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BMEE204L
Module -7, Lecture-1
Hydraulic Machines

Centrifugal Pumps & Turbines

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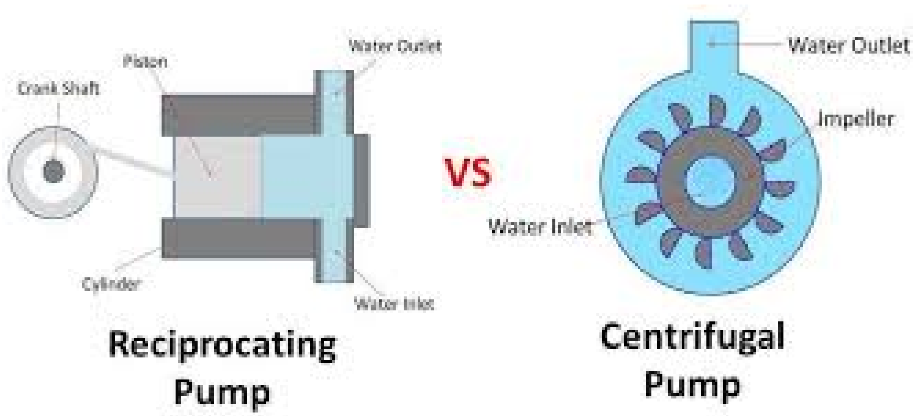
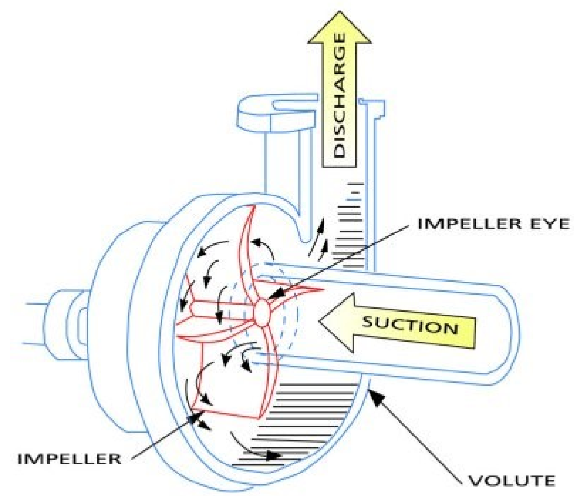
Pumps

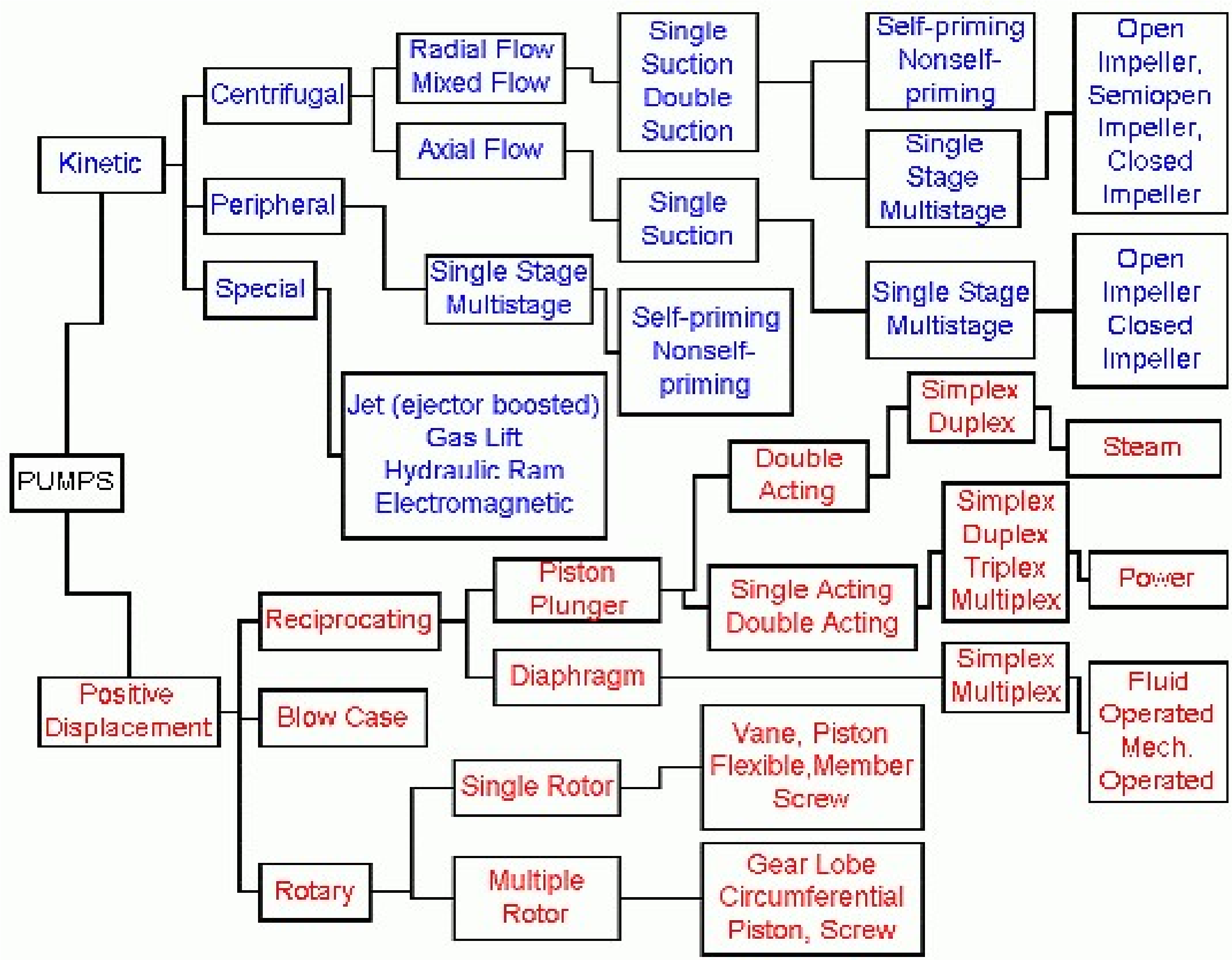
- A **pump** is a device used to move gases, liquids or slurries.
- A pump moves liquids or gases from lower pressure to higher pressure, and overcomes this difference in pressure by adding energy to the system.

Mechanical Energy → Hydraulic energy





Pumps - Classification



Pumps - Classification

- Pumps are divided into two fundamental types based on the manner in which they transmit energy to the pumped media: kinetic or positive displacement.
- In **kinetic displacement**, a centrifugal force of the rotating element, called an impeller, “impels” kinetic energy to the fluid, moving the fluid from pump suction to the discharge.
- **Positive displacement** uses the reciprocating action of one or several pistons, or a squeezing action of meshing gears, lobes, or other moving bodies, to displace the fluid from one area into another (i.e., moving the material from suction to discharge).
- Sometimes the terms ‘inlet’ (for suction) and ‘exit’ or ‘outlet’ (for discharge) are used.

