Lecture Nine

Pumps

Pumps are mechanical devices used to move fluids (liquids or gases) from one place to another by increasing their pressure or flow rate. They're essential in systems like water supply, oil and gas, chemical processing, and heating/cooling systems

There are many different types of pumps are in use depending on the flow properties of the fluid as well as the required pressure.

Pumping requires energy and the wrong selection may leads to higher costs and poor performance. Therefore, it is essential to use the correct pump that meets the system requirement.

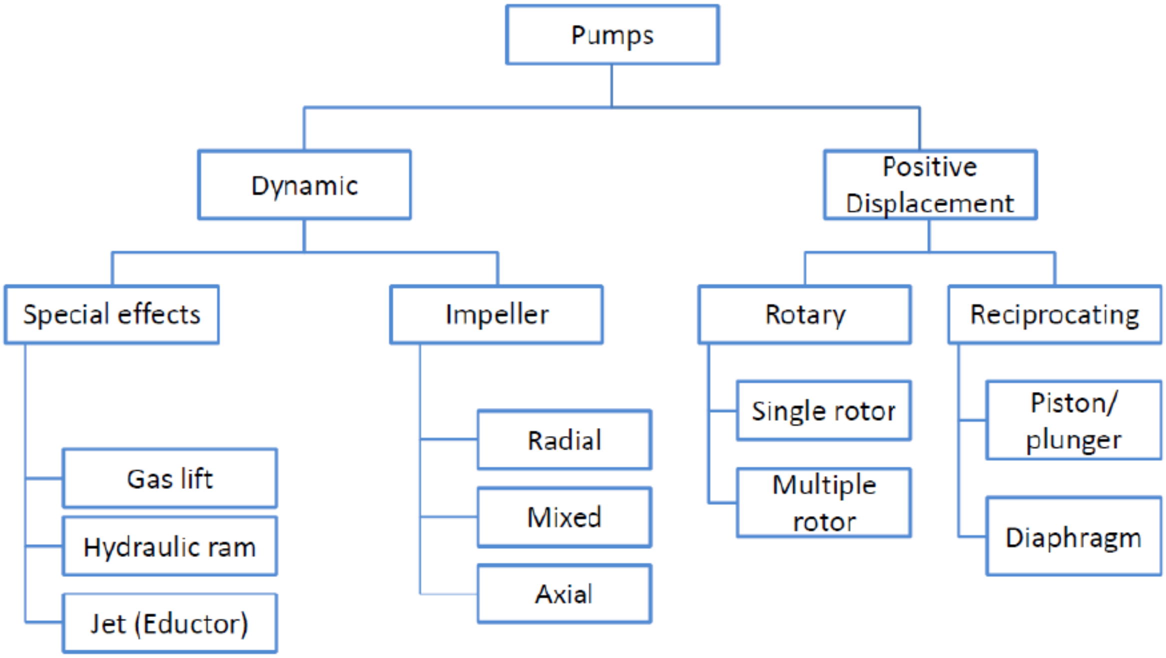
Classification of pumps

Pumps move liquid from one point to the other by adding energy to the liquid it pumps. This energy converts into a higher pressure generating a flow. A closer look shows that, even though there are many different types, there are only two forms of energy addition to the fluids:

(1) continuously working on the fluid generating higher kinetic energy that converts into pressure .

(2) increasing pressure by displacing the liquid.

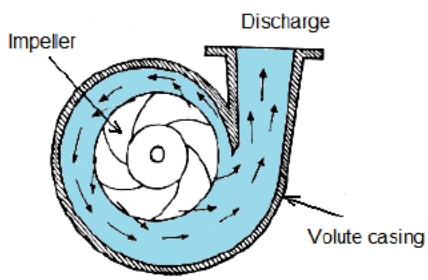
Pumps that use the first mechanism are called the dynamic pumps. Positive displacement pumps use the second mechanism to generate the flow.

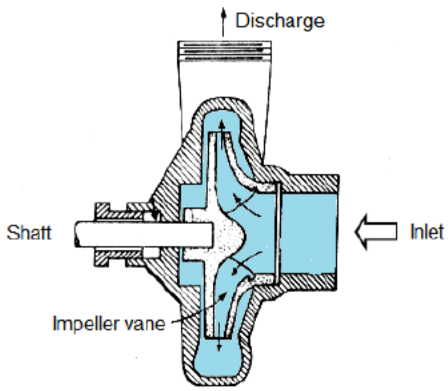


Dynamic pumps

The dynamic pumps mostly have Impellers that rotates around its center axis at a high frequency. Some pumps have inlet feeding liquid to the centre of the fast rotating impeller. The liquid is forced radially outward due to the centrifugal force. The discharge flow direction is usually normal to the inlet flow direction in these pumps. These are called **radial or centrifugal pumps**.

