Centrifugal Pump Fundamentals

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CONTENTS

1. THE ACTION OF PUMPING

1.1 What does a pump do?

*Please note that the primary purpose of a pump is to generate flow and **NOT** pressure (or head). Pressure is just an indication of the amount of resistance to flow*

A pump is a device used to move fluids, such as gases, liquids or slurries through pipelines from one reservoir, tank or vessel to another. A pump displaces a volume by physical or mechanical action. One common misconception about pumps is the thought that they create pressure. Pumps alone do not create pressure; they only displace fluid, causing a flow. Adding resistance to flow causes pressure to be developed. The primary purpose of any pump is to generate the desired flow rate and the pressure or head helps in delivering the flow.

1.2 Pump types based on action

Based on how the pumping action is achieved, pumps are classified in two types: **positive displacement pumps** and **rotodynamic pumps**.

1.2.1 Positive Displacement Pumps

A positive displacement pump causes a fluid to move by trapping a fixed amount of it then forcing (displacing) that trapped volume into the discharge pipe.

1.2.2 Rotodynamic (Centrifugal) Pumps

Rotodynamic (Centrifugal) pumps are those in which kinetic energy is added to the fluid by increasing the flow velocity (by an impeller). This increase in energy is converted to a gain in potential energy (pressure / head) when the velocity is reduced prior to or as the flow exits the pump into the discharge pipe. This conversion of kinetic energy to pressure can be explained by the First law of thermodynamics or more specifically by Bernoulli's principle for incompressible liquids.

One practical difference between dynamic and positive displacement pumps is their ability to operate under closed valve conditions. Positive displacement pumps physically displace the fluid; hence closing a valve downstream of a positive displacement pump will result in a continual build up in pressure resulting in mechanical failure of either pipeline or pump. Centrifugal pumps differ in that they can be safely operated under closed valve conditions (for short periods of time).

A rotodynamic pump can further be classified into three categories depending on the impeller type: radial flow, mixed flow & axial flow.

1.2.2.1 Radial Flow (referred to as centrifugal pumps)

The fluid enters along the axial plane, is accelerated by the impeller and exits at right angles to the shaft (radially). Radial flow pumps operate at higher pressures and lower flow rates than axial and mixed flow pumps.

1.2.2.2 Axial Flow

Axial flow pumps differ from radial flow in that the fluid enters and exits along the same direction parallel to the rotating shaft. The fluid is not accelerated but instead "lifted" by the action of the impeller. They are similar to a propeller spinning in a length of tube. Axial flow pumps operate at much lower pressures and higher flow rates than radial flow pumps.

1.2.2.3 Mixed Flow

Mixed flow pumps, as the name suggests, function as a compromise between radial and axial flow pumps. The fluid experiences both radial acceleration and lift and exits the impeller somewhere between 0-90 degrees from the axial direction. As a consequence mixed flow pumps operate at higher pressures than axial flow pumps while delivering higher discharges than radial flow pumps. The exit angle of the flow dictates the pressure head-discharge characteristic in relation to radial and mixed flow.

2. HOW CENTRIFUGAL PUMPS WORK?

2.1 Working mechanism

A centrifugal pump is one of the simplest pieces of equipment in any process plant; however, plant engineers consider it as the heart of their plant. A centrifugal pump indeed is one of the most critical equipments ensuring the continuity of any process. Its purpose is to transfer the desired liquid to the desired point in the desired quantity. The pump delivers the flow by converting energy of a prime mover (an electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy. Thus, by creating resistance to flow (pressure or head) the centrifugal pump delivers the required flow.

2.1.1 Generation of centrifugal force

The process liquid enters the suction nozzle and then into eye (centre) of a revolving device known as an impeller. When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and provides centrifugal acceleration. As the liquid leaves the eye of the impeller, a low-pressure area is created causing more liquid to flow towards the inlet. Because the impeller blades are curved, the fluid is pushed in a tangential and radial direction by the centrifugal force. This force acting inside the pump is the same as the one that keeps water inside a bucket that is rotating at the end of a string.

2.1.2 Energy imparted by the impeller

Once the liquid enters the eye of the impeller, it moves outward along the impeller. By virtue of its rotation, the impeller imparts kinetic energy to the liquid as it moves outward along the impeller. The liquid accelerates and its kinetic energy increases and at the outer tip of the impeller the liquid possesses the highest velocity. The key idea is that the energy created by the centrifugal force is kinetic energy. The amount of energy given to the liquid is proportional to the velocity at the edge or vane tip of the impeller. The faster the impeller revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid.

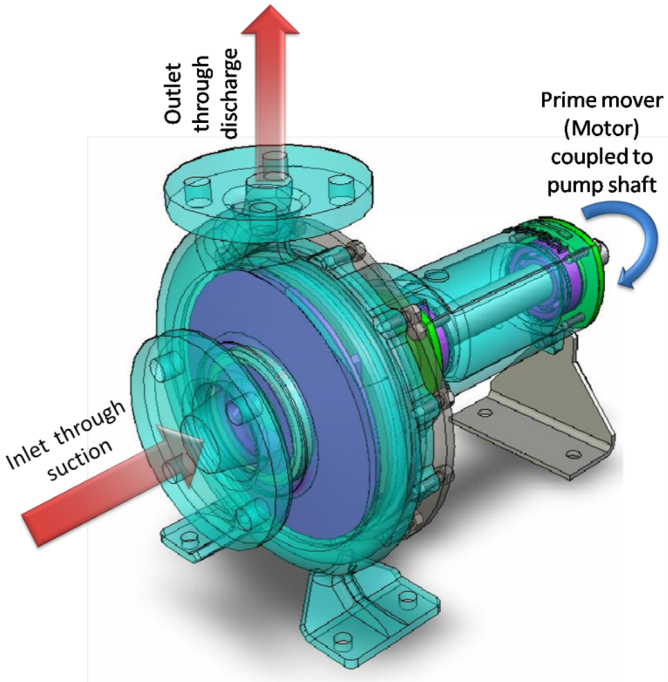
2.1.3 Conversion of kinetic energy to pressure energy (head)

The rapidly moving liquid leaves the pump impeller and the liquid enters the diffusing element of the pump (the volute in the casing). Here an increase in the cross-sectional area of the flow passage occurs, causing the liquid to slow down. The deceleration of the liquid in the diffusing element converts the kinetic energy of the liquid to pressure energy. Therefore, the head (pressure in terms of height of liquid) developed is approximately equal to the velocity energy at the periphery of the impeller expressed by the following well-known formula:

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

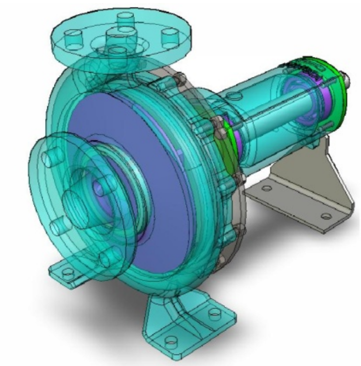
Where H = head developed in metres, v is velocity in m/s, g = 9.81 m/s^2.

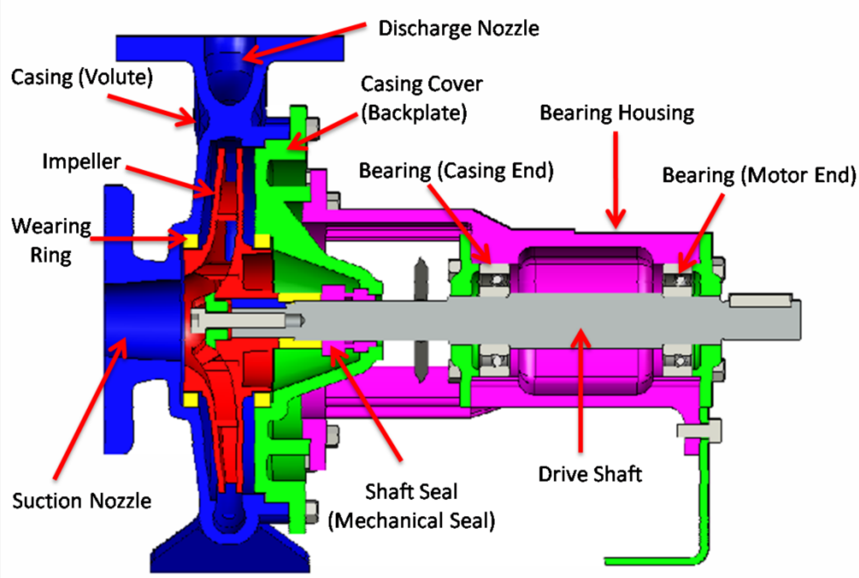
After understanding the working principle of a centrifugal pump we now look at the basic mechanical design of a typical horizontal end-suction centrifugal pump. Henceforth the term PUMP will always refer to CENTRIFUGAL PUMP. The below figure depicts the operation of a typical end-suction back pullout horizontal centrifugal pump.