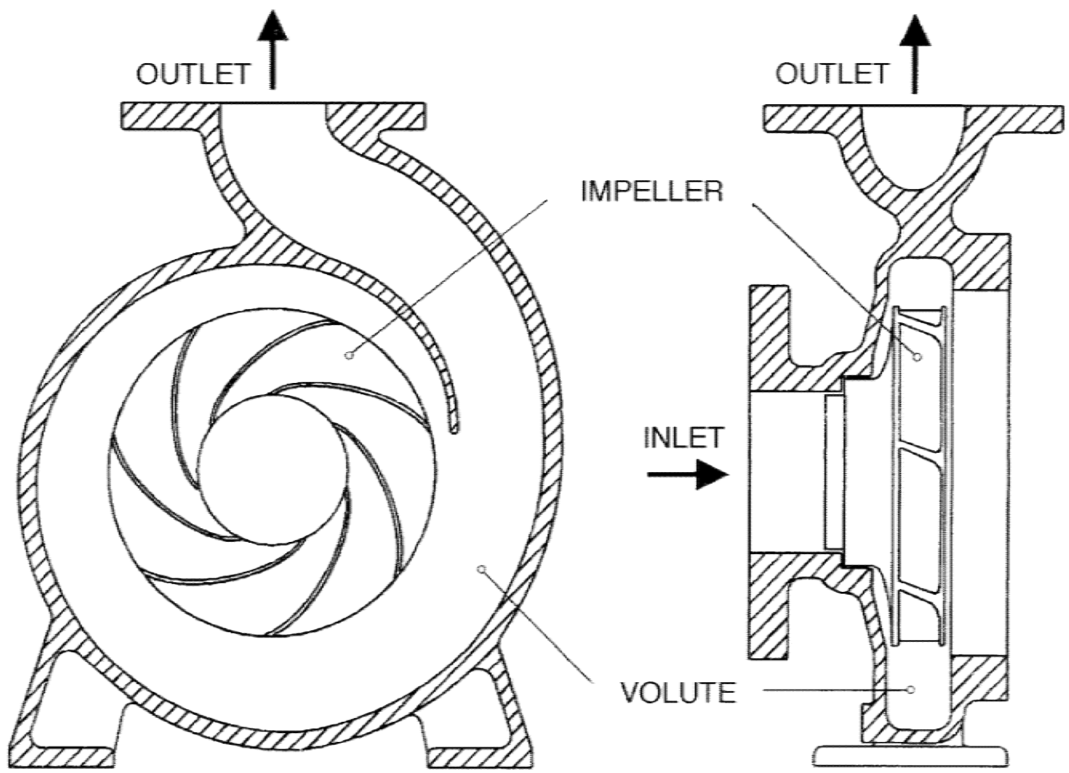
Pumps - Applications

- To deliver fluid at a higher elevation or at a long distance.
- To deliver fluid at a pressurized device
- For the control of hydraulic systems
- For drainage system, removing slurries, mud, water
- For irrigation systems
- Cleaning, car wash

Centrifugal Pumps

- The hydraulic machines that converts the mechanical energy into pressure energy by means of centrifugal force acting on the fluid are called centrifugal pumps.
- The centrifugal pumps works on the principle of forced vortex flow which means that when a certain mass of fluid is rotated by an external torque, the rise in pressure of the rotating liquid takes place.
- Rise in pressure head = $\left(i.e., \text{ rise in pressure head } = \dfrac{V^2}{2g} \text{ or } \dfrac{\omega^2 r^2}{2g} \right)$.
- At the outlet of the impeller, radius is more, the rise of pressure will be more and the liquid will be discharged at the outlet with high pressure head. Due to this pressure head, the liquid can be lifted to a high level.

Centrifugal Pumps



Centrifugal Pumps – Components & Working

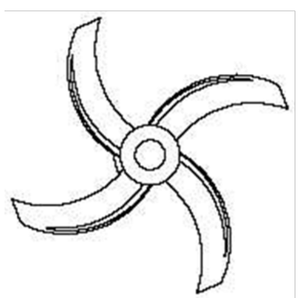
The following are the main parts of a centrifugal pump :

1. Impeller.
2. Casing.
3. Suction pipe with a foot valve and a strainer.
4. Delivery pipe.

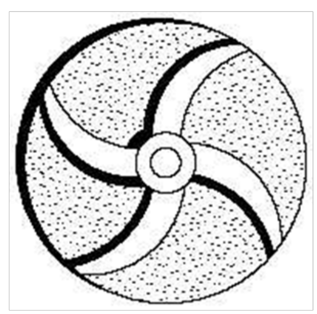
All the main parts of the centrifugal pump are shown in Fig. 19.1.

1. Impeller. The rotating part of a centrifugal pump is called 'impeller'. It consists of a series of backward curved vanes. The impeller is mounted on a shaft which is connected to the shaft of an electric motor.

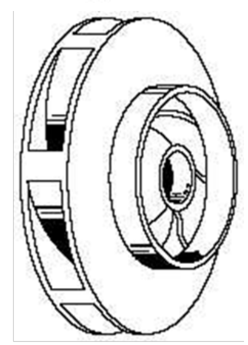
2. Casing. The casing of a centrifugal pump is similar to the casing of a reaction turbine. It is an air-tight passage surrounding the impeller and is designed in such a way that the kinetic energy of the water discharged at the outlet of the impeller is converted into pressure energy before the water leaves the casing and enters the delivery pipe. The following three types of the casings are commonly adopted :



Open

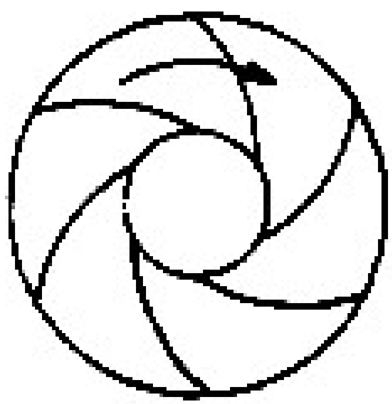


Semi - Open

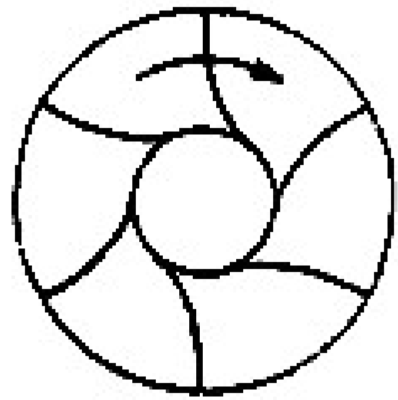


Closed

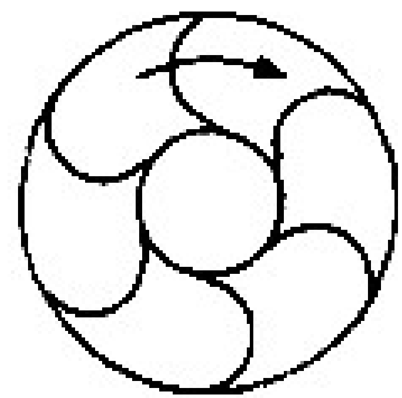
Centrifugal Pumps – Components & Working



