1 Introduction

1.1 What is a pump?

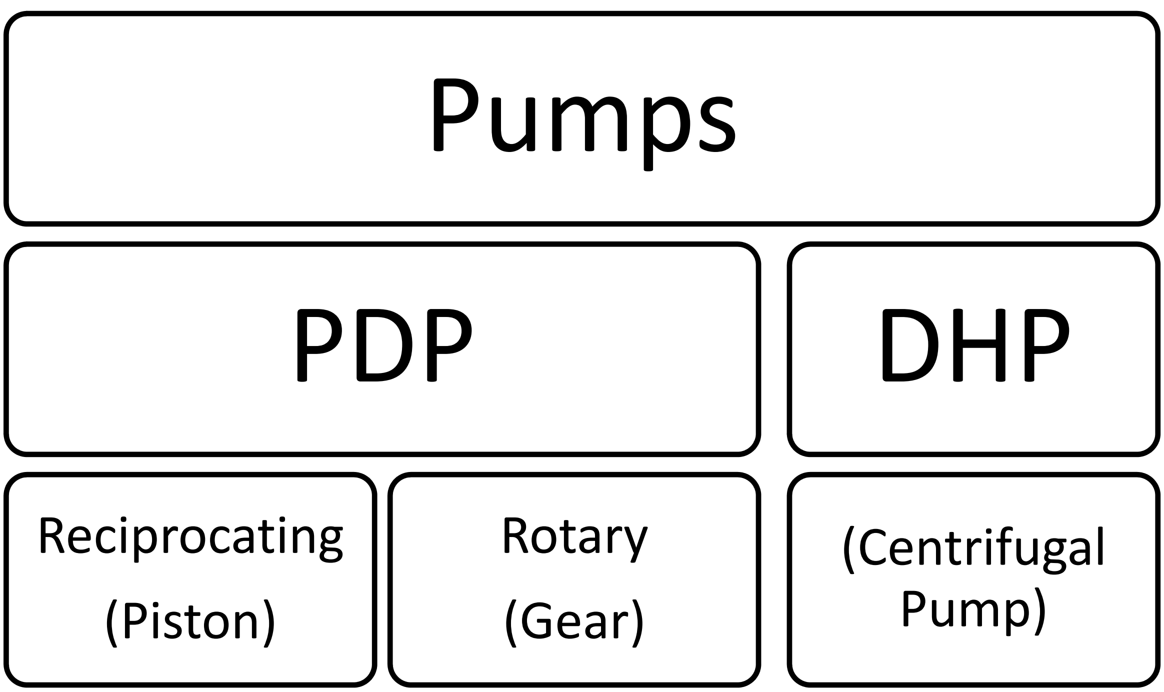
A pump is a mechanical device that is used to give energy to a flowing liquid such that the liquid can overcome the resistance in the hydraulic system. Simply the pump converts mechanical energy into hydraulic energy given to the flow.

1.2 Applications

Pumps are found in numerous applications in industry and everyday life such as:

- Pumping oil and petroleum derivatives from production or storage site to the market (e.g. SUMED pipeline).
- Pumping drinking/waste water to/from homes.
- Firefighting applications.
- In any automobile exists at least three pumps of different types:
    - Lubrication pump.
    - Cooling water pump.
    - Fuel pump.

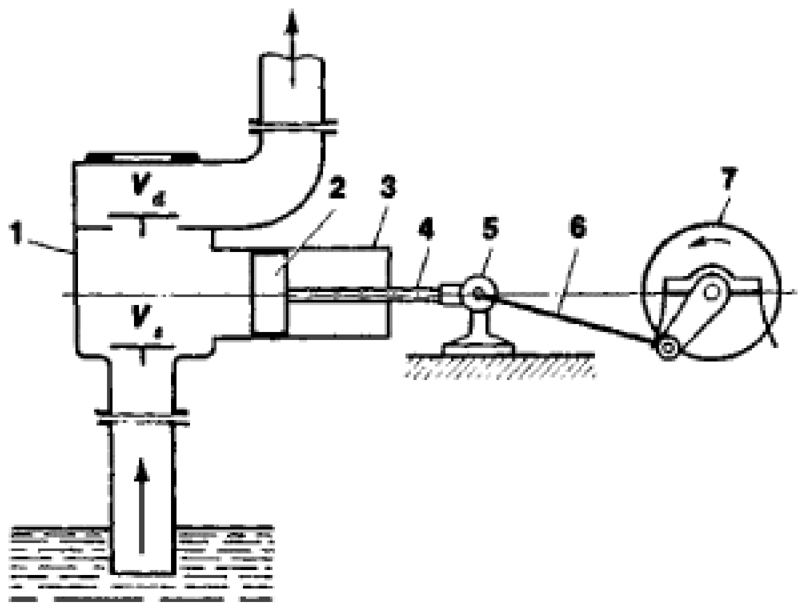
1.3 Types



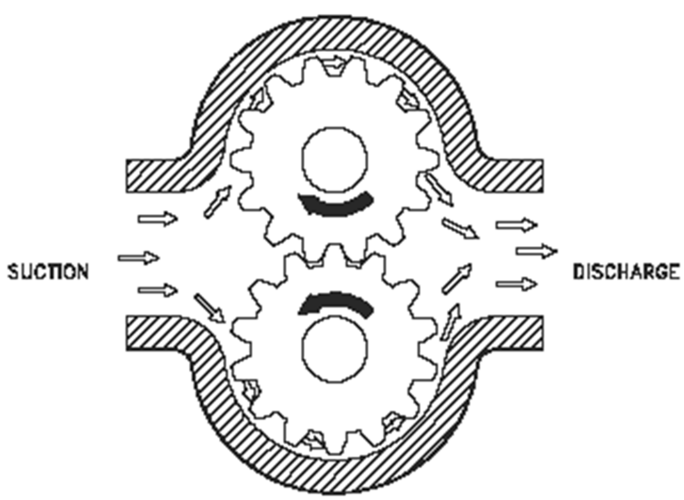
1.3.1 Positive Displacement Pumps (PDP)

PDPs displace a fixed amount of liquid from suction side to discharge side. These pumps give very high pressures but little flow rates. So they are used in fluid power applications to pump oil in heavy duty machines (cranes, excavators, etc.).

Piston pump



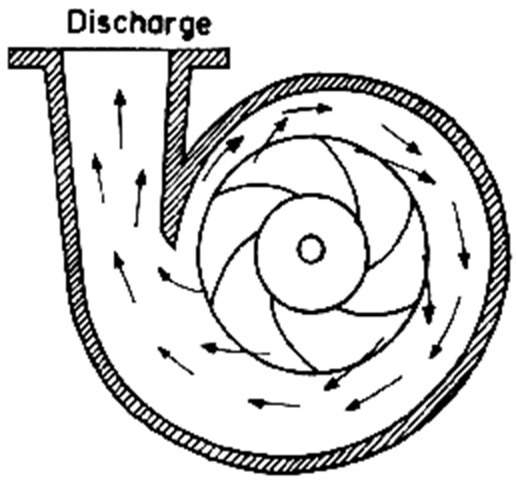
Gear pump



1.3.2 Dynamic Head Pumps (DHP)

DHPs increase the kinetic energy of the flow which is then converted to pressure. These pumps give very large quantities at low pressures. So they are used in liquid transportation to pump e.g. to pump water from treatment stations to homes.

Centrifugal pump



a. Volute centrifugal pump cross section

1.3.3 Comparison

There are three main performance differences between the two pumps:

- DHPs provide a smooth, continuous flow; PDPs have a pulse with each stroke or each time a pumping chamber opens to an outlet port.
- Pressure can reduce a DHP's delivery. High outlet pressure can stop any output; the liquid simply recirculates inside the pump. In a PDP, pressure affects the output only to the extent that it increases internal leakage.
- DHPs, with the inlets and outlets connected hydraulically, cannot create a vacuum sufficient for self-priming i.e. suck liquid from a low-level suction tank; they must be started with the inlet line full of liquid and free of air. PDPs often are self-priming when started properly.

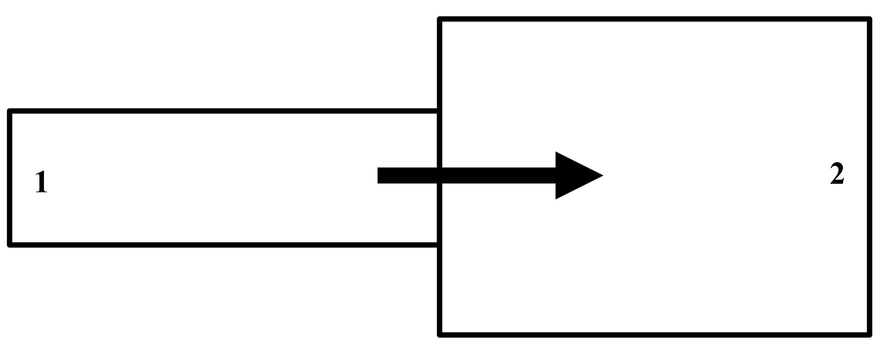
	PDP	DHP
Pressure	High	Low
Flow rate	Low	High
Applications	Fluid power	Fluid transportation
Fluid	Heavy liquids (high viscosity) e.g. oils	Light liquids (low viscosity) e.g. water
Relief (Safety) valve	Needed	Not needed
Flow control valve	Can't be used	Used
Check (Non-return valve) valve	Needed at delivery side only	Needed at delivery side and sometimes at suction side
What if closed the delivery valve	The pump continues displacing liquid at the same rate till causing damage to the weakest part in the pump	The pump simply stirs the liquid in its casing. After a long time the liquid temperature rises and may destroy items with low temperature tolerance
Filter	Fine filter	Coarse filter (strainer)

2 Fluid mechanics

2.1 Basics of fluid flow

2.1.1 Basic equations

For the liquid flow in the shown pipeline:



Continuity equation:

$$Q = A_1 V_1 = A_2 V_2$$

Bernoulli's equation:

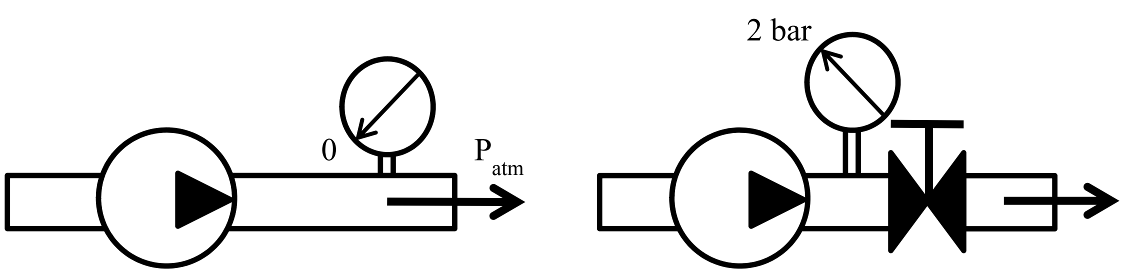
$$\frac{P_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + Z_2 + \frac{V_2^2}{2g} + h_l$$

Where;

h_l	=	the losses in the pipe
	=	friction loss + eddy loss
	=	$f\frac{l}{d}\frac{V^2}{2g} + \sum k\frac{V^2}{2g}$

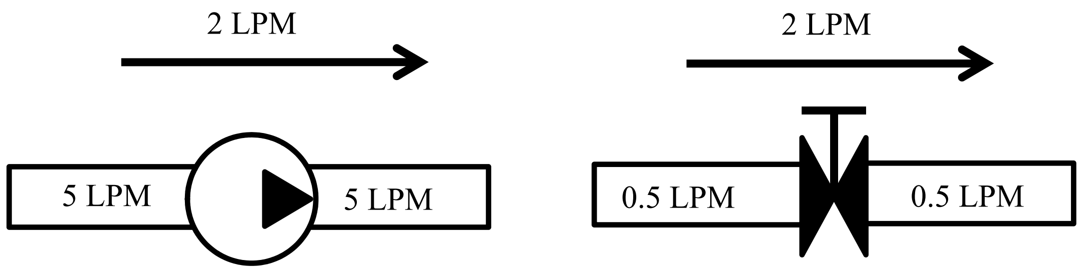
2.1.2 System pressure

The pump doesn't create pressure; it just pushes the liquid against system resistance. As the system resistance increases, the pump gives the liquid a greater force and hence the pressure increases. Therefore, the pressure depends on the system resistance rather than the pump.

