# 9

# Centrifugal Pumps

## Contents

## 9.1 Introduction

***"The hydraulic machines which convert the mechanical energy into hydraulic energy are called pumps."***

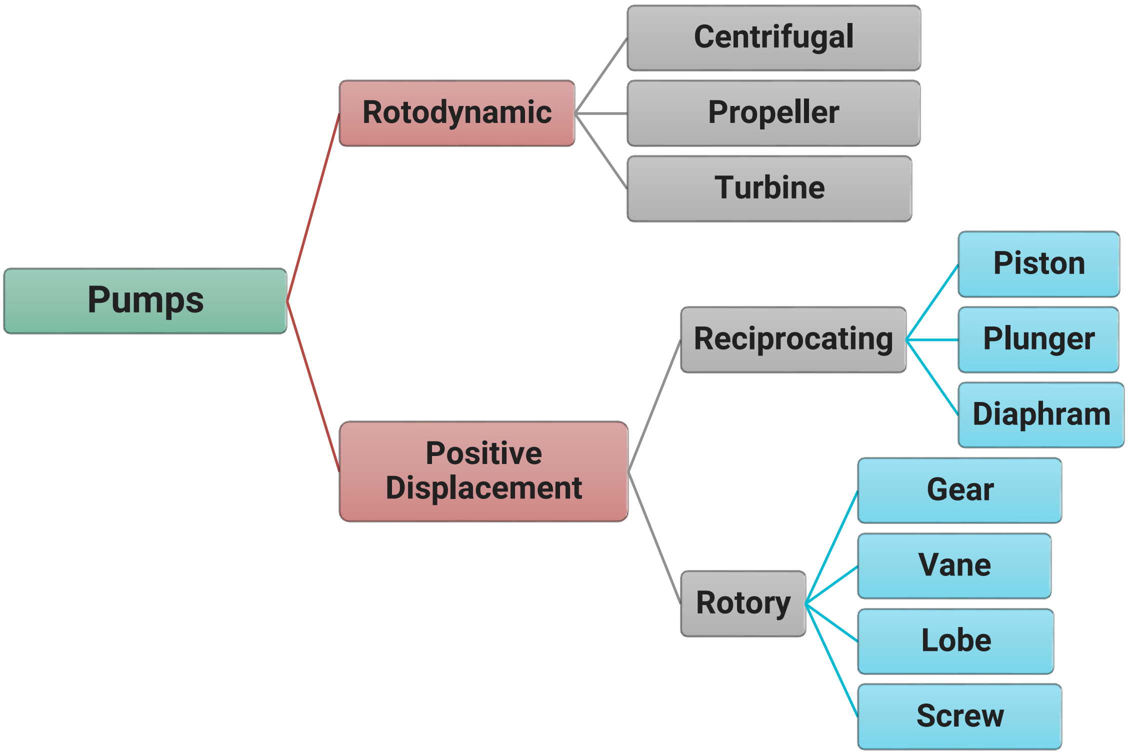
It increases pressure energy or kinetic energy or both by using mechanical energy. The energy level of the fluid can be increased by either rotodynamic action or by positive displacement of the fluid.

***"If the mechanical energy is converted into pressure energy or kinetic energy by means of centrifugal force acting on the fluid, the hydraulic machine is called Centrifugal pump."***

They work on the same principle of a reaction turbine. The basic difference between a pump and a turbine is that in a turbine, flow takes place from the high-pressure side to the low-pressure side while in a pump flow takes place from low-pressure side to high-pressure side.

### 9.1.1 Classification of Hydraulic Pumps

The classification of hydraulic pumps on the basis of the transfer of mechanical energy is as follows:




### 9.1.2 Selection Criterion of a Hydraulic Pumps

The selection of a suitable pump depends on:

- The pressure and the capacity of the liquid being handled
- Properties such as viscosity, temperature and the corrosiveness of the flowing fluid
- Initial and maintenance cost
- Pump duty
- Availability of space, size and position of locating the pump
- Speed of rotation and power required
- Standardisation with respect to the types and makes of pumps already available at the site
- Scale-up problems.