Backward curved



Radial curved



Forward curved

- For Incompressible fluids (water) backward curved vanes are used (pumps)
- For compressible fluids (air) forward curved vanes are used (compressors)

(*a*) **Volute Casing.** Fig 19.1 shows the volute casing, which surrounds the impeller. It is of spiral type in which area of flow increases gradually. The increase in area of flow decreases the velocity of flow. The decrease in velocity increases the pressure of the water flowing through the casing. It has been observed that in case of volute casing, the efficiency of the pump increases slightly as a large amount of energy is lost due to the formation of eddies in this type of casing.

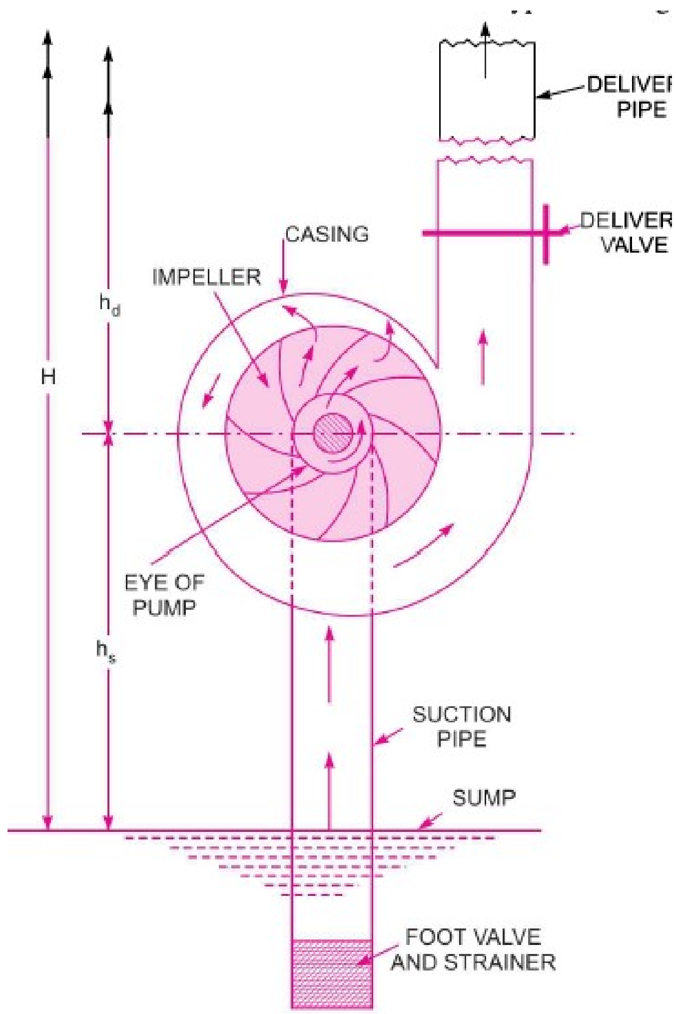


Fig. 19.1 *Main parts of a centrifugal pump.*

Centrifugal Pumps - Casing

(*b*) **Vortex Casing.** If a circular chamber is introduced between the casing and the impeller as shown in Fig. 19.2 (*a*), the casing is known as Vortex Casing. By introducing the circular chamber, the loss of energy due to the formation of eddies is reduced to a considerable extent. Thus the efficiency of the pump is more than the efficiency when only volute casing is provided.

(*c*) **Casing with Guide Blades.** This casing is shown in Fig. 19.2 (*b*) in which the impeller is surrounded by a series of guide blades mounted on a ring which is known as diffuser. The guide vanes are designed in such a way that the water from the impeller enters the guide vanes without stock. Also the area of the guide vanes increases, thus reducing the velocity of flow through guide vanes and consequently increasing the pressure of water. The water from the guide vanes then passes through the surrounding casing which is in most of the cases concentric with the impeller as shown in Fig. 19.2 (*b*).

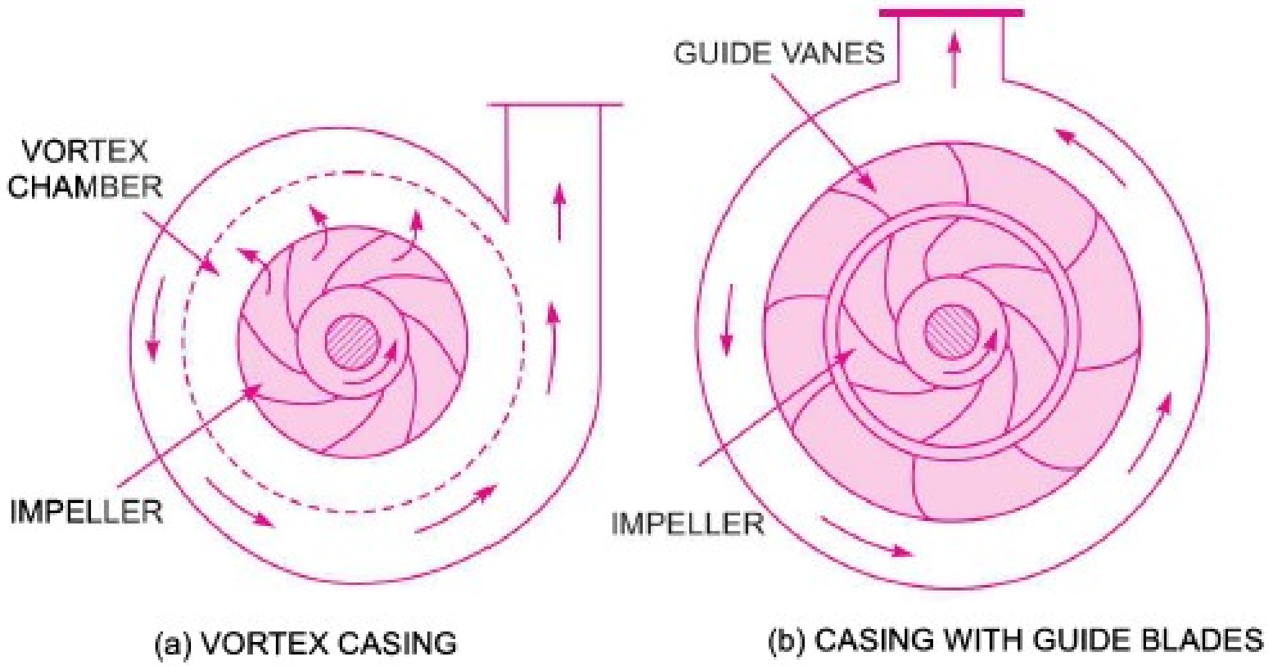


Fig. 19.2 *Different types of casing.*

Centrifugal Pumps – Major components

3. Suction Pipe with a Foot valve and a Strainer. A pipe whose one end is connected to the inlet of the pump and other end dips into water in a sump is known as suction pipe. A foot valve which is a non-return valve or one-way type of valve is fitted at the lower end of the suction pipe. The foot valve opens only in the upward direction. A strainer is also fitted at the lower end of the suction pipe.