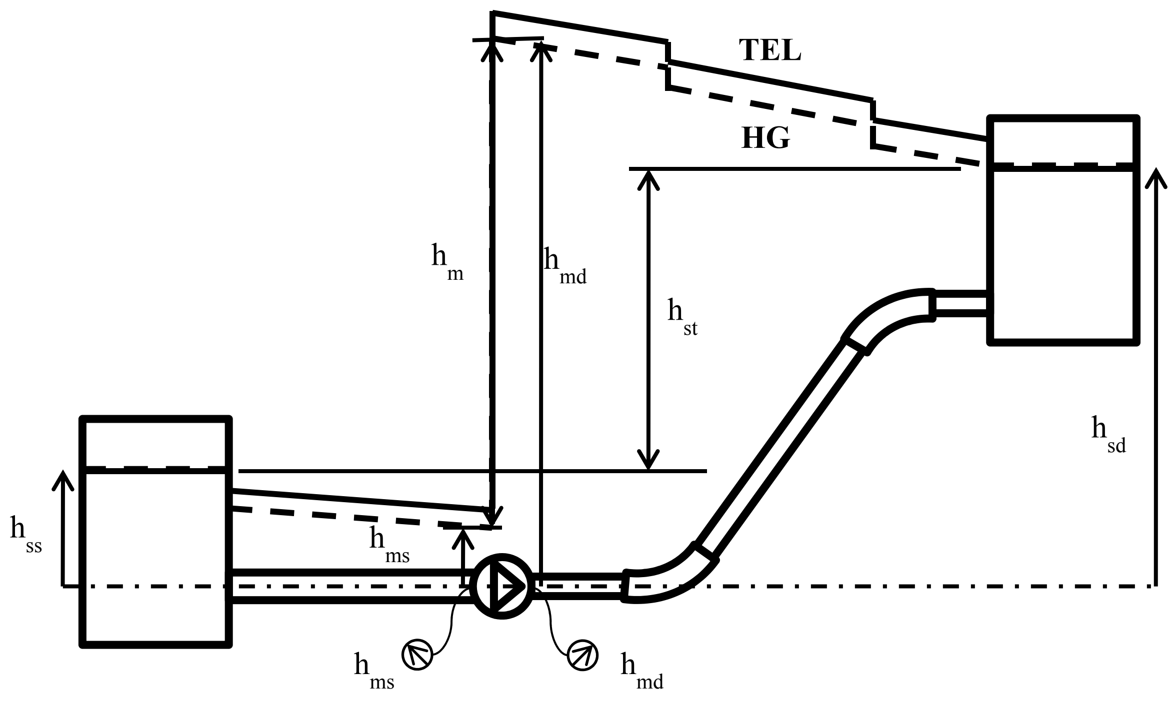


2.1.3 Pump and valve

Neither the pump nor valve creates or destroys liquid mass i.e. the liquid flow rate is the same up/downstream of the pump or valve. The pump/valve just increases/decreases liquid pressure which increases/decreases the liquid flow rate throughout the system.



2.2 System curve



Where;

h_{ms}	=	pump suction head = manometer (gage) reading in the suction side
	=	$h_{ss} - h_{ls} - \frac{V_s^2}{2g}$
h_{md}	=	pump delivery head = manometer (gage) reading in the delivery side
	=	$h_{sd} + h_{ld}$

h_m = the head developed by the pump = system resistance on the pump

$$= h_{md} - h_{ms}$$

$$= h_{st} + h_{lt} + \frac{V_s^2}{2g}$$

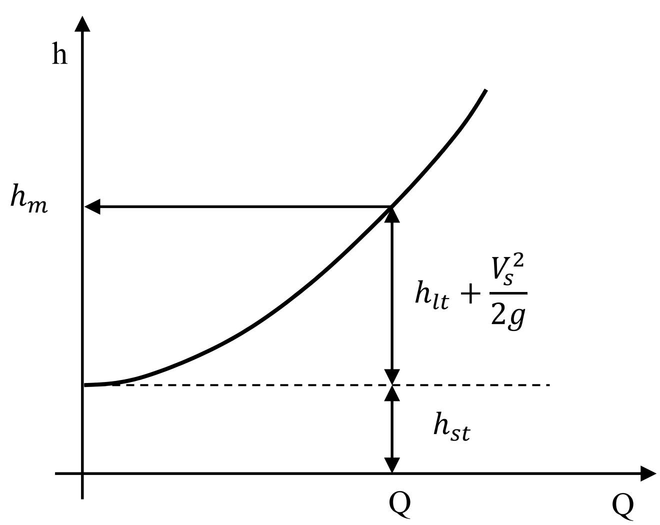
The last equation is called "system equation". This equation states that the pump develops head to withstand three kinds of system resistance; namely,

- the static head i.e. the head difference between the suction and discharge tanks,
- the losses (friction and eddy) in the pipeline, and
- the energy required to accelerate the static fluid in the suction tank.

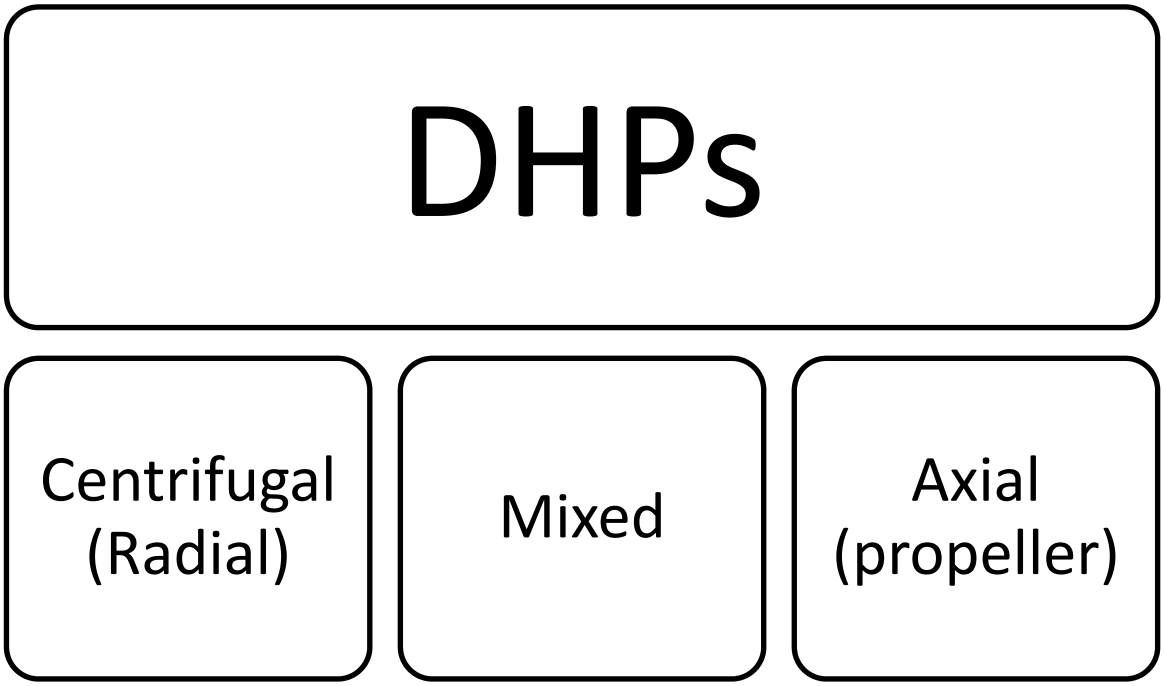
Knowing that the losses (both of friction and eddy types) are functions of the kinetic energy. Replacing the velocity with Q/A yields;

$$h_m = h_{st} + kQ^2$$

which is another form of the system equation.

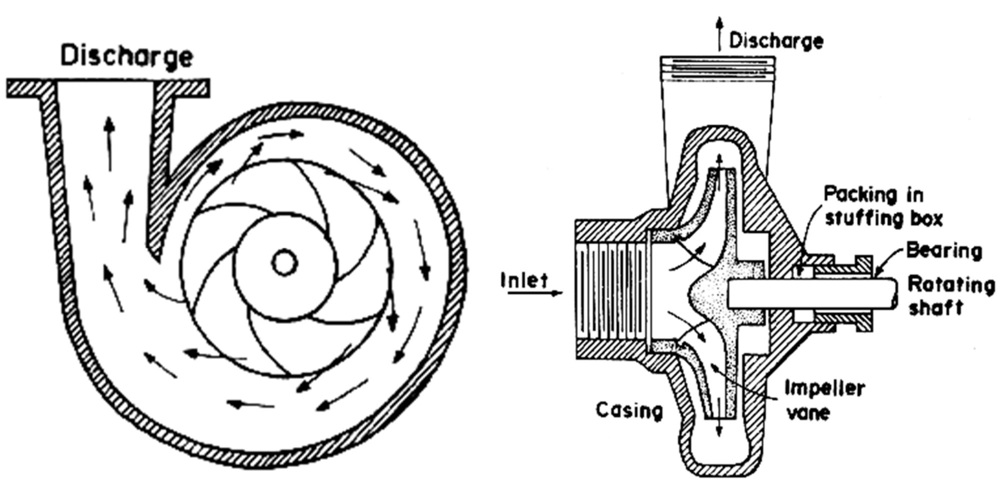


3 Dynamic Head Pumps (DHPs)



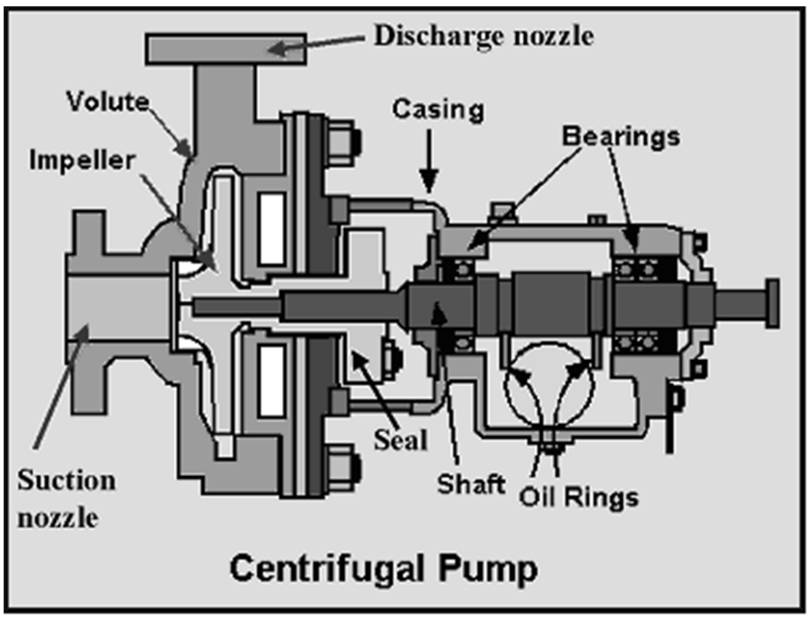
3.1 Centrifugal pump

3.1.1 Construction and theory of operation

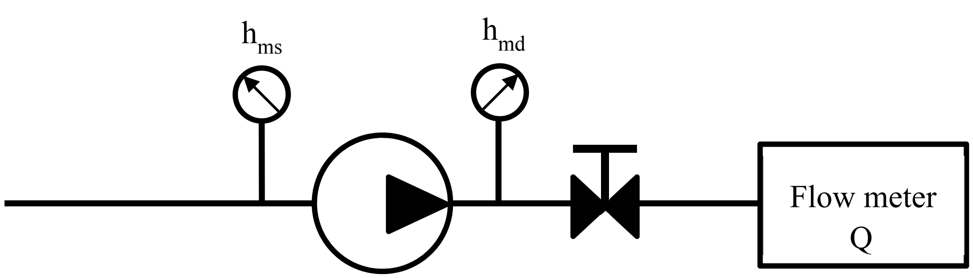


- The rotation of the impeller produces centrifugal force that sucks liquid from the impeller eye and discharges it to the periphery. The pressure in the emptied eye decreases and hence it sucks a new amount of liquid. Whereas the pressure at the periphery of the impeller increases and liquid is pumped out of the centrifugal pump through a pipe connected to the periphery of the casing.

- The space between the impeller tip and volute casing increases gradually along the spiral path (in the front view). The liquid flow increases along the spiral as more liquid comes from the successive blades. The increase in area keeps the velocity constant along the path and hence reduces friction losses.
- The streamlined shape of the vanes (in the side view) aims at reducing the eddy losses at the impeller hub.



3.1.2 Performance



The pump performance can be obtained by testing the pump at different flow rates.