### 9.1.3 Applications of Hydraulic Pumps

- Agriculture and irrigation works
- Municipal waterworks and drainage system
- Condensate, boiler feed, sump drain and such other services in a steam power plant
- Hydraulic control systems
- Oil pumping
- Transfer of raw materials and finished products in the industry.

## 9.2 Components and Working of Centrifugal Pump

### 9.2.1 Components of Centrifugal Pump

The main components of the centrifugal pump are:

1. Impeller
2. Casing
3. Suction Pipe with Strainer and Foot-Valve
4. Delivery Pipe and Delivery Valve

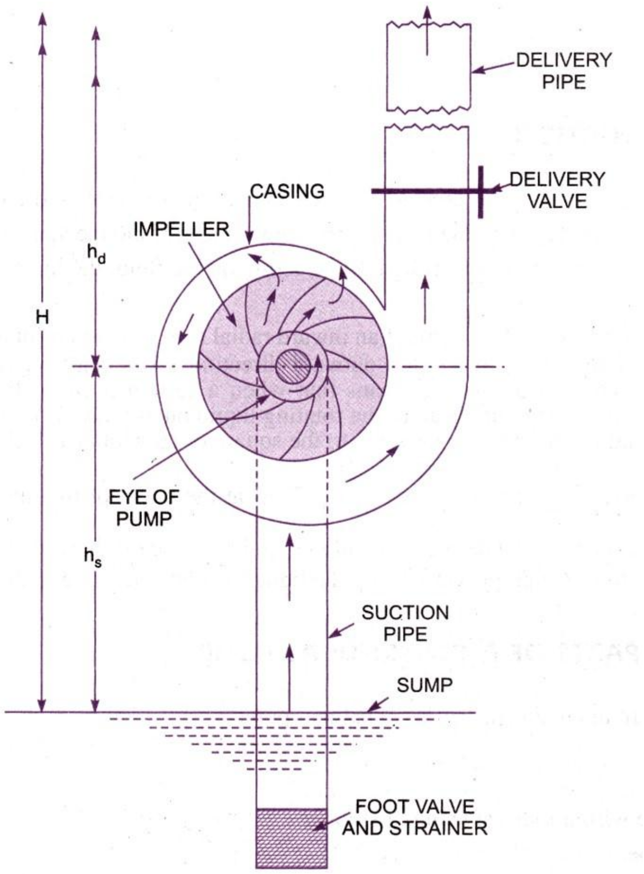



*Fig.9.1 –Main parts of a centrifugal pump*

**1. Impeller**

It is a wheel or rotor which is provided with a series of backward curved vanes or blades. It is mounted on a shaft which is coupled to an external source of energy (electric motor), which imparts required energy to the impeller.

It gets mechanical energy and converts it to kinetic and pressure energy of the fluid.

Liquid enters the impeller through an eye of the impeller, high energy liquid than enters the pump casing.

**2. Casing**

It is an airtight passage surrounding the impeller, designed in such a way that 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 material of the casing is generally cast iron or cast steel.

The efficiency of the pump depends on the type of casing used. The following three types of casings are commonly used:

A. Volute Casing
B. Vortex Casing and
C. Casing with Guide Blades

**A. Volute Casing**

It is of spiral type in which area of flow increases gradually and hence pressure increases.

It is observed that in the case of a volute casing, a large amount of kinetic energy is lost due to eddy formation and hence it lowers the overall efficiency and hence such type of pump gives comparatively low head. The centrifugal pump with the volute casing is shown in *Fig.9.1*.

**B. Vortex Casing**

In this type of casing, a circular chamber is provided in between the casing and the impeller, which is known as vortex or whirlpool chamber (refer *Fig.9.2*).

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 the only volute casing is provided.

