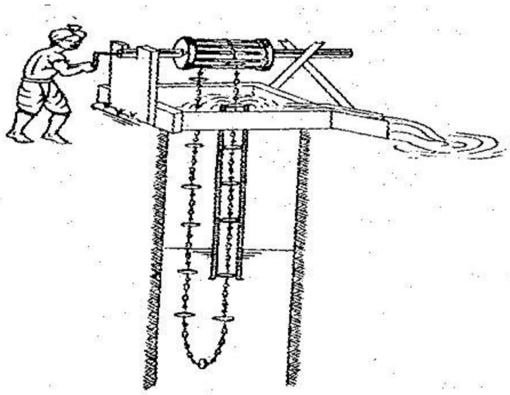


. 3.6 (a). Sketch showing the construction details
a manually operated chain pump.

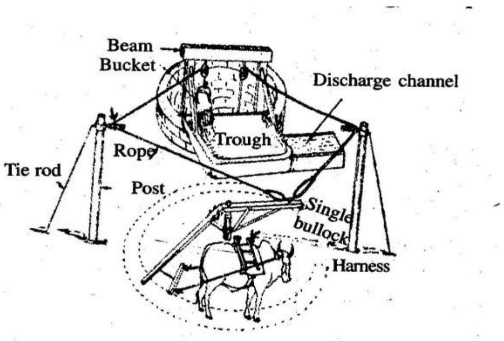


Fig. 3.8. Schematic view of the two-buckets circular lift showing the arrangement of rope and pulleys and the self-emptying bucket.

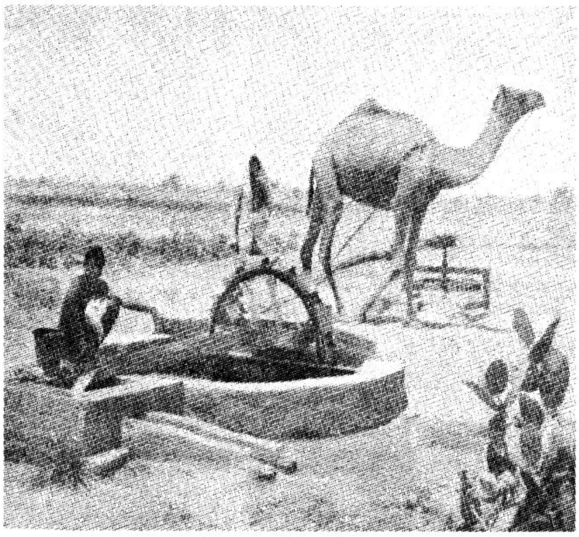


Fig. 3.5. A Persian wheel operated by a camel.

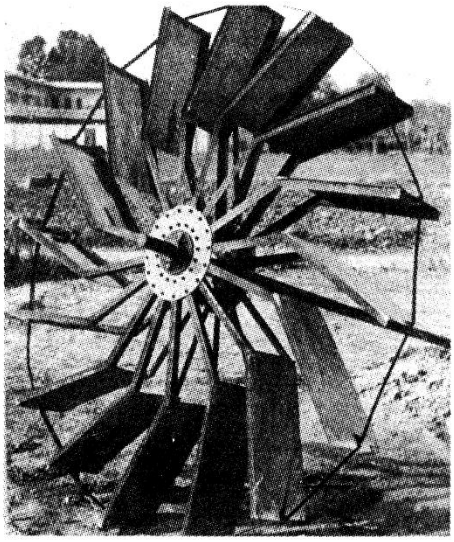


Fig. 3.4 (b). Close view showing details of construction of a water wheel.

Defining Pump

Pump can be broadly defined as 'a mechanical device to increase the pressure energy of a fluid in order to lift it from a lower to a higher elevation'. Pumps are mostly used for lifting fluids (liquids or gases) from a lower level to a higher level. This is achieved by creating a low pressure at the pump inlet or suction end and a high pressure at the pump outlet or delivery end of the pump. Thus the principle of working of a pump is distinctly different from the indigenous water lifts in which water is lifted by displacement through buckets, water wheels or screws.

Because of the low inlet pressure, the fluid rises from a depth where it is available and the high outlet pressure forces the fluid to a desired height. Here, work is done by a prime mover on the pump to enable it to impart energy to the fluid.

Classification of Pump

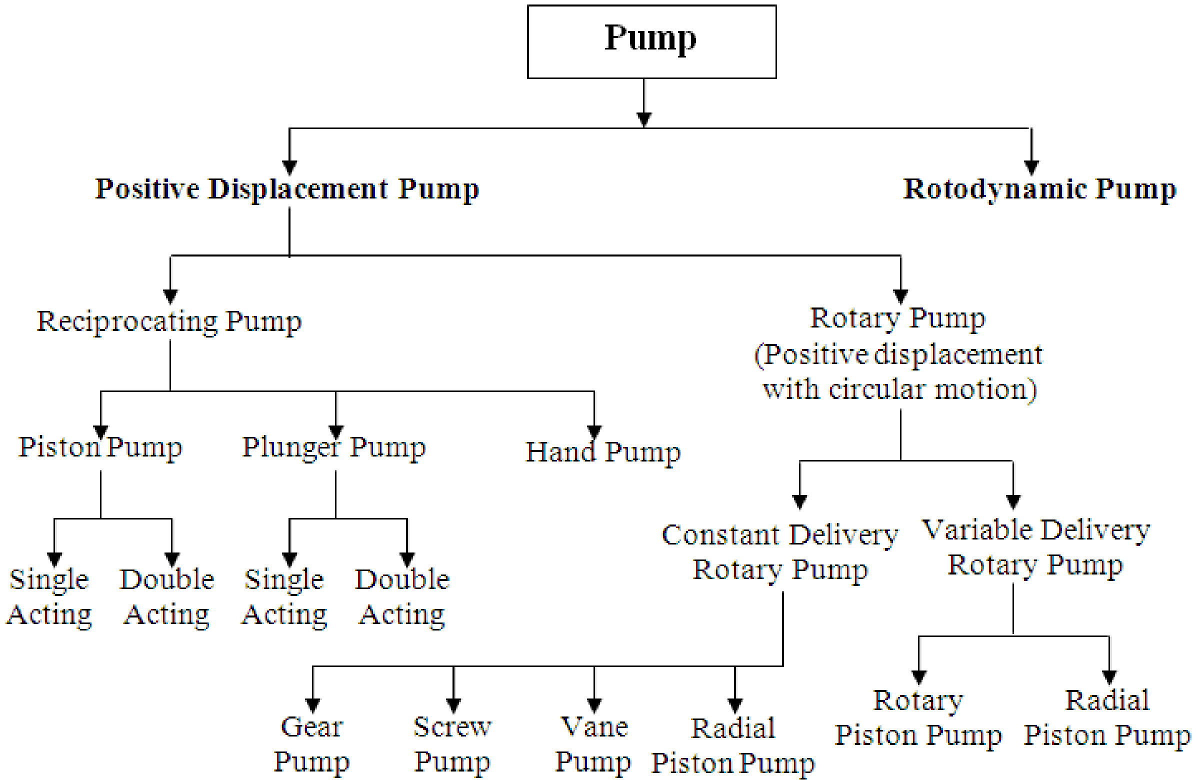


Fig. Classification of different types of pumps

Pumps are classified into two basic groups based on the method by which energy is imparted to the fluid. They are: positive displacement pumps and variable displacement pump (Roto-dynamic pumps).