3. BASIC COMPONENTS OF A PUMP

A centrifugal pump construction consists of rotary and stationary components that deliver the desired flow when coupled to a prime mover (motor, turbine, engine, etc.). A typical end-suction back pullout horizontal centrifugal pump is shown below. Irrespective of the type of design of a centrifugal pump, it will have the rotating components and stationary components. The basic mechanism of operation remains the same irrespective of the construction of a pump.



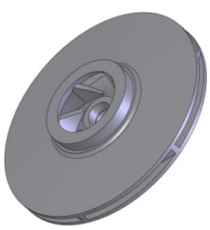


End – suction horizontal back pullout centrifugal pump

3.1 Rotating components

The rotating components consist of the impeller and the shaft.

3.1.1 Impeller

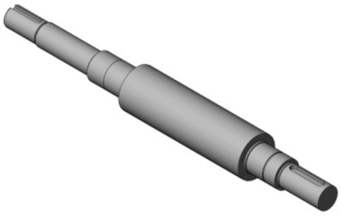


Closed impeller

An impeller is a rotating component of a centrifugal pump; usually made of iron, steel, bronze, aluminum, stainless steel or high corrosion resistant alloys, which transfers energy from the motor that drives the pump to the fluid being pumped by accelerating the liquid outwards from the center of rotation. The velocity achieved by the impeller transfers into pressure when the outward movement of the fluid is confined by the pump casing. The liquid enters at the centre (eye of the impeller) and gets accelerated by the centrifugal force imparted by the rotating impeller. The vanes of the impeller, rotating at high speed, impart energy to the liquid. The vanes of the impeller are held together by shrouds. The impeller is keyed to the shaft. The impeller is classified based on a) Direction of flow generated in reference to the axis of rotation (i.e.) radial flow, axial flow or mixed flow (as discussed in section 1.2.2)

b) Mechanical construction: closed, open or semi-open

3.1.2 Shaft



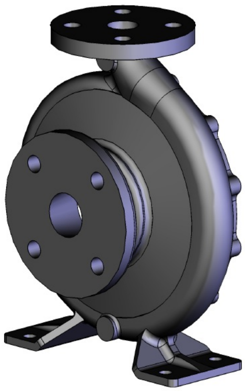
Shaft

The shaft is the main rotating member of the pump with the impeller mounted on it. The shaft is coupled to a prime mover (often an electric motor) that provides the torque for rotation of the shaft. A shaft sleeve is often mounted on the shaft to avoid the physical contact of the shaft and the liquid being pumped primarily for corrosion reasons. Normally, the shaft is made of standard material like SS 410 for better mech. properties.

3.2 Stationary components

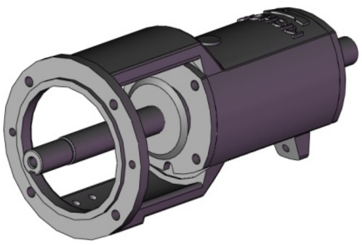
The stationary components of a pump include the casing (volute), casing cover or casing backplate, bearings & bearing housing.

3.2.1 Casing (Volute)



Casing with Volute

The casing contains the volute. A volute is a curved funnel increasing in cross-sectional area toward the discharge port. The casing consists of the suction and the discharge nozzle which are connected to the volute. The liquid enters the volute after acquiring energy from the impeller. As the liquid enters the volute, the increasing cross-sectional flow area reduces the velocity of the liquid and creates resistance to flow which generates the pressure required to drive the liquid out of the pump and to the desired location.



Bearing housing / Drive Bracket

3.2.2 Casing cover or casing backplate

The casing cover or backplate is attached to the casing and ensures that the compartment remains pressurized and restricting the liquid outflow from the discharge nozzle only.

3.2.3 Bearings & bearing housing

Grease lubricated ball bearing

The bearings support the shaft and keep the shaft or rotor in correct alignment with the stationary parts under the action of radial and axial loads resulting during the pump operation. The bearing housing encloses the bearings mounted on the shaft.

3.3 Shaft Sealing

The main purpose of a shaft sealing mechanism is to prevent the liquid being pumped from leaking outside the pressurised casing. A common application of sealing devices is to seal the rotating shaft of a centrifugal pump. Shaft sealing is achieved in two ways: a) using gland packing & b) using mechanical seal.

3.3.1 Gland Packing

Compared to compression sealing using gland packing, mechanical seals provide lower leakage of liquid, lower maintenance cost and better pumping efficiency.

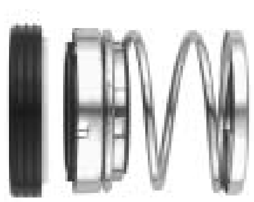
Sealing is achieved by compression packing using packings held in a stuffing box and mounted on the shaft either inside the casing backplate or held in place by a gland plate attached to the casing backplate. The function of packing is to control leakage and not to eliminate it completely. The packing must be lubricated for proper operation. The packings exert pressure on the shaft because of which more torque and hence some power is wasted.

3.3.2 Mechanical Seal

Traditionally, mechanical seals used to be much more expensive than gland packing; however, the cost difference is diminishing day by day and mechanical seals are preferred over gland packing.

A mechanical seal is a sealing device which forms a running seal between rotating and stationary parts. Mechanical seals consist of one rotary member and one stationary member. They overcome the disadvantages of compression packing by gland packing. Mechanical seals are operationally a better option than compression packing type of sealing, since mechanical seals reduce the leakage of the pumped liquid, improve the pumping efficiency and reduce maintenance cost. Advantages of mechanical seals over conventional packing are as follows:

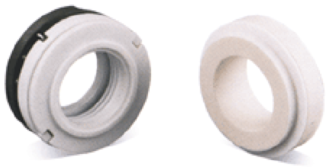
1) Zero or limited leakage of product.
2) Reduced friction and power loss.
3) Elimination of shaft or sleeve wear.
4) Reduced maintenance costs.
5) Keeps environment clean.



***Single coil spring**: For liquids with fine solids*

The stationary member of the seal is fixed to either the cavity in the backplate in the casing backplate or on to a gland plate which is attached to the casing backplate. The rotary member is mounted on the shaft with the lapping face of the rotary member in touch with the lapping surface of the stationary member. One of the faces is usually a non-galling material such as carbon-graphite. The other is usually a relatively hard material like silicon-carbide. Dissimilar materials are usually used for the stationary insert and the rotating seal ring face in order to prevent adhesion of the

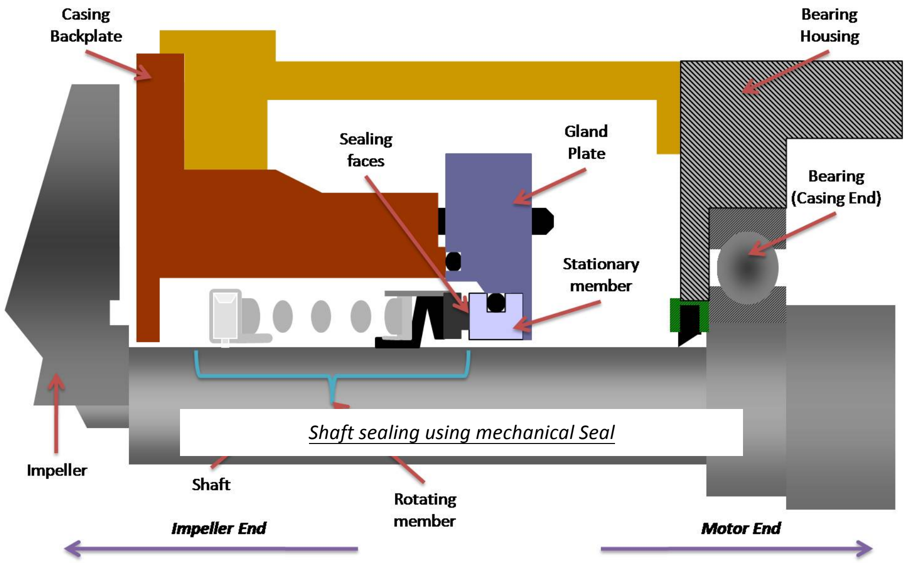
***Rubber bellow seal**: For liquids with fine solids, for general applications like water pumping solids*