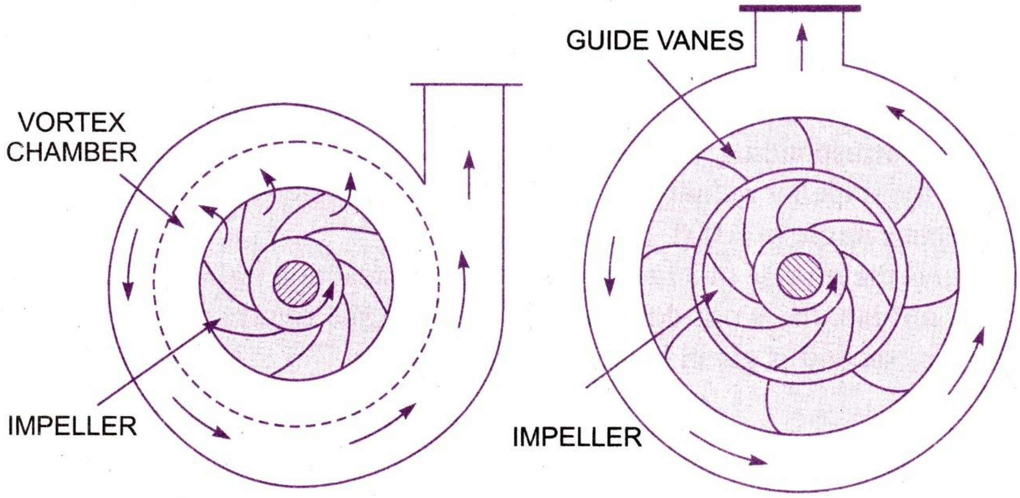



*Fig.9.2 – Types of Casing*

**C. Casing with Guide Blades**

Most efficient casing. In this, the impeller is surrounded by a series of guide blades mounted on a ring which is known as a diffuser (refer *Fig.9.2*).

The guide vanes are designed in such a way that the water from the impeller enters the guide vanes without shock which avoids hydraulic losses.

Also, the area of guide vanes increases, thus reducing the velocity of flow and consequently increases the pressure of water.

Used for developing high heads and hence mostly used as vertical pumps and very suitable for installations in deep wells, mines, etc.

The casing is in most of the cases concentric with the impeller.

**3. <u>Suction Pipe with Strainer and Foot-Valve</u>**

It carries liquid from the sump to the pump. Its lower end is dipped into the sump and upper end is connected with the eye of the pump (i.e. inlet of the pump).

A strainer and foot-valve are connected with the lower end. Strainer keeps the debris away from entering into the suction pipe and hence only clear water enters the impeller. Foot-valve is a kind of non-return valve which does not allow the liquid to go back into the sump.

Cavitation may be caused due to negative pressure at the suction of the pump and hence losses in the inlet pipe must be minimized. To keep low velocity in the suction pipe, normally the diameter of the suction pipe is kept more than that of the delivery pipe.

### 4. Delivery Pipe and Delivery Valve

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

The velocity of liquid in the delivery pipe is kept slightly higher than that in the suction pipe. A valve is provided just near the pump outlet to regulate the flow of liquid in the delivery pipe.

### 9.2.2 Working of a Centrifugal Pump

***"A centrifugal pump works on a principle that when the liquid is rotated by an external prime mover, it is thrown away from the axis of rotation and a centrifugal head is imparted which makes it possible to raise to the higher elevation."***

Before starting a centrifugal pump, the liquid is filled in the suction pipe, impeller, casing and a delivery pipe up to a delivery valve. This is known as **priming**. During the priming, the delivery valve is kept closed.

After priming, a prime mover (electric motor) is started. The energy given to the impeller by a prime mover builds up the centrifugal force which throws the liquid towards the impeller periphery. This causes a pressure gradient in the suction pipe, i.e. a partial vacuum exists at the impeller eye while the liquid in the sump is at atmospheric pressure.

So, the liquid from the sump is sucked in towards the impeller eye. When the liquid passes through the impeller, it receives energy and hence, both the pressure and velocity increase.

Liquid enters into the casing. Due to the incremental cross-sectional area of the casing towards the delivery pipe, the velocity of liquid decreases and pressure energy increases.

With high-pressure energy and negligible kinetic energy, liquid enters into the delivery pipe and is lifted to the required height. The process is continuous as long as motion is given to the impeller and there is a supply of liquid.