Centrifugal pumps are the most widely used. Liquid is introduced at the center of the fast rotating impeller (eye of the impeller). The centrifugal force acting on the liquid enforces radial flow. The fluid gains velocity increasing the kinetic energy. The curved vanes minimize the energy losses. As the liquid leaves the impeller it follows the channel with gradually increasing flow area between the impeller and the volute casing. As the cross sectional area increases pressure is gained at the expense of the kinetic energy. As a result a higher pressure is realised at the outlet. The pressure it generated is called the pressure head or simply the *head*.





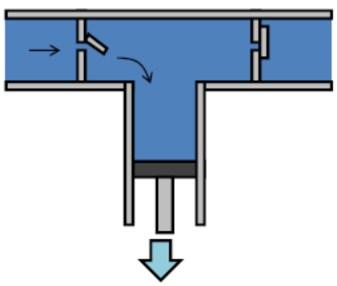
(a) A centrifugal pump

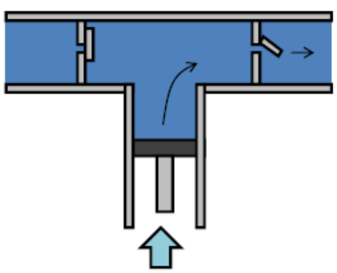
In another type of pumps, the impeller is placed in concentric with the conduit as shown in Figure 7.3(b). A propeller is used as the impeller that induces axial flow when rotating. They are called **axial pumps**.

(b) An axial pump

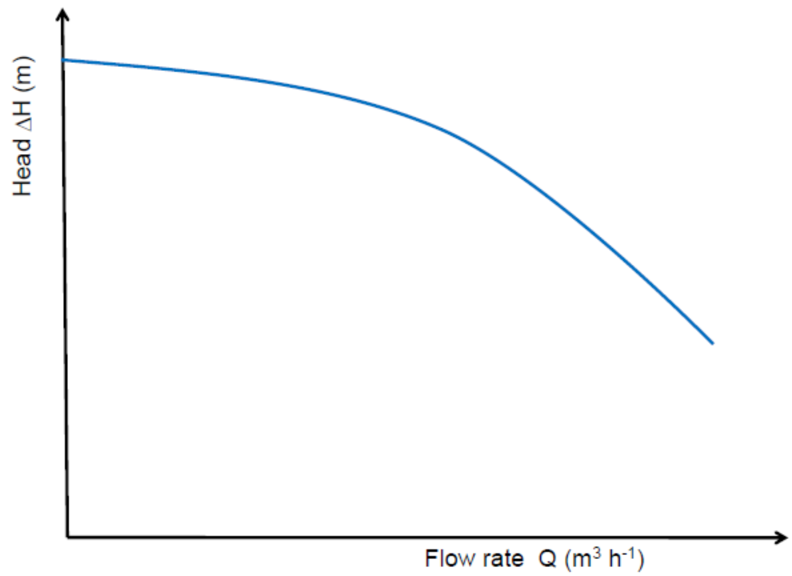
Positive displacement pumps

Positive displacement pumps effectively push the liquid creating higher pressure. The periodic operation of a piston (reciprocating pumps) or a diaphragm displaces the liquid continuously. Figure 7.4 shows the concept of the reciprocating pump. Consider a pipe section with a Tee. The two ends on the straight section are fitted with non-return valves and the side third is fitted with a piston. The non-return valves are fitted in a way that flow would occur only in one direction; left to right in this example. When piston withdraws, the non-return valve on the left hand side opens allowing liquid to fill the cavity. The non-return valve on the right remains closed preventing the back flow. On the compression stroke, the left valve closes and the valve on the right will open allowing liquid to flow out under the pressure generated by the piston. Diaphragm pumps works on the same principle but instead of a piston a flexible diaphragm is used.