***Teflon bellow seal**: For corrosive liquids*

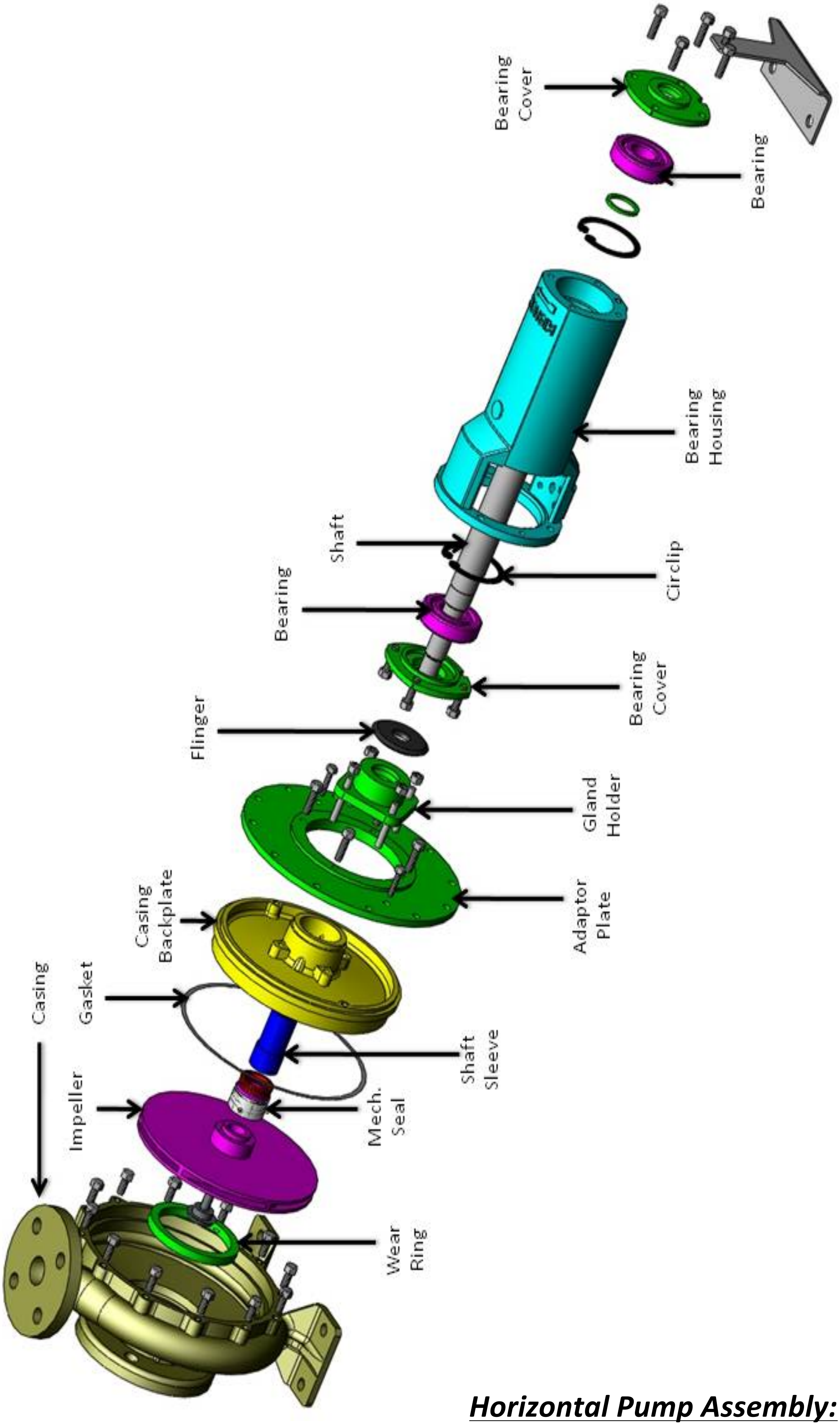
***Metal bellow seal**: For wide variety of liquids and high temperature*

two faces. When the pump starts pumping, the liquid enters the seal portion and is prevented from leaking into the environment by the rotary member. However, some amount of liquid passes onto the lapping faces where a thin film of the liquid is held by the lapping faces. This liquid film prevents heat build up on the lapping faces and lubricates the lapping faces (within certain temperature). This mechanism allows some liquid to escape into the environment (albeit at a much lower rate than compression sealing). If the regulations do not allow any amount of liquid into the environment, a double mechanical seal arrangement can be used.

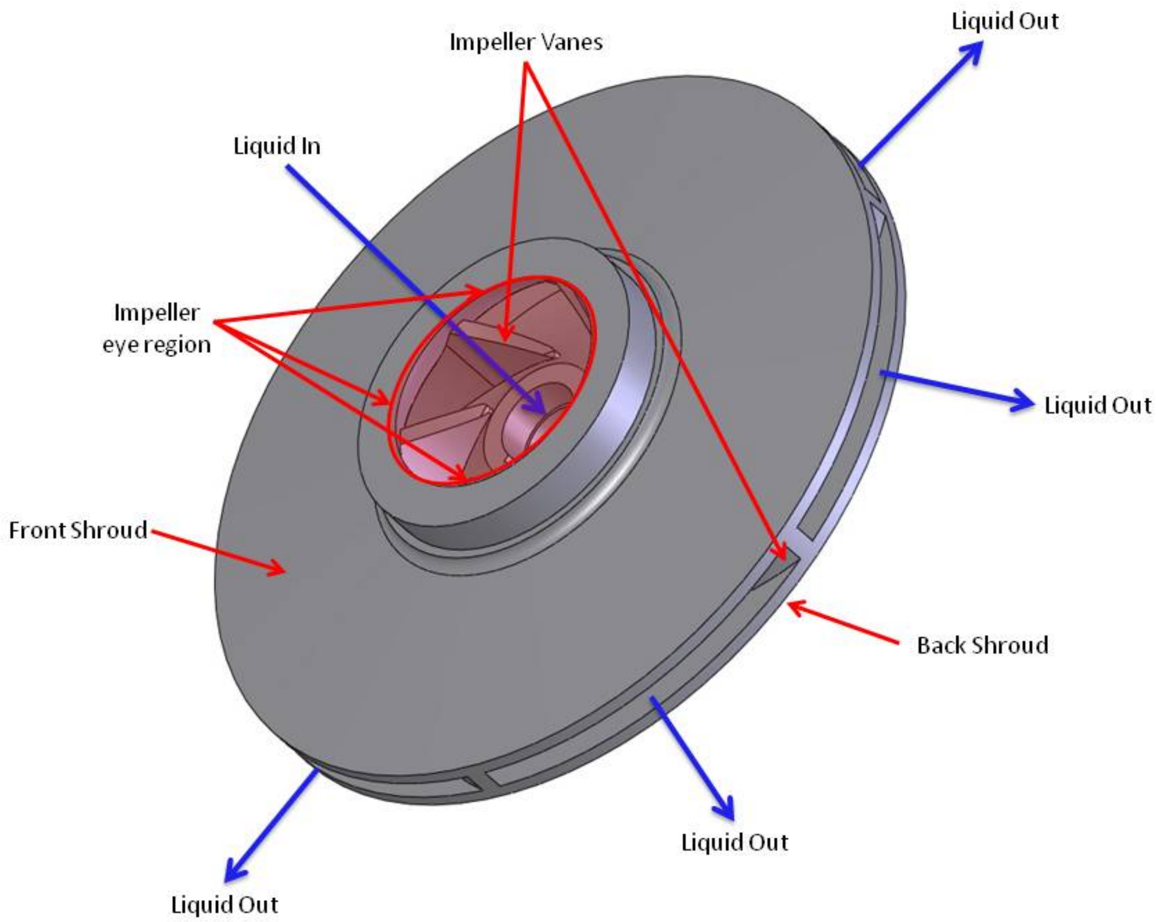


Shaft sealing using mechanical Seal

pending on the type of operation, the liquid type being handled and the local environmental regulation, a variety of seals can be used.