4. Delivery Pipe. A pipe whose one end is connected to the outlet of the pump and other end delivers the water at a required height is known as delivery pipe.

Work Done by a Centrifugal Pump

▶ 19.3 WORK DONE BY THE CENTRIFUGAL PUMP (OR BY IMPFLLER) ON WATER

In case of the centrifugal pump, work is done by the impeller on the water. The expression for the work done by the impeller on the water is obtained by drawing velocity triangles at inlet and outlet of the impeller in the same way as for a turbine. The water enters the impeller radially at inlet for best efficiency of the pump, which means the absolute velocity of water at inlet makes an angle of 90° with the direction of motion of the impeller at inlet. Hence angle $\alpha = 90°$ and $V_{w_1} = 0$. For drawing the velocity triangles, the same notations are used as that for turbines. Fig. 19.3 shows the velocity triangles at the inlet and outlet tips of the vanes fixed to an impeller.

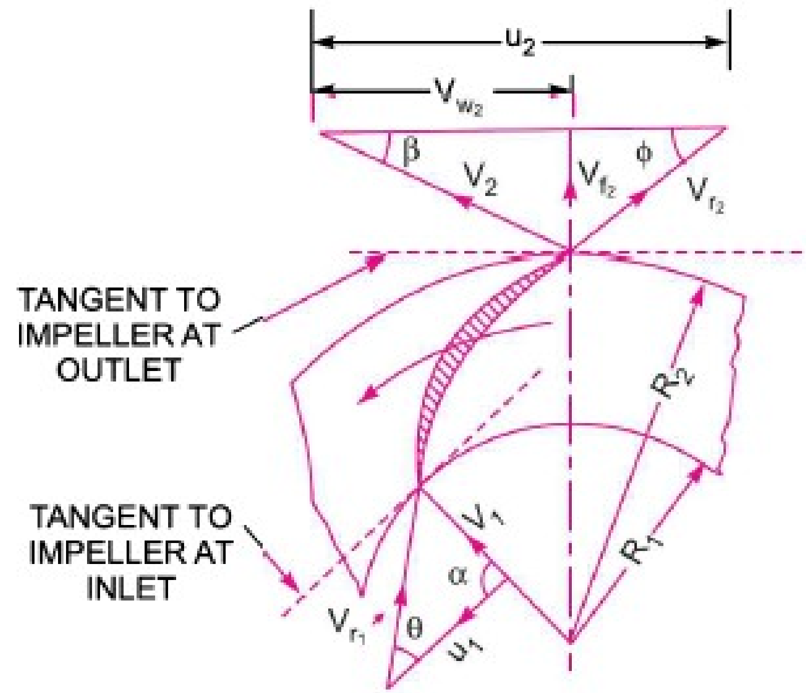
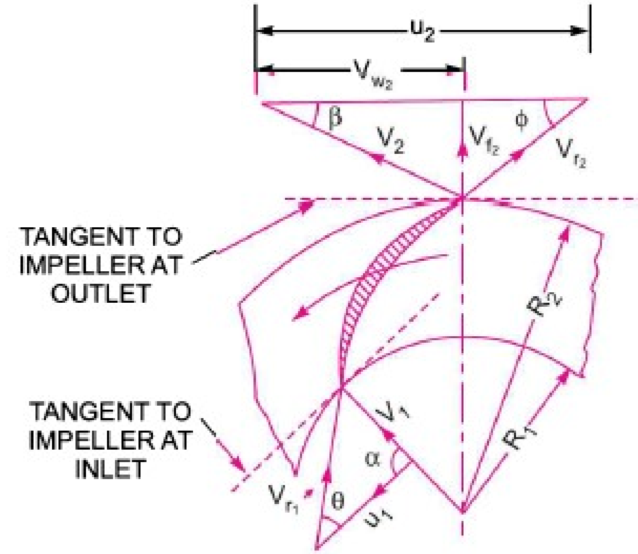


Fig. 19.3 *Velocity triangles at inlet and outlet.*

Let N = Speed of the impeller in r.p.m.,

D_1 = Diameter of impeller at inlet,

u_1 = Tangential velocity of impeller at inlet,



$$= \frac{\pi D_1 N}{60}$$

D_2 = Diameter of impeller at outlet,

u_2 = Tangential velocity of impeller at outlet

$$= \frac{\pi D_2 N}{60}$$

V_1 = Absolute velocity of water at inlet,

V_{r_1} = Relative velocity of water at inlet,

α = Angle made by absolute velocity (V_1) at inlet with the direction of motion of vane,

θ = Angle made by relative velocity (V_{r_1}) at inlet with the direction of motion of vane, and V_2, V_{r_2}, β and ϕ are the corresponding values at outlet.

As the water enters the impeller radially which means the absolute velocity of water at inlet is in the radial direction and hence angle $\alpha = 90°$ and $V_{w_1} = 0$.

A centrifugal pump is the reverse of a radially inward flow reaction turbine. But in case of a radially inward flow reaction turbine, the work done by the water on the runner per second per unit weight of the water striking per second is given by equation (18.19) as

$$= \frac{1}{g}[V_{w_1}u_1 - V_{w_2}u_2]$$

Work Done by a Centrifugal Pump

$\therefore$ Work done by the impeller on the water per second per unit weight of water striking per second

$$= -\text{ [Work done in case of turbine]}$$

$$= -\left[\frac{1}{g}\left(V_{w_1}u_1 - V_{w_2}u_2\right)\right] = \frac{1}{g}\left[V_{w_2}u_2 - V_{w_1}u_1\right]$$

$$= \frac{1}{g}V_{w_2}u_2 \qquad (\because \quad V_{w_1} = 0 \text{ here}) \quad \text{...(19.1)}$$

Work done by impeller on water per second

$$= \frac{W}{g}.V_{w_2}u_2 \qquad \text{...(19.2)}$$

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

where Q = Volume of water

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

$$= \pi D_2 B_2 \times V_{f_2} \qquad \text{...(19.2A)}$$

where B_1 and B_2 are width of impeller at inlet and outlet and V_{f_1} and V_{f_2} are velocities of flow at inlet and outlet.