POSITIVE DISPLACEMENT PUMPS

In a positive displacement pump, the fluid is physically displaced by mechanical devices such as the plunger, piston, gears cams, screws, diaphragms, vanes or other similar devices. **Positive displacement pumps discharge the same volume of water regardless of the head against which they operate.** These are the pumps in which the liquid is sucked and then it is actually pushed due to the thrust exerted on it by a moving element which results in lifting the liquid to a desired height. As such the discharge of liquid pumped by these pumps almost fully depends on the speed of the pump. The most common examples of the positive displacement pump are reciprocating pumps and rotary pumps. As the capacity is small, these pumps are not very popular in irrigation and drainage. This type of pump must be powered to meet the maximum load resulting from its discharge capacity and the greatest head under which it will operate.

The positive displacement pumps are classified into two major groups: reciprocating pumps and rotary pumps.

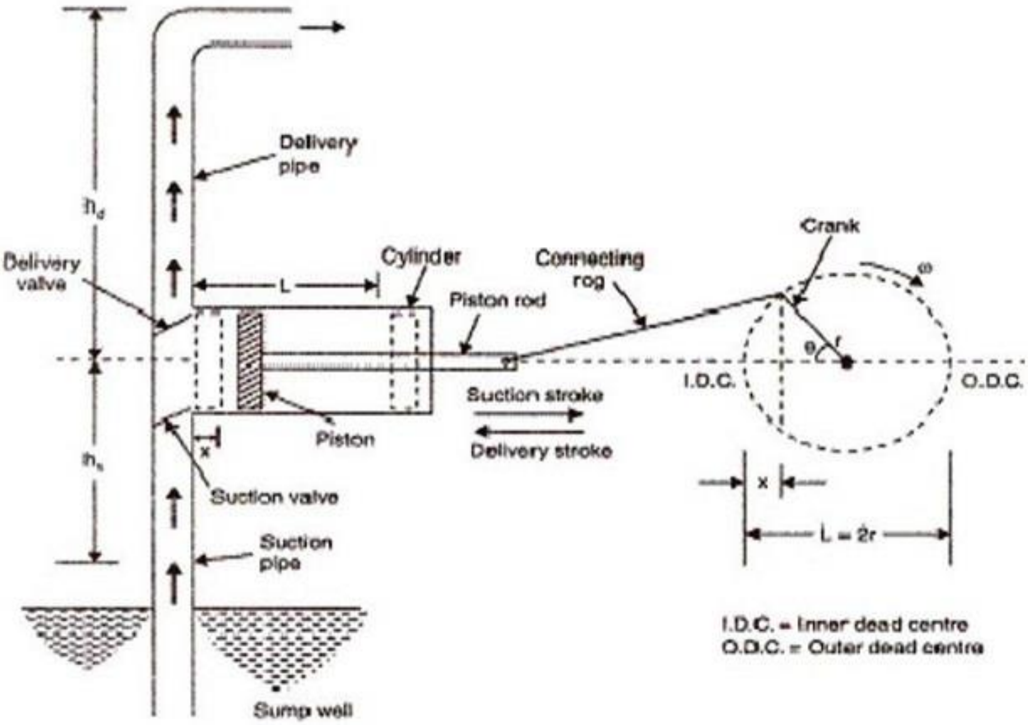
1. Reciprocating Pump

A reciprocating pump consists of a piston or plunger working in close fitting cylinder. The movement of the piston displaces the water in the cylinder. The capacity of reciprocating pumps depends on the size of the cylinder chamber and the length and speed of the piston stock.

Reciprocating type pumps are broadly classified into two types as described follows.

a) Lift pumps: These pumps are designed to pump water from the source of water to the level of pump spout only. They are used in locations where the water is to be delivered into a bucket, trough, tank or other receptacles at the pump location. They utilize atmospheric pressure to raise the water to pump column.

b) Force pumps: These pumps are designed to pump water to a higher elevation than the pump body. They are usually used to pump water from deep wells or to storage tanks in domestic water supply. They are similar in construction to lift pumps, except that they are enclosed at the top and hence can be used to force water to higher elevations.



Computation Pump discharge

1. Area swept by the pump piston, $a = (\pi/4)\, d^2$ [d=diameter of piston]
2. Volume swept per stroke, $V = a \cdot s$ [s = length of piston travel]
3. Volumetric efficiency, $\eta_{vol.}$ = % of swept volume that is actually swept
4. Discharge per stroke, $q = \eta_{vol.} \cdot V$
5. Pump discharge rate, $Q = n \cdot Q$ [n = no. of piston stroke per minute]

Force required for working a reciprocating pump

The force required to lift the piston will be the weight of the piston and pump rods plus the weight of column of water having a cross-sectional area equal to the piston and a height to the head.

Let, a = Area of cylinder (m^2)
l = length of stroke (m)
h = total height through which water is raised (m)
P = force required to lift the piston (kg)
w = specific weight of water (kg/m^3)

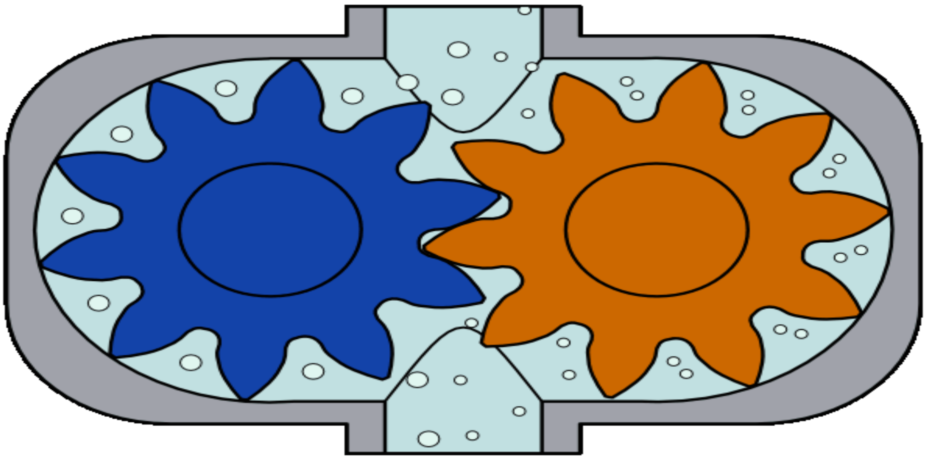
Thus weight of water raised in one stroke = $w \cdot a \cdot l = 1000 \cdot a \cdot l$
Work done in one upstroke = $1000 \cdot a \cdot l \cdot h$
Therefore, $P = 1000 \cdot a \cdot l$

2. Rotary pump

A rotary pump is a positive displacement pump with a circular motion. It has one or more rotating elements that revolve continuously within a fixed casing. It has no valves and the liquid flows through the passage in a continuous stream.

The designs commonly encountered are those using gears, cams or vanes. The given figure illustrates the construction details of a gear rotary pump. The pump body is a plain housing with inlet and outlet pipes and opening for shafts which carry the gears, cams or vanes.

In the gear pump, one of the gears is the driver which is rotated by an outside source of power. The other is the idler gear driven by the driver. The two gears are fitted closely in the housing, mesh with minimum clearance. They rotate in the direction shown, push the water between the teeth as they mesh together and force it out through the discharge opening. This creates a partial vacuum and brings in a replacement supply of water along the inlet. Such an operation creates an even, continuous flow. As in the case of reciprocating pumps, the amount of water delivered is constant, regardless of the pressure against which the pump operates. However the power requirement increases with increase in pressure and discharge.