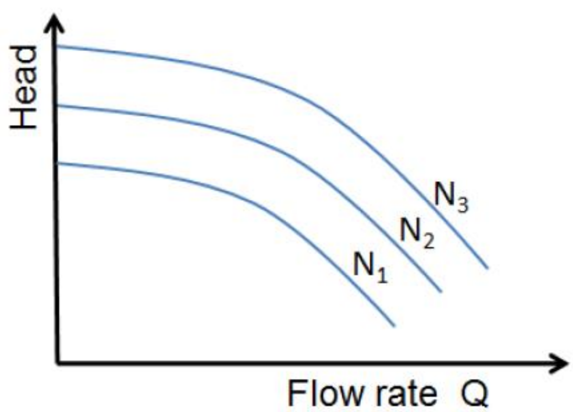




There is a direct relationship between the head that a pump can generate and the through put of the pump. The head a pump can generate depends on the impeller diameter and the rotational speed (rpm). For a fixed impeller speed, the total head against the capacity curve is shown in Figure 7.7.



With increasing impeller speed the head increases. This appears as a shift of the curve as a whole.



Why Does Head Decrease as Flow Rate Increases?

When flow rate increases, the pump is trying to push more fluid through the same space. As a result:

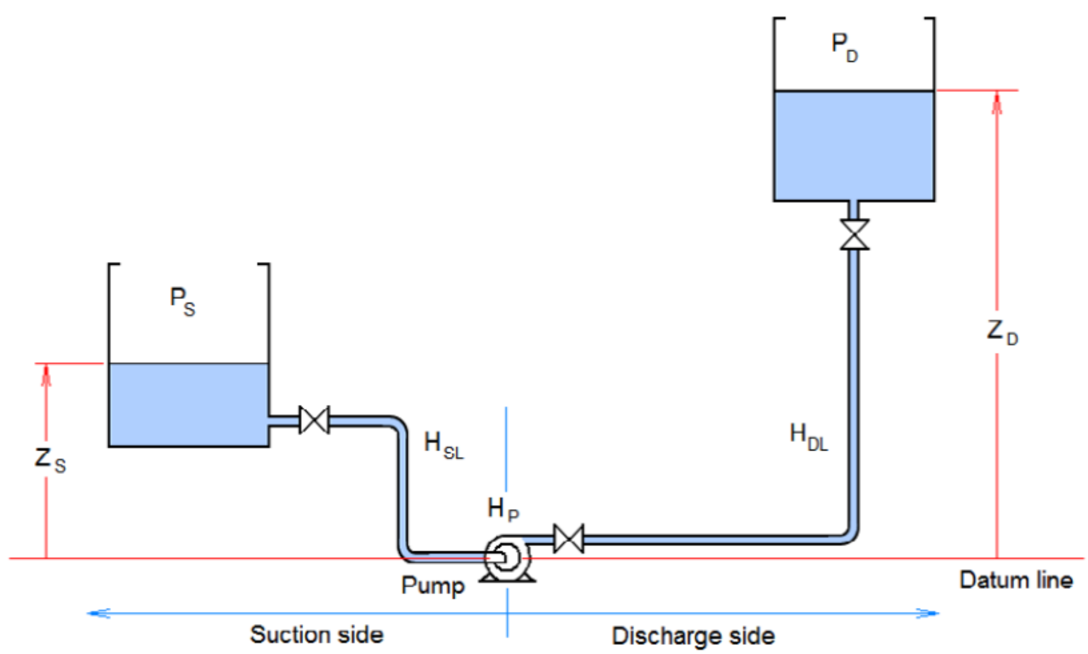
- More energy is used just to move the larger volume of fluid
- Less energy is available per unit of fluid to convert into pressure (head)

This means:

Higher flow → lower pressure head per unit volume

Pump head requirements

Consider a typical pumping system that contains a reservoir from which the liquid is pumped from and a discharge reservoir in to which the liquid is pumped into with a pump placed in between as shown in Figure 7.10. All three are linearly connected using appropriate pipes and other fittings. Usually there should be two valves that isolate the two reservoirs from the rest of the piping system and another valve immediately after the pump for throttling.



Consider a hypothetical vertical line that passes through the centre of the pump. The side on which the inlet line is called the suction side and all the variables on this side are denoted with a subscript "S". The side to which the pump is pumping liquid is called the discharge side and the variables are denoted by a subscript "D".