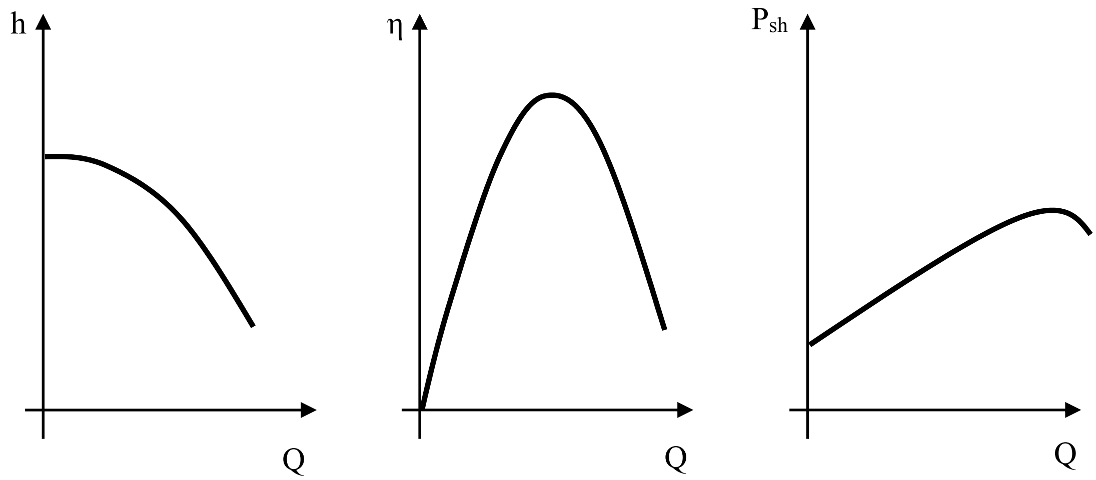
The pump efficiency is related to the shaft (input) power according to the relation:

$$P_{sh} = \frac{PQ}{\eta} = \frac{\gamma h Q}{\eta}$$

Where;

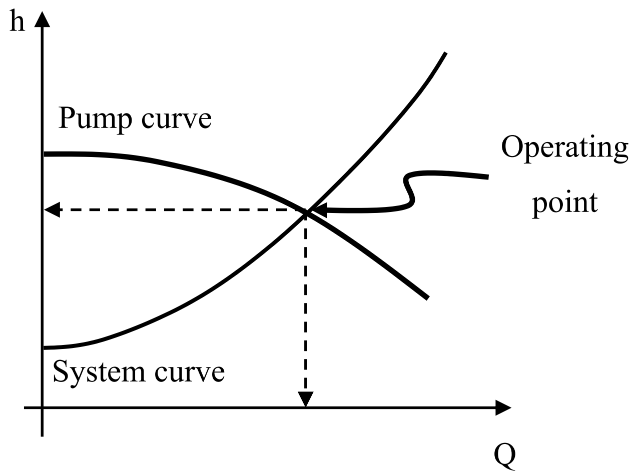
P = pressure difference across the pump

h = head difference across the pump (manometric head)



3.1.2.1 Operating point

The operating point is the point at which the force of the pump balances the resistance force of the system. This occurs at the intersection point between the pump performance curve and the system resistance curve.



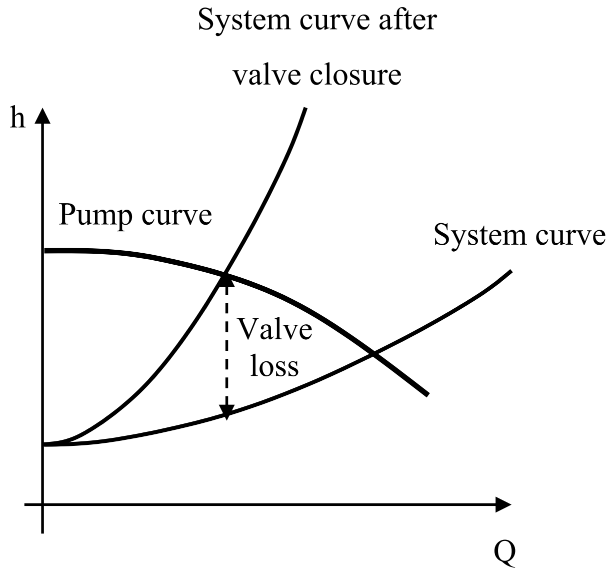
If the flow accidently increases/decreases beyond the operating point the pump force becomes lesser/greater than the system resistance and hence the flow decelerates/accelerates till the two forces get balanced again.

3.1.2.2 Flow control by valve closure

If the pump delivery valve is partially closed, the system resistance increases. Hence, the operating point shifts to a lower flow rate.

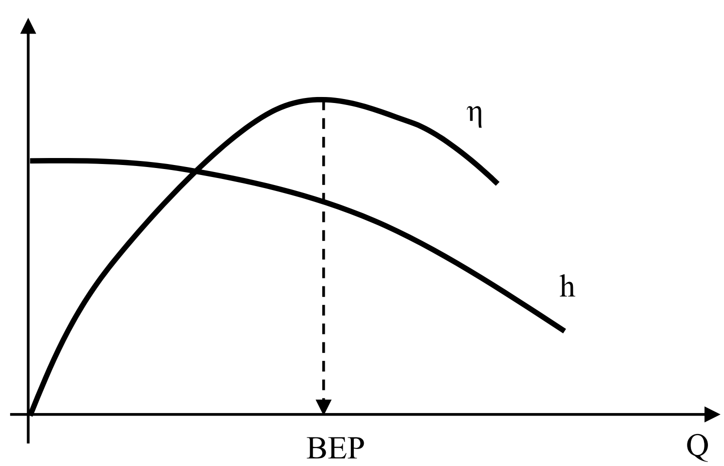
$$h_m = h_{st} + h_{lt} + \frac{V_s^2}{2g} = h_{st} + kQ^2$$

When the valve is partially closed, h_{lt} increases, k increases, the system curve becomes sharper and crosses the pump curve at a lower flow rate.



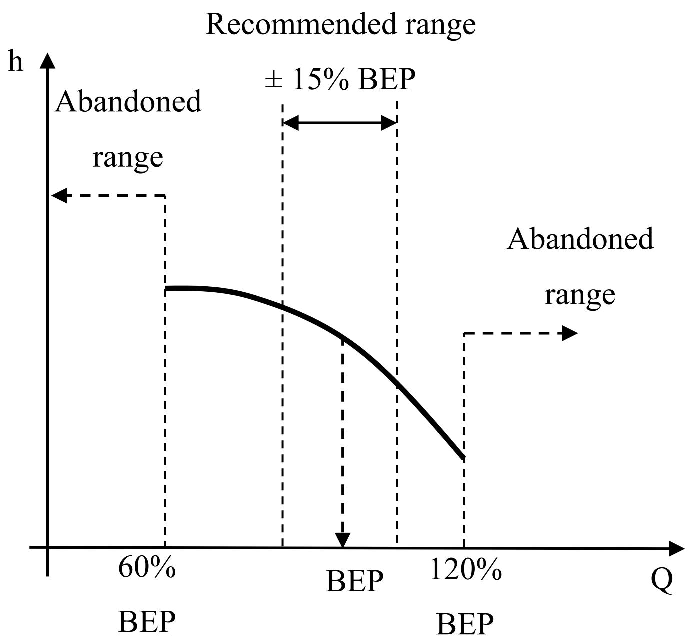
3.1.2.3 The Best Efficiency Point (BEP)

The pump design is held at a single point (flow rate and head) this point is called the Design Point. When operating the pump at this point it has the maximum efficiency. So the point is also called the Best Efficiency Point (BEP). When selecting the pump, it is normally targeted to operate the pump at this point; hence it is also called the normal flow point.



3.1.2.4 Operating range

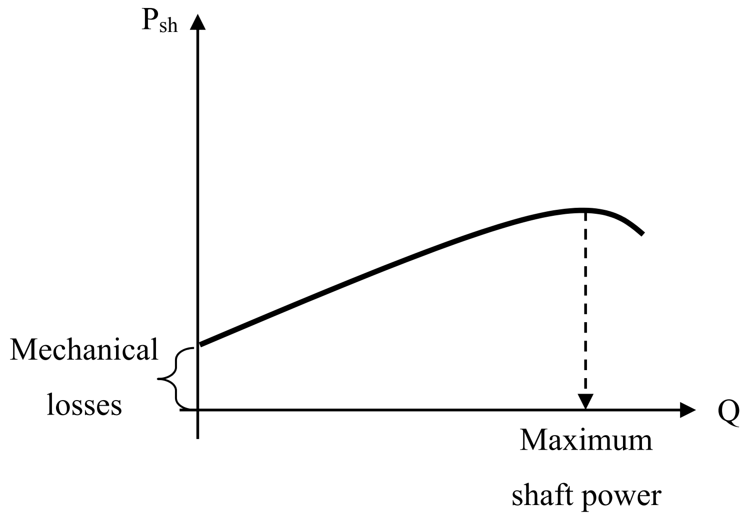
Operating the pump beyond the BEP (design point) not only decreases its efficiency but also subjects it to mechanical and hydraulic problems. Therefore the pump is recommended to operate in a range of ±15% around the BEP. On the other hand, the pump should never be operated at a flow rate lower than 60% of the BEP or it will be subjected to excessive vibrations that can destroy its bearings, or at a flow rate higher than 120% of the BEP or it will be subjected to cavitation that destroys its impeller as will be shown later.



3.1.2.5 Motor selection and starting

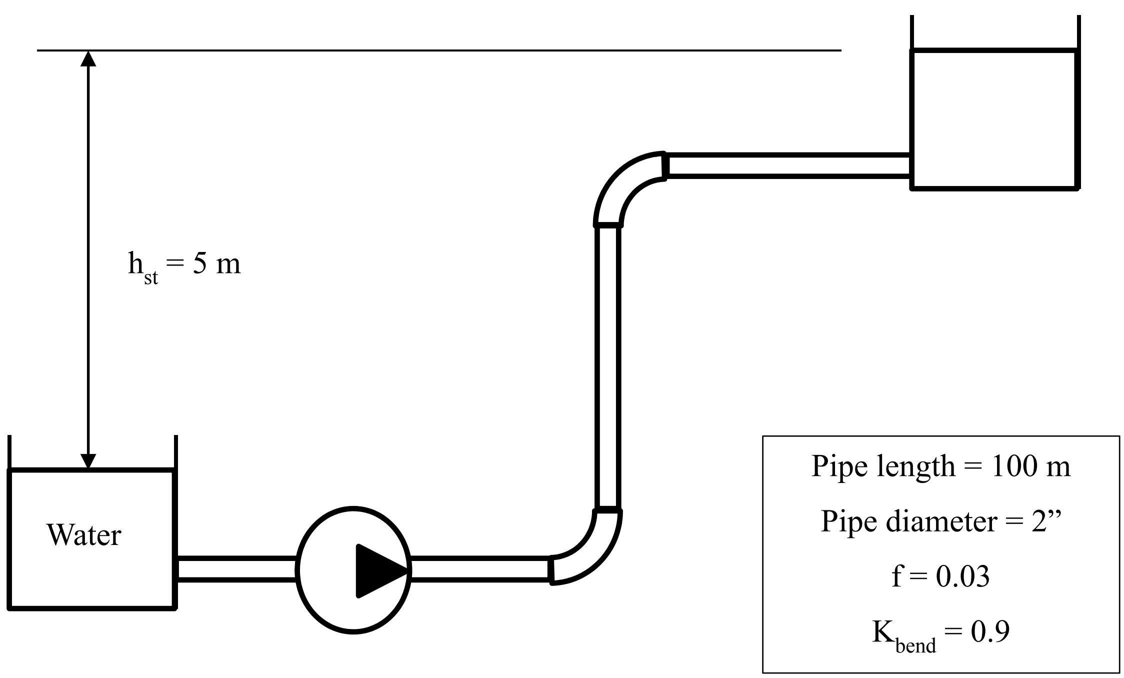
The motor is selected based on the pump maximum shaft power. This can be determined from the shaft power curve of the pump. A 15% safety margin is considered when selecting the motor.

One of the well-known characteristics of the induction electric motor is its high starting electric current i.e. when it is started it passes a current that is almost three times the load current. So it is preferred to start the equipment driven by the motor at its minimum load to protect the motor from overload. This applies to all the equipment driven by the induction motor such as centrifugal pumps, axial pumps compressors, etc. For the centrifugal pump, the pump loads minimum when the flow is zero. Hence, it is recommended to start the centrifugal pump with its delivery valve completely closed and open the valve gradually after a short period of time.