The capacity of the gear pump depends on the speed of operation and width of gear teeth. Rotary pumps are essentially low speed pumps. They could be used to pump water from shallow water bodies requiring a minimum of suction lift. The water should be free of sand and grit, since these materials could cause considerable wear on the gear teeth. Rotary pumps work best and last long when pumping liquids having lubricating qualities.

VARIABLE DISPLACEMENT PUMP / ROTO-DYNAMIC PUMP

The distinguishing function of variable displacement pump is the **inverse relationship between the discharge rate and the pressure head.** As the pumping head increase, the rate of pumping decreases. Variable displacement pump of the impeller type including centrifugal, mixed flow and propeller pumps are predominantly used in irrigation pumping. They have a rotating element (called 'impeller') through which when the liquid passes; its angular momentum changes which results in an increase of the pressure energy of the liquid. The most common example of a variable displacement pump is centrifugal pumps.

Note that the use of reciprocating pumps has become out of date for the water supply purpose, except for some popular indigenous water lifting devices used in rural areas. **Variable pumps, especially of centrifugal type, have almost totally replaced the reciprocating pumps for lifting water**.

Centrifugal Pumps

Operating Principle of Centrifugal Pumps

A centrifugal pump is a rotary machine consisting of two basic parts – the rotary element called impellor and the stationary element called casing. The impellor is a wheel mounted on a shaft and provided with a number of vanes/blades usually curved in form. The vanes are arranged in a circular array around an inlet opening at the centre. The impellor is secured on a shaft mounted on a suitable bearing. The casing surrounds the impellor and is usually in the form of spiral or volute curve with a cross-sectional area decreasing towards the discharge opening.

A centrifugal pump may be defined as one in which an impellor rotating inside a close fitting case draws in the liquid at the centre and by virtue of centrifugal force throws out liquid through an opening at the side of the casing. The underlying hydraulic principle in the design of an impeller is the production of high velocity and the partial transformation of this velocity into pressure head.

In operation, the pump is filled with water and the impeller is rotated. The blade causes the liquid to rotate with impellor and in turn impart a high velocity to water. Centrifugal force causes it to be thrown outward from the impeller into the casing. The outward flow through the impeller reduces the pressure at the inlet, allowing more water to be drawn in through the suction pipe by atmospheric pressure. The liquid passes into the casing where the high velocity is reduced and converted into pressure and water is pumped out through the discharge pipe. The conversion of velocity energy into pressure energy is accomplished in the casing.

Components of a Centrifugal Pump

Commonly used centrifugal pumps have two basic components: a rotary element called impeller and a stationary element known as casing. Along with these two major components, it may also have some other components such as pump inlet, pump outlet, suction valve, delivery valve, priming device, foot valve with a screen and/or pressure gauge. A brief description about these components is given below.

(1) Impeller: It is a rotor, which is provided with a series of backward curved blades. It is mounted on a shaft, which is coupled to an external source of energy, which imparts the required energy to the impeller thereby making it to rotate.

(2) Casing: It is an air-tight chamber which surrounds the impeller and is usually in the form of a spiral or volute curve with a cross-sectional area increasing towards the discharge opening.

(3) Pump Inlet (Suction Port): Liquid enters through the suction port or the pump inlet and flows into the pump casing. In centrifugal volute pumps the suction ports are located axially.

(4) Pump Outlet (Delivery Port): Liquid present inside the pump casing is thrown out of the casing and exits the pump through the delivery port or pump outlet.

(5) Delivery Valve: Sometimes centrifugal pumps are fitted with a one-way valve on the delivery pipe to regulate pump discharge and/or help in priming.

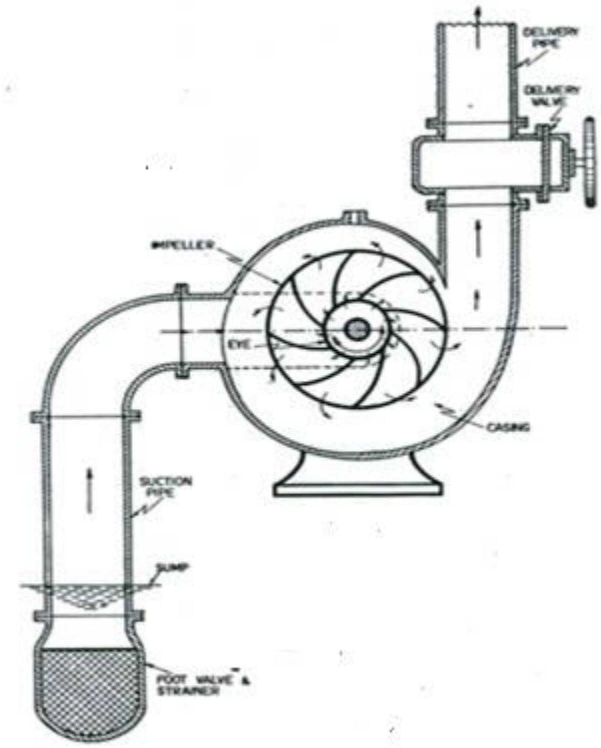


Fig. Components of a centrifugal pump.

(6) Priming Device (optional): When the pump is shut down, the liquid in it drains out of the suction line. At the bottom of the casing in a priming device, a small quantity of liquid is retained. When the pump is started again, this water is pushed by the impeller out the discharge line, along with some air. This creates a vacuum at the impeller inlet, which draws liquid up the suction line. The priming cycle continues until all of the air is pushed out. It is known as a self-priming centrifugal pump.

(7) Foot Valve with a Screen (optional): The suction side of the pump consists of foot valve at the bottom of suction line. The foot valve is a one-way valve which helps to prevent the trash from entering the suction side and at the same time retains water in the suction line to help priming of the pump.
(8) Pressure Gauges (optional): A pressure gauge on the discharge side close to the outlet of the pump helps to diagnose pump system problems. It is also useful to have a pressure gauge on the suction side; the difference in pressure is proportional to the total head.

Types of Centrifugal Pumps

Centrifugal pumps possess some characteristic features based on which they are classified. These characteristic features are as follows:

1. Working head
2. Casing design (type of energy conversion)
3. Number of impellers/ number of stages
4. Relative direction of flow through the impeller
5. Number of entrances to the impeller / type of suction inlet
6. Disposition of pump shaft
7. Split of casing (Horizontally-split casing pumps and Vertically-split casing pumps),
8. Connection of the pump to the prime mover (Close-coupled/Monoblock centrifugal pumps, and Flexible-coupled centrifugal pumps)
9. Type of impeller and
10. Specific speed of the pump.