Horizontal Pump Assembly: Exploded View

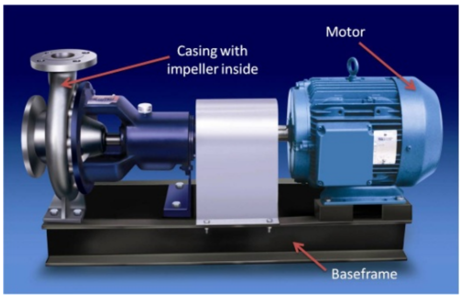


<u>Pump Impeller Configuration (Closed Impeller)</u>

4. TYPES OF CENTRIFUGAL PUMPS

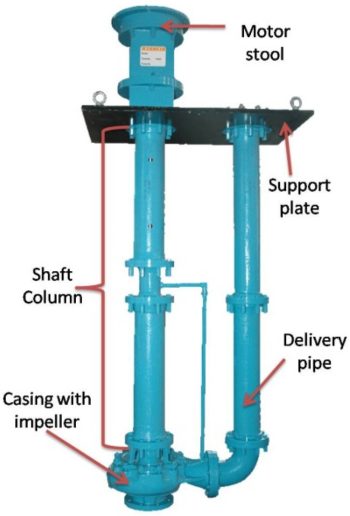
Centrifugal pumps types are primarily based on the manner in which the pumps are installed on the site.

4.1. HORIZONTAL EXECUTION



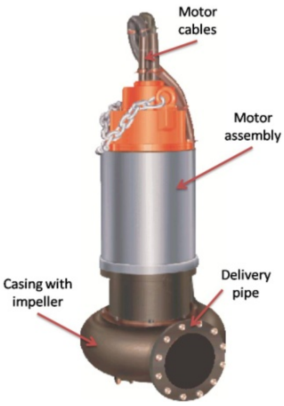
These types of centrifugal pumps are installed and operated with the impeller axis of rotation parallel to the ground level. This is the most common type of installation. For such installation, the suction side piping arrangement is very critical in ensuring smooth operation of the pump. The prime mover (motor), is either coupled to the shaft of the pump, or the impeller is directly mounted on the motor shaft (mono block type).

4.2. VERTICAL EXECUTION



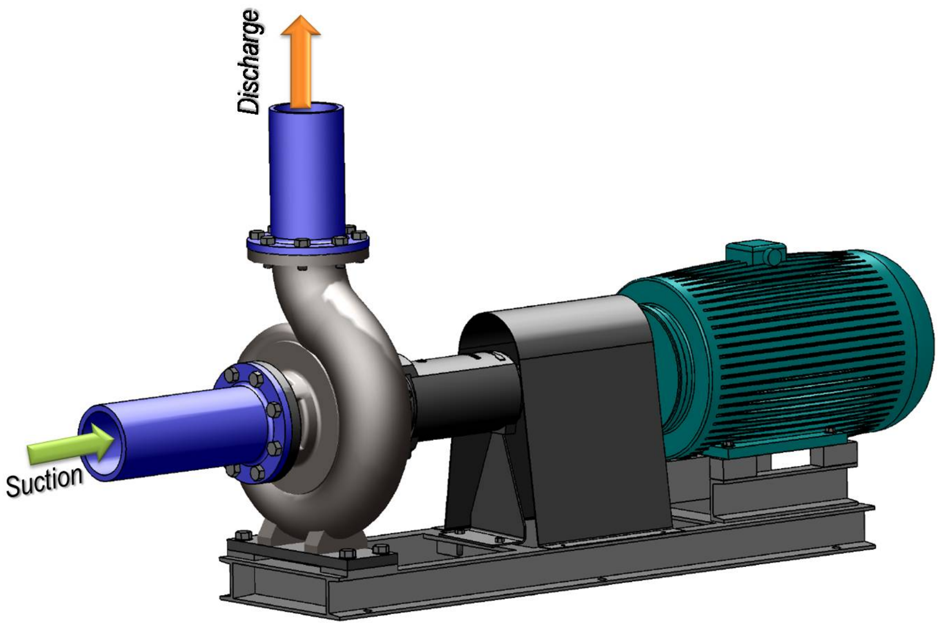
In vertical type execution, the impeller axis is perpendicular to the ground level. The motor is mounted on the top of the shaft. Such type of pump can be closely coupled motor shaft or extended shaft pumps with distance of the hydraulic components as much as 12 metres from the support plate. These pumps are very popular in corrosive application or when the NPSH conditions are critical since the hydraulic components can be completely submerged in the liquid.

4.3. SUBMERSIBLE MOTOR PUMPS

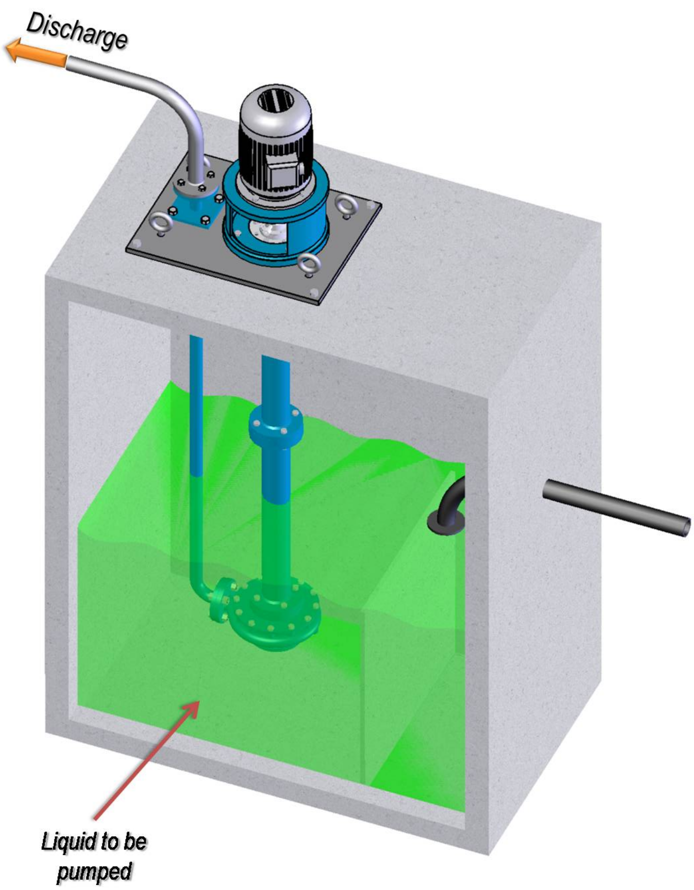


Submersible motor pumps are installed with the entire pump assembly, including the motor, is completely submerged inside the liquid to be pumped. In such installations, the motor is made of special leak proof construction and the impeller is directly mounted on the motor shaft with shaft sealing between the electric and the hydraulic components. Since the pump assembly is completely submerged inside the liquid, no pump parts are visible on the ground level. It also eliminates noise arising from pump operation.