3.1.3 Pump selection

Assume we need to select a centrifugal pump that transfers 15 m^3/h in the shown hydraulic system.



- The first step is to derive the system equation:

$$h = h_{st} + h_l + \frac{{v_s}^2}{2g}$$

$$= 5 + f\frac{l}{d}\frac{v^2}{2g} + 0.5\frac{v^2}{2g} + 2K\frac{v^2}{2g}$$

$$= 5 + \left[0.03 \times \frac{100}{0.05} + 0.5 + 2 \times 0.9\right]\frac{v^2}{2g}$$

$$= 5 + 62.3\frac{v^2}{2g}$$

$$v = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}d^2}$$

$$h = 5 + 824{,}465Q^2$$

- Then calculate the pump manometric head at the required flow rate:

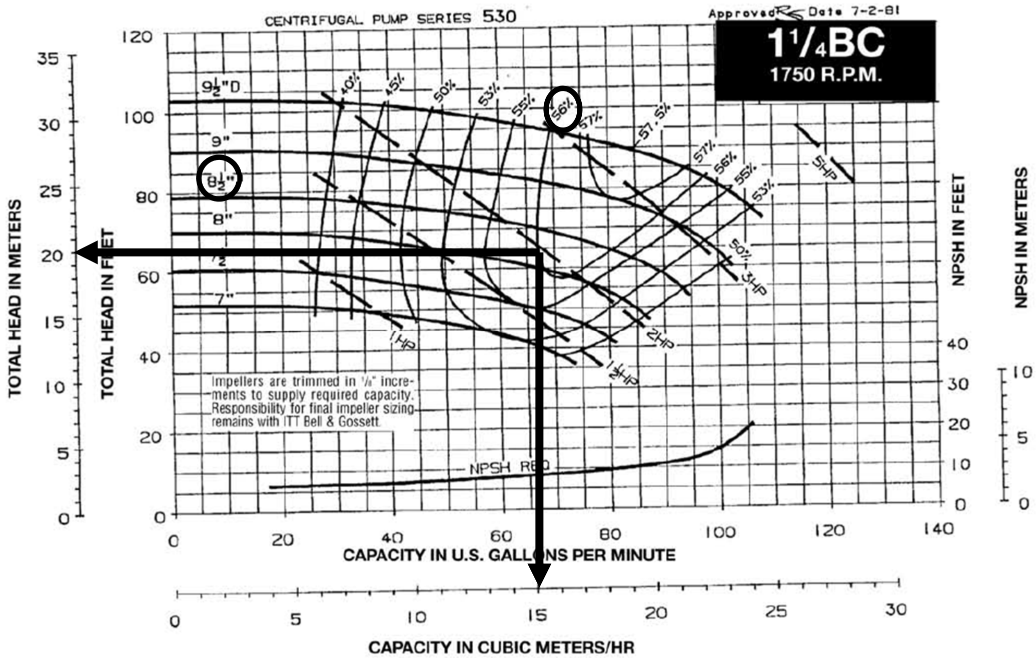
$$h = 5 + 824{,}465Q^2$$

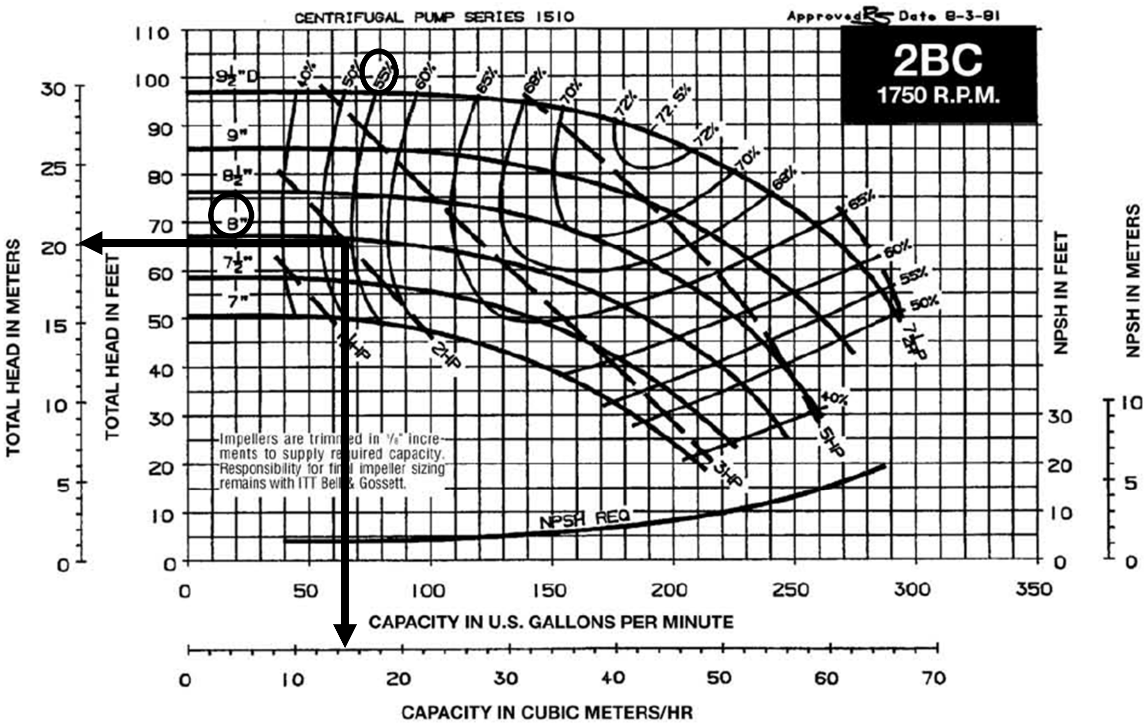
$$Q = 15\frac{m^3}{h} = \frac{15}{3600}\frac{m^3}{s}$$

Substitute…

$$\boxed{h = 19.31\ m}$$

- Go to the company selection manual or software and select the pump that satisfies the required head and flow rate at the maximum efficiency.



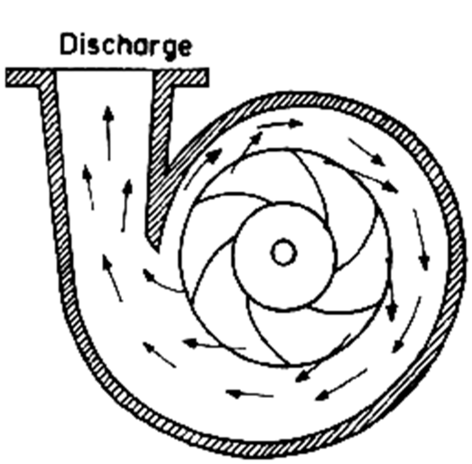


Select pump type **$1\frac{1}{4}$ BC** of diameter **8”**.

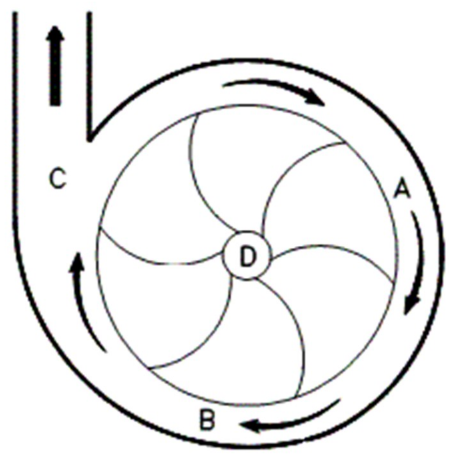
3.1.4 Types of centrifugal pump

3.1.4.1 Forward, radial and backward

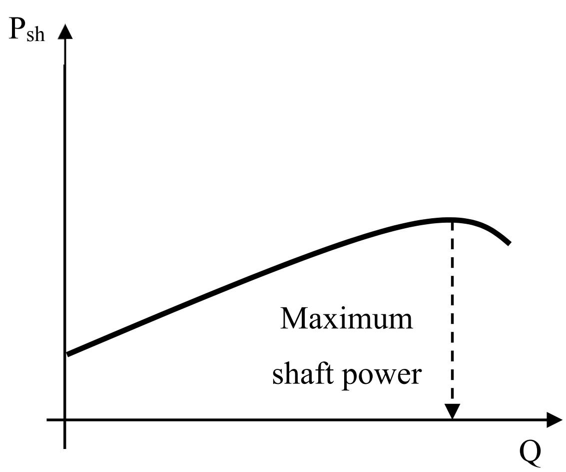
The theory of operation of the centrifugal pump is based on the centrifugal force. This centrifugal force would be generated (there will be flow from suction to delivery pipes) whatever the shape of the impeller blades. However, the backward blades have "self-limiting" power characteristics that protect the motor from overload.



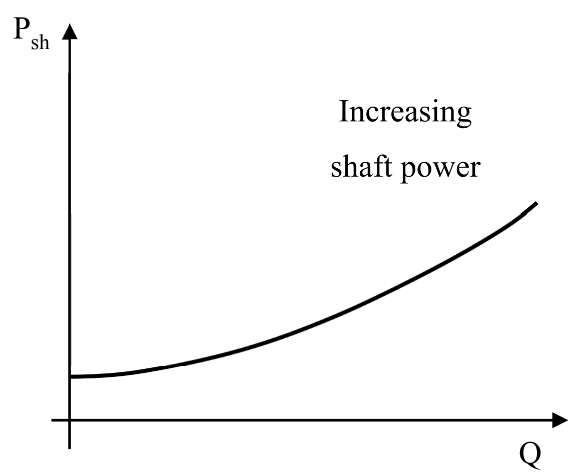
Backward blades



Forward blades



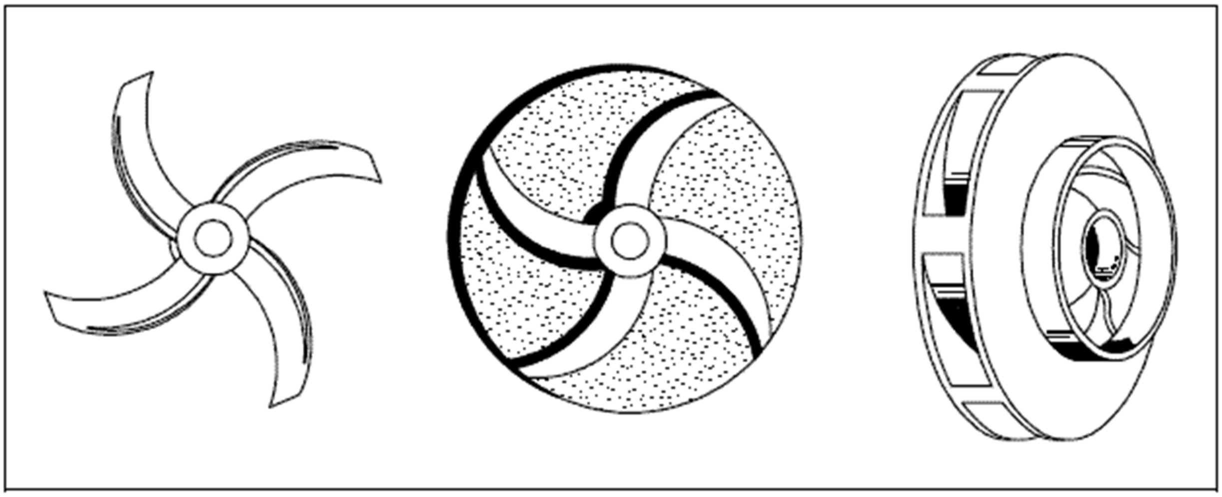
Backward blades



Forward blades

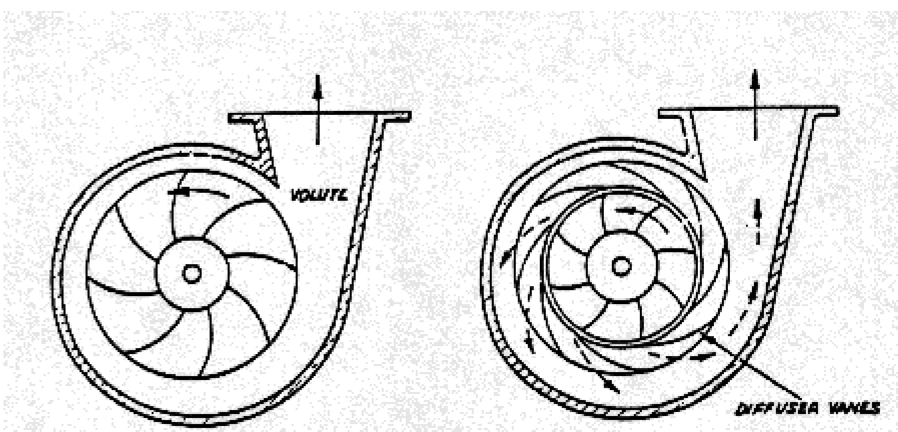
3.1.4.2 Open, semi-open and closed impeller

The open impeller is less prone to clogging by dirt so it’s used with unclean liquids or slurries. While the closed impeller is more sealed against leakage; hence it gives higher pressures.