1. Working Head

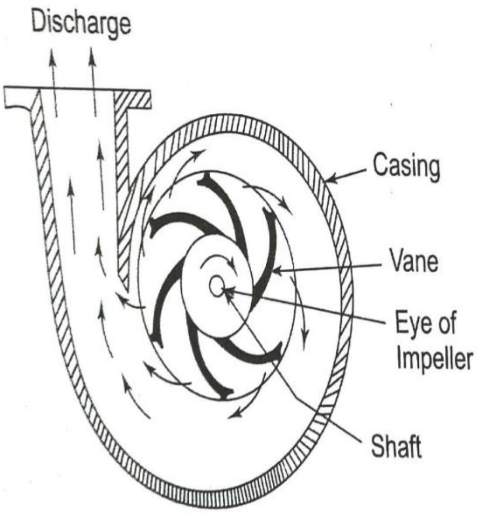
It is the head against which water is delivered by a pump. Based on the working head, centrifugal pumps could be classified as follows:
(1) Low-Head Centrifugal Pumps: They can produce heads up to 15 m. The impeller is usually surrounded by a volute and there are no guide vanes.
(2) Medium-Head Centrifugal Pumps: They are capable of generating heads as high as 40 m. They are usually provided with guide vanes. Water may enter from one or both sides depending on the quantity of water to be pumped.
(3) High-Head Centrifugal Pumps: They can generate heads greater than 40 m. They are generally multi-stage pumps because an ordinary single impeller cannot build up such a high pressure. High-head centrifugal pumps is mostly used in deep wells.

2. Casing Design

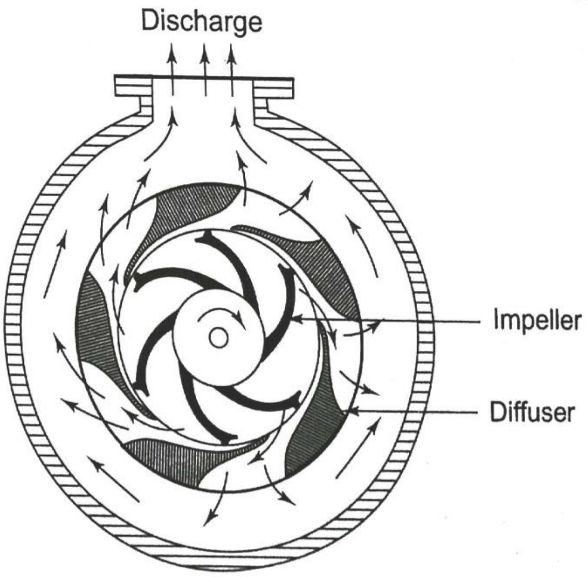
Pump casing should be so designed as to minimize the loss of kinetic head through eddy formation, etc. Efficiency of the pump largely depends on the type of casing. In general, the casings are of two types and the pump is named after the type of casing it has. They are: (i) volute pump, (ii) diffuser pump (or turbine pump). A brief description about these pump types is given below.

(i) Volute Pump: It has a volute casing (spiral shaped casing, which is known as volute chamber) into which the impeller discharges water at a high velocity. The shape of the casing is such that the cross-sectional area of the flow around the impeller periphery gradually increases from the tongue towards the delivery pipe.

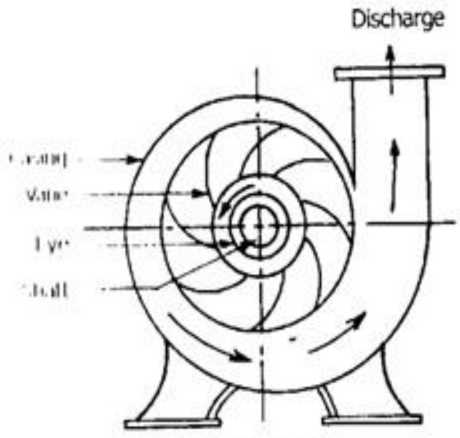
(ii) Diffuser Pump: In this pump, the impeller is surrounded by a series of 'guide vanes' (stationary vanes) or 'diffusers' mounted on a ring called 'diffuser ring'. Diffuser pump is also known as a turbine pump. Diffuser pumps may be either horizontal or vertical shaft type.



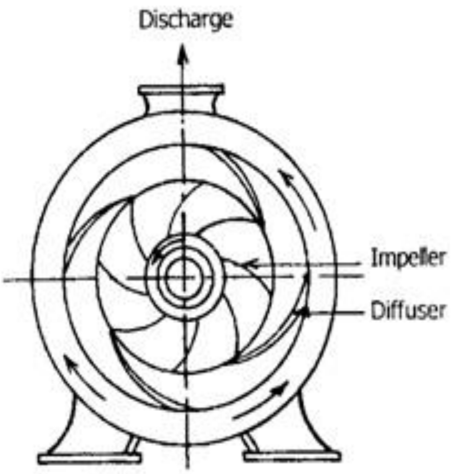
Volute type pump



Diffuser type pump



(a) Volute type



(b) Diffuser type

3. Number of Impellers

Based on the number of impellers per shaft, centrifugal pumps are classified as: (i) single-stage centrifugal pump, and (ii) multi-stage centrifugal pump. They are succinctly discussed below.

(i) Single-Stage Centrifugal Pump

Single-stage centrifugal pumps have only one impeller fitted to the pump shaft. It is usually a low-lift (low-head) pump. Vertical turbine pumps can have 1 to about 25 stages.

(ii) Multi-Stage Centrifugal Pump

Multi-stage centrifugal pumps have two or more identical impellers fitted to a single shaft and enclosed in the same casing. Thus, pressure is built up in steps. The impellers are surrounded by guide vanes and the water is led through a by-pass channel from the outlet of one stage to the entrance of the next until it is finally discharged into a wide chamber from where it is pushed on to the delivery pipe.

Multi-stage pumps are used essentially for high working heads and the number of stages depends on the head required. Usually, not more than 15 stages are employed for ordinary multi-stage centrifugal pumps. According to the number of impellers fitted to a single shaft, a multi-stage pump is designated as two-stage, three-stage, four-stage, and so on. Multi-stage vertical turbine pumps can develop heads up to about 1500 m. However, some specially designed multi-stage pumps can have a discharge up to 946 L/s and can develop heads up to about 2100 m. Remember that for a given type of impeller, the head and power requirements of a multi-stage pump increase in direct proportion to the number of stages. However, the discharge and efficiency of a multi-stage pump are almost the same as for the single-stage pump operating alone.

4. Relative Direction of Flow

On the basis of the direction of water flow through the impeller, the centrifugal pumps are classified as: (a) radial flow pump, (b) axial flow pump, and (c) mixed flow pump as shown in Figs. a, b, c.

(a) Radial Flow Pump: In this pump, liquid flows through the impeller in the radial direction only. Generally, all centrifugal pumps are manufactured with radial flow impellers.

(b) Axial Flow Pump: In this pump, the flow through the impeller is in the axial direction only. Axial flow pumps are designed to deliver very large quantities of water at relatively low heads. Thus, they are ideally suited for irrigation purposes.

(c) Mixed Flow Pump: In this pump, the liquid flows through the impeller axially as well as radially; that is there is a combination of radial flow and axial flow. A mixed flow impeller is just a modification of radial flow type enabling it to pump a large quantity of water. As such, mixed flow pumps are generally used where a large quantity of liquid is to be discharged at a low head. In older designs, a large quantity of water was delivered by running several pumps in parallel, but this arrangement is now obsolete.