## 9.3 Velocity Diagram and Work Done of a Centrifugal Pump

In the 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 liquid is obtained by drawing velocity triangles at the inlet and outlet of the impeller in the same way as for a turbine.

*Fig.9.3* shows the vane of impeller and velocity triangles at the inlet and outlet of the impeller.

The water enters the impeller radially at the inlet for the 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 the inlet. Hence $\alpha = 90° \; and \; V_{w1} = 0$.

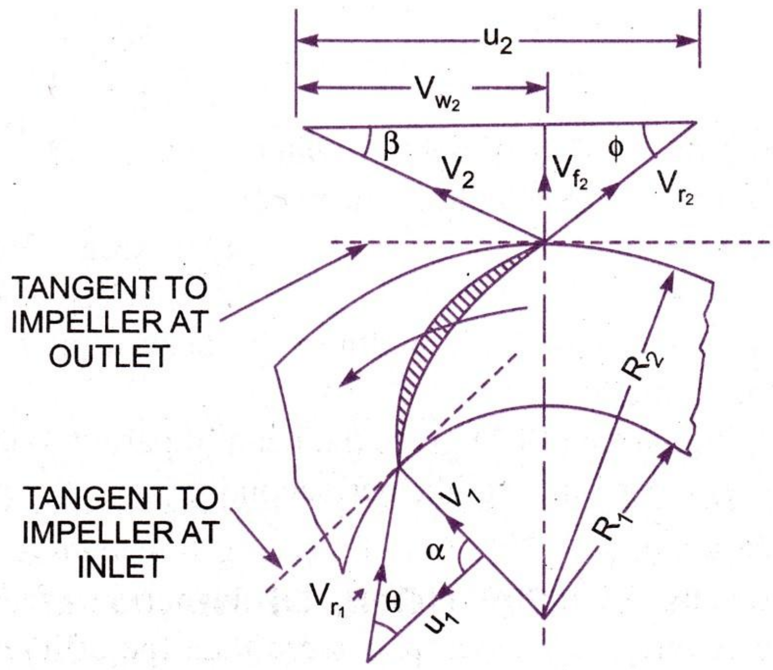



*Fig.9.3 – Velocity diagram of a centrifugal pump*

### 9.3.1 Equation of Work Done of a Centrifugal Pump

**Assumptions:**

- No energy losses due to friction and eddy formation
- No loss due to shock at entry
- Liquid enters the impeller eye in a radial direction
- Uniform velocity distribution in the passage between two adjacent vanes.

  Let,

  $N =$ Speed of the impeller in rpm.

  $D_1 =$ Diameter of the impeller at the inlet

  $D_2 =$ Diameter of the impeller at the outlet

  $u_1 =$ Tangential velocity of the impeller at the inlet $= \frac{\pi D_1 N}{60}$

  $u_2 =$ Tangential velocity of the impeller at the outlet $= \frac{\pi D_2 N}{60}$

  $V_1 =$ Absolute velocity of water at the inlet

  $V_{r1} =$ Relative velocity of water at the inlet

  $\alpha =$ Angle made by the absolute velocity at the inlet with the direction of motion of vane

  $\theta =$ Angle made by the relative velocity at the inlet with the direction of motion of vane and

  $V_2, V_{r2}, \beta\ and\ \varphi$ are corresponding values at the outlet.

- 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 sec per unit weight is given by (Refer Unit-8),

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

- Therefore, **the work done by the impeller on the water per sec per unit weight**,

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

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

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

  Now, as the water enters the impeller radially, hence $V_{w1} = 0$ and we get,

$$\therefore \boldsymbol{W_{pump} = \frac{1}{g}(V_{w2}u_2)} \qquad \textit{Eq. (9.1)}$$

  ***Eq. (9.1) gives the head imparted to the water by the impeller or energy given by impeller to water per sec per unit weight.***

- **Power or the work done by the impeller on water per sec**,

$$P_{pump} = \dot{m}(V_{w2}u_2)$$

$$\therefore P_{pump} = \rho Q(V_{w2}u_2) \qquad \textit{Eq. (9.2)}$$

Where, the discharge through the impeller is given by,

$$Q = Area\ of\ flow\ \times Velocity\ of\ flow$$

$$\therefore Q = \pi D_1 B_1 \times V_{f1} = \pi D_2 B_2 \times V_{f2} \qquad \text{Eq. (9.3)}$$

Where,

$B_1\ and\ B_2$ are the width of the impeller at the inlet and outlet respectively.

