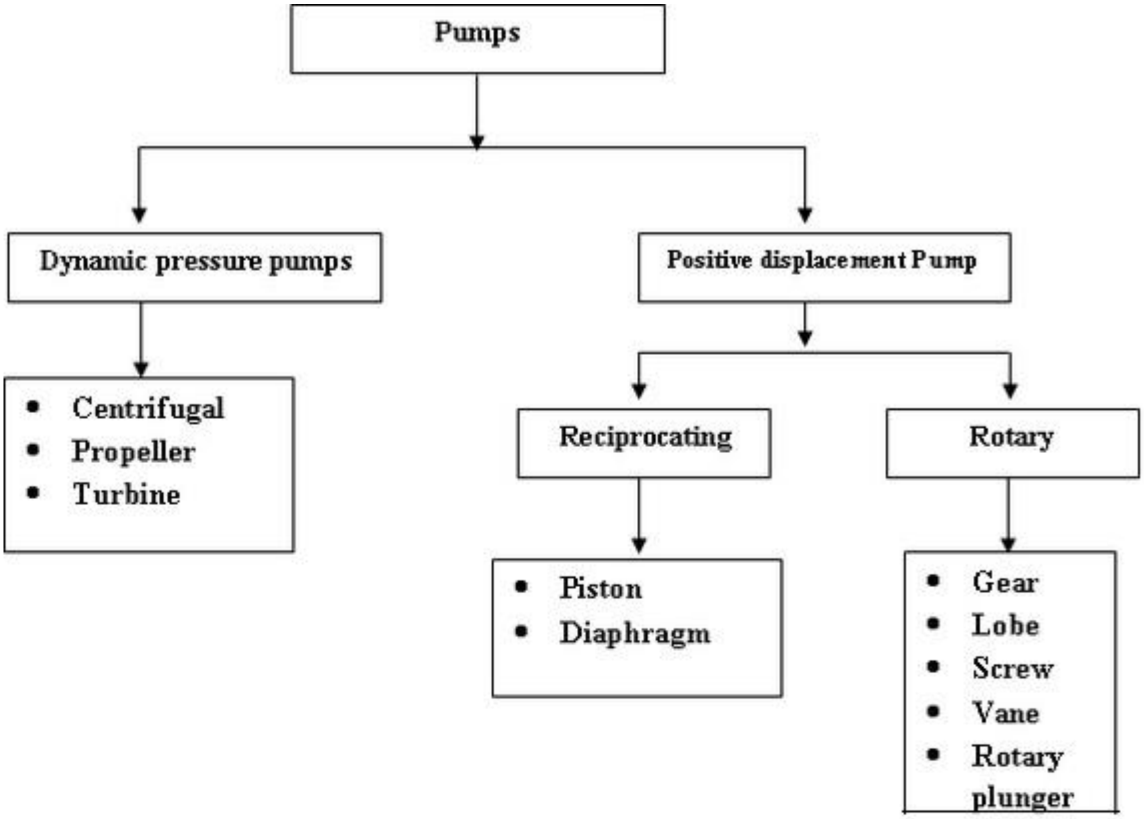
Unit 4: Centrifugal Pumps:

Purpose: To lift the liquid to the required height.

Pump: A hydraulic machine which converts mechanical energy of prime mover (Motors, I.C. Engine) into pressure energy

Classification of Pumps



Application:

1. Agriculture & Irrigation

2. Petroleum

3. Steam and diesel Power plant

4. Hydraulic control system

5. Pumping water in buildings

6. Fire Fighting

Positive Displacement:

Amount of liquid taken on suction side is equal to amount of liquid transferred to deliver side. Hence discharge pipe should be opened before starting the pump to avoid the bursting of casing.

Rotodynamic Pump:

Increase in energy level is due to a combination of centrifugal energy, Pressure energy and kinetic energy. i.e. fluid is not displaced positively from suction side to delivery side. Pumps can run safely even the delivery valve is closed.

Centrifugal Pump: Mechanical energy of motor is converted into pressure energy by means of centrifugal force acting on the fluid.

Sr. No.	Centrifugal Pump	Inward Flow Turbine
1	It consumes power	It produces power
2	Water flows radially outward	Water flows radially inward from periphery
3	Flow from low pressure to high pressure	Flow from high pressure to low pressure
4	Flow is decelerated	Flow is accelerated

Construction and working of centrifugal Pump

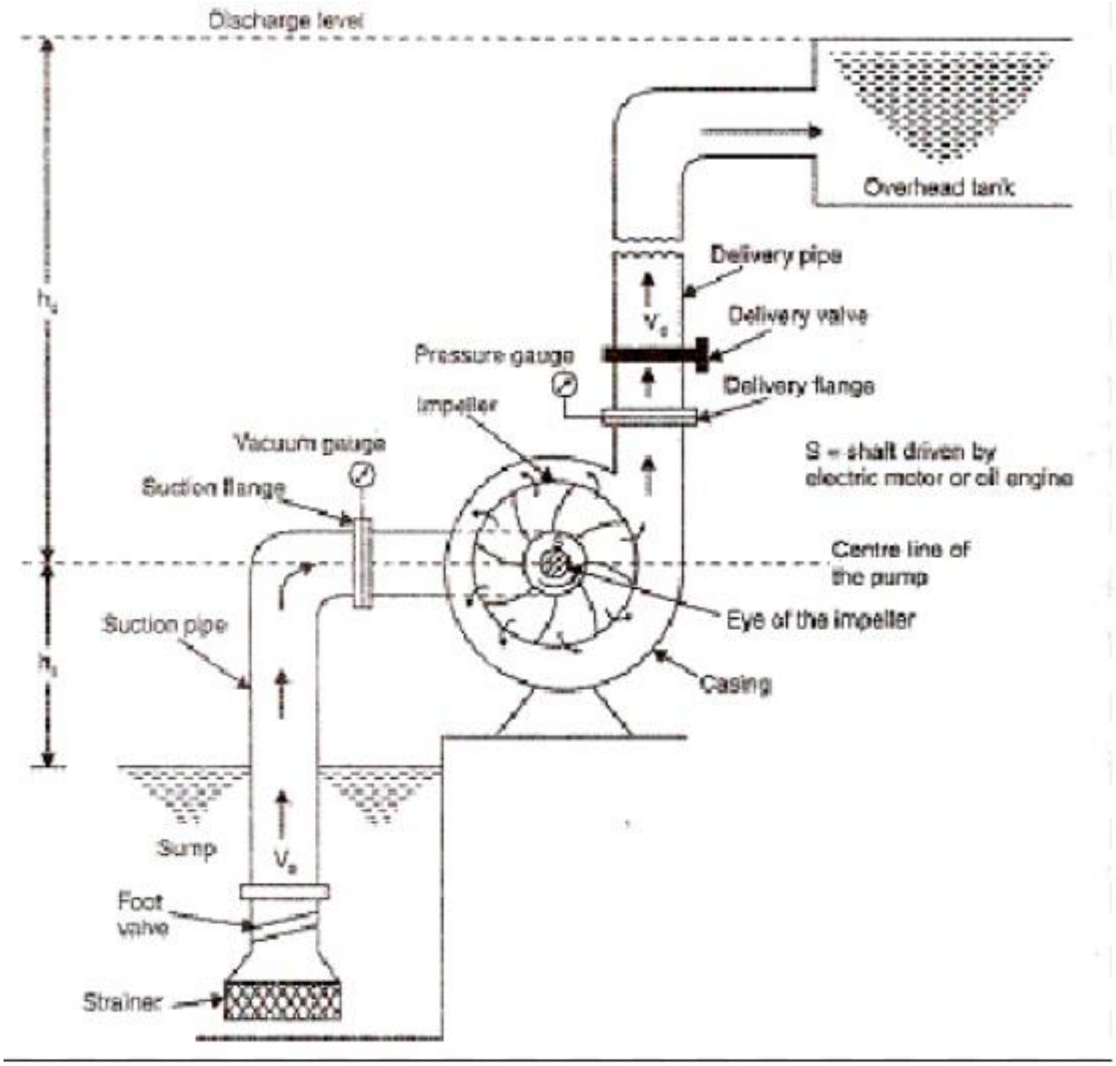
Components:

1. Impeller: A wheel with series of backward curved vanes.
2. Casing: Air tight chamber surrounding the impeller.
3. Suction Pipe: One end is connected in eye and other is dipped in a liquid.
4. Delivery pipe: One end is connected to eye, other to overhead tank.
5. Foot valve: Allow water only in upward direction.
6. Strainer: Prevent the entry of foreign particle/material to the pump

Working of Centrifugal Pump:

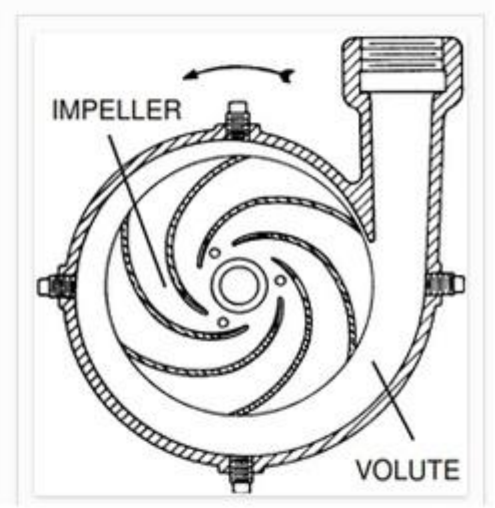
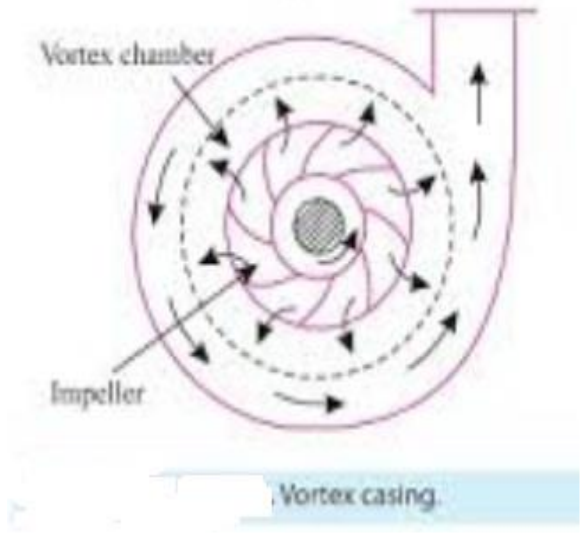
When a certain mass of fluid is rotated by an external source, it is thrown away from the central axis of rotation and centrifugal head is impressed which enables it to rise to a higher level.

1. The delivery valve is closed and pump is primed i.e. suction pipe, casing and portion of delivery pipe up to the delivery valve are completely filled with water so that no air pocket is left.
2. Keeping the delivery valve is closed the impeller is rotated by motor, strong suction is created at the eye.
3. Speed enough to pump a liquid when is attained delivery valve is opened. Liquid enter the impeller vane from the eye, come out to casing.
4. Impeller action develops pressure energy as well as velocity energy.
5. Water is lifted through delivery pipe upto required height.
6. When pump is stopped, delivery valve should be closed to prevent back flow from reservoir.



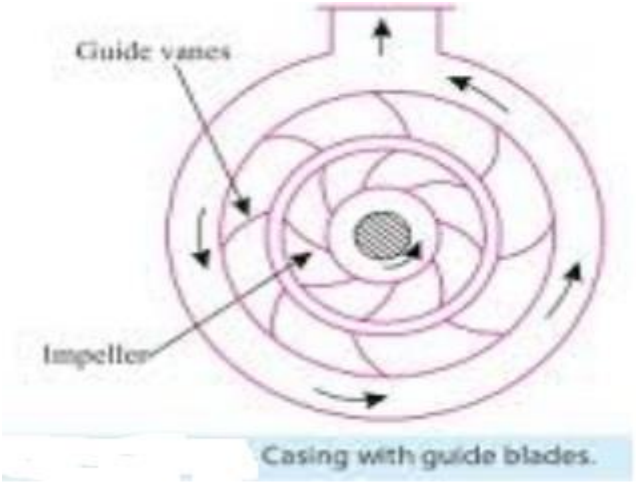
Types of casing

1. **Volute Casing:** Area of flow gradually increases from the eye of impeller to the delivery pipe. Same as shown in fig of components. Formation of eddies.