3.1.4.3 Volute casing and diffuser casing

As mentioned before, the pump casing is designed of volute type to make the flow velocity constant or decrease, on the behalf of pressure. Sometimes, when high head is required, a diffuser is inserted around the impeller to contribute to the velocity decrease and pressure increase.

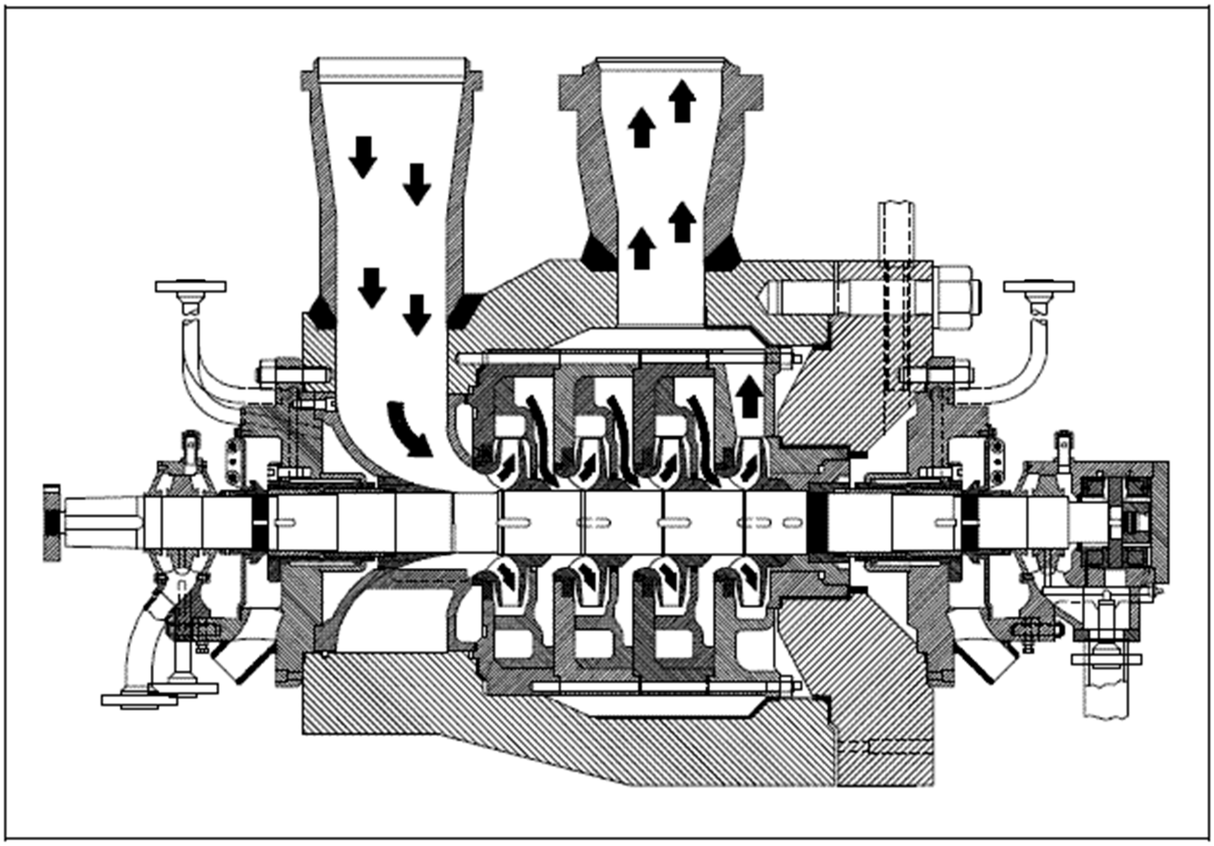


Centrifugal Pump with Volute

Centrifugal Pump with Vaned Diffuser Ring

3.1.4.4 Single and multistage

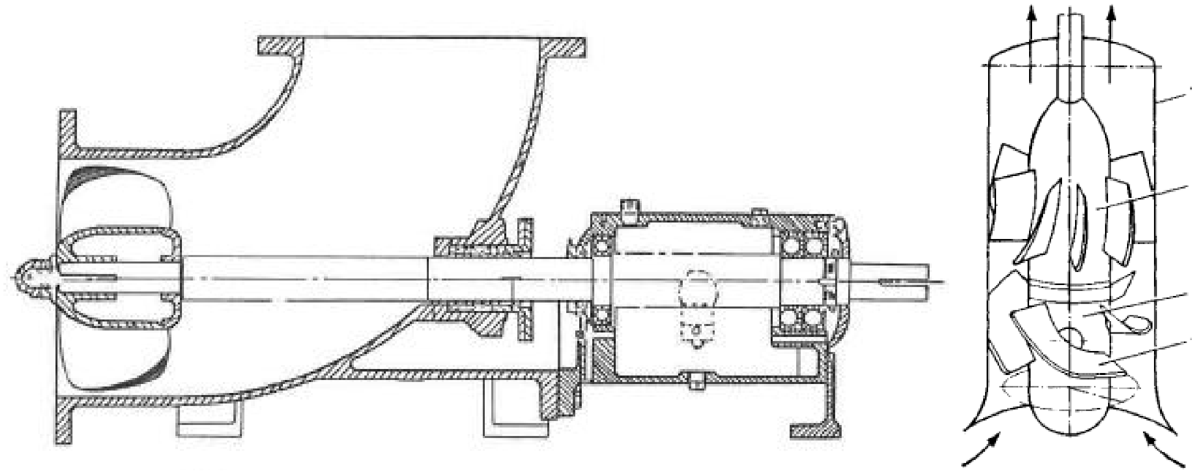
Whenever the head required can’t be attained by a single pump, another pump(s) is connected in series or for more convenience more impellers are arranged in series in the same pump casing. That is we get a “multistage centrifugal pump”.



3.2 Axial flow pump

3.2.1 Construction and theory of operation

In the axial flow pump (propeller pump) the propeller-like impeller pushes the flow such that it enters the pump and leaves it parallel to its axis, hence the name “axial flow pump” or simply “axial pump”.

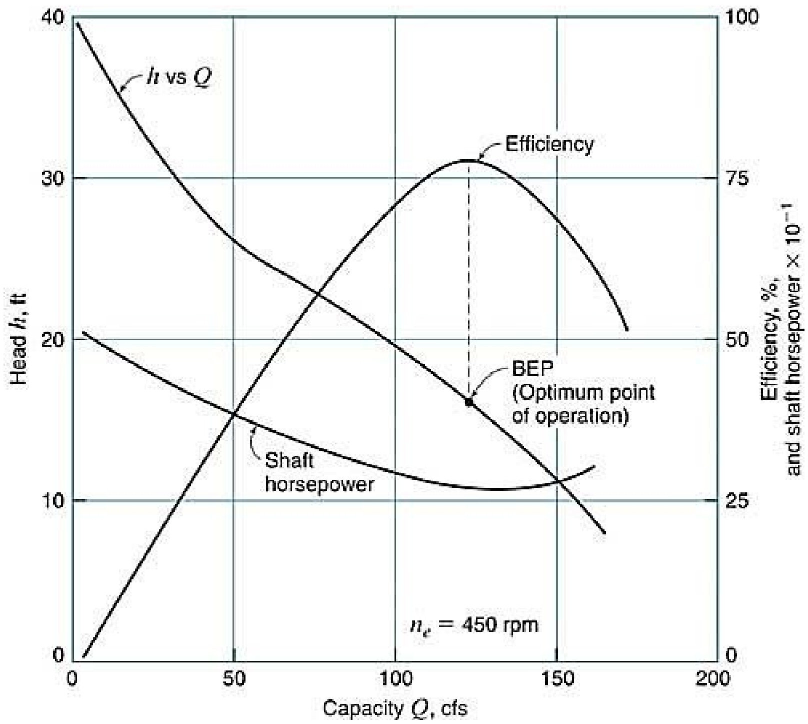


(1) casing, (2) straightening apparatus, (3) impeller, (4) vanes

The moving vanes are sometimes preceded by a row of fixed vanes that directs the flow tangent to the moving vanes to minimize the eddy loss in the pump. For the same reason, another row of fixed vanes may be inserted after the pump to straighten the vortex flow leaving the impeller.

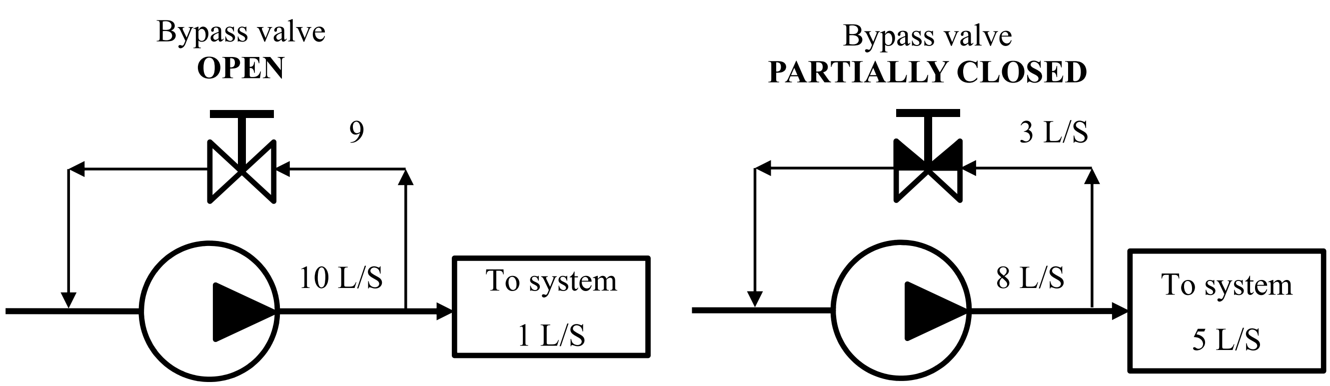
3.2.2 Performance

The axial pump gives a larger flow rate but can sustain a lower head relative to the centrifugal pump. So it is used in applications requiring very large liquid quantities under a head below 6 m such as water irrigation, sewage systems, and thermal power plant cooling water circulation and so on.



3.2.2.1 Flow control

From the performance curves of the axial pump it is seen that it is not power-wise efficient to use the delivery valve to control the axial pump flow rate. As the flow rate decreases the shaft power increases! So the best practice is to use the bypass valve.



3.2.2.2 Motor starting

As mentioned before, any equipment driven by the electric induction motor should be started at its minimum load to protect the motor from overload. In case of the axial pump the minimum power consumption occurs at maximum flow rate, hence the pump should be started with the bypass control valve fully open.

4 Cavitation

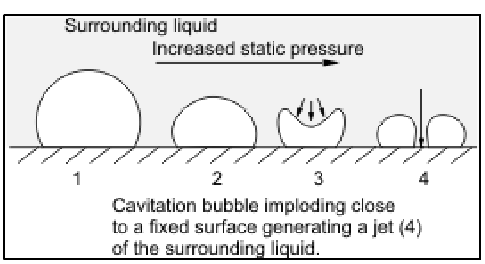
4.1 Vapor pressure

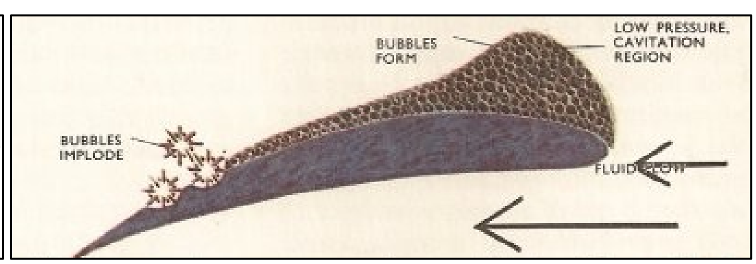
To boil any liquid, there are always two choices; increasing liquid temperature or decreasing its pressure. As the liquid temperature increases, its molecules receive more energy and at a certain temperature (boiling temperature or saturation temperature) the molecules obtain very high energy that allows them to get free from the liquid (evaporate). On the other hand, decreasing the liquid pressure allows the molecules to get free although still having the same energy (at the same temperature). This means we can boil water at the room temperature by only decreasing its pressure. The pressure at which the liquid evaporates at the working temperature is called the "vapor pressure". The vapor pressure of water at 20^{o} C is 0.023 bar (always absolute value).