## 9.4 Definitions of Heads and Efficiencies of a Centrifugal Pump

### 9.4.1 Heads

1. **Suction Head or Suction Lift ($h_s$):**

   It is the vertical distance between the top surface of the liquid in the sump and the center of the pump impeller. (Refer to *Fig.9.1*)

2. **Discharge Head or Discharge Lift ($h_d$)**:

   The vertical distance between the center of the pump impeller and the top surface of liquid in the discharge tank.

3. **Total Static Head ($H_s$)**:

   The total static head or veritcal lift is the vertical distance between the top surface of liquid in the sump and discharge tank. It is the sum of suction and delivery lift.

   Thus, the static head may be expressed as,

$$H_s = h_s + h_d$$

   The static head is the net total vertical height through which the liquid is lifted by the pump. In addition to the static lift, the pump has to work against all the losses in suction and delivery pipes and provide the necessary kinetic energy to liquid on the discharge side.

4. **Manometric Head ($H_m$)**:

   "It is defined as the head against which a centrifugal pump has to work."

   **Or**

   "It is the total head that must be produced by the pump to satisfy the external requirements."

   It is given by the following expressions:

- The net head developed by the impeller or the energy given to the liquid by the impeller is given by,

$$H = \frac{1}{g}(V_{w2}u_2)$$

Hence, Manometric head will be less than the head developed by the impeller due to losses in the impeller and casing of the pump,

$$\therefore H_m = \frac{1}{g}(V_{w2}u_2) - loss\ of\ head\ in\ impeller\ \&\ casing \qquad \text{Eq. (9.4)}$$

$$\therefore H_m = \frac{1}{g}(V_{w2}u_2) - loss\ of\ head\ in\ impeller\ \&\ casing$$

$$\therefore H_m = \frac{1}{g}(V_{w2}u_2) \qquad (if\ losses\ are\ neglected)$$

- Manometric head is the difference of total head at the outlet and total head at the inlet of the pump.

$$\therefore H_m = \left(\frac{P_o}{\rho g} + \frac{V_o^2}{2g} + Z_o\right) - \left(\frac{P_i}{\rho g} + \frac{V_i^2}{2g} + Z_i\right) ---------(4.6)$$

- Whole of the manometric head is not used to lift the liquid against the static lift; a part of it is used to overcome the losses in the pipes and fittings and to provide the kinetic energy at delivery outlet.

  ∴ Manometric head = static head + head losses in suction and delivery pipes + velocity head in delivery pipe

$$\therefore H_m = (h_s + h_d) + (h_{fs} + h_{fd}) + \frac{V_d^2}{2g} ---------(4.7)$$

## 9.4.2 Efficiencies

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.

The followings are the important efficiencies of a centrifugal pump:

1) Manometric Efficiency
2) Mechanical Efficiency and
3) Overall Efficiency

### 1) Manometric Efficiency

It is defined as the ratio of the manometric head developed by the pump to the head imparted by the impeller to the liquid.

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

$$\therefore \eta_{man} = \frac{H_m}{\left(\frac{V_{w2}u_2}{g}\right)} = \frac{gH_m}{V_{w2}u_2} \qquad \text{Eq. (9.5)}$$

The power at the impeller of the pump is more than that of the power delivered by the liquid at the outlet of the pump due to loss of head in impeller and casing.

$$Power\ given\ by\ water\ at\ outlet\ of\ the\ pump = \frac{WH_m}{1000} = \frac{\rho gQH_m}{1000}\ kW$$

$$Power\ at\ the\ impeller = \frac{WD\ by\ the\ impeller\ per\ sec}{1000} = \frac{\rho Q(V_{w2}u_2)}{1000}\ kW$$

### 2) Mechanical Efficiency

It is defined as the ratio of the power actually delivered by the impeller to the power at the shaft of the centrifugal pump.