Equation (19.1) gives the head imparted to the water by the impeller or energy given by impeller to water per unit weight per second.

▶ 19.4 DEFINITIONS OF HEADS AND EFFICIENCIES OF A CENTRIFUGAL PUMP

1. Suction Head (h_s). It is the vertical height of the centre line of the centrifugal pump above the water surface in the tank or pump from which water is to be lifted as shown in Fig. 19.1. This height is also called suction lift and is denoted by 'h_s'.

2. Delivery Head (h_d). The vertical distance between the centre line of the pump and the water surface in the tank to which water is delivered is known as delivery head. This is denoted by 'h_d'.

3. 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

$$H_s = h_s + h_d. \quad \text{...(19.3)}$$

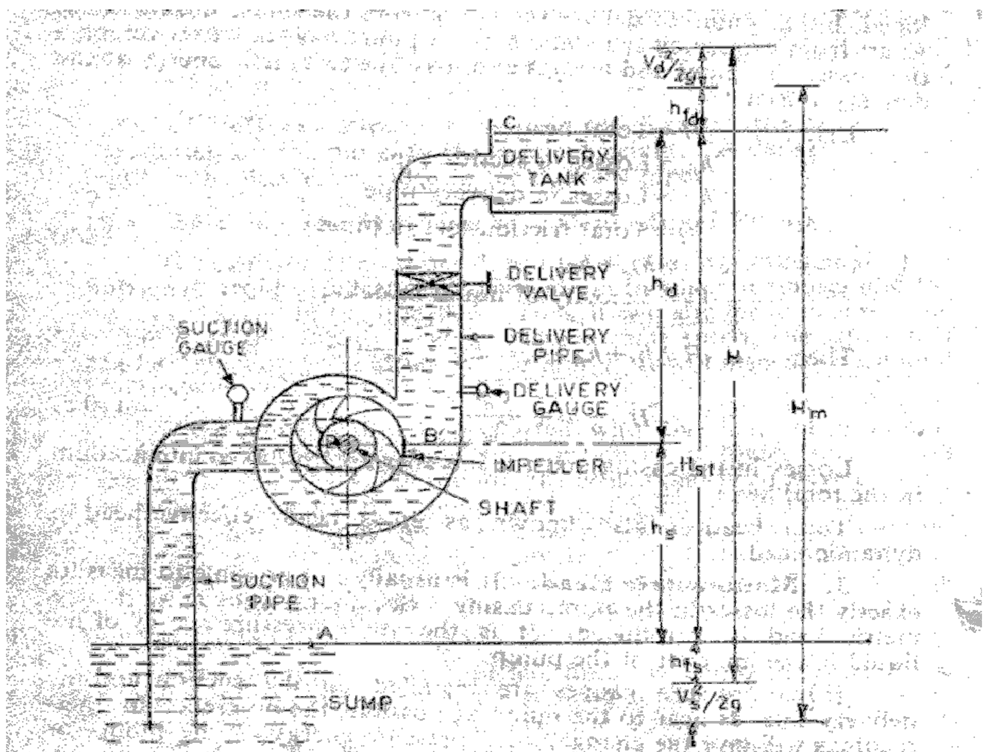


Fig. 10·8. Heads of a pump.

4. 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

$$= \frac{V_{w_2} u_2}{g} - \text{Loss of head in impeller and casing} \qquad \text{...(19.4)}$$

$$= \frac{V_{w_2} u_2}{g} \text{ ...if loss of pump is zero} \qquad \text{...(19.5)}$$

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

$$= \left(\frac{P_o}{\rho g} + \frac{V_o^2}{2g} + Z_o\right) - \left(\frac{p_i}{\rho g} + \frac{V_i^2}{2g} + Z_i\right) \qquad \text{...(19.6)}$$

where $\frac{p_o}{\rho g}$ = Pressure head at outlet of the pump = h_d

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

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

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

$\frac{p_i}{\rho g}, \frac{V_i^2}{2g}$, Z_i = Corresponding values of pressure head, velocity head and datum head at the inlet of the pump,

i.e., $h_s, \frac{V_s^2}{2g}$ and Z_s respectively.

(*c*)
$$H_m = h_s + h_d + h_{f_s} + h_{f_d} + \frac{V_d^2}{2g} \qquad \text{...(19.7)}$$

where h_s = Suction head, h_d = Delivery head,

h_{f_s} = Frictional head loss in suction pipe, h_{f_d} = Frictional head loss in delivery pipe, and

V_d = Velocity of water in delivery pipe.

5. Efficiencies of a Centrifugal Pump. In case of a centrifugal pump, the power is transmitted from the shaft of the electric motor to the shaft of the pump and then to the impeller. From the impeller, the power is given to the water. Thus power is decreasing from the shaft of the pump to the impeller and then to the water. The following are the important efficiencies of a centrifugal pump :

(*a*) Manometric efficiency, η_{man} (*b*) Mechanical efficiency, η_m and

(*c*) Overall efficiency, η_o.

(*a*) **Manometric Efficiency (η_{man}).** The ratio of the manometric head to the head imparted by the impeller to the water is known as manometric efficiency. Mathematically, it is written as

$$\eta_{man} = \frac{\text{Manometric head}}{\text{Head imparted by impeller to water}}$$

(*b*) **Mechanical Efficiency (η_m).** The power at the shaft of the centrifugal pump is more than the power available at the impeller of the pump. The ratio of the power available at the impeller to the power at the shaft of the centrifugal pump is known as mechanical efficiency. It is written as

$$\eta_m = \frac{\text{Power at the impeller}}{\text{Power at the shaft}}$$

$$\text{The power at the impeller in kW} = \frac{\text{Work done by impeller per second}}{1000}$$

(*c*) **Overall Efficiency (η_o).** It is defined as ratio of power output of the pump to the power input to the pump. The power output of the pump in kW

$$= \frac{\text{Weight of water lifted} \times H_m}{1000} = \frac{WH_m}{1000}$$

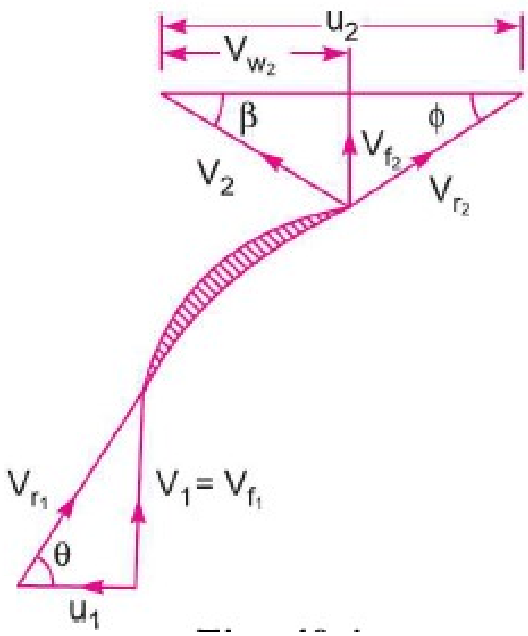
Power input to the pump = Power supplied by the electric motor