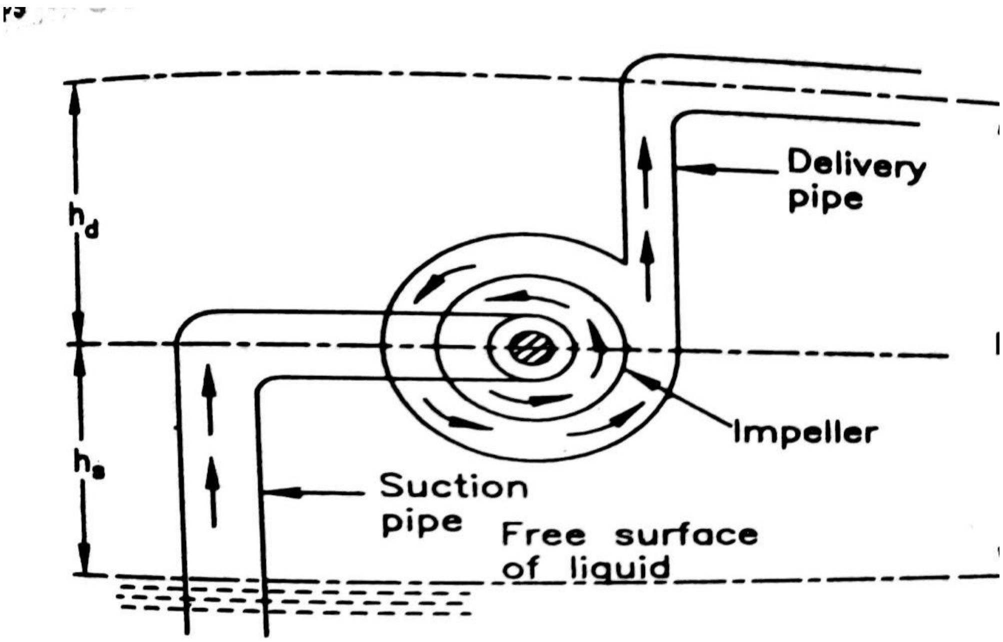
 Fig: Volute casing	 Fig: Vortex casing

2. **Vortex casing:** Circular chamber provided between the impeller and volute chamber.

   Loss of energy due to formation of eddies is reduced.
3. **Casing with guide blades:** Casing impeller is surrounded by a series of guide vanes mounted on a ring which is known as diffuser. Water enters the impeller without shock.



Various head of centrifugal Pump



The heads of a centrifugal pump are as follows:

(1)Suction head (2) delivery head

(3)Static head (4) Monometric head

1. Suction head (h_s) : It is vertical distance between level of sump and eye of an impeller. It is also called suction lift.
2. Delivery head (h_d): It is the vertical distance between between eye of an impeller and the level at which water is delivered.
3. Static head (H_s): It is sum of suction head and delivery head. It is given by

   $H_s = (h_s + h_d)$
4. Manometric head (H_m): The head against which the centrifugal Pump has to work. It is given by following equations:

   (i) H_m = (Head imparted by the impeller to the water) – (Loss of head in the pump impeller and casing)

$$H_m = \frac{V_{w2} u_2}{g} - (h_{Li} + h_{Lc})$$

Where, h_{Li}= Loss in impeller

h_{lc} = Loss in casing

$H_m = \frac{V_{w2} u_2}{g}$ (if losses are neglected)

(ii) H_m = Static head + losses in pipes + Kinetic head at delivery

$= H_s + (h_{fs} + h_{fd}) + \frac{V_d^2}{2g}$

$= (h_s + h_d) + (h_{fs} + h_{fd}) + \frac{V_d^2}{2g}$ --------------------------------(8)

Where,

h_s and h_d = Suction and delivery head

h_{fs} and h_{fd} = Loss of head due to friction in suction and delivery pipe.

V_d = Velocity pipe in delivery pipe.

(iii) H_m = (Total head at outlet of pump) – (Total head at inlet of Pump)

Total head at outlet $= \frac{P_d}{\rho g} + \frac{V_d^2}{2g} + Z_d = h_d + \frac{V_d^2}{2g} + Z_d$

Total head at inlet $= \frac{P_s}{\rho g} + \frac{V_s^2}{2g} + Z_s = h_s + \frac{V_s^2}{2g} + Z_s$

$H_m = (h_d + \frac{V_d^2}{2g}) - (h_s + \frac{V_s^2}{2g})$ -------------------------------------(9)

Inlet and outlet velocity triangles for Centrifugal Pump

Work done By Impeller on liquid

1. Liquid enters eye of impeller in radial direction i.e. $\alpha = 90^0$, $V_{w1} = 0$, $V_1 = V_{f1}$
2. No energy loss in impeller due to eddy formatting
3. No loss due to shock at entry
4. Velocity distribution in vanes is uniform.

Let,

N = Speed of impeller (rpm)

$\omega = Angular\ velocity = \frac{2\pi n}{60}$ (rad/s)

Tangential velocity of impeller

$u_1 = \omega R_1 = \frac{\pi D_1 N}{60}$ m/s

$u_2 = \omega R_2 = \frac{\pi D_2 N}{60}$ m/s

V_1 = Absolute velocity of water at inlet

$V_{w1} = Velocity\ whirl\ at\ inlet$

$V_{r1} = Relative\ Velocity\ at\ inlet$

$V_{f1} = velocity\ of\ flow\ at\ inlet$

α = angle made by V_1 at inlet with direction of motion of vane

$\theta =$ Angle made by V_{r1} at inlet with direction of motion of vane

V_1 , V_{w1}, V_{r1}, V_{f1}, β, ϕ -----Corresponding values at outlet

A Centrifugal pump is the reverse of radially inward flow reaction turbine.