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

$$\therefore \boldsymbol{\eta_m = \frac{\dot{m}(V_{w2}u_2)/1000}{S.P.\ in\ kW}} \qquad \textit{Eq. (9.6)}$$

### 3) Overall Efficiency

It is defined as the ratio of power output of the pump to the power input to the pump.

- $Power\ output\ of\ the\ pump = \frac{Weight\ of\ water\ lifted \times H_m}{1000} = \frac{WH_m}{1000} = \frac{\rho g Q H_m}{1000}\ kW$
- $Power\ input\ to\ the\ pump = Shaft\ power\ of\ the\ pump = S.P.\ in\ kW$

$$\therefore \eta_o = \frac{\left(\frac{\rho g Q H_m}{1000}\right)}{S.P.\ in\ kW} \qquad \textit{Eq. (9.7)}$$

Also,

$$\therefore \eta_o = \eta_{man} \times \eta_m$$

## 9.5 Net Positive Suction Head (NPSH)

"It is defined as the total head developed at the pump inlet above the vapor pressure of the liquid."

It is also defined as the absolute pressure head at the inlet to the pump minus the vapor pressure head plus the velocity head. Thus,

$$\therefore NPSH = \frac{P_1}{\rho g} - \frac{P_v}{\rho g} + \frac{V_s^2}{2g} \qquad \textit{Eq. (9.8)}$$

Now, applying Bernoulli's equation at the free surface of liquid in the sump and at the eye of impeller i.e. in the suction pipe just at the inlet of the pump (Refer *Fig.9.1*).

Take free surface of liquid as datum line, we get,

$$\frac{P_a}{\rho g} + \frac{V_a^2}{2g} + Z_a = \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 + h_L$$

Where,

$P_a$ = Atmospheric pressure on the free surface of liquid

$V_a$ = Velocity of liquid at the free surface $\cong 0$

$Z_a$ = Height of free surface from datum line $= 0$

$P_1$ = Absolute pressure at the inlet of the pump

$V_1$ = Velocity of liquid through suction pipe $= V_s$

$Z_1$ = Height of inlet of pump from datum line $= h_s$

$h_L$ = Loss of head in foot valve, strainer and suction pipe $= h_{fs}$

$$\therefore \frac{P_a}{\rho g} + 0 + 0 = \frac{P_1}{\rho g} + \frac{V_s^2}{2g} + h_s + h_{fs}$$

$$\therefore \frac{P_1}{\rho g} = \frac{P_a}{\rho g} - \left(\frac{V_s^2}{2g} + h_s + h_{fs}\right) \quad \textit{Eq. (9.9)}$$

Introducing the value of $\frac{P_1}{\rho g}$ from *Eq. (9.9)* in the *Eq. (9.8)*, we get,

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

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

$$\therefore NPSH = \left(H_a - h_s - h_{fs}\right) - H_v \quad \textit{Eq. (9.10)}$$

In other words, NPSH may also be defined as the total head required to make the liquid to flow through the suction pipe to the impeller.

For any pump installation a distinction is made between the required NPSH and the available NPSH.

**Required NPSH**

- The value of required NPSH is given by the pump manufacturer.
- The value of required NPSH varies with the pump design, the speed of the pump, and the capacity of the pump.
- The value of required NPSH can be calculated experimentally. For determining its value, the pump is tested with different suction lifts and minimum value of $h_s$ is obtained at which the pump gives maximum efficiency without any objectional noise (i.e. Cavitation free).