= S.P. of the pump.

$$\therefore \qquad \eta_o = \frac{\left(\dfrac{WH_m}{1000}\right)}{\text{S.P.}} \qquad \text{...(19.10)}$$

$$\text{Also} \qquad \eta_o = \eta_{man} \times \eta_m. \qquad \text{...(19.11)}$$

Problem 19.1 *The internal and external diameters of the impeller of a centrifugal pump are 200 mm and 400 mm respectively. The pump is running at 1200 r.p.m. The vane angles of the impeller at inlet and outlet are 20° and 30° respectively. The water enters the impeller radially and velocity of flow is constant. Determine the work done by the impeller per unit weight of water.*



Internal diameter of impeller, $D_1 = 200$ mm $= 0.20$ m
External diameter of impeller, $D_2 = 400$ mm $= 0.40$ m
Speed, $N = 1200$ r.p.m.
Vane angle at inlet, $\theta = 20°$
Vane angle at outlet, $\phi = 30°$
Water enters radially* means, $\alpha = 90°$ and $V_{w_1} = 0$
Velocity of flow, $V_{f_1} = V_{f_2}$
Tangential velocity of impeller at inlet and outlet are,

$$u_1 = \frac{\pi D_1 N}{60} = \frac{\pi \times 0.20 \times 1200}{60} = 12.56 \text{ m/s}$$

and

$$u_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times 0.4 \times 1200}{60} = 25.13 \text{ m/s.}$$

From inlet velocity triangle, $\tan\theta = \frac{V_{f_1}}{u_1} = \frac{V_{f_1}}{12.56}$

$\therefore$ $V_{f_1} = 12.56 \tan\theta = 12.56 \times \tan 20° = 4.57$ m/s

$\therefore$ $V_{f_2} = V_{f_1} = 4.57$ m/s.

From outlet velocity triangle, $\tan\phi = \frac{V_{f_2}}{u_2 - V_{w_2}} = \frac{4.57}{25.13 - V_{w_2}}$

or

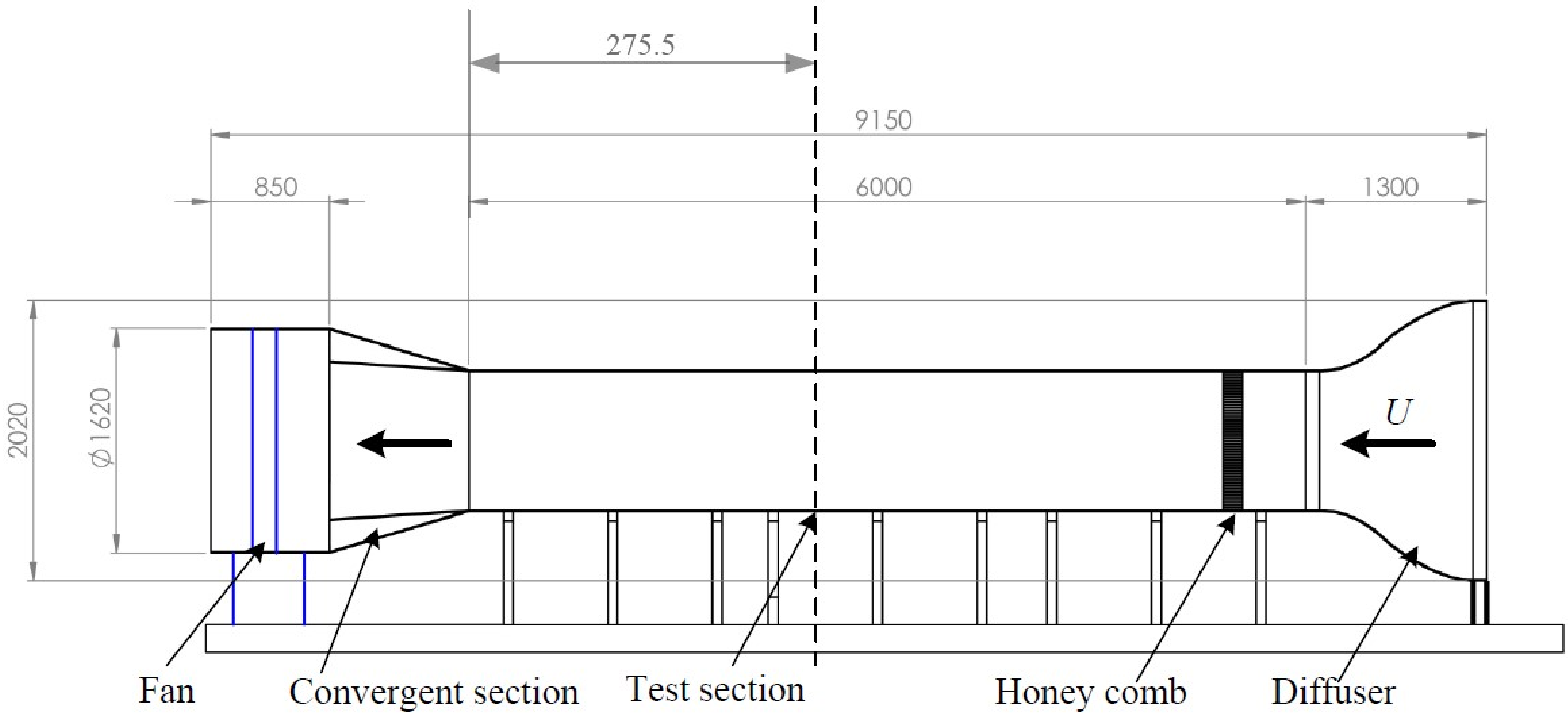
$$25.13 - V_{w_2} = \frac{4.57}{\tan\phi} = \frac{4.57}{\tan 30°} = 7.915$$

$\therefore$ $V_{w_2} = 25.13 - 7.915 = 17.215$ m/s.