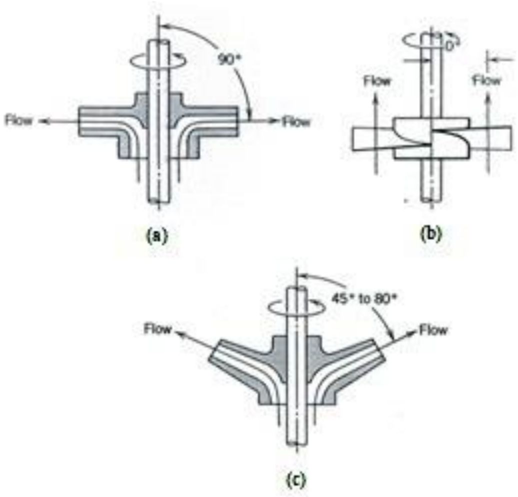


Fig. (a) Radial flow pump; (b) Axial flow pump; (c) Mixed flow pump.

5. Number of Entrances to the Impeller

Based on the number of entrances to the impeller, the centrifugal pumps are classified as: (i) single suction (entry) pump, and (ii) double suction (entry) pump.

In the single suction pump, water from a suction pipe enters into the impeller from one side of the impeller only. However, in a double suction pump, water enters into the impeller from both sides of the impeller. The double suction centrifugal pump is suitable for pumping large quantities of liquid, because it provides a larger inlet area. The provision of double suction/entry has an added advantage that the axial thrust on the impeller is neutralized.

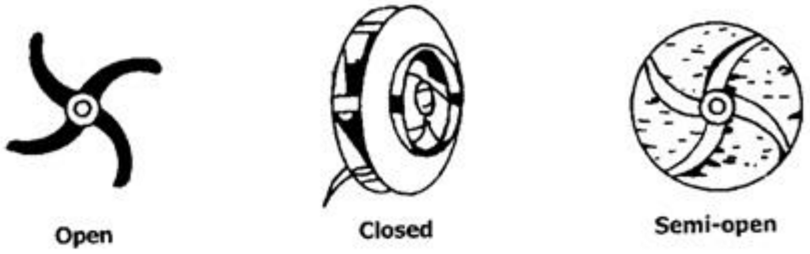
6. Disposition of Shaft

The shaft of a centrifugal pump can be disposed horizontally or vertically, and accordingly the centrifugal pump is called a horizontal centrifugal pump or vertical centrifugal pump.

Normally, centrifugal pumps are designed with horizontal shafts and impellers are mounted vertically on the shafts. They are most commonly used for irrigation. Vertical centrifugal pumps have vertical shafts and impellers are mounted horizontally on the shafts. Vertical disposition of the shaft provides an economy in space occupied, and hence vertical pumps are suitable for deep wells, mines, etc. They can also be used for irrigation purposes.

7. Type of Impeller

Depending on the type and viscosity of liquid to be pumped, the pump may have a closed, semi-open, or open impeller [Figs. (a, b, c)]; accordingly the centrifugal pumps are classified as: (i) closed impeller pump, (ii) semi-open impeller pump, and (iii) open impeller pump.



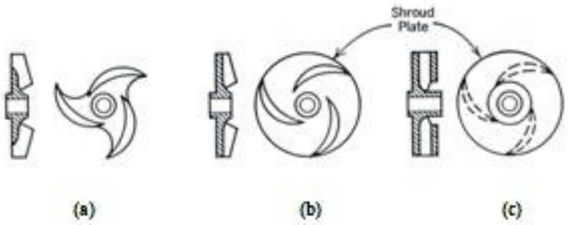


Fig. Types of centrifugal pumps based on type of impeller: (a) Closed impeller pump; (b) Semi-open impeller pump; (c) Open impeller pump

(i) Closed Impeller Pump

Closed impeller pumps have shrouded impellers. Shrouded or closed impeller is the one in which the vanes are covered with metal plates (also called ‘shrouds’) on both sides. These plates/shrouds are known as crown plate (i.e., top plate) and base plate (i.e., bottom plate). The closed impeller provides better guidance for the liquid and is the most efficient. However, *this type of impeller is most suited when the liquid to be pumped is free from debris and other such impurities. That is, the closed impeller is meant for handling non-viscous liquids such as ordinary water, hot water, hot oil and chemicals like acids, etc.*

(ii) Semi-Open Impeller Pump

This type of pump is equipped with an impeller having a shroud on one side only, i.e., the vanes have only the base plate and there is no crown plate. It is used for viscous liquids such as sewage water, paper pulp, sugar molasses, etc.

(iii) Open Impeller Pump

Open impeller pumps have the impellers which are not provided with any shroud. The vanes are attached to a central hub. These are used in dredgers and elsewhere for handling a mixture of water, sand, clay and pebbles, wherein the solid contents may be as high as 25%. The open impeller is meant for performing very rough duty. It is generally made of forged steel.

8. Specific Speed

The specific speed is a sound basis for a technical classification of centrifugal pumps. It is the only characteristic index of a pump when several impellers can be used for the same head and capacity. It should be noted that the performance and dimensional proportions of pumps having same specific speed will be the same even though their outside diameters and actual operating speeds may vary.

Definition: Specific speed of a centrifugal pump is defined as the speed of a geometrically similar pump when delivering 1 litre/sec. against a head of 1 meter. The pump should be single stage and single suction. The most commonly adopted expression for the specific speed of pumps is:

$$N_s = N\frac{Q^{\frac{1}{2}}}{H^{\frac{3}{4}}}$$

Where, N = speed of the pump (rpm), Q = discharge of the pump (L/s), and H = total dynamic head (m).

Here, note that the values of Q and H to be used in above Eqn. for the purpose of calculating specific speed (N_S) are those corresponding to the maximum efficiency of the pump at its normal working speed. Furthermore, for a multi-stage pump, the value of H to be used for the calculation of N_s is obtained by dividing the actual head developed with the number of stages. Similarly, the value of Q for a double-suction pump is taken as half the actual discharge delivered by the pump.

3.2 POWER REQUIREMENTS AND EFFICIENCY OF CENTRIFUGAL PUMPS

Calculation of Power Requirement for a Pumping System

Power requirements for a pumping system can be calculated for a given pump installation. Power of a pumping system can be classified into four classes:

1. Water Horse Power (WHP)
2. Shaft Horse Power (SHP)
3. Brake Horse Power (BHP)
4. Input Power (IP)

They are described in the subsequent sub-sections.

1. Water Horse Power (Water Horse Power)

Water power is the theoretical power required for pumping. It is the power required by a pump in lifting a given quantity of water in a unit time assuming no losses of power in the pump. The water power (WP) of a pump can be calculated using the following equation:

$$WHP = \frac{Q\ X\ H}{76}$$

Where, WHP = water power (W), Q = discharge of the pump (litre/sec), and H = total head or total dynamic head (m).

OR

$$WHP = \frac{Q\ X\ H}{273}$$

Where, Q = discharge of the pump (m^3/hr)

Shaft Power (Shaft Horse Power)

Shaft power is the power required at the pump shaft. It takes into account the loss of power in the pump. Shaft power (SP) of a pump can be computed using the following equation:

$$SHP = \frac{WHP}{\eta_{Pump}}$$

Where, η_{Pump} is the overall efficiency of the pump (in fraction) and the remaining symbols have the same meaning as defined earlier.

2. Brake Power (Brake Horse Power)

It is the actual power to be supplied by the prime mover (engine or electric motor) for driving a pump. When there is direct drive from an engine or electric motor to the pump, the brake power is equal to the shaft power. In this case, the drive efficiency is assumed to be 100%. However, if belt or other indirect drives are used to run a pump, the brake power (BP) needs to be computed. Brake power (BP) can be calculated as:

$$BHP = \frac{WHP}{\eta_{Pump}\, X\, \eta_{Drive}}$$

Where, η_{Drive} is the efficiency of the drive (in fraction) and the remaining symbols having the same meaning as defined earlier.