**Available NPSH**

- When the pump is installed the available NPSH can be determined from the equation 4.21.
- ***In order to have Cavitation free operation of centrifugal pump, the available NPSH should be greater than the required NPSH.***

[**Note:** NPSH is a measure of how much spare pull you have before the bubbles form]

## 9.6 Priming of a Centrifugal Pump

- Before starting a centrifugal pump, the suction pipe, casing and portion of the delivery pipe up to delivery valve is completely filled with water by external source of water to remove the air from the suction pipe and casing. This is known as priming of a pump.
- The work done by the impeller per unit weight of liquid per sec is known as the head developed by an impeller.
- Head developed by the impeller is given by $\frac{u_2 V_{w2}}{g}$ meter. Since this equation is independent of the density of the liquid, the head developed will be in terms of meters of air when pump is running in the air.

- If the pump is primed with water, the head generated is same meter of water. But as the density of air is very low, the generated head of air is negligible compared to meter of water head. Hence the water may not be sucked from the pump. To avoid this difficulty, priming is necessary.

## 9.7 Characteristic Curves of Centrifugal Pump

Characteristic curves of centrifugal pumps are plotted from the results of several tests on the centrifugal pump. These curves are necessary to predict the behaviour and performance of the pump when the pump is working under different flow rate, head and speed. The followings are the important characteristic curves for pumps:

1) Main Characteristic Curves,
2) Operating Characteristic Curves and
3) Constant Efficiency or Muschel Curves.

### 1) Main Characteristic Curves

The main characteristic curves of a centrifugal pump consisting of a variation of head $(H_m)$, power and discharge to the speed.

For plotting curves of manometric head versus speed, discharge is kept constant. For plotting curves of discharge versus speed, the manometric head is kept constant and for plotting curves of power versus speed, the manometric head and discharge are kept constant.

*Fig.9.4* shows main characteristic curves of a pump.

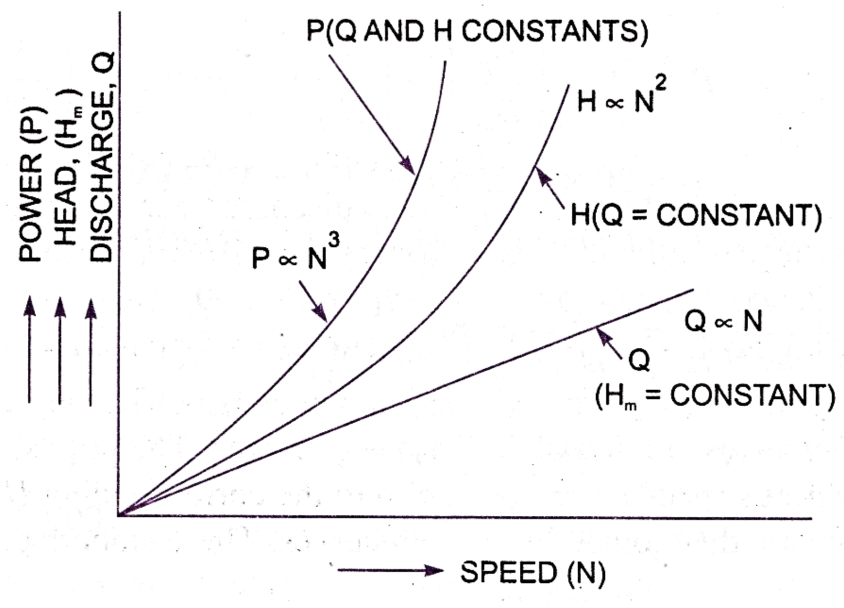



*Fig.9.4 – Main characteristic curves of a centrifugal pump*

### 2) Operating Characteristic Curves

If the speed is kept constant, the variation of the manometric head, power and efficiency to the discharge gives the operating characteristic curves of the pump. Fig. 4.8 shows the operating characteristic curves of a pump.

The input power curve for pumps shall not pass through the origin. It will be slightly away from the origin on the y-axis, as even at zero discharge some power is needed to overcome mechanical losses.

The head curve will have a maximum value of head when discharge is zero.

The output power curve will start from the origin as at $Q = 0$, output power $(\rho g Q H)$ will be zero.

The efficiency curve will start from the origin as at $Q = 0, \eta = 0$.