The work done by impeller per kg of water per second is given by equation (19.1) as

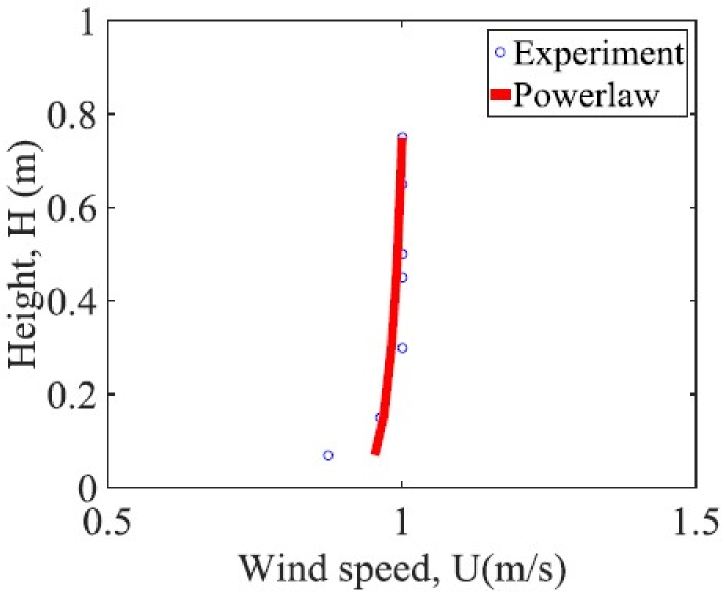
$$= \frac{1}{g} V_{w_2} u_2 = \frac{17.215 \times 25.13}{9.81} = \textbf{44.1 Nm/N. Ans.}$$

Schematic view of the Wind tunnel

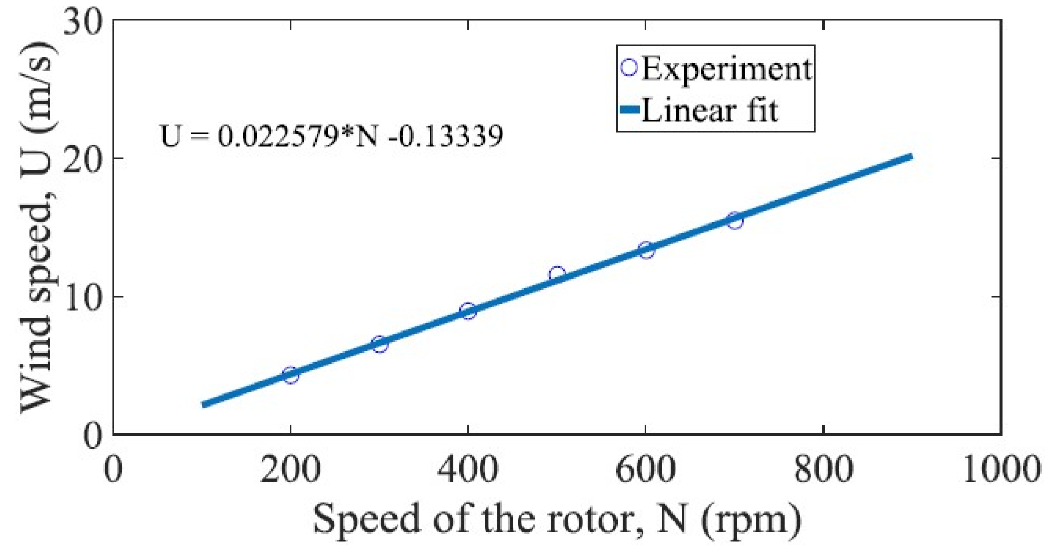


Suction type wind tunnel

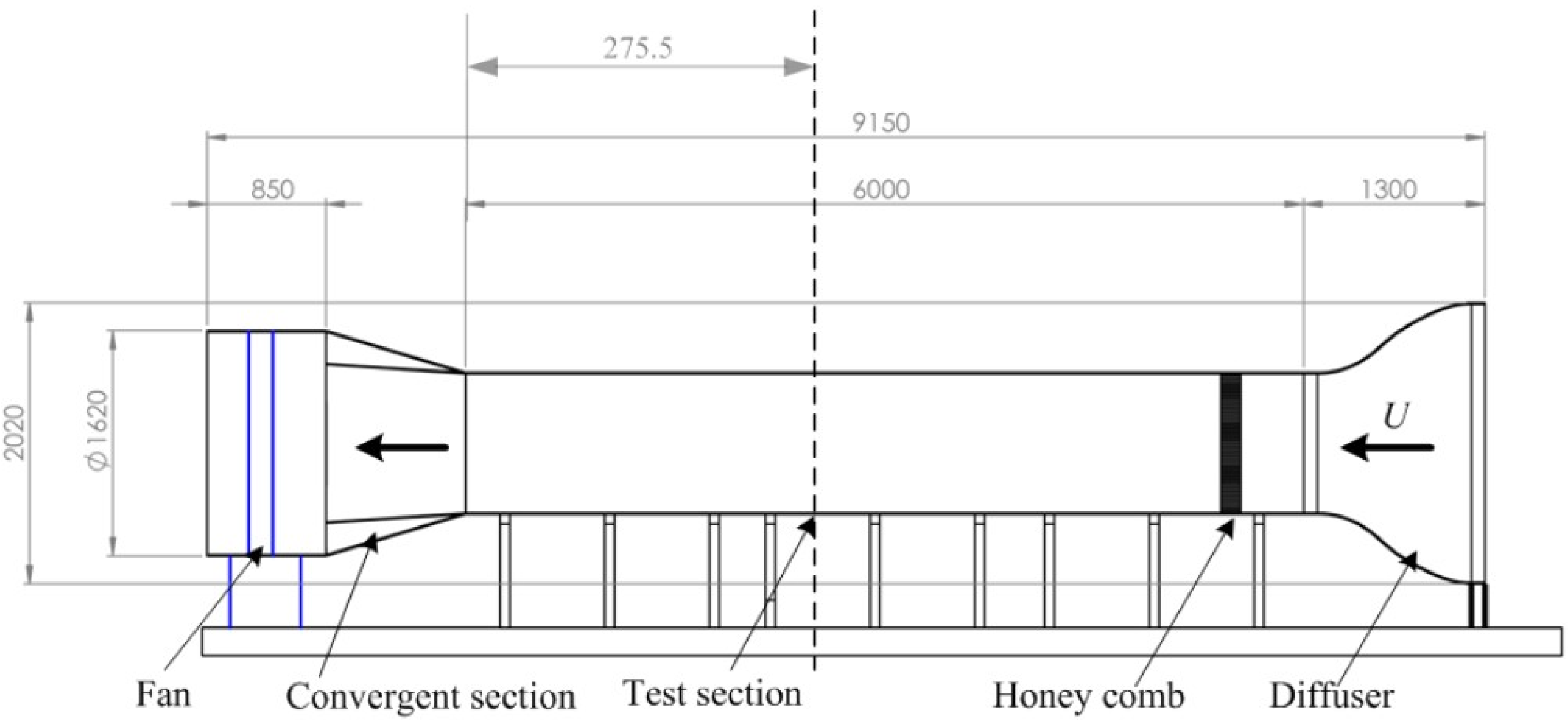
All Dimensions are in mm



Experiment
Powerlaw
Height, H (m)
Wind speed, U(m/s)
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5



Experiment
Linear fit
U = 0.022579*N -0.13339
Wind speed, U (m/s)
Speed of the rotor, N (rpm)
30
20
10
0
0
200
400
600
800
1000



275.5
9150
850
6000
1300
2020
ϕ1620
U
Fan
Convergent section
Test section
Honey comb
Diffuser

Hydraulic machinery

- Turbine is a device that extracts energy from a fluid (converts the energy held by the fluid to mechanical energy)

- Pumps are devices that add energy to the fluid (e.g. pumps, fans, blowers and compressors).