The phenomenon of liquid evaporation in a hydraulic system may cause many problems. For instance liquid evaporation generates vapor bubbles that may accumulate to cause pipeline blockage, which is called "vapor lock". Also, these bubbles if swallowed by hydraulic machinery (e.g. pumps) may cause their damage, which is called "cavitation".

4.2 Mechanism of cavitation

In the hydraulic system if the liquid pressure drops below vapor pressure, the liquid evaporates. If the vapor bubbles reach the pump, they collapse (condense) again as they move from the low pressure region to the high pressure region. The bubble collapse and their volume decrease to 1/800 of their original volume which leaves a "cavity" where the surrounding liquid rushes at very high speed through which to "pit" the pump blade or the other solid surfaces. This procedure repeats, at the same point on the blade, about 1500 or 3000 times per minute (depending on motor speed) and results in blade damage (in a similar manner to corrosion). This phenomenon is known as "cavitation".

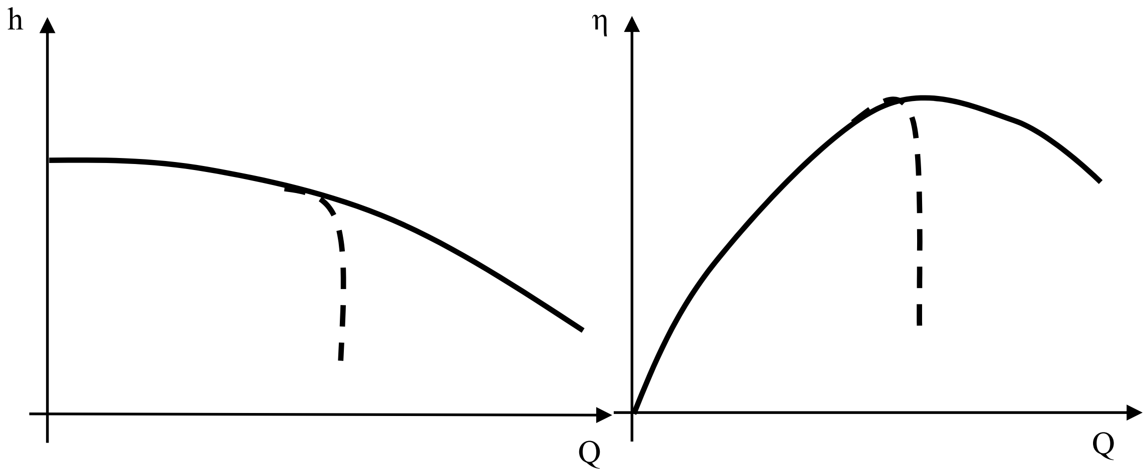




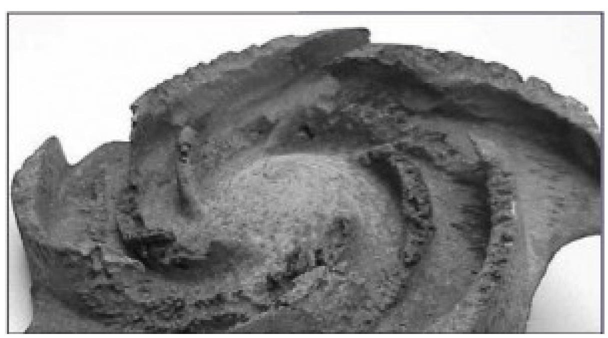
4.3 Effect of cavitation

Cavitation causes many problems in hydraulic machines some of them are listed below (signs of cavitation):

- Drop of performance (head and efficiency) since the blades can't generate head or centrifugal force by pushing massless bubbles.



- Premature failure of pump blades.



- Vibration and gravel noise.

4.4 Prevention of cavitation

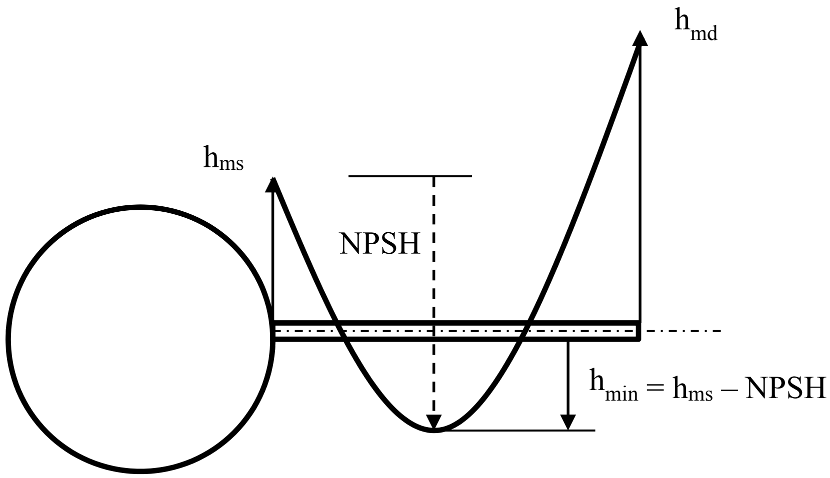
To prevent cavitation in any hydraulic system, the minimum pressure in system should be higher than the vapor pressure i.e.

$$P_{min} > P_{vap} - P_{atm}$$

Or in terms of pressure head:

$$h_{min} > h_{vap} - h_{atm}$$

Having a look at the graph of the TEL and HG of a pump hydraulic system, it can be concluded, from the first impression, that the minimum head is that at the suction of the pump, h_{ms}. However, in case of DHPs the pressure of the liquid suffers a depression due to velocity increase at the eye of the impeller. This depression is named "Net Positive Suction Head" (NPSH).



Pressure distribution along pump blade

Thus the cavitation protection condition is:

$$h_{ms} - NPSH > h_{vap} - h_{atm}$$

Rearranging,

$$h_{atm} - h_{vap} + h_{ms} > NPSH$$

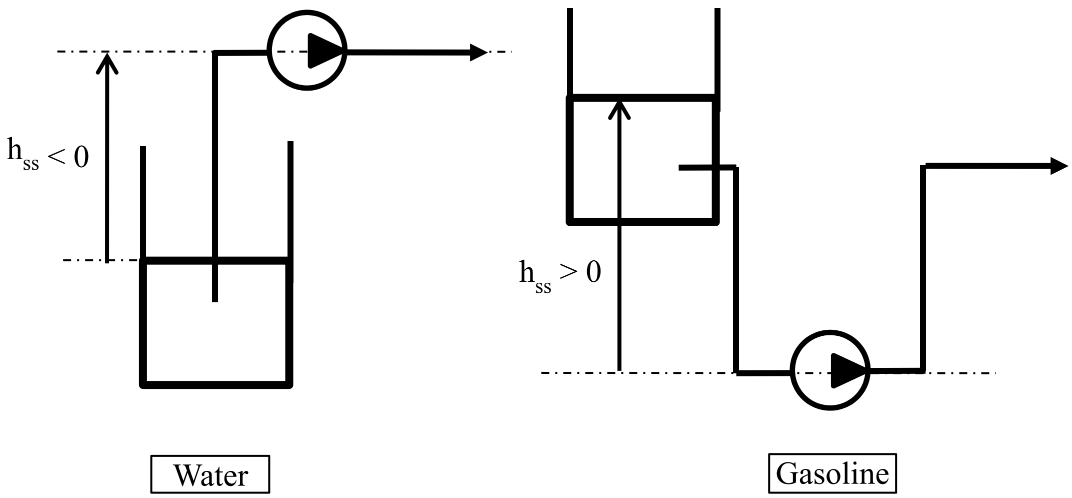
Expanding h_{ms}:

$$\boxed{h_{atm} - h_{vap} + h_{ss} - h_{ls} - \frac{v_s^2}{2g} > NPSH}$$

The L.H.S. is sometimes called NPSH Required (NPSHR) whereas the R.H.S. is sometimes called NPSH Available (NPSHA).From the above equation we can deduce the precautions required to protect the pump from cavitation:

- <u>Raising the suction tank level (h_{ss}):</u>

  From a rough estimation for water flow ($h_{atm} - h_{vap} = 10$ m, $V_s = 2$m/s and NPSH = 4 m), we find that the suction level should not drop more than 4 m below the pump level ($h_{ss} > -4$ m). Some liquids such as gasoline are volatile ($h_{atm} - h_{vap} = 4$ m). For these liquids the suction level should be much higher than the pump level, so a hole is dug in the ground to place the pump in it.

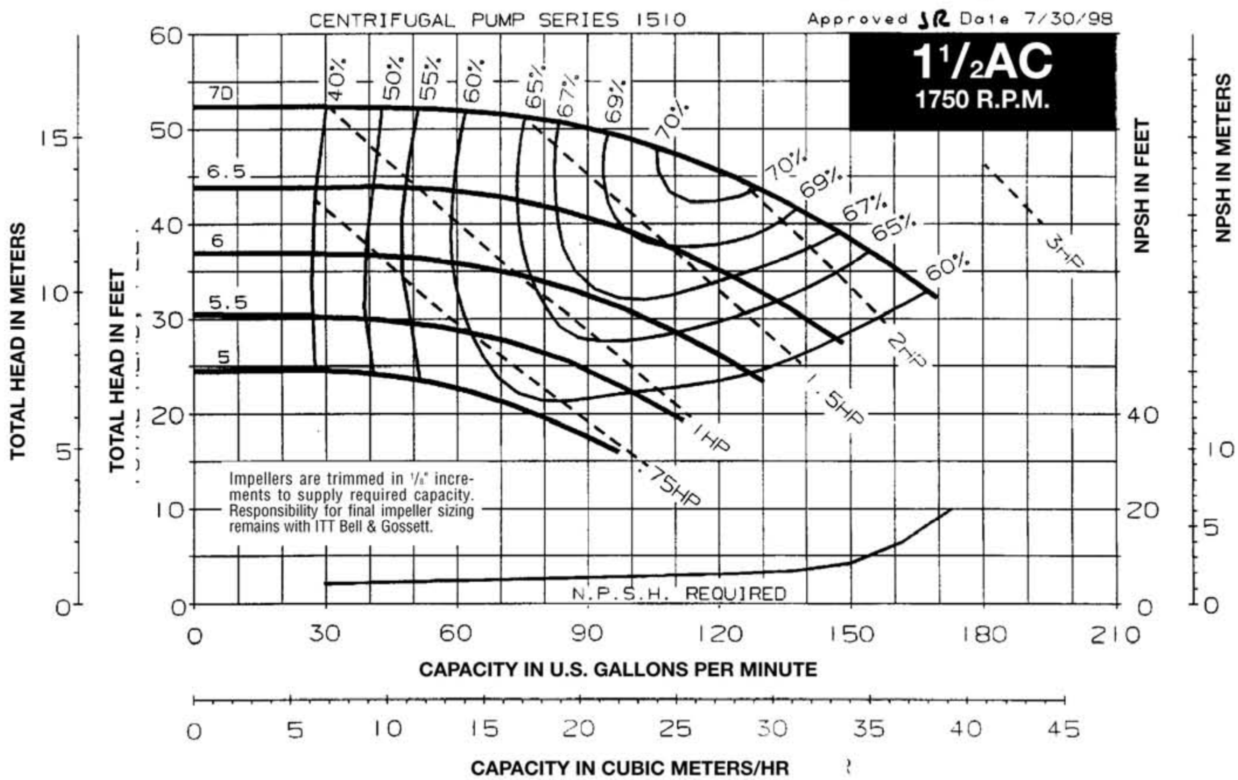


- <u>Decreasing the losses (friction and eddy types) in the suction type:</u>

  That means placing the pump as close as possible to the suction tank, although theoretically its operating point is not affected by its place along the pipeline, to decrease suction pipe length. Also increasing the suction pipe diameter (sometimes it is designed larger than the delivery pipe) to decrease losses and kinetic energy. Finally, one important point is excluding any unnecessary fittings (e.g. elbows) and using suction valves of types that make minimum losses when fully open (e.g. gate valve and ball valve).

4.5 NPSH

The NPSH depends on the design of the pump and its flow rate. It is usually given as a supplementary graph with the performance curves of the DHP.