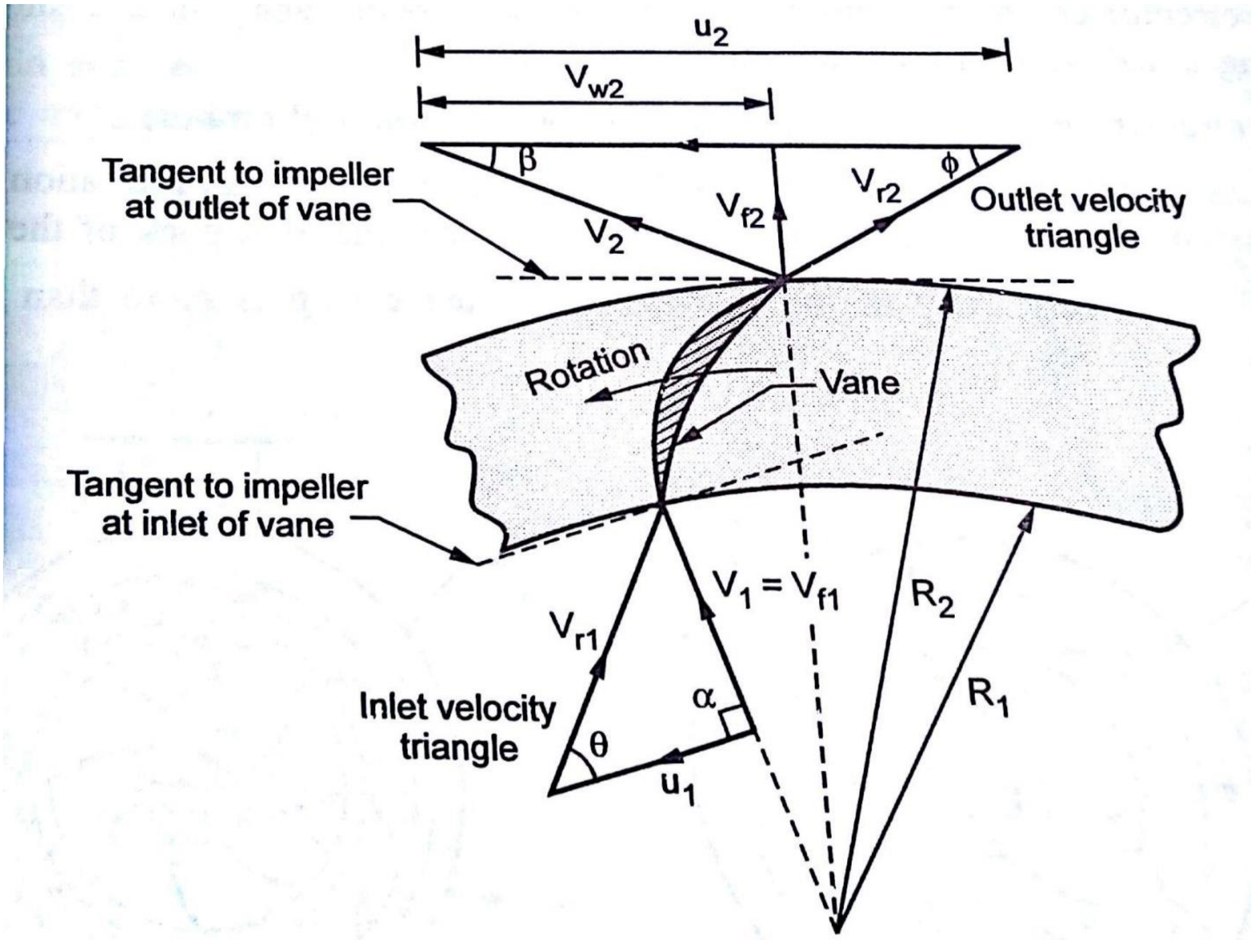


Fig. : Velocity triangle for an impeller

Work done by water on runner of turbine per sec per unit weight of water = $\frac{1}{g}(V_{w1}u_1 \pm V_{w2}u_2)$

W.D. by impeller on water per sec per unit weight of water = - (WD in case of turbine)

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

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

Eqn. (1) is known as Euler momentum equation for pump or Euler head.

Since radial entry $V_{w1} = 0$ *and* $V_1 = V_{f1}$

W.D. per unit weight = $\frac{1}{g}(V_{w2}u_2)$ N-m/N ------------------------ (2)

Q = Area x velocity of flow

Q = $\pi D_1 B_1$ x V_{f1}

Continuity equation Q = $\pi D_1 B_1$ x $V_{f1} = \pi D_2 B_2$ x V_{f2}

From the outlet velocity triangle

$V_{r2}^2 = V_{f2}^2 + (u_2 - V_{w2})^2$

$V_{f2}^2 = V_{r2}^2 - (u_2 - V_{w2})^2$--------------------------(3)

Also,

$V_{f2}^2 = V_2^2 - V_{w2}^2$-------------------------------------(4)

From equation 3 and 4

$V_2^2 - V_{w2}^2 = V_{r2}^2 - (u_2 - V_{w2})^2$

$V_2^2 - V_{w2}^2 = V_{r2}^2 - u_2^2 + 2u_2V_{w2} - V_{w2}^2$

$2u_2V_{w2} = V_2^2 + u_2^2 - V_{r2}^2$

$u_2V_{w2} = \frac{1}{2}(V_2^2 + u_2^2 - V_{r2}^2)$

Similarly from inlet velocity triangle

$u_1V_{w1} = \frac{1}{2}(V_1^2 + u_1^2 - V_{r1}^2)$

Putting in equation 1

W.D = $\frac{1}{g}\left[\frac{1}{2}\left(V_2^2 + u_2^2 - V_{r2}^2\right) - \frac{1}{2}(V_1^2 + u_1^2 - V_{r1}^2)\right]$

W.D = $\frac{V_2^2 - V_1^2}{2g} + \frac{u_2^2 - u_1^2}{2g} + \frac{V_{r1}^2 - V_{r2}^2}{2g}$--------------------------(5)

W.D per sec/unit weight =Increase in K.E head +Increase in static pressure + Change in K.E due to retardation

Equation 5 is known as fundamental equation centrifugal Pump.

Losses in Centrifugal Pump

1. Hydraulic losses : Friction loss shock , eddy losses
2. Mechanical losses: Bearing friction, impeller
3. Leakage losses: leakage of liquid

Efficiencies of a Centrifugal Pump

1. Manometric efficiency (η_{mano}):

$$\eta_{mano} = \frac{Manometric\ head}{head\ imparted\ by\ impeller} = \frac{H_m}{\frac{V_{w2}u_2}{g}} = \frac{g\ H_m}{V_{w2}u_2}$$

Francis Turbine,

$$\eta_{b=}\frac{V_{w1}u_1}{gH}$$

2. Volumetric Efficiency (η_v)

$$\eta_v = \frac{Liquid\ discharged\ per\ second\ from\ the\ Pump}{Quantity\ of\ liquid\ passing\ per\ second\ through\ the\ impeller}$$

$$= \frac{Q}{Q+q}$$

Where,

Q = Actual liquid discharged at the pump outlet per second

q = Leakage of liquid per second from impeller

3. Mechanical efficiency (η_{mech}):

$$\eta_{mech} = \frac{Poer\ at\ Impeller}{Power\ at\ shaft} = \frac{\rho g Q(\frac{V_{w2}u_2}{g})}{P}$$