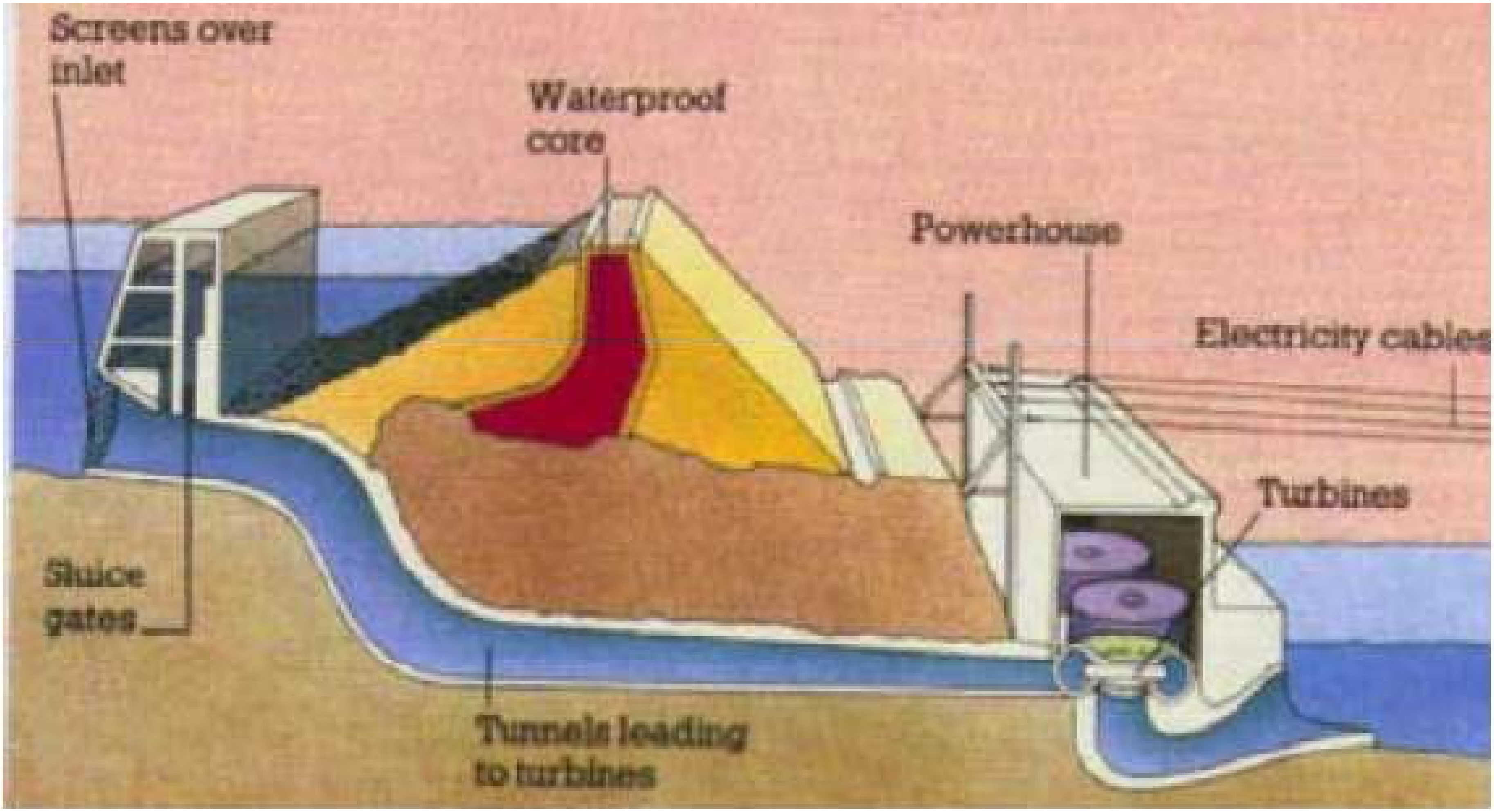
Turbines

- Hydro electric power is the most remarkable development pertaining to the exploitation of water resources throughout the world
- Hydroelectric power is developed by hydraulic turbines which are hydraulic machines.
- Turbines convert hydraulic energy or hydro-potential into mechanical energy.
- Mechanical energy developed by turbines is used to run electric generators coupled to the shaft of turbines
- Hydro electric power is the most cheapest source of power generation.

Turbines

- J.V. Poncelet first introduced the idea of the development of mechanical energy through hydraulic energy
- Modern hydraulic turbines have been developed by L.A. Pelton (impulse), G. Coriolis and J.B. Francis (reaction) and V Kaplan (propeller)

Turbines



Screens over inlet
Waterproof core
Powerhouse
Electricity cables
Turbines
Sluice gates
Tunnels leading to turbines

Types of turbines

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 heads more than 250m. The quantity of water needed in case of high head turbines is usually small. The Pelton turbines are the usual choice for high heads.

Classification of turbines

- Based on head and quantity of water

  b) Medium head turbines

  The turbines that work under a head of 45m to 250m 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 45m are called low head turbines. Owing to low head, large quantity of water is required. Kaplan turbines are used for low heads.

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

  If the runner of a turbine rotates by the impact or impulse action of water, it is an impulse turbine.

  b) Reaction turbines

  These turbines work due to reaction of the pressure difference between the inlet and the outlet of the runner.

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

- Based on specific speed of turbines

  Specific speed of a turbine is defined as the speed of a geometrically similar turbine which produces a unit power when working under a unit head.

  The specific speed of Pelton turbine ranges between 8-30, Francis turbines have specific speed between 50-250, Specific speed of Kaplan lies between 250-850.

- Based on disposition of shaft of runner

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

Heads, Losses and Efficiencies of Hydraulic Turbines

- 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.

Heads, Losses and Efficiencies of Hydraulic Turbines

- 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.

Heads, Losses and Efficiencies of Hydraulic Turbines

(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.

Heads, Losses and Efficiencies of Hydraulic Turbines

- 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 / Actual power supplied to runner

= Runner output / (ρQgH)

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

H = Net head available at the turbine inlet

Heads, Losses and Efficiencies of Hydraulic Turbines

- Efficiencies

(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.

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

Heads, Losses and Efficiencies of Hydraulic Turbines

- Efficiencies

(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

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

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

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

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

Thank you