The elevation head is measured upwards from the arbitrarily selected datum line. It is customary to select the datum line to pass through the center of the pump. The elevation head on suction and discharge sides are taken as Z_S and Z_D respectively. The pressure above the liquid level in the suction side is P_S and the pressure above the liquid level on the discharge side reservoirs is P_D.

The losses in pipe lines are due to the pipe friction and the fittings. Consider the suction side. There is a sudden contraction imparting head loss where the liquid enters the pipe. The head loss in the valve depends on the degree it is opened. There are two long radius bends causing head loss too. Total of all these losses in the suction side is taken as H_{SL}. Similarly the total head loss due to friction and fittings in discharge side is denoted by H_{DL}.

Bernoulli's equation and system head

$$P + \frac{1}{2}\rho V^2 + \rho g z = \text{constant}$$

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + z_2 = E$$

Consider a fluid element starting at the free liquid surface in the suction reservoir that goes passing the pump to the free surface of the discharge reservoir. The total mechanical energy it possesses when it is at the suction side free surface is given by:

$$E_S = \frac{P_S}{\rho g} + \frac{v_s^2}{2g} + Z_s$$

As this fluid particle flows through the suction side H_{SL} amount of head is lost due to the friction and fittings. The pump adds energy to this element as it passes through the pump. The amount of the energy it gains is the head provided by the pump H_P. Further H_{DL} amount of head is lost due to the friction and fittings on the discharge side. If we take the inventory for the head (energy per unit weight) the total head of the fluid element is given by:

$$E_S - H_{SL} + H_P - H_{DL} \quad \dots (9.1)$$

Since the energy is conserved, this should be equal to the energy of the fluid particle, E_D, when it is at the free surface of the discharge reservoir.

$$E_D = \frac{P_D}{\rho g} + \frac{v_D^2}{2g} + Z_D$$

Therefore,

$$E_S - H_{SL} + H_p - H_{DL} = \frac{P_D}{\rho g} + \frac{v_D^2}{2g} + Z_D \quad \dots (9.2)$$

By substituting (9.1) in (9.2) and rearranging terms gives the following equation for the pump head:

$$H_P = \frac{(P_D - P_S)}{\rho g} + \frac{(v_D^2 - v_s^2)}{2g} + (Z_D - Z_s) + (H_{DL} + H_{SL}) \quad \dots (9.3)$$

Considering that the v_D and v_S in above equation refer to the velocities at the free surfaces of the reservoirs the difference $(v_D{}^2 - v_S{}^2)$ can be neglected. The velocity is simply the time rate at which the liquid level drops in the suction side and the rate at which the liquid level rises in the discharge side. These are not considerably large values since the cross sectional areas of the two reservoirs are rather large compared to the pipe diameters used. Hence the difference is even smaller compared to the datum head difference and the losses. Therefore, the equation (9.3) can be reduced to:

$$H_P = \frac{(P_D - P_S)}{\rho g} + (Z_D - Z_s) + (H_{DL} + H_{SL}) \quad \dots (9.4)$$

Equation (9.4) could be rewritten as below:

$$H_P = \left(\frac{P_D}{\rho g} + Z_D + H_{DL}\right) - \left(\frac{P_S}{\rho g} + Z_s - H_{SL}\right)$$

Where:

Suction head $H_S = \frac{P_S}{\rho g} + Z_s - H_{SL}$

Discharge head $H_D = \frac{P_D}{\rho g} + Z_D + H_{DL}$

The difference between the discharge head and the suction head gives the required pump head to pump liquid from suction reservoir to discharge reservoir at a given flow rate.

Further simplification is possible if the reservoirs are open to the atmosphere. Then (P_D - P_S) vanishes. The equation (9.4) simplifies to:

$$H_P = (Z_D - Z_s) + (H_{DL} + H_{SL})$$

If the suction side reservoir is below the datum line, then ZS is negative and the sum of the elevation is taken rather than the difference. The SI units of the pump head Hp is metres.