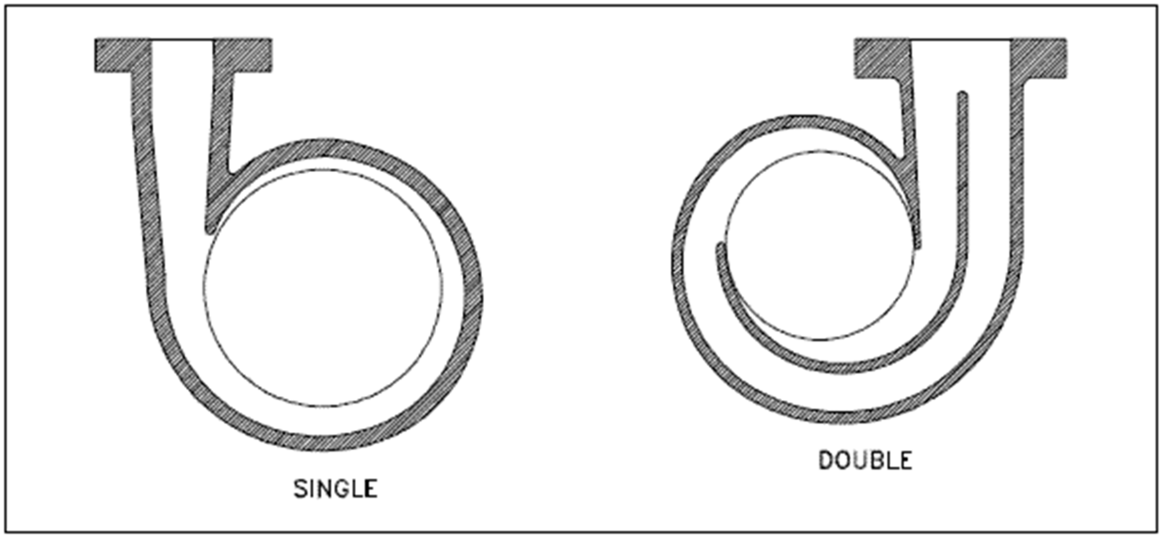


As can be seen from the graph; the curve of the NPSH increases slightly around 4 m, and increases sharply when the flow increases beyond 120% of the BEP. Hence it is recommended to avoid this region in operation.

5 Radial and axial force balancing

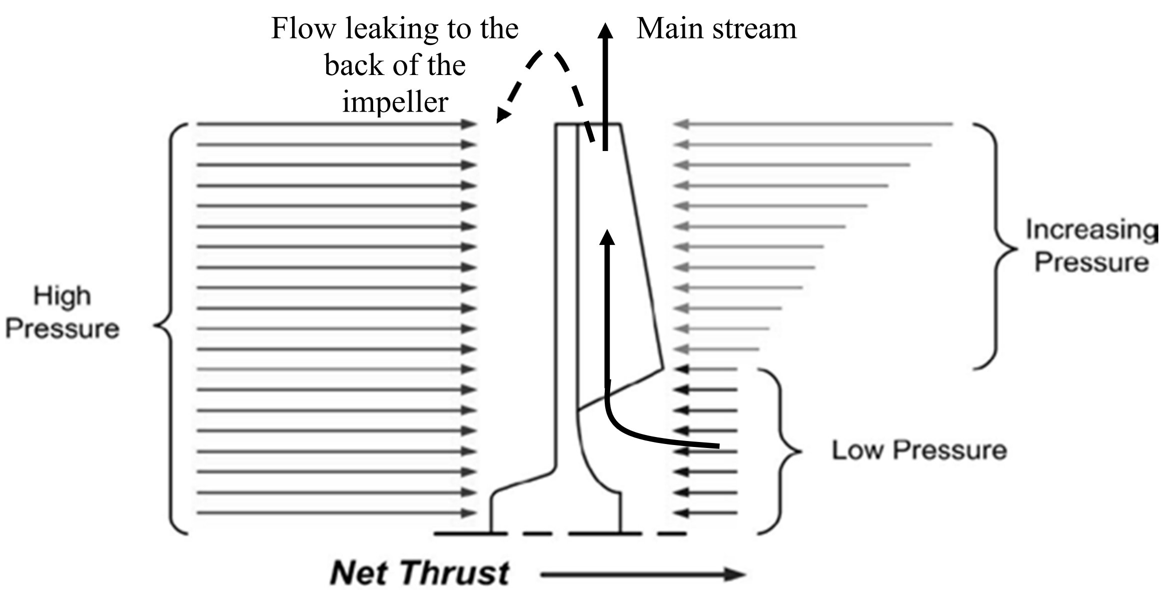
5.1 Radial force

The irregular shape of the centrifugal pump volute casing results in irregular pressure force distribution around its impeller especially at off-design condition. This unbalanced force distribution causes unwanted vibrations that can damage bearings. As the operating point shifts from BEP the unbalance increases. Hence it is recommended not to operate the pump at a flow rate less than 60% of the BEP. To reduce the radial thrust, double volute casing is used.



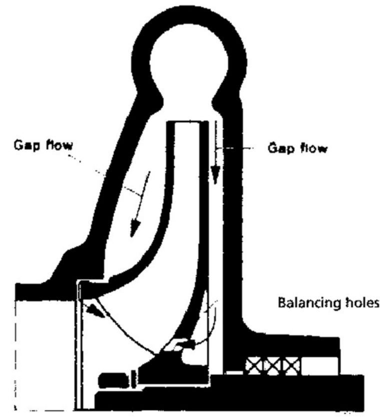
5.2 Axial force

According to Newton's 3rd law, as the pump sucks the liquid, the liquid pulls the pump as well i.e. the pump impeller is subjected to axial force towards the suction pipe. In other words the pressure in front of the impeller (suction flow) is lower than the pressure that leaks to its back from the discharge pipe.

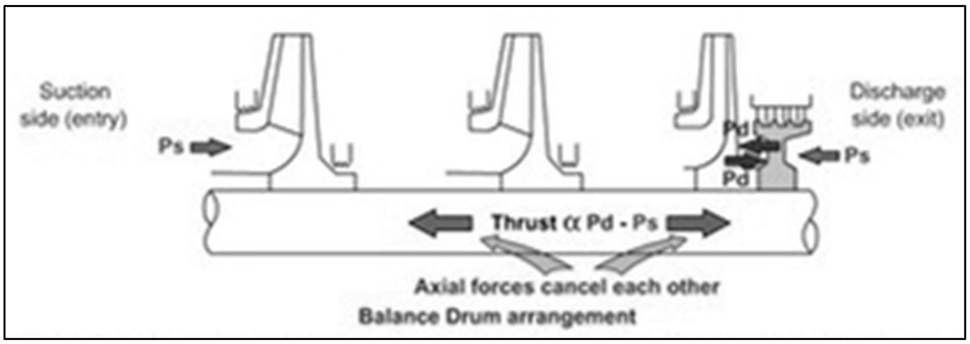


This thrust force is sustained by the pump bearing. In case of high pressure or multistage pumps where the thrust is too high, it may be balanced by:

- **Balancing holes:** Transfers part of the high pressure on the back of the impeller to its front, or



- **Balancing disk:** Placed behind the last impeller to be subjected to thrust force opposite to (cancels) the thrust force on the impellers.

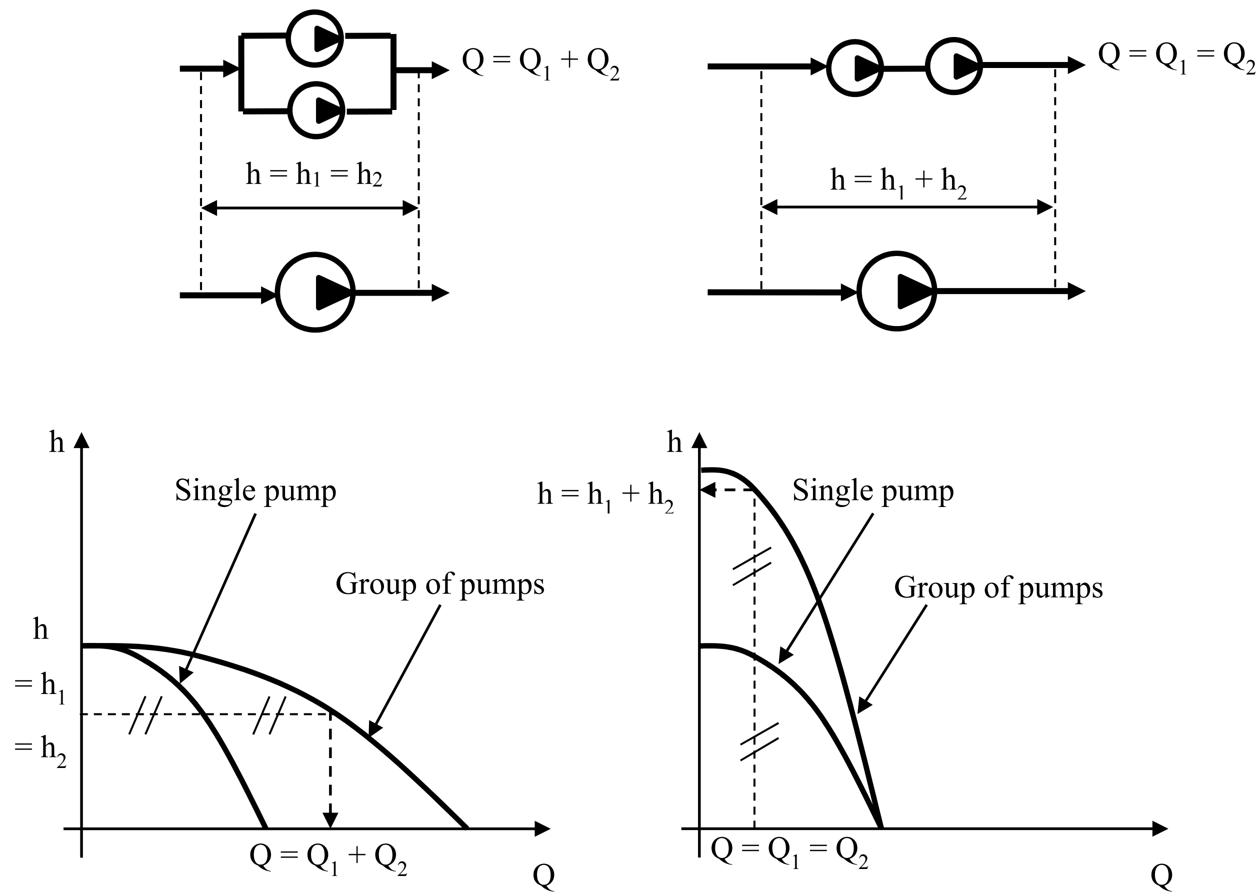


6 Pump grouping

In many cases it is required to use more than one pump in the system. A group of pumps can be arranged either in series or in parallel.

6.1 Equivalent performance

The equivalent performance of two identical pumps connected in series of parallel can be deduced as shown in figure.

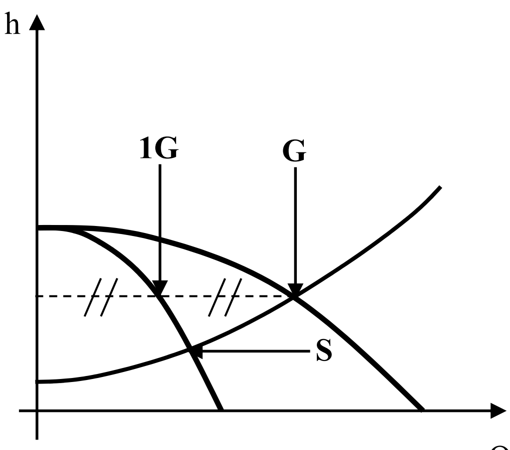


Parallel connection   Series connection

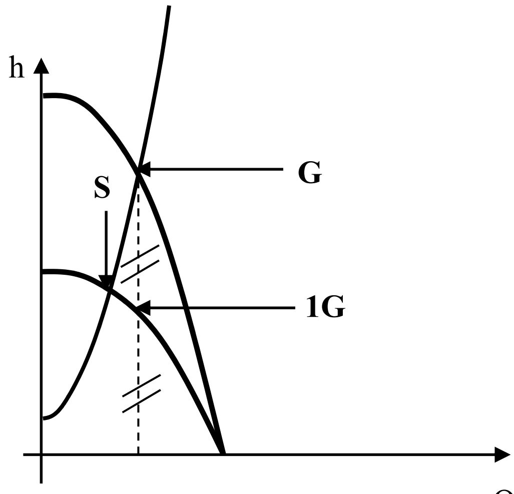
6.2 Single and group

On the performance curves of two pumps connected in group exist three operating points:

- S: the operating point when one pump operates alone in the system.
- G: the operating point when a group of pumps operate in the system.
- 1G: the operating point of one pump in a group of pumps that work together in the system.