4. Overall efficiency η_o

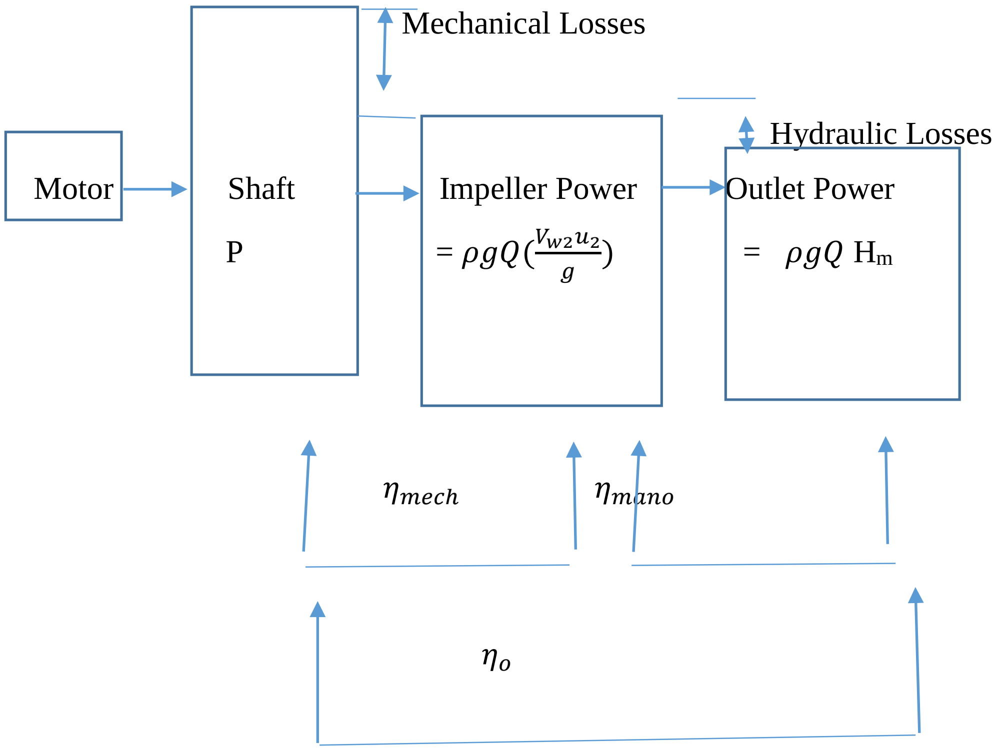
$$\eta_o = \frac{Output\ Power\ of\ Pump}{input\ Power\ of\ pump} = \frac{\rho g Q\ \mathrm{Hm}}{P}$$

$$\eta_o = \eta_{mech} \text{ x } \eta_{mano}$$

Turbine,

$$\eta_o = \frac{p}{\rho g Q\ \mathrm{Hm}}$$

The various losses and corresponding efficiencies of a centrifugal Pump are tabulated as follow



Effect of Outlet blade angle on Manometric Efficiency η_{mano}

At outlet of an impeller the energy available in liquid has the pressure energy equal to the sum of manometric head (H_m) and velocity head ($\frac{V_2^2}{2g}$)

Neglecting the losses in pump we have

$$\frac{V_{w2}u_2}{g} = H_m + (\frac{V_2^2}{2g})$$

$$H_m = \frac{V_{w2}u_2}{g} - \frac{V_2^2}{2g}$$

From outlet velocity triangle,

$V_2^2 = V_{w2}^2 + V_{f2}^2$ and

$$V_{w2} = u_2 - \frac{V_{f2}}{tan\ \phi}$$

$$= u_2 - V_{f2} \cot \phi$$

Substituting the above values in Hm equation

$$H_m = \frac{(u_2 - \mathrm{Vf2}\cot\phi)u_2}{g} - \frac{(u_2 - \mathrm{Vf2}\cot\phi)^2 + V_{f2}^2}{2g}$$

After simplification we get,

$H_m = \frac{u_2^2 - V_{f2}^2 cosec^2 \phi}{2g}$

Substituting this value in Manometric Efficiency η_{mano},

$\eta_{mano} = \frac{u_2^2 - V_{f2}^2 cosec^2 \phi}{2u_2(u_2 - \mathrm{Vf2}\cot\phi)}$ ---------------------(A)

- In the equation (A) if we vary the value of ϕ from 20^0 to 90^0 by keeping the other parameters constant then η_{mano}, is between 0.73 to 0.47
- If we further reduce the value of ϕ (below 20^0), it increases the efficiency but also results in long size of blades and increased friction losses.
- Therefore the discharge vane angle(ϕ) is kept more than 20^0 for a centrifugal pump.

Cavitation

Whenever the pressure in the pipe falls below the vapour pressure corresponding to the existing temperature of the liquid, the liquid will vaporize and bubbles are formed collapse and this process is continued rapidly and creates high pressure which can damage the impeller very easily. This phenomenon is known as cavitation which is highly undesirable. The cavitation is generally occurs in centrifugal pumps near the inlet of the impeller.

Thomas cavitation factor

The cavitation factor is used to indicate whether it will occur or not. The cavitation factor σ for pump is given by

$$\sigma = \frac{NPSH}{H_m}$$

If the value of σ is less than the critical value of σ_c , then the cavitation occurs in the pump.

$$\sigma_c = 1.03\, x\, 10^{-3} x \left[N_s^{4/3} \right]$$

Where N_s = Specific speed of the pump

The cavitation in the pump can be avoided by

- reducing the velocity in the suction pipe, and avoiding the bends
- reducing h_{fs} in suction pipe by using smooth pipe,
- reducing the suction head and
- Selecting the pump whose specific speed is low.

Effects of cavitation

It is undesirable as it has following disadvantages.

1. The large number of vapour bubbles formed are carried with liquid a high pressure region is reached, where these bubbles suddenly collapse. This includes the rush of surrounding liquid and produces shock and noise. This phenomenon is known as ***water hammer***.
2. The surface of blades and impeller are worn out because of bursting of bubbles.
3. The water hammer phenomenon is fatigue for the metal parts and it reduces the life by blow action.

Net Positive suction head (NPSH)

The term is very commonly used in pump industry because the minimum suction conditions are specified in terms of NPSH

Let,

P_1= Absolute pressure at inlet of the Pump

P_a = Absolute atmospheric pressure

P_v = Vapour pressure of the liquid

V_s = Velocity suction pipe.

h_{fs} = losses in suction pipe

H_a = Atmospheric pressure head

H_v = vapour pressure head

NPSH = Absolute pressure head at inlet – Vapour pressure head + Inlet (suction) velocity head

$$\text{NPSH} = \frac{P_1}{\rho g} - \frac{P_v}{\rho g} + \frac{V_s^2}{2g} \quad \text{----------------(i)}$$

But absolute pressure head at inlet of pump is given by

$$\frac{P_1}{\rho g} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right)$$

Substituting the above value in equation (i)

$$\text{NPSH} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right) - \frac{P_v}{\rho g} + \frac{V_s^2}{2g}$$

$$\text{NPSH} = \frac{P_a}{\rho g} - \frac{P_v}{\rho g} - h_s - h_{fs}$$

$$\text{NPSH} = H_a - H_v - h_s - h_{fs} \quad \text{--------------------------------------(24)}$$

- The NPSH is also defined as the net head required to make the liquid flow through suction pipe from sump to impeller.
- NPSH term is also used to check cavitation in pump

Required NPSH

- It is value given by pump manufacturer
- This value can be determined experimentally and it varies with pump design, speed of the pump and capacity of the pump.

Available NPSH

- When pump is installed the value of available NPSH is calculated from equation 24
- The available NPSH should be greater than required NPSH for cavitation free operation of Pump.