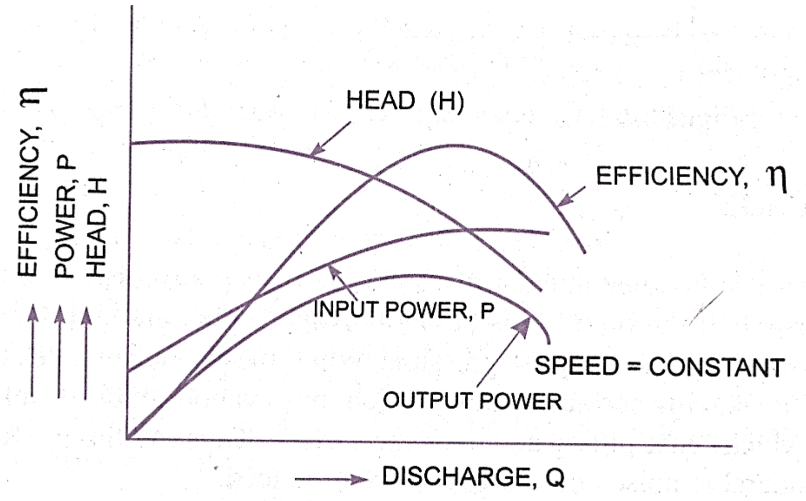



*Fig.9.5 – Operating characteristic curves of a centrifugal pump*

### 3) Constant Efficiency or Muschel Curves

For obtaining constant efficiency curves (iso-efficiency curves) for a pump, the head versus discharge curves and efficiency versus discharge curves for different speeds are used.

*Fig.9.6(a)* shows the head versus discharge curves for different speeds. The efficiency versus discharge curves for the different speeds is shown in *Fig.9.6(b)*.

By combining these curves $(H{\sim}Q\ curves\ and\ \eta{\sim}Q\ curves)$, constant efficiency curves are obtained as shown in *Fig.9.6(a)*.

For obtaining constant efficiency curves, horizontal lines representing constant efficiencies are drawn on the $\eta{\sim}Q$ curves.

The points at which these lines cut the efficiency curves at various speeds are transferred to the corresponding $H{\sim}Q$ curves.

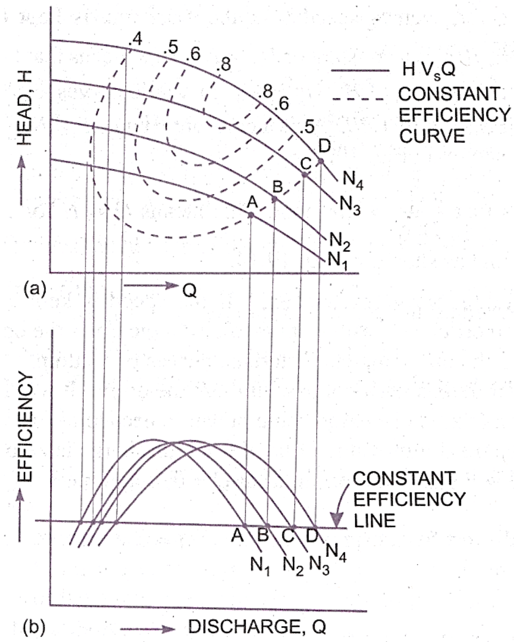



*Fig.9.6 – Constant efficiency curves*

The points having the same efficiency are then joined by smooth curves. These smooth curves represent iso-efficiency or constant efficiency curves.

## 9.8 References


1) G. S. Sawhney "Fundamentals of Fluid Mechanics", 2008, I. K. International Publishing House Pvt. Ltd.
2) Yunus A. Cengel & John M. Simbala, "Fluid Mechanics: Fundamentals & Applications", 4th Edition, 2017, McGraw-Hill Education (India) Pvt. Ltd.
3) D. S. Kumar, "Fluid Mechanics & Fluid Power Engineering", S. K. Kataria & Sons.
4) R. K. Bansal, "Fluid Mechanics & Hydraulic Machines", 3rd Edition, 2007, Laxmi Publications (P) Ltd.