3. Input Power (Input Horse Power)

Input power (IP) of a pump is defined as the ratio of brake power to the efficiency of the motor or engine used for driving the pump. Mathematically, it is expressed as:

$$IHP = \frac{BHP\ X\ 0.746}{\eta_{Motor}} \text{ watt}$$

Where, η_{Motor} is the efficiency of the motor or engine (in fraction).

4. Energy Consumption by a Pump

The energy consumption by a pump can be calculated as follows:

Energy Consumption = Input Horse Power × Hours of Pump Operation

Illustrative Example

Problem (Michael et al., 2008): A pump lifts 100,000 litres of water per hour against a total head of 20 m. Calculate water power of the pump. If the pump has an efficiency of 75%, what size of prime mover is required to operate the pump? If a direct drive electric motor with an efficiency of 80% is used to operate the pump, compute the cost of electric energy in a month of 30 days. Assume that the pump is operated for 12 hours per day for 30 days and that the cost of electricity is Rs 5.00 per Unit.

Solution: From the question, we have: Discharge of the pump (Q) = 100,000 L = 0.028 m^3/s,

Total head (H) = 20 m, Efficiency of the pump () = 75%, Efficiency of the motor = 80%, and Cost of electricity = Rs 5.00/Unit.

Water Power, WP = $\gamma \times Q \times H = 9.815 \times 0.028 \times 20 = 5.49$ KW, Ans. [note: 1 hp = 0.746 watt]

Shaft Power, $SP = \frac{WP}{\eta_{pump}} = \frac{5493.6}{0.75}$ = 7.32 KW, Ans.

Note that since direct drive is used to operate the pump, the shaft power determines the required size of the prime mover.

Now, Input Power, $IP = \frac{BP}{\eta_{motor}} = \frac{7324.8}{0.80}$ = 9.156 KW

Total energy consumption per month = Input Power × Hours of Pump Operation
= 9.156 × 12 × 30
= 3296.16 Kilowatt-hours (kWh)

As we know that 1 kWh is equal to 1 Unit, therefore, the cost of electric energy = Rs. (3296.16 × 5) = Rs. 16480.80, Ans.

EFFECT OF SPEED AND IMPELLER DIAMETER ON PUMP PERFORMANCE

Introduction

As we know that the total head, discharge and power of a centrifugal pump are related to the size and speed of its impeller. Changing the size or speed of an impeller significantly affects the operational characteristics of a centrifugal pump. Therefore, such knowledge allows the pump manufacturers and/or users to modify the performance of a single pump so as to match the system need or understand the pump performance under different operating conditions.

Affinity Laws: The mathematical relationships of total head, discharge and power with the pump speed and with the impeller diameter are known as affinity laws.

A) Effect of Changes in Pump Speed on the Pump Performance

When the speed of a centrifugal pump is changed, the operation of the pump is changed as follows,

1. The capacity varies directly as the speed.
2. The head varies as the square of speed.
3. The break horse power varies as the cube of the speed.

It can expressed mathematically as,

$$Q = Q_1 \frac{n}{n_1}$$

$$H = H_1\left(\frac{n}{n_1}\right)^2$$

$$P = P_1\left(\frac{n}{n_1}\right)^3$$

Or

$$\frac{n}{n_1} = \frac{Q}{Q_1} = \sqrt{\frac{H}{H_1}} = \sqrt[3]{\frac{P}{P_1}}$$

in which, n = new desired speed;
Q = capacity at desired speed n (lit/s.);
H = head at desired speed n for capacity Q;
P = BHP sat the desired speed n at H and Q;
N_1 = speed at characteristics are known;
Q_1 = capacity at speed N1;
H_1 = head at capacity Q1 and speed n1;
P_1 = BHP at speed n1 at H1 and Q1.

B) Effect of Changes in impeller diameter on the Pump Performance

Changing the impeller diameter has the same effect on the pump performance as changing the speed. Therefore the following relationships apply.

1. The capacity varies directly as the diameter.
2. The head varies as the square of diameter.
3. The break horse power varies as the cube of the diameter.

It can expressed mathematically as,

$$Q = Q_1\frac{D}{D_1}$$

$$H = H_1\left(\frac{D}{D_1}\right)^2$$

$$P = P_1\left(\frac{Dn}{D_1}\right)^3$$

or

$$\frac{D}{D_1} = \frac{Q}{Q_1} = \sqrt{\frac{H}{H_1}} = \sqrt[3]{\frac{P}{P_1}}$$

In which, D = changed diameter of impeller (mm)
D_1 = Original diameter of impellor (mm)

When pumps are driven by belts, it is possible to change the operating speed. Many pumps are directly coupled to electric motor and must run at constant speed. In this case, it is necessary to change the impeller diameter to alter the pump performance.

If changes are made to both impeller diameter and pump speed, the equations can be combined as

$$Q = Q_1 \left(\frac{D \text{ x } n}{D_1 \text{ x } n_1} \right)$$

Illustrative Example

Problem: A centrifugal pump requires 5 kW power when it runs at 1450 rpm and delivers water against a head of 10 m. If the pump is operated at 1750 rpm, calculate the head developed and the power required by the pump.

Solution: From the question, N_1 = 1450 rpm, N_2 = 1750 rpm, H_1 = 10 m, and P_1 = 5 kW. The head developed by the pump (H_2) and the power required (P_2) at 1750 rpm can be calculated by using the Affinity Law I.

From the Affinity Law I, we have:

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2} \right)^2$$

$$\therefore \quad H_2 = H_1 \times \left(\frac{N_2}{N_1} \right)^2$$

$$= 10 \times \left(\frac{1750}{1450} \right)^2$$

= 14.57 m, Ans.

Also, from the Affinity Law I we have:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2} \right)^3$$

$$\therefore \quad P_2 = P_1 \times \left(\frac{N_2}{N_1} \right)^3$$

$$= 5 \times \left(\frac{1750}{1450} \right)^3$$

= 8.79 kW, Ans.

SELECTION OF SUITABLE PUMP

A variety of pumps (centrifugal and other types) and their different models are manufactured by a large number of manufacturers in almost every country. These pumps are available in a wide range of sizes and have widely varying characteristics. Therefore, a proper selection of pump for a given purpose is necessary. A properly selected pump not only effectively meet the desired water demand but also operates efficiently, thereby enhancing its service life and minimizing OMR (operation, maintenance and replacement) costs.