Priming of centrifugal Pumps:

- The priming of centrifugal pump is the process of filling the suction pipe, casing of the pump and portion of the delivery pipe from outside source of the fluid to be raised.
- This removes the air, gas or vapour from these parts.
- Priming is done before the starting the pump
- It is necessary to avoid discontinuity of flow or dry running of pump
- The dry running of pump may result in rubbing and seizing of the wearing rings and cause severe damage.
- Also when the pump is running with air instead of water, the head generated is in terms of meters of air. But as the density of air very low, the generated head of air in terms of equivalent meter of water head is negligible and hence water may not be sucked from the pump.

For all above reason priming is necessary.

The following are the some of the methods for priming the centrifugal pump.

i. Priming of small pumps: It is done by pouring the fluid into the funnel provided for priming. During this the air vent valve is kept open and priming is continued till all the air is removed.

ii. Priming of large Pumps: It is done by removing the air from casing and suction pipe with the help of vacuum pump or by an ejector. This helps in drawing the liquid from sump and fill the pump with liquid.

There are some pumps having internal constructions for supply of liquid in suction pipe known as ***self-priming pumps***

Installation of Centrifugal Pump

The following steps are used for efficient installation of the centrifugal Pump.

i. Location of Pump
ii. Suction piping
iii. Delivery piping
iv. Foundation
v. Grouting
vi. Alginment

i. Location

- The pump unit should be located close to the water surface to minimize the vertical suction lift. The suction lift of length more than 5 m must be avoided.

ii. Suction piping:

- Suction pipe must be continuously flooded have length of 3 times diameter for straight run and it can accommodate a strainer.
- Entire suction piping should be inclined slightly and all the flanged joints should be fitted with gasket and be airtight.

iii. Deliver piping

- The discharge valve must be of butterfly or ball or globe type if it is used as flow or pressure throttling device.
- The maximum flow velocity in the discharge line should not exceed 2 m/s

iv. Foundation and grouting

- The pump must be installed on a base plate. The base plate is attached to a foundation and grouting is placed between it.
- The foundation and grouting will help to damp out the vibrations.

v. Alignment

- The pump alignment is extremely important.
- The suction and discharge piping should be naturally aligned with pump.
- The alignment should be done prior to grouting it and it is checked after grouting and during startup.

Specific Speed of a centrifugal pump

It is defined as the speed of geometrically similar pump which would deliver one cubic meter of liquid per second against a unit head (one meter)

The discharge through impeller of a centrifugal pump is given by

Q = Area x velocity of flow

$= \pi DB \ x \ V_f$

$Q \propto D \ x \ B \ x \ V_f$---------------------------(i)

$Q \propto D^2 \ x \ V_f$ (as $B \propto D$)------------(ii)

Now tangential velocity is given by

$u = \frac{\pi DN}{60}$

$u \propto DN$-----------------------------(iii)

Also from the relation of tangential velocity (u) and flow velocity (V_f) to the manometric head (H_m),

$u \propto V_f \propto \sqrt{H_m}$------------------------(iv)

Now substituting the value of u from eqn. (iv) in equation (iii) we get

$\sqrt{H_m} \propto DN$

$D \propto \frac{\sqrt{H_m}}{N}$ --------------------------(v)

Substitute iv and v in equation (ii) we get

$Q \propto \frac{H_m}{N^2} \ x \ \sqrt{H_m}$

$Q = K\frac{H_m^{3/2}}{N^2}$ -----------(vi) K= constant of proportionality

From the definition of of specific speed of if H_m= 1, Q= 1 m^3/s then $N = N_s$

$1 = K\frac{1^{3/2}}{N_s^2}$, $K = N_s^2$

Substituting the value of k in equation (vi) we get

$$Q = N_s^2 \frac{H_m^{3/2}}{N^2}$$

$$\boxed{N_s = \frac{N\sqrt{Q}}{H_m^{3/4}}}$$

Minimum speed for starting of Centrifugal Pump

For minimum speed to start the pump

$$\frac{u_2^2 - u_1^2}{2g} \geq H_m \quad \text{------------------------(a)}$$

$$and \qquad \eta_{mano} = \frac{g\, H_m}{V_{w2} u_2}$$

$$H_m = \eta_{mano} \times \frac{V_{w2} u_2}{g}$$

Also $u_1 = \frac{\pi D_1 N}{60}$ and $u_2 = \frac{\pi D_2 N}{60}$

Substituting above value in equation a

$$\frac{u_2^2 - u_1^2}{2g} = \eta_{mano} \times \frac{V_{w2} u_2}{g}$$

$$u_2^2 - u_1^2 = 2\, \eta_{mano} V_{w2} u_2$$

$$\left(\frac{\pi D_2 N}{60}\right)^2 - \left(\frac{\pi D_1 N}{60}\right)^2 = 2\, \eta_{mano} V_{w2} u_2$$

$$\left(\frac{\pi N}{60}\right)^2 (D_2^2 - D_1^2) = 2\, \eta_{mano} V_{w2} u_2$$

$$\left(\frac{\pi N}{60}\right)^2 (D_2^2 - D_1^2) = 2\, \eta_{mano} V_{w2}\, x\, \frac{\pi D_2 N}{60}$$

$$\left(\frac{\pi N}{60}\right)(D_2^2 - D_1^2) = 2\, \eta_{mano} V_{w2} D_2$$

$$N = \frac{2\, \eta_{mano} V_{w2} D2}{(D_2^2 - D_1^2)} \times \frac{60}{\pi}$$

$$\boxed{N_{min} = \frac{120\, \eta_{mano} V_{w2} D_2}{\pi\, (D_2^2 - D_1^2)} \text{---------------------------(18)}}$$

Performance characteristics of Centrifugal Pump

The following are the important characteristics curves of centrifugal pump.

i. Main characteristics curves

ii. Operating characteristics curves

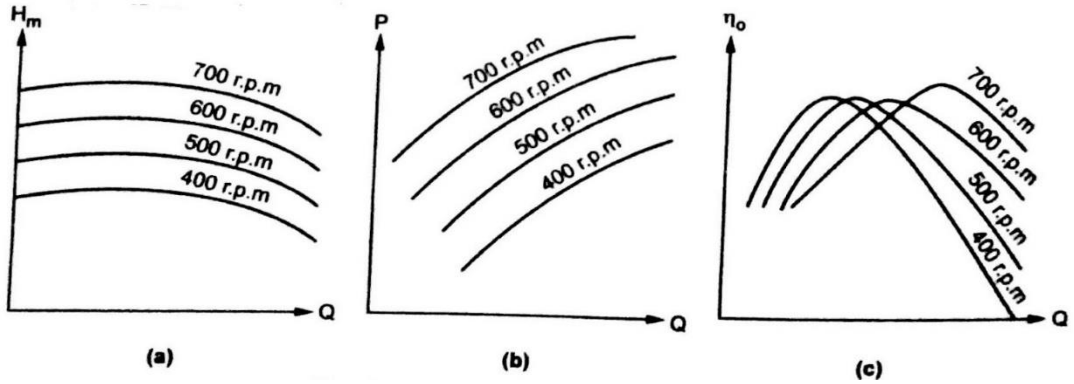
iii. Constant efficiency curves or Muschel curves

iv. Constant head and constant discharge curves.

