velocity head in the delivery pipe = $\frac{V_d^2}{2g}$,

z_2 = Vertical height of the pump outlet from the datum line, and

$\frac{p_1}{w}, \frac{V_1^2}{2g}, z_1$ = corresponding values of pressure head, velocity head and datum head at inlet

3.8.1. Losses in Centrifugal Pump

When a centrifugal pump operates, the various losses which occur are as follows:

1. **Hydraulic losses:**
   - (*i*) *Hydraulic losses in the pump:*
     - (*a*) Shock or eddy losses at the entrance to and exit from the impeller.
     - (*b*) Losses due to friction in the impeller.
     - (*c*) Friction and eddy losses in the guide vanes/diffuser and casing.
   - (*ii*) *Other hydraulic losses:*
     - (*a*) Friction and other minor losses in the suction pipe.
     - (*b*) Friction and other minor losses in the delivery pipe.
2. **Mechanical losses:**
   - (*i*) Losses due to disc friction between the impeller and the liquid which fills the clearance spaces between the impeller and casing.
   - (*ii*) Losses pertaining to friction of the main bearing and glands.
3. **Leakage loss:**

The loss of energy due to leakage of liquid is known *as leakage loss*. The various losses in a centrifugal pump are shown diagramatically in Fig. 3.6.

(*i*) Manometric efficiency (η_{mano}). *The ratio of the manometric head developed by the pump to the head imparted by the impeller to the liquid is known as* ***manometric efficiency.*** Thus,

$$\eta_{mano} = \frac{\text{Manometric head}}{\text{Head imparted by impeller to liquid}}$$

or,
$$\eta_{mano} = \frac{H_{mano}}{\left(\frac{V_{w2}u_2}{g}\right)} = \frac{gH_{mano}}{V_{w2}u_2} \qquad ...(3.9)$$

(*iii*) Mechanical efficiency (η_m). *The ratio of the power delivered by the impeller to the liquid to the power input to the pump shaft is known as* ***mechanical efficiency.*** Thus,

$$\eta_m = \frac{\text{Power delivered by the impeller to the liquid}}{\text{Power input to the pump shaft (P)}}$$

or,
$$\eta_m = \frac{w\,(Q+q)\,(V_{w2}u_2/g)}{P} \qquad ...(3.11)$$

$$= \frac{P - P_{mech.loss}}{P} \qquad ...[3.11(a)]$$

(*iv*) Overall efficiency (η_0). *The ratio of power output of the pump to the power input to the pump is known as* ***overall efficiency.*** Thus,

$$\eta_0 = \frac{\text{Power output of the pump}}{\text{Power input to the pump / shaft}} = \frac{wQH_{mano}}{P} \qquad ...(3.12)$$

Also,
$$\eta_0 = \eta_{mano} \times \eta_v \times \eta_m$$

$$= \frac{H_{mano}}{(V_{w2}u_2/g)} \times \frac{Q}{(Q+q)} \times \frac{w(Q+q)\,(V_{w2}u_2/g)}{P}$$

$$= \frac{wQH_{mano}}{P}, \text{ which is the same as eqn. (3.12)}$$

ADVANTAGES OF CENTRIFUGAL PUMP OVER DISPLACEMENT (RECIPROCATING) PUMP

The centrifugal pump claims the following *advantages* with reference to a positive displacement (reciprocating) pump.

1. The cost of a centrifugal pump is less as it has fewer parts.
2. Installation and maintenance are easier and cheaper.
3. Its discharging capacity is much greater than that of a reciprocating pump.
4. It is compact and has smaller size and weight for the same capacity and energy transfer.
5. Its performance characteristics are superior.
6. It can be employed for lifting highly viscous liquid such as paper pulp, muddy and sewage water, oil, sugar molasses etc.
7. It can be operated at very high speeds without any danger of separation and cavitation.
8. It can be directly coupled to an electric motor or an oil engine.
9. The torque on the power source is uniform, the output fron the pump is also uniform.

However, because of higher efficiency the reciprocating pumps are still employed for high heads and small discharges. A reciprocating pump can build up very high pressures (as high as 700 bar or even more) and as such these pumps are used for lifting oils from very deep oil wells.



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