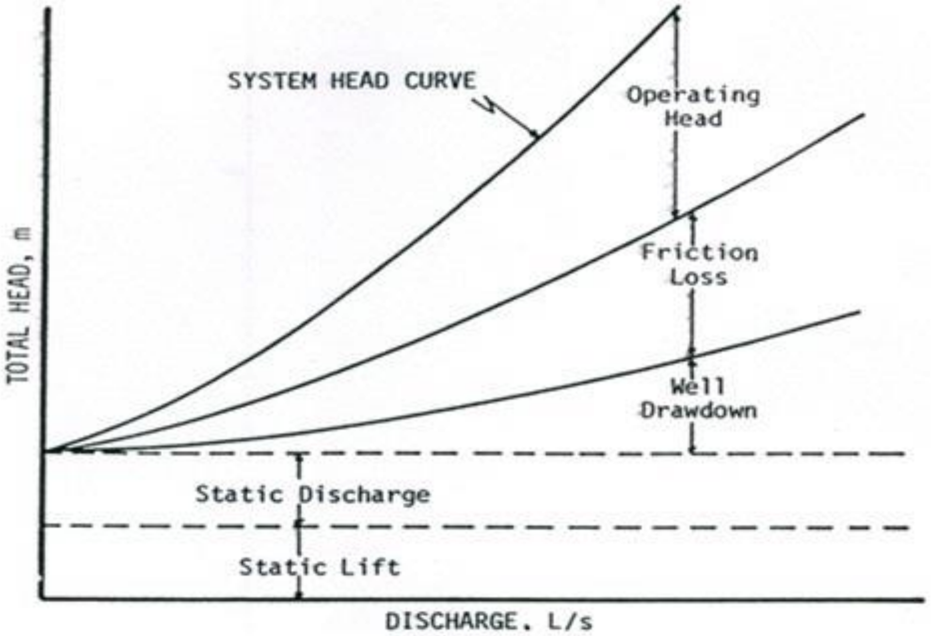
The information required for selecting a suitable pump is:

1) Total head (system head curve).
2) Design discharge.
3) Pump characteristic curves.

1) Total head

The total pumping head (total head) is the energy imparted to the water by the pump. The energy in pumping is often expressed in units of length.

System head curve (Fig.) is a relationship between total head and discharge for a given pumping system and it illustrates how the total head varies with an increase in discharge. It essentially describes the head-discharge (H-Q) requirements of a pumping system. It indicates that the more head is required to increase flow (discharge) through the system.



A typical ‘system head curve’ with its different components

System head curves are developed by computing the total head required by a pumping system to deliver different discharges. The following equation, which shows different head components contributing to the system head curve, is used to calculate system head (SH) or total head for a pumping system:

$$SH = h_s + h_d + h_f + S_w + h_0 + \frac{v^2}{2g}$$

Where, h_s = static suction head,

h_d = static delivery head,

h_f = friction head losses (major and minor),
s_w = drawdown during pumping,
h_o = operating head and
$v^2/2g$ = velocity head.

Practically, there could be two situations in pumping, 1) The free surface of the source of water supply below the centre line of pump and 2) It is above the centre line of the pump i. e. submersible pump, turbine pump etc. The various terms used in designating pressure heads in pumping sets are defined below.

1. Pump capacity: volume of water pumped per unit time (litre/sec.)
2. Suction **lift**: it exists when **source of water supply is below the centre line of the pump**.
    A) Static suction **lift** (L_{ss}): it is the vertical distance from the free suction water level to the centre line of pump.
    B) Total suction **lift** (L_{ts}): It is the **sum** of static suction lift, friction and entrance losses in the suction piping (h_{fs}).
    $L_{ts} = L_{ss} + L_{fs}$ [L_{fs} = Friction and Entrance Losses]
3. Suction **head:** It exists when **source of water supply is above the centreline of the pump**.
    A) Static suction **head** (H_{ss}): It is the vertical distance from the centre line of the pump to the free level of water surface to be pumped.
    B) Total suction **head** (H_{ts}): It is the vertical distance from the centre line of the pump to the free level of the liquid to be pumped **minus** all friction losses in suction pipe and fitting plus any pressure head existing on the suction supply.
    $H_{ts} = H_{ss} - H_{fs}$ [L_{fs} = Friction and Entrance Losses]

4. **Discharge head:**
    A) Static discharge head: It is the vertical distance from the centre line of pump to the discharge water level.
    B) Total discharge head: it is the sum of static discharge head, friction and losses exist in the discharge piping plus the velocity head and pressure head at the point of discharge.
5. Total static head: It is the vertical distance from suction water level to discharge water level
    a) It is the sum of static suction lift and static discharge head, if source of water supply is below the centre line of the pump (static suction lift exists) OR
    b) It is the static discharge head minus static suction head, if source of water supply is above the centre line of the pump (static suction head exists).
6. Total head: It is the energy imparted to water by the pump.
    a) It is the sum of total discharge head and total suction lift, if suction lift exists.
    b) It is total discharge head minus suction head, if suction head exist.
7. Friction head: It is the head required to overcome the resistance to flow in the pipe and fittings. It is dependent upon the size and type of pipe flow rate, and nature of the liquid.

It is the equivalent head, expressed in meters of water required to overcome the friction caused by the flow through the pipe and pipe fittings.

8. Pressure head: pressure head must be considered when a pumping system either begins or terminates in a tank which is under some pressure other than atmospheric. The pressure in such a tank must first be converted to feet of liquid. A vacuum in the suction tank or a positive pressure in the discharge tank must be added to the system head, whereas a positive pressure in the suction tank or vacuum in the discharge tank would be subtracted. It is the pressure expresses in meters of water in a closed vessel from which the pump takes its suction. It is expressed as,

$$H_p = \frac{p}{w}$$

Where, H_p = Pressure head (m); p = pressure inside vessel (kg/m^2); w = Specific weight of water (kg/m^3).

9. Velocity head: velocity head is the energy of a liquid as a result of its motion at some velocity. It is the equivalent head through which the water would *have to fall to acquire the same velocity*, or in other words, the *head necessary to accelerate the water.* It is the pressure required to create the velocity of flow. It is expressed as,

$$H_v = \frac{v^2}{2g}$$

Where, H_v = velocity head (m); v = velocity of water through pipe (m/sec); g = acceleration due to gravity (m/sec^2).

The velocity head is usually insignificant and can be ignored in most high head systems. However, it can be a large factor and must be considered in low head systems.

The above forms of head, namely static, friction, velocity, and pressure are combined to make up the total system head at any particular flow rate.

10. Net Positive Suction Head (NPSH):

In case of centrifugal pumps, installed above the water level, certain amount of energy is required to move the water into the eye of the impeller. The source of energy available for this purpose is the atmospheric pressure. The maximum suction lift of centrifugal pumps is dependent upon the atmospheric pressure.

NPSH is the total suction head determined at the suction nozzle minus vapour pressure of water at the pumping temperature.

In pumping of liquids, the pressure at any point in the suction line must not be reduced to the vapour pressure of a liquid. The vapour pressure of a liquid at any given temperature is that pressure at which it will vaporise if heat is added to the liquid. In other words, vapour pressure is the pressure required to boil a liquid at a given temperature. Water will not boil at room temperature since its vapour pressure is lower than the surrounding a pressure. But, raise the water's temperature 100°C and the vapours are released because at that increased temperature the vapour pressure is greater than the atmospheric pressure.

If sufficient energy is not present on the suction side of the pump to move the water into the eye of impeller, the liquid will vaporize and cavitation will occur. Cavitation could move metal particles, cause severe vibrations and damage the functioning of the pump. Pump cavitation occurs when the pressure in the pump inlet drops below the vapour pressure of the liquid.

The vapour pressure in a fluid depends on the temperature. Water, our most common fluid, starts boiling at 20 ^{o}C if the absolute pressure is 2.3 kN/m^2. For an absolute pressure of 47.5 kN/m^2 the water starts boiling at 80 ^{o}C. At an absolute pressure of 101.3 kN/m^2 ***(normal atmosphere)*** the boiling starts at 100 ^{o}C.