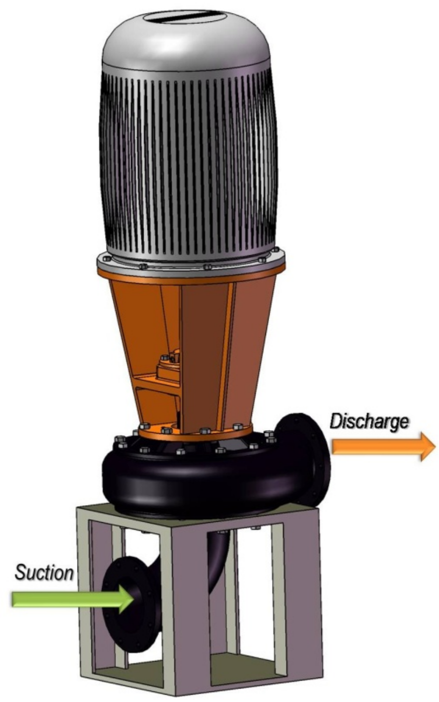
Horizontal 'H type' installation



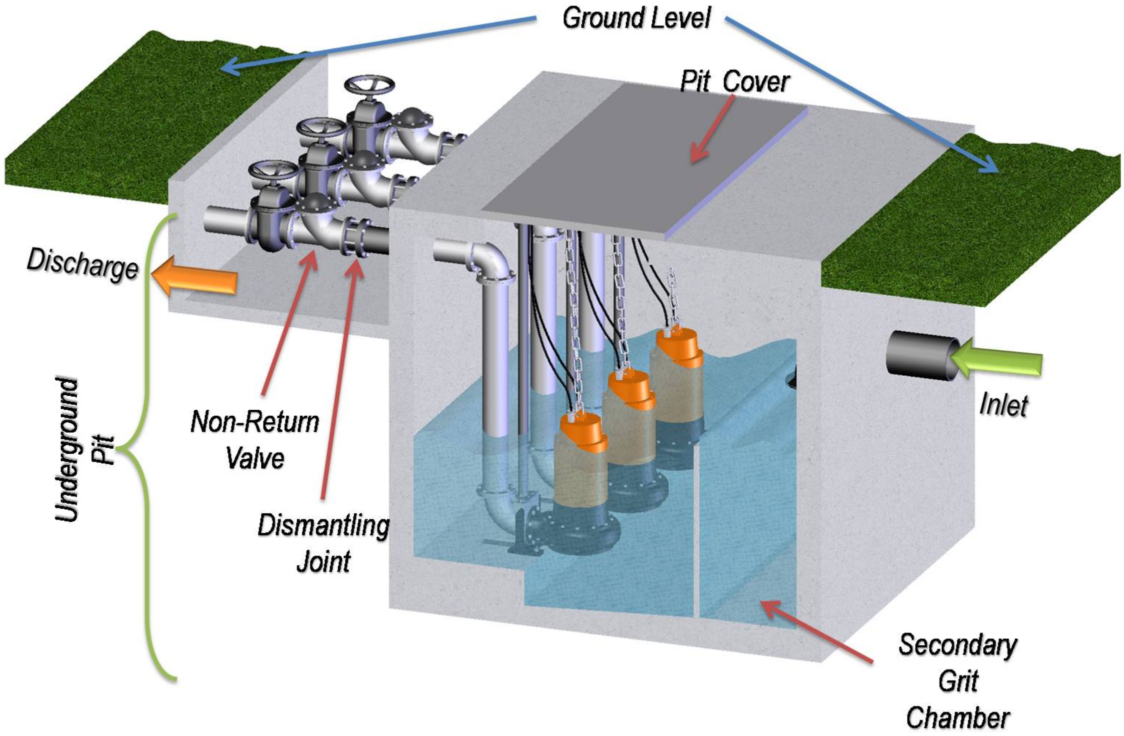
Vertical Extended Shaft 'E type' installation



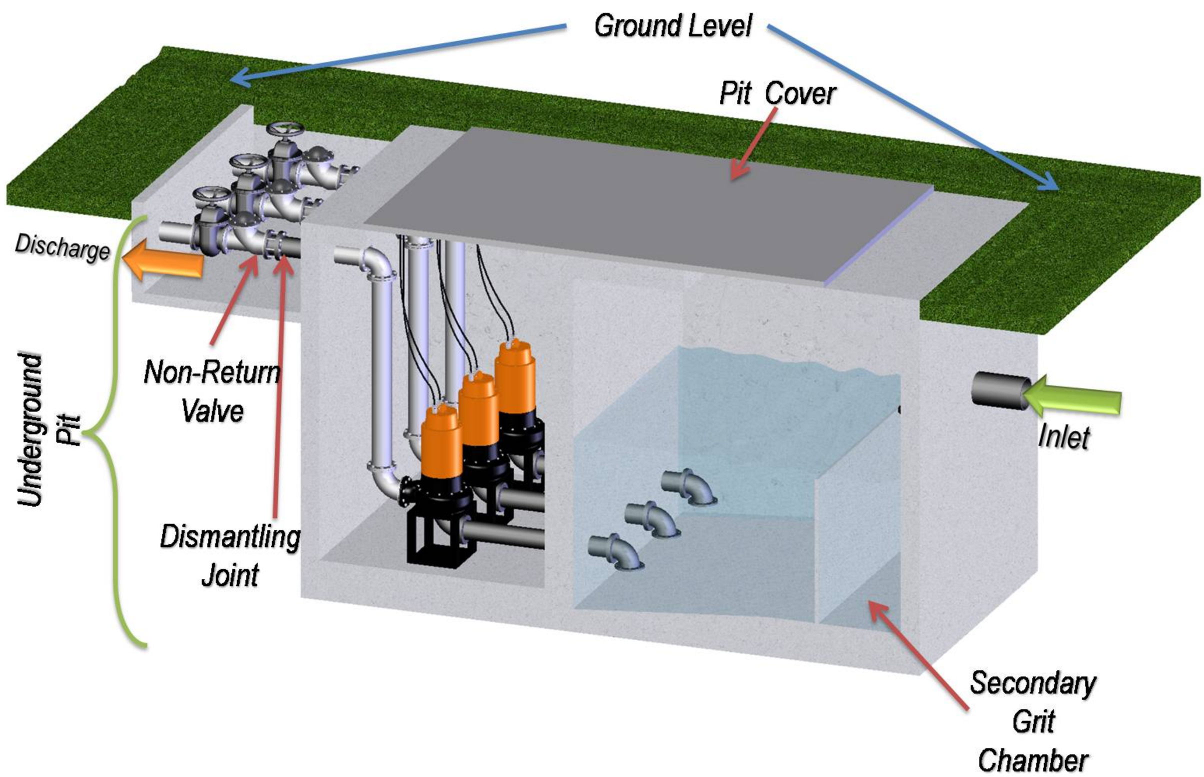
Vertical Short Shaft 'V type' installation



Dry motor submersible 'S type' installation for wet pit



Dry motor submersible 'S type' installation for dry pit



5. HYDRAULIC FUNDAMENTALS

5.1 Capacity / Flow rate

Capacity means the flow rate with which liquid is moved or pushed by the pump to the desired point in the process. It is commonly measured in either cubic meters per hour (m^3/hr) or gallons per minute (gpm) (US). The capacity usually changes with the changes in operation of the process. As liquids are essentially incompressible, the capacity is directly related with the velocity of flow in the suction pipe.

$$Q = A \times \frac{v}{3{,}600} = \frac{\pi}{4} D^2 \times \frac{v}{3{,}600}$$

Q is Flow rate in m^3/hr, A is cross sectional area of flow in m^2, D is diameter of pipe in metres & v is velocity of liquid in m/s.

5.2 Head (Pressure)

5.2.1 Definition

A given pump with a given impeller diameter and speed will raise a liquid to a certain height regardless of the weight of the liquid.

The pressure at any point in a liquid can be thought of as being caused by a vertical column of the liquid due to its weight. The height of this column is called the static head and is expressed in terms of metres of liquid. The same 'head' term is used to measure the kinetic energy created by the pump. In other words, head is a measurement of the height of a liquid column that the pump could create from the kinetic energy imparted to the liquid. Imagine a pipe shooting a jet of water straight up into the air, the height the water goes up would be the head. The head is not equivalent to pressure. Head is a term that has units of a length and pressure has units of force per unit area. The main reason for using head instead of pressure to measure the energy of a centrifugal pump is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not change. Since any given centrifugal pump can move a lot of different fluids, with different specific gravities, it is simpler to discuss the pump's head and forget about the pressure.