Power requirement

The pump head in this case is the energy received by a unit weight of the liquid. Therefore, the hydraulic power input can be calculated by multiplying the pump head by the mass flowrate and the acceleration due to gravity.

$$P = H_P \dot{m} g$$

The mass flowrate can be expressed in terms of the density and the volumetric flowrate.

$$P = H_P \dot{Q} \rho g$$

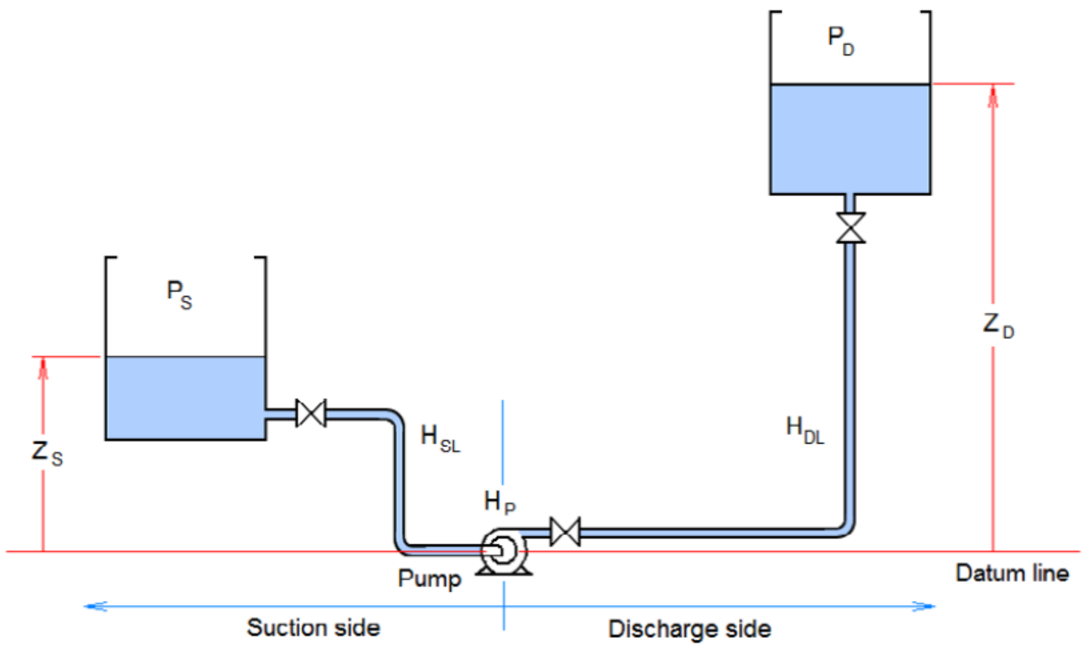
P is the amount of power received by the liquid. The shaft power, P_{Shaft}, could be calculated if the efficiency of the pump, η is known.

$$P_{Shaft} = \frac{P}{\eta} = \frac{H_P \dot{Q} \rho g}{\eta}$$

Example:

Dilute sulphuric acid is to be pumped between two storage tanks using 800 m long pipe with 5 cm inner diameter at a rate of 10 ton/h. The overall vertical difference between the liquid levels of the two tanks is 15m. The tanks are open to atmosphere through vents. The specific gravity of the acid is 1.3 and the viscosity is 0.001 Pa s. What actual power requirement of the centrifugal pump used if the efficiency of the pump is 63%? Given that, the sum of losses in both suction and discharge section is

$$(H_{DL} + H_{SL}) = 23.6\ m$$



Soln:

First, calculate the head that has to be provided by the pump using equation (9.4).

$$H_P = \frac{(P_D - P_S)}{\rho g} + (Z_D - Z_s) + (H_{DL} + H_{SL})$$

The tanks are open to the atmosphere. Therefore, $(P_D\text{-}P_S) = 0$.

$$H_P = (Z_D - Z_s) + (H_{DL} + H_{SL})$$

The overall vertical difference between the liquid levels in the two tanks is given as 15 m. Therefore,

$$(Z_D - Z_s) = 15m$$

The required pump head:

$$H_P = (Z_D - Z_s) + (H_{DL} + H_{SL}) = 15m + 23.6\ m = 38.6\ m$$

Then, the required power is:

$$P = H_P \dot{m} g$$

When: $Mass\ flowrate = 10\frac{Tonns}{hr} = \frac{10\times1000}{3600}\frac{kg}{s} = 2.78\ kg\ s^{-1}$

$$P = 38.6 \times 2.78 \times 9.81\ \mathrm{W}$$

$$= 1.053\ kW$$

The pump efficiency is 63 %. Therefore, the actual power (shaft power) is:

$P_{Shaft} = \frac{P}{\eta}$ = 1.053 kw/0.63=1.67 kw