1. Main characteristics curves

The main characteristics curves are obtained by keeping the pump at constant speed and varying the discharge over desired range.

The discharge is varied by means of deliver valve. For different values of discharge the measurements are taken or calculated for manometric head, shaft power and efficiency These curve are useful in evaluating the performance of pump at different speeds.



(a) (b) (c)

2. Operating characteristics curve

The maximum efficiency occurs when centrifugal pump operates at the constant designed speed.

If the speed is kept constant, the variation in manometric head power and efficiency with respect to discharge gives the operating characteristic curves for pump.

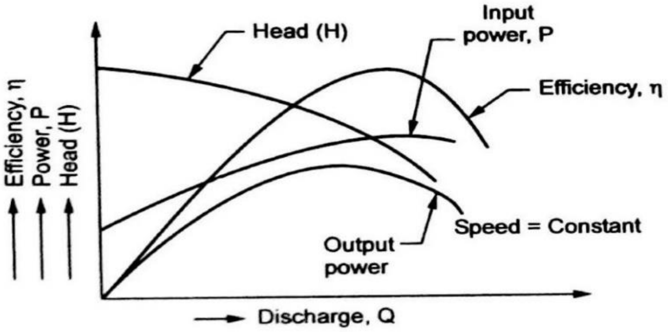


Fig. : Operating characteristics curves of a pump

3. Constant efficiency curve

   The constant efficiency or iso efficieny curve gives the performance of pump over its entire range of operations.

   With the help of data obtained in main characteristic curves the constant efficiency curves are plotted.

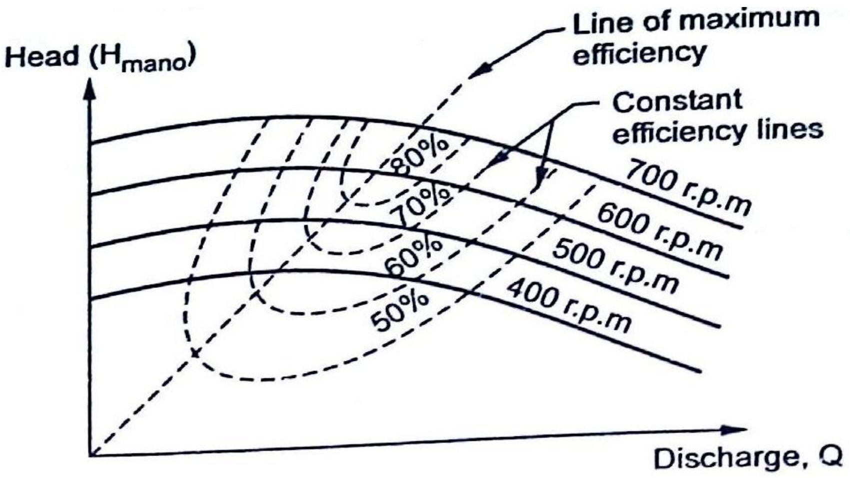
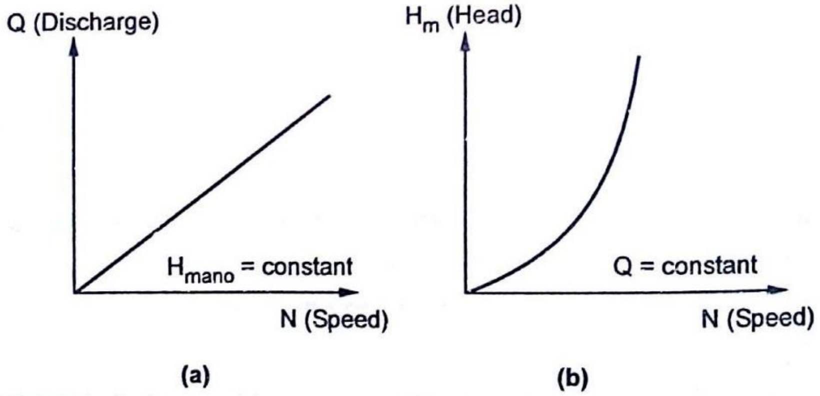


Fig. : Constant efficiency or Muschel curve

4. Constant head and constant discharge curves

   These curves are helpful in determining the performance of variable speed pump.

   These curves are plotted as follows.



(a)

(b)

Fig. : (a) Q v/s N and (b) H_m v/s N curves of a centrifugal pump

Multistage Centrifugal Pump

A multistage centrifugal pump consist of two or more identical impellers monted on the same shaft or on different shafts.

To produce the heads higher than that of using single impeller keeping the discharge constant. This is achieved by ***Series arrangement of pumps***

To discharge the large quantity of fluid keeping the head constant. This is achieved by ***parallel arrangement of pumps.***

Series Arrangement of Pumps

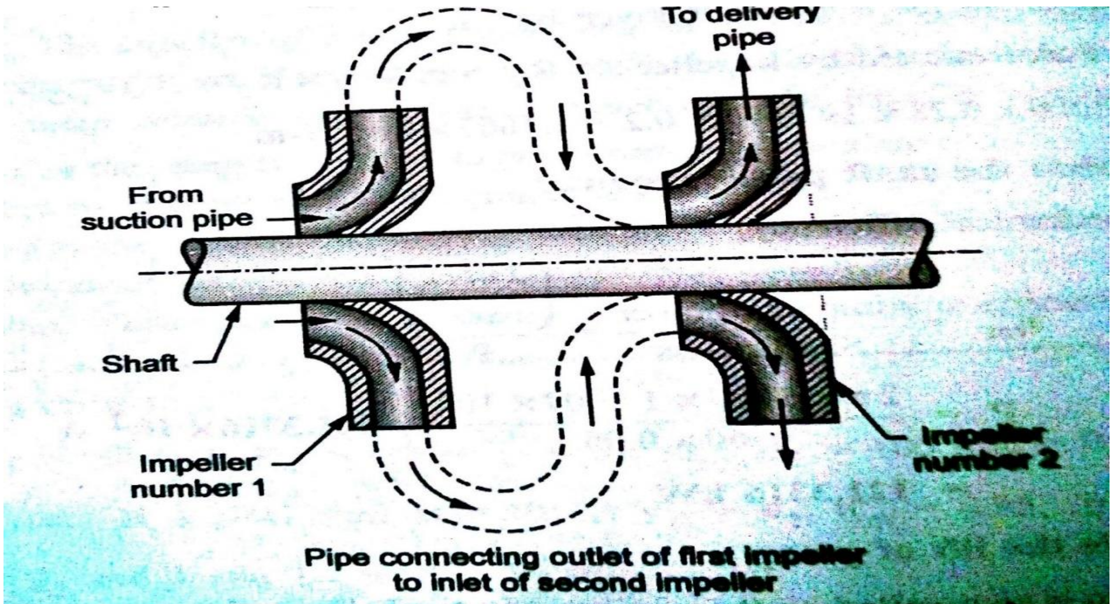


Fig. [illegible] : Two-stage pumps with impellers in series

The discharge from first impeller having high pressure is fed to second impeller through guided passage.