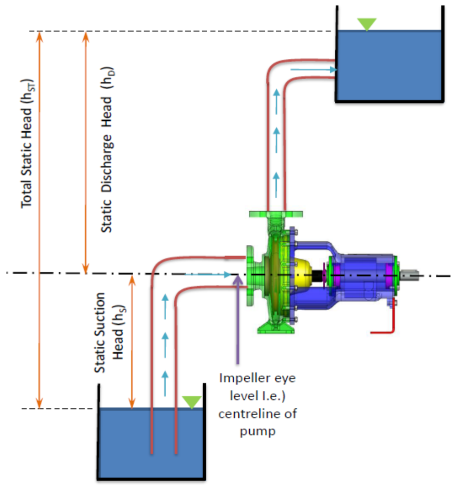
Liquids have specific gravities typically ranging from 0.5 (like light hydrocarbons) to 1.8 (like concentrated sulphuric acid). Water is a benchmark, having a specific gravity of 1.0.

$$H = \frac{P}{Sp.Gr. \times g \times 1{,}000}$$

H is head in metres, P is pressure in N/m^2 (Pascal), Sp. Gr. Is the specific gravity of the liquid and g is acceleration due to gravity which is 9.81 m/s^2.

5.2.2 Static suction head (h_S)

The head resulting from elevation of the liquid relative to the pump centre line (i.e.) relative to the eye level of the impeller. Thus the static suction head is the vertical distance in metres from the centreline of the pump to the free level of the liquid to be pumped. If the liquid level is above the pump centreline, then static suction head is positive. If the liquid level is below pump centerline, static suction head is negative. Negative static suction head condition is commonly denoted as a “suction lift” condition.



5.2.3 Static discharge head (h_D)

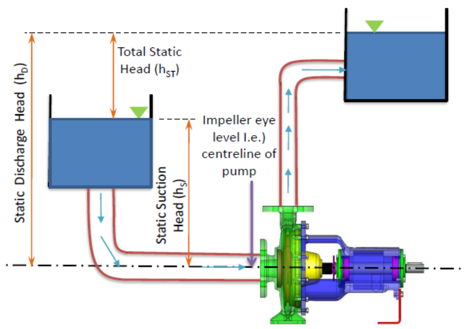
Static discharge head is the vertical distance in metres between the pump centreline and the point of free discharge or the surface of the liquid in the discharge tank.

5.2.4 Total Static Head (h_{ST})

Total static head is the vertical distance in metres between the free level of the source of supply and the point of free discharge or the free surface of the discharge liquid.

5.2.4 Friction head (h_F)

Friction head is the head required to overcome the resistance to flow in the pipe and fittings. It is dependent upon the size, condition and type of pipe, number and type of pipe fittings, flow rate, and nature of the liquid.



5.2.5 Pressure head (h_P)

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 metres of liquid. Pressure head refers to absolute pressure on the surface of the liquid reservoir supplying the pump suction, converted to metres of head. If the system is open, pressure head equals atmospheric pressure head. 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.

5.2.6 Velocity head (h_V)

Velocity head refers to the energy of a liquid as a result of its motion at some velocity 'v'. It is the equivalent head in metres through which the water would have to fall to acquire the same velocity, or in other words, the head necessary to accelerate the water. 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.

5.2.7 Vapour pressure head (h_{VP})

Vapour pressure is the pressure at which a liquid and its vapour co-exist in equilibrium at a given temperature. The vapour pressure of liquid can be obtained from vapour pressure tables. When the vapour pressure is converted to head, it is referred to as vapour pressure head. The vapour pressure of a liquid is defined as the tendency of the liquid to vaporise at a given temperature. It increases with the rising temperature and in effect, opposes the pressure on the liquid surface; the positive force that tends to cause liquid flow into the pump suction i.e. it reduces the suction pressure head.

5.2.8 Total dynamic suction head (H_S)

Total dynamic suction head is the suction reservoir pressure head plus the static suction head plus the velocity head at the pump suction flange minus the friction head in the suction line. The total dynamic suction lift, as determined on pump test, is the reading of a gauge on the suction flange, converted to feet of liquid and corrected to the pump centreline, minus the velocity head at the point of gauge attachment.

$$H_s = h_{Ss} - h_{Fs} + h_{Ps} + h_{Vs}$$

5.2.9 Total dynamic discharge head (H_d)

Total dynamic discharge head is the static discharge head plus the velocity head at the pump discharge flange plus the total friction head in the discharge line. The total dynamic discharge head, as determined on pump test, is the reading of a gauge at the discharge flange, converted to feet of liquid and corrected to the pump centreline, plus the velocity head at the point of gauge attachment.

$$H_d = h_{Dd} - h_{Fd} + h_{Pd} + h_{Vd}$$

5.2.10 Total dynamic head (H_T)

Total dynamic head (TDH) is the total dynamic discharge head minus the total dynamic suction head.

$$\text{For static suction lift: } H_T = H_d + H_s$$

$$\text{For static suction head: } H_T = H_d - H_s$$

5.2.11 Net positive suction head (NPSH)

NPSH is simply a measure of the amount of suction head present to prevent the vaporization of the liquid at the lowest pressure point in the pump. It is the excess pressure of the liquid in metres absolute over its vapour pressure as it arrives at the pump suction

NPSH is defined as the total suction head in metres absolute, determined at the suction nozzle and corrected to datum, less the vapour pressure of the liquid in metres absolute. Simply stated, it is an analysis of energy conditions on the suction side of a pump to determine if the liquid will vaporize at the lowest pressure point in the pump.

The energy imparted by the impeller is directly related to the density of the matter being pumped. Thus, for the impeller to effectively impart its energy to the liquid being pumped by virtue of increase in the kinetic energy of the liquid, it is critical that the liquid does not vaporise. The satisfactory operation of a pump requires that vaporization of the liquid being pumped does not occur at any condition of operation.

*The pressure which a liquid exerts on its surroundings is dependent upon its temperature. This pressure, called **vapour pressure**, is a unique characteristic of every fluid and increased with increasing temperature. When the vapour pressure within the fluid reaches the pressure of the surrounding medium, the fluid begins to vaporize or boil.*

The pressure which a liquid exerts on its surroundings is dependent upon its temperature. This pressure, called vapour pressure, is a unique characteristic of every fluid and increased with increasing temperature. When the vapour pressure within the fluid reaches the pressure of the surrounding medium, the fluid begins to vaporize or boil. The vaporization begins when the vapour pressure of the liquid at the operating temperature equals the external system pressure, which, in an open system is always equal to atmospheric pressure. Any decrease in external pressure or rise in operating temperature can induce vaporization and the pump stops pumping. Thus, the pump always needs to have a sufficient amount of suction head present to prevent this vaporization at the lowest pressure point in the pump. NPSH is simply a measure of the amount of suction head present to prevent this vaporization at the lowest pressure point in the pump. The lowest pressure point in the pump is at the point where the liquid just enters the impeller (eye of the impeller).

5.2.11.1 NPSH Required (NPSHr)

The NPSHr varies with speed and capacity within any particular pump. The NPSHr increases as the speed or capacity increases because the velocity of the liquid increases, since increased velocity lowers the pressure of the liquid. The NPSHr is independent of the liquid density.

NPSH Required (NPSHr) is a function of the pump design. As the liquid passes from the pump suction to the eye of the impeller, the velocity increases and the pressure decreases. There are also pressure losses due to shock and turbulence as the liquid strikes the impeller. The centrifugal force of the impeller vanes further increases the velocity and decreases the pressure of the liquid. The NPSHr is the positive head in feet absolute required at the pump suction to overcome these pressure drops in the pump and maintain the majority of the liquid above its vapour pressure. The NPSHr varies with speed and capacity within any particular pump. The NPSH required increases as the speed & capacity increases because the velocity of the liquid increases and as anytime the velocity of a liquid goes up, the pressure or head comes down. Pump manufacturer's curves normally provide this information.

5.2.11.2 NPSH Available (NPSHa)

The NPSH available (NPSHa) must always be greater than the NPSH required (NPSHr) for the pump to operate properly. It is normal practice to have at least 5 to 10% of extra NPSHa at the suction flange to avoid any problems at the duty point.

Net Positive Suction Head Available is a function of the system in which the pump operates. It is the excess pressure of the liquid in metres absolute over its vapour pressure as it arrives at the ***pump suction***, to be sure that the pump selected does not cavitate. It is calculated based on system or process conditions. NPSHa value is given by the buyer of the pump.