Cavitation refers to the localised formation and collapse of bubbles in a liquid. Bubbles can form when the local pressure at a point falls below the vapour pressure of the liquid, although they can also form at rather higher pressure due to dissolved gases coming out of solution. Cavitation means the process where the local absolute pressure of the fluid drops below the vapour pressure of the fluid and vapour bubbles are formed. Impeller inlet region is more prone to cavitation since the lowest pressure appears there.

i) Net Positive Suction Head Available: The absolute pressure at the suction port of the pump.

ii) Net Positive Suction Head Required: The minimum pressure *required at the suction port* of the pump to keep the pump from cavitations. In other words, the amount of energy required *to move the water into the eye* of impeller is referred as NPSHR. It is a function of the pump speed, impeller shape, liquid properties and discharge rate.

NPSHA must be greater than NPSHR for the pump system to operate without cavitations. Put another way, you must have more suction side pressure available than the pump requires. In order to satisfy this condition, the pump may have to be lowered towards the water surface or the suction pipe could be changed to reduce the friction loss. If NPSHA is less than NPSHR, driving energy is not sufficient to requirement, air and water will be pumped together which will damage the pump.

The formula for calculating NPSH$_A$:

$$NPSH_A = H_A \pm H_Z - H_F + H_V - H_{VP}$$

Term	Definition	Notes
H_A	The absolute pressure on the surface of the liquid in the supply tank	• Typically atmospheric pressure (vented supply tank), but can be different for closed tanks. • Don't forget that altitude affects atmospheric pressure (HA in Denver, CO will be lower than in Miami, FL). • Always positive (may be low, but even vacuum vessels are at a positive absolute pressure)
H_Z	The vertical distance between the surface of the liquid in the supply tank and the centerline of the pump	• Can be positive when liquid level is **above** the centerline of the pump (called static head) • Can be negative when liquid level is **below** the centerline of the pump (called suction lift) • Always be sure to use the lowest liquid level allowed in the tank.
H_F	Friction losses in the suction piping	• Piping and fittings act as a restriction, working against liquid as it flows towards the pump inlet.
H_V	Velocity head at the pump suction port	• Often not included as it's normally quite small.
H_{VP}	Absolute vapor pressure of the liquid at the pumping temperature	• Must be subtracted in the end to make sure that the inlet pressure stays above the vapor pressure. • Remember, as temperature goes up, so does the vapor pressure.

11. Maximum practical suction lift: For the operation of a centrifugal pump without cavitations, the suction lift plus all other losses must be less than the theoretical atmospheric pressure. The maximum practical suction lift can be computed by the equation,

$$H_s = H_a - H_f - e_s - NPSH - F_s$$

Where, H_s = Maximum practical suction lift;
H_a = Atmospheric pressure at water surface;
H_f = Friction losses in the strainer, pipe, fitting and valves on the suction line (m);
e_s = Saturated vapour pressure of water (m);
NPSH = Net positive suction head *at the suction port* of the pump.
F_s = Factor of safety, which is usually taken as about 0.6 m.

Assignment-3: What is Head?

Calculations of Friction Head Losses

Head losses due to friction are known as friction head losses, which constitute significant components of the total pumping head for a particular pumping system.

Friction head losses are classified as:

(a) Major friction head losses: Major friction head losses are defined as the friction head losses due to the roughness of the inner surface of pipe-network, and the viscosity and density of the flowing fluid.

(b) Minor friction head losses: Minor friction head losses are defined as the head losses due to pipe fittings, bends, entry and exit, sudden expansion and contraction, valves, screen, and so on.

The major friction head losses (h_f) in the suction and delivery pipes of a pumping system can be calculated by the Darcy-Weisbach equation, which is given as:

$$h_f = \frac{fL\,v^2}{2gd}$$

Where, f = friction factor (its value is usually obtained from the Moody diagram), L = length of the pipe, v = velocity of flow, d = inside diameter of the pipe, and g = acceleration due to gravity.

Moreover, minor friction head losses can be calculated with the help of standard tables. The sum of major and minor friction head losses constitutes the ‘total friction head losses’. Generally, the value of major friction head losses is much higher than that of minor friction head losses, and hence the minor friction head losses are often neglected while computing the total head of a pumping system (i.e., TDH). However, if the value of minor friction head losses is significantly large, they must not be neglected during the calculation of pumping head (TDH).

2. Design Discharge

The discharge of the pump used for irrigation should meet the peak demand of water for a given cropping pattern. The rate of pumping (pump discharge) depends on the area under different crops, water requirements of the crops, irrigation interval and the duration of pump operation in a day. Hence, the design discharge or capacity of an irrigation pump can be calculated as :

$$Q = \frac{27.78}{t_p} \sum_{i=1}^{n} \frac{A_i d_i}{t_i}$$

Where, Q = design discharge of the pump (L/s); A_i = area under the i^{th} crop (ha); d_i = depth of irrigation for the i^{th} crop (cm); t_i = irrigation interval (day); and t_p= duration of pumping (hr/day).

3. Characteristic Curves of Centrifugal Pumps

A pump is usually designed for one speed, flow rate and head, but in actual practice the operation may be at some other condition of head or flow rate, and for the changed conditions the behaviour of the pump may be quite different. For instance, if the flow through the pump is less than the designed quantity, the magnitude of flow velocity through the impeller will be changed, thereby changing the head developed by the pump, and at the same time the losses will increase so that the efficiency of the pump will be lowered. Therefore, in order to predict the behaviour and performance of a pump under varying conditions, pump tests are performed, and the results of the tests are plotted. The curves thus obtained are known as the 'characteristics curves' of the pump.

Most pump manufacturers have their own pump testing laboratories. They normally publish a set of characteristic curves for each pump model manufactured by them. These curves are developed by testing several pumps of a specific model.

Defining Pump Characteristic Curves

The pump characteristic curves can be defined as 'the graphical representation of a particular pump's behaviour and performance under different operating conditions'.

The operating properties of a pump are established by the geometry and dimensions of the pump's impeller and casing. Curves relating total head, efficiency, power, and net positive suction head (NPSH) to discharge or pump capacity (Q) are utilized to describe the operating properties (characteristics) of a pump. This set of four curves is known as the pump characteristic curves or pump performance curves.

Classification of Pump Characteristic Curves

Pump characteristics curves can be classified into four groups:

1. Main characteristic curves,
2. Operating characteristic curves
3. Constant efficiency curves
4. Constant head and constant discharge curves.

Each group characterizes one aspect of the pump's performance. They are described in subsequent sections.

1. Main Characteristic Curves

The pump is usually designed to run at the same speed as the driving unit (i.e., prime mover), which is generally an electric motor of the AC induction type. When the electric power is not available, the pump may be driven by a diesel engine, or may be coupled to the tractor engine. In such circumstances, it is necessary to know the performance of a pump at different speeds, which can be best seen from the main characteristic curves of a pump.

In order to obtain the main characteristic curves of a pump, it is operated at different speeds. For each speed, the pump discharge (Q) is varied by means of a delivery valve and for the different values of Q, the corresponding values of Manometric head - H_m (total head) , shaft power (SP) and overall efficiency - h_o (overall pump efficiency) are measured or calculated. Thereafter, H_m vs Q; SP vs Q, and h_o vs Q curves for different speeds are plotted as shown in Fig., which represent the main characteristics of a pump. Clearly, these curves are useful in indicating the performance of a pump at different speeds.