The pressure at the outlet of second impeller will be more than the pressure at the outlet of first impeller.

If the more number of impellers are mounted on the same shaft in series arrangement then the pressure will be increases further.

For each stage, the head developed will be H_m hence for number of stages (n) total head developed will be given by

$H_{total} = n \times H_m$

Parallel Arrangement of Pumps

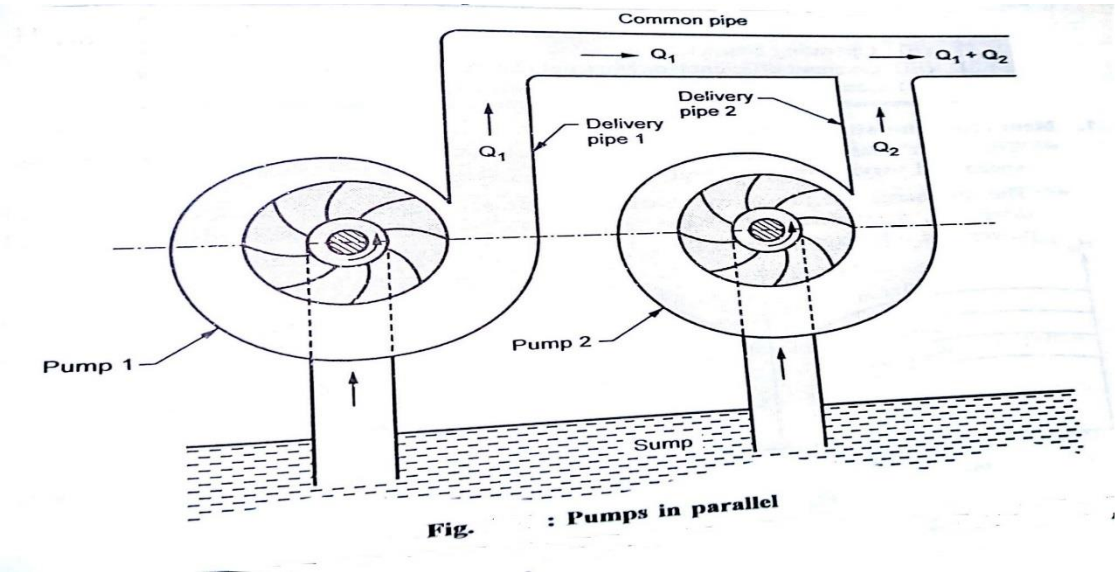


Fig. : Pumps in parallel

To obtain a high discharge at relatively small head number of impellers are mounted in parallel arrangement.

The pumps are arranged such that each of these pump is working separately to lift the liquid from common sump and deliver it to the common delivery pipe

In this arrangement the head remains constant and the discharge of each pump gets added to give large quantity of liquid at the outlet

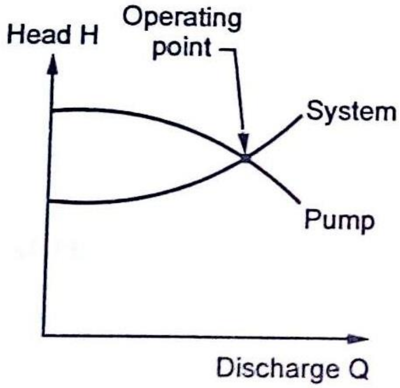
$Q_{total} = Q_1 + Q_2 + \ldots\ldots Q_n$

Selection pump based on system resistance curve

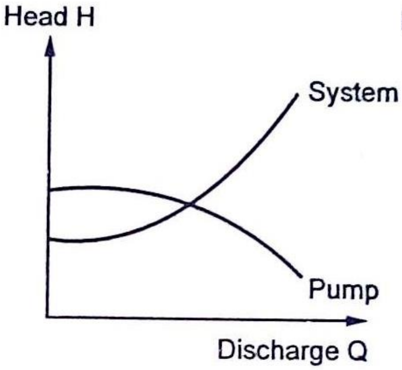
The pump manufacture always gives the head discharge characteristic curve for their manufactured pump and operated under different test conditions.

But in actual application this pump is required to operate under different conditions with respect to suction and discharge pipelines elbows and number of valves.

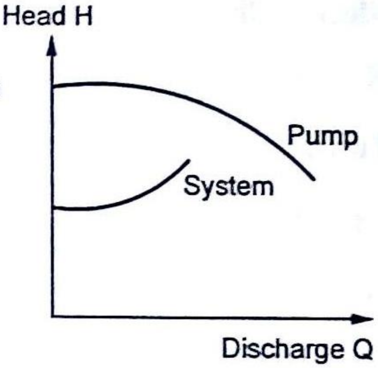
The user of the pump find out his system requirement and a head discharge curve is drawn. This curve is called as system resistance curve or system characteristic curve. As shown in following figure.



(a) System resistance curve



(b) Undersized pump



(c) Oversized pump

Now the pump characteristics curve (supplied by manufacture) are superimposed on system characteristic curve.as shown in above figure.

The point of intersection represent the operating point of pump .

If the pump can not meet the head and discharge requirements of the pump the it is called as undersized or under capacity pump. (refer fig (b))

If the pump delivers much higher head and discharge than the requirements the it is called ad oversized pump.(refer fig. c)

Selection of Pumps:

Selection of pump is based on the specific speed for the pump.

The specific speed is calculated from the values of discharge (Q) head (H) and speed (N)

For low heads of about 6 m and large discharge, axial flow pumps are used.

For high heads, radial flow pumps are used.

If it is possible to increase the speed for low specific pump, multistage pump are suitable.

Depending upon type of impeller, the pump is selected for particular operation as follows

i) Shrouded type impeller are used for pumping fresh and clean water.

ii) Unshrouded or propeller type impeller is used for pumping solid-liquid mixture.

iii) Mixed flow impellers with diffusers vanes are used for deep well or submersible pumps.