In a nutshell, NPSHa is defined as:

NPSHa = Pressure head + Static head - Vapour pressure head of liquid being pumped – Friction head loss in the piping, valves and fittings.

5.2.11.3 Cavitation

Figure: Impeller damaged by cavitation

Cavitation is a term used to describe the phenomenon, which occurs in a pump when there is insufficient NPSHa. When the pressure of the liquid is reduced to a value equal to or below its vapour pressure the liquid begins to boil and small vapour bubbles or pockets begin to form. As these vapour bubbles move along the impeller vanes to a higher pressure area above the vapour pressure, they rapidly collapse. The collapse or "implosion" is so rapid that it may be heard as a rumbling noise, as if you were pumping gravel. In high suction energy pumps, the collapses are generally high enough to cause minute pockets of fatigue failure on the impeller vane surfaces. This action may be progressive, and under severe (very high suction energy) conditions can cause serious pitting damage to the impeller. The accompanying noise is the easiest way to recognize cavitation.

Any discussion of NPSH or cavitation is only concerned about the suction side of the pump. There is almost always plenty of pressure on the discharge side of the pump to prevent the fluid from vaporizing.

Besides possible impeller damage, excessive cavitation results in reduced capacity due to the vapour present in the pump. Also, the head may be reduced and/or be unstable and the power consumption may be erratic. Vibration and mechanical damage such as bearing failure can also occur as a result of operating in excessive cavitation, with high and very high suction energy pumps.

The way to prevent the undesirable effects of cavitation in standard low suction energy pumps is to insure that the NPSHa in the system is greater than the NPSHr by the pump. High suction energy pumps require an additional NPSH margin, above the NPSHr.

5.3 Power & Efficiency

The work performed by a pump is a function of the total head and the weight of the liquid pumped in a given time period. Pump input or brake power (BkW) is the actual horsepower delivered to the pump shaft. Pump output or hydraulic or pump power (PkW) is the liquid horsepower delivered by the pump. These two terms are defined by the following formulas.

$$P_{PkW} = Q \times H_T \times g \times \rho$$

Where P_{PkW} = Power delivered by the pump in Watts, Q is capacity in m^3/s, HT is the total dynamic (differential) head in metres, g is the acceleration due to gravity (9.81 m/s^2) & ρ is the density of liquid being pumped in kg/m^3.

$$P_{BkW} = \frac{Q \times H_T \times g \times \rho}{Efficiency}$$

Where P_{BkW} = Power consumed by the pump in Watts, Q is capacity in m^3/s, HT is the total dynamic (differential) head in metres, g is the acceleration due to gravity (9.81 m/s^2) & ρ is the density of liquid being pumped in kg/m^3.

The power delivered to the pump can also be determined by taking the product of the motor output current and voltage.

The brake horsepower or input to a pump is greater than the hydraulic horsepower or output due to the mechanical and hydraulic losses incurred in the pump. Therefore the pump efficiency is the ratio of these two values.

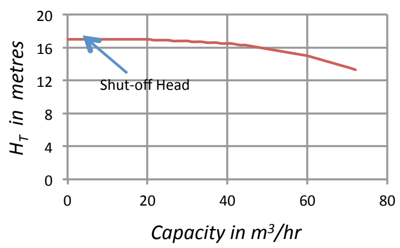
$$Pump\ Efficiency = \frac{P_{PkW}}{P_{BkW}}$$

6. OPERATION OF A CENTRIFUGAL PUMP

6.1 PUMP CHARACTERISTIC CURVES

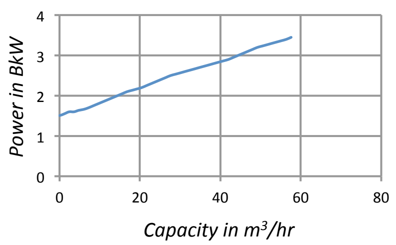
The performance of a centrifugal pump can be shown graphically on a characteristic curve. A typical characteristic curve shows the total dynamic head, brake horsepower, efficiency, and NPSHr all plotted over the capacity range of the pump.

6.1.1 TOTAL DYNAMIC HEAD VS. CAPACITY



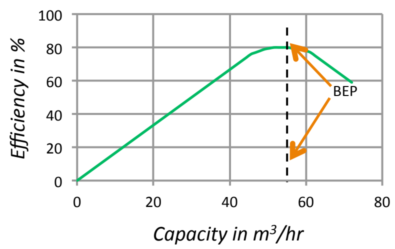
This curve is the plot of the total dynamic head (H_T) on y-axis and capacity on x-axis. The head at zero flow is called shut-off head. For a radial flow centrifugal pump, the curve is flat at low flow region and slopes downwards as flow increases. For simplicity we consider on the radial flow centrifugal pump operation. ***This plot is also called the head – flow curve***. This curve gives the "duty condition" of the pump.

6.1.2 POWER VS. CAPACITY



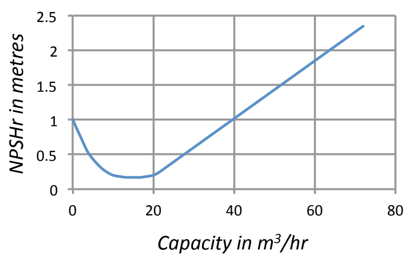
This curve is a plot of the power consumed by the pump (*BkW*) on y-axis and capacity on x-axis. Please note that this curve shows the electric power consumed by the pump or the electric power delivered by the motor and ***NOT*** the hydraulic (*PkW*) power delivered by the pump.

6.1.3 EFFICIENCY VS. CAPACITY

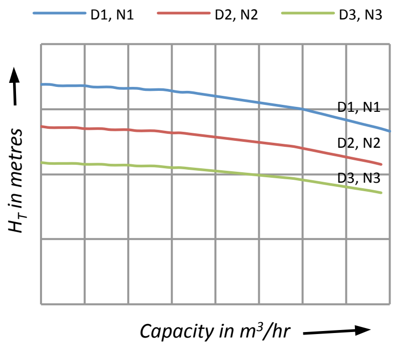


This curve is a plot of the efficiency by which pump delivers the hydraulic power on y-axis and capacity on x-axis. The efficiency increases at first with increasing flow, levels off at a certain flow rate and falls after the flow rate is further increased. The point where the efficiency is maximum is the called the ***Best Efficiency Point (BEP)*** is of critical importance in pump selection and operation as will be discussed later.

6.1.4 NPSHr VS. CAPACITY



This curve is a plot of NPSHr on y-axis and capacity on x-axis. Determining the value NPSHr is a long process and many precautions need to be taken to arrive at the value of NPSHr. This curve is used to check whether the NPSHr of the pump is less than the NPSHa mentioned by the buyer at the desired flow rate. A typical plot of NPSHr vs Q is shown. This plot is dependent on many external factors in addition to pump design.



D1 > D2 > D3 ; N1 > N2 > N3

6.2 Affinity Laws

The affinity laws express the mathematical relationship between the several variables involved in pump performance. They apply to all types of rotodynamic pumps. They are as follows:

1) With impeller diameter (*D*) held constant:

a) $$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

b) $$\frac{H_{T1}}{H_{T2}} = \left(\frac{N_1}{N_2}\right)^2$$

c) $$\frac{P_{BkW1}}{P_{BkW2}} = \left(\frac{N_1}{N_2}\right)^3$$

2) With speed (*N*) held constant:

a) $$\frac{Q_1}{Q_2} = \frac{D_1}{D_2}$$

b) $$\frac{H_{T1}}{H_{T2}} = \left(\frac{D_1}{D_2}\right)^2$$

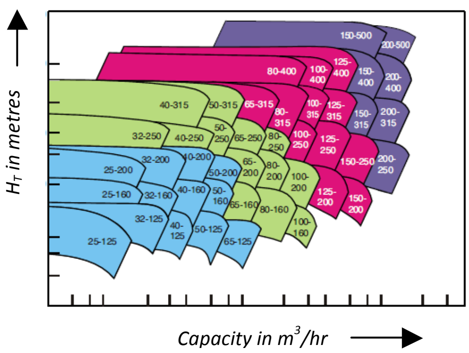
c) $$\frac{P_{BkW1}}{P_{BkW2}} = \left(\frac{D_1}{D_2}\right)^3$$

The Affinity Laws are valid only under conditions of constant efficiency.

Where, *D* is the diameter of the impeller in mm, *N* is the speed of rotation of impeller in rpm, *Q* is capacity in m^3/hr, H_T is the total dynamic head in metres, P_{BkW} is the power consumed by the pump in kW.

When the performance (Q_1, H_{T1}, & P_{BkW1}) is known at some particular speed (N_1) or diameter (D_1), the formulas can be used to estimate the performance (Q_2, H_{T2}, & P_{BkW2}) at some other speed (N_2) or diameter (D_2). The efficiency remains nearly constant for speed changes and for small changes in impeller diameter.

6.3 Centrifugal Pump Family Curves

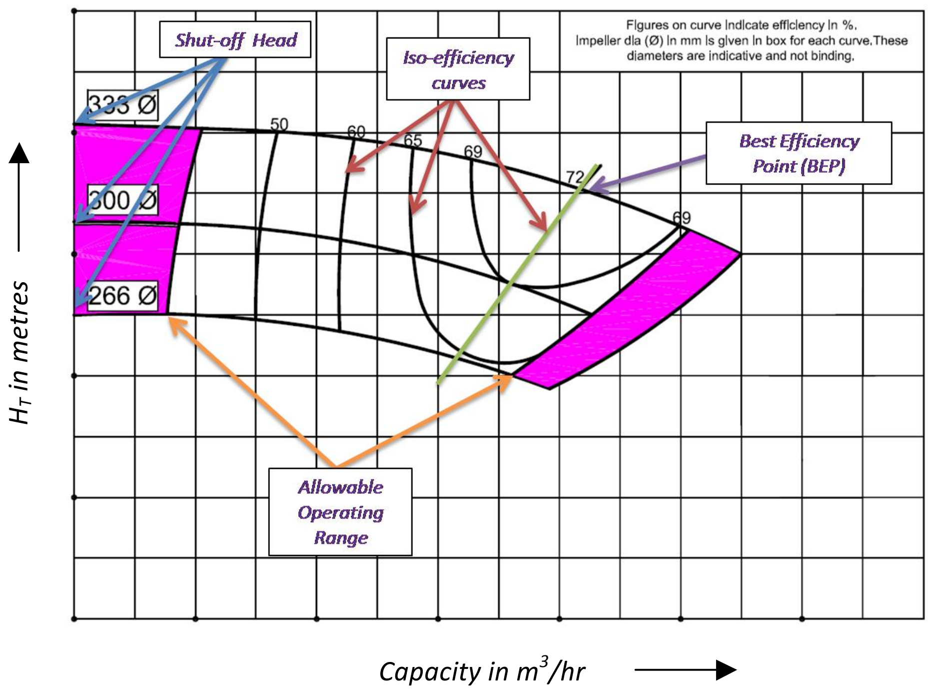


As discussed above, a given centrifugal pump will provide a range of head – flow values by reducing the speed of rotation of the impeller and/or the diameter of the impeller. The head – flow curves of a set of varying centrifugal pump sizes (*family of centrifugal pumps*) covering a wide range of head – flow values are plotted on a single covering known as the family curve of the set of pumps. The family curve is used to quickly select a suitable pump size for the given duty condition. Pump manufacturers have different nomenclatures for naming the size of a pump. In this case, the pump size is defined in the format "XXX-YYY" e.g: 100-250, where the first number signifies the delivery diameter of the casing in mm and second number signifies the nominal diameter of the impeller in mm (i.e.) 100-250 means delivery diameter of casing is 100 mm and nominal impeller diameter is 250 mm.

6.4 Understanding Head – Flow Curve

The head – flow curve of a centrifugal is the fundamental document in pump selection, operation, maintenance and troubleshooting. The head flow curve signifies how the pump will behave when the duty conditions on-site change from the specified condition. The various parameters of a head – flow curve are shown below and explained.

Typical centrifugal pump curve @ 1450 rpm for three impeller diameters



6.4.1 Shut-off Head

Shut-off head is the condition of zero flow where no liquid is flowing through the pump, but the pump is primed and running. It is obtained by closing the discharge valve in the delivery piping of the pump. This is an important landmark used in determining the condition of the pump or the slope of the pump curve. Operating a pump at shut-off can be mechanically severe and must be limited to a few seconds needed to collect the suction and discharge pressure readings.

6.4.2 Allowable Operating Range (AOR)

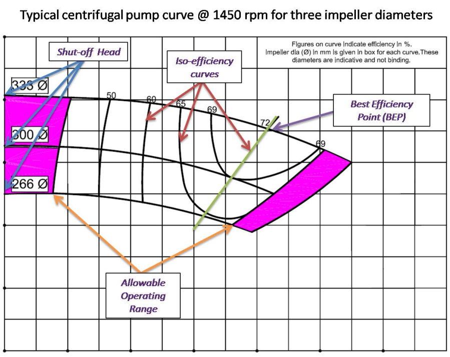
The allowable operating range or AOR, is the range of flow rates recommended by the pump manufacturer in which the service life of the pump is not seriously reduced by continuous operation. The manufacturer provides this AOR based on the pumped liquid being free of entrained vapour, gases or suspended solids. In the figure above, the region between the pink bands is the AOR for the pump.

6.4.3 Best Efficiency Point (BEP)

The best efficiency point or BEP is the flow rate on the head – flow curve at which the efficiency of the pump is maximum. In the figure above, the green line indicates the BEP. At the BEP the hydraulic efficiency is maximum and internal losses are minimum. All flow rates to the right or left of BEP have lower efficiencies.

6.4.3.1 Significance of BEP

1) *BEP as a measure of optimum energy conversion*



When sizing and selecting centrifugal pumps for a given application the pump efficiency at design should be taken into consideration. The efficiency of centrifugal pumps is stated as a percentage and represents a unit of measure describing the change of centrifugal force (expressed as the velocity of the fluid) into pressure energy. The BEP is the area on the curve where the change of velocity energy into pressure energy at a given flow rate; in essence, the point where the pump is most efficient.

2) BEP as a measure of mechanically stable operation

The impeller is subject to non-symmetrical forces when operating to the right or left of the BEP. These forces manifest themselves in many mechanically unstable conditions like vibration, excessive hydraulic thrust, temperature rise, and erosion and separation cavitation. Thus the operation of a centrifugal pump should not be outside the AOR. Performance in these areas induces premature bearing and mechanical seal failures due to shaft deflection, and an increase in temperature of the process fluid in the pump casing causing seizure of close tolerance parts and cavitation.

3) BEP as an important parameter in calculations

BEP is an important parameter in that many parametric calculations such as specific speed, suction specific speed, hydrodynamic size, viscosity correction, head rise to shutoff, etc. are based on capacity at BEP. Many users prefer that pumps operate within 80% to 110% of BEP for optimum performance.

6.4.4 Maximum Flow (Pump Runout)

Pumps are never operated at flow rates beyond a certain point since severe mechanical damage occurs and the motor overloads. This is the reason why head – flow curves are not plotted all the way upto zero head point.

The end of the manufacturer's pump curve is the maximum flow rate, beyond which the pump may experience excessive cavitation and vibration. At high flow rates, the velocity of liquid of liquid is very high which leads to increased losses in the pump and drop in pressure of the liquid. Radial flow pumps may overload or overheat the motor if operated beyond the end of the curve.

Process duty or Transfer duty?

Pump selection criteria lay substantial emphasis on the type of duty the pumps will be subjected to in the field. Depending on whether the required operation is for process or for transfer, the pump may selection may vary.

1) *Process duty:* In this case, the pump is expected to deliver the desired constant flow against a constant head i.e. the duty point of the pump does not vary substantially with time. In this scenario it is important to select the pump where the duty point is as close as possible to the BEP.
2) *Transfer duty:* In case of transfer duty, the pump is expected to merely transfer a certain amount of liquid from place A to B against a constant (or sometimes varying) head. In this case, the operation point of the pump shifts with time. The pump selected must be stable within the expected variation of the duty point and the selection must incorporate a margin to the left and right of the BEP.