Parallel connection

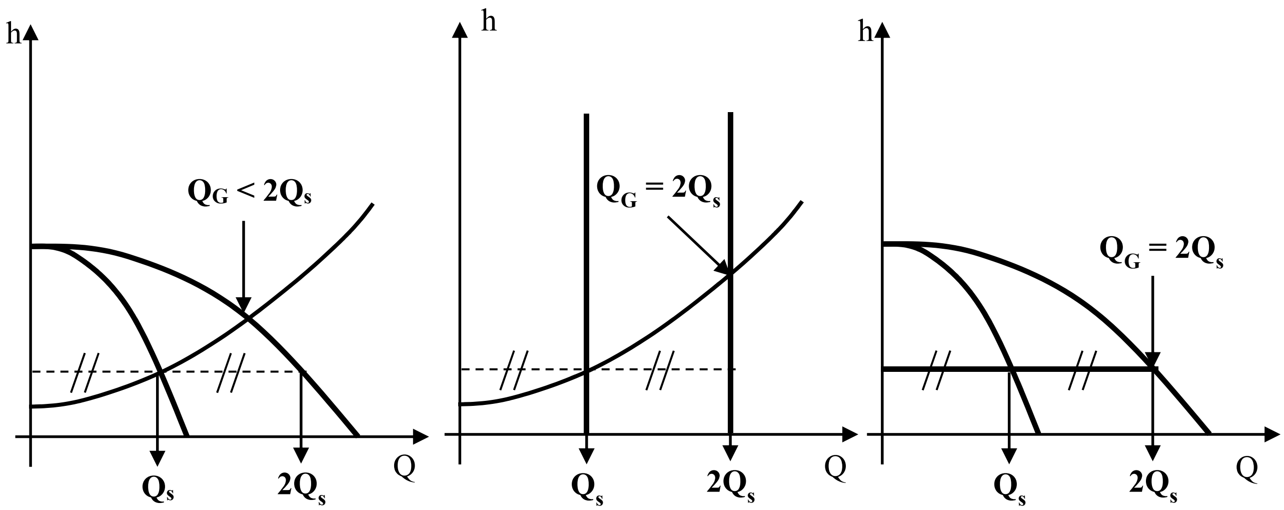


Series connection

6.3 Why isn't the flow doubled?

Assume a DHP pump that gives 10 L/s in a system, when another identical pump is connected to it in parallel the total flow rate will be 17 L/s! To get 20 L/s, double the flow, one of two things should happen:

- The pump has a fixed flow rate, which is the case in PDPs.
- The system has constant losses, rather than the parabolic relation with Q.

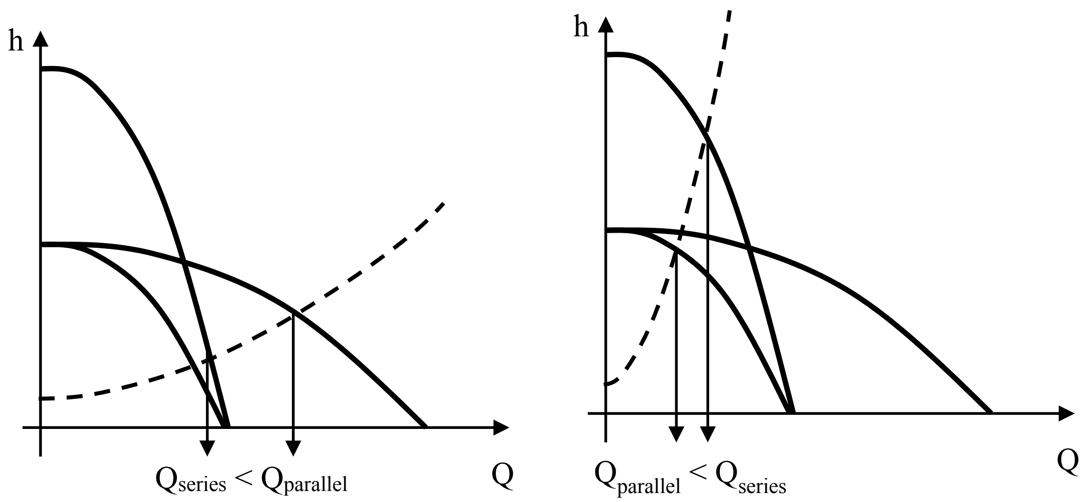


Fixed flow pump (PDP)

Flat system

6.4 Which connection gives more flow rate?

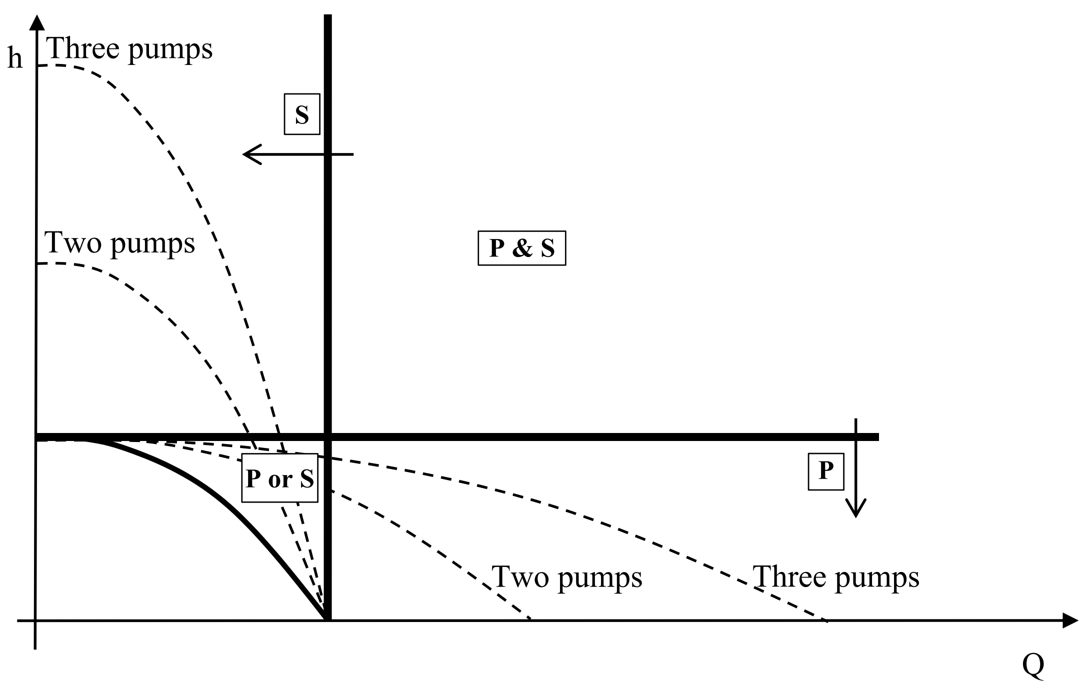
Assume two hydraulic systems as the shown in figure. For both systems, connect two identical in parallel at one time and in series at another time.



From the graphs it can be concluded that the type of connection that gives higher flow rate depends on the system resistance. If the system resistance is low, the parallel connection gives higher flow rate and vice versa.

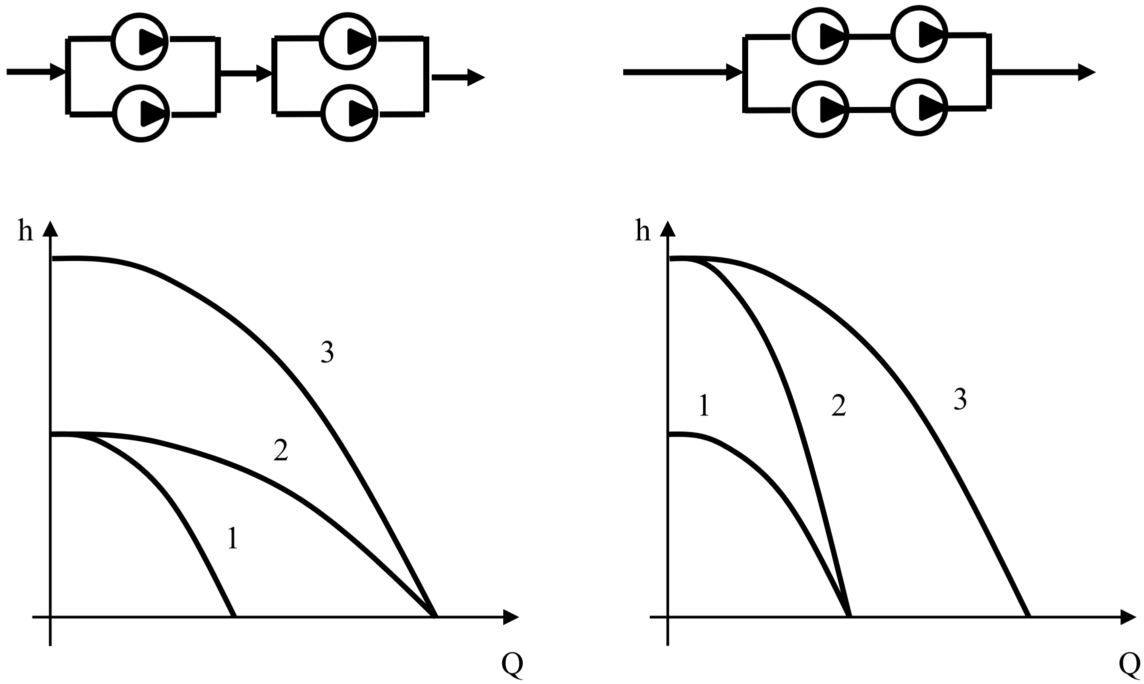
6.5 Series or parallel

The following graph shows the zones of operation of each type of connection.



From the graph, four regions can be distinguished:

- P: the operating point can be achieved by connecting pumps in parallel.
- S: the operating point can be achieved by connecting pumps in series.
- P & S: the operating point can be achieved by connecting pumps in parallel and in series.



- P or S: the operating point can be achieved by connecting pumps in parallel or in series. In this case the best type of connection is the one that achieves the operating point by minimum number of pumps and minimum power consumption.

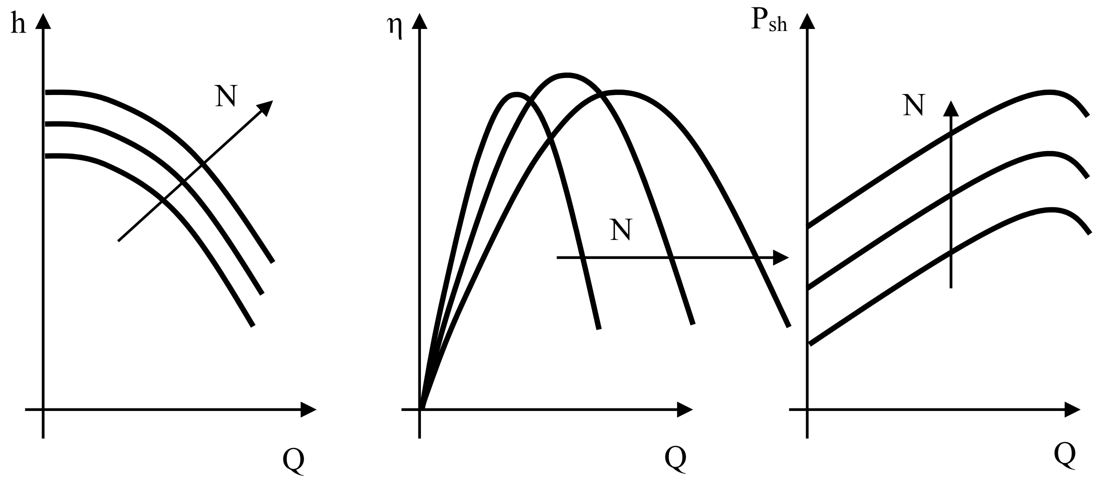
6.6 Motor selection

As has been shown from the previous study, a pump in a group of pumps connected in parallel gives lower flow rate than it would give if operating alone and the opposite is true in case of series connection. But it is known that the pump power consumption increases as the flow rate increases. So if a pump is to be operated in a group of pumps connected in parallel, the motor is to be selected based on the power it consumes when operated alone. While if a pump is to be operated in a group of pumps connected in series, the motor is to be selected based on the power it consumes if operated in the group.

7 Affinity laws

7.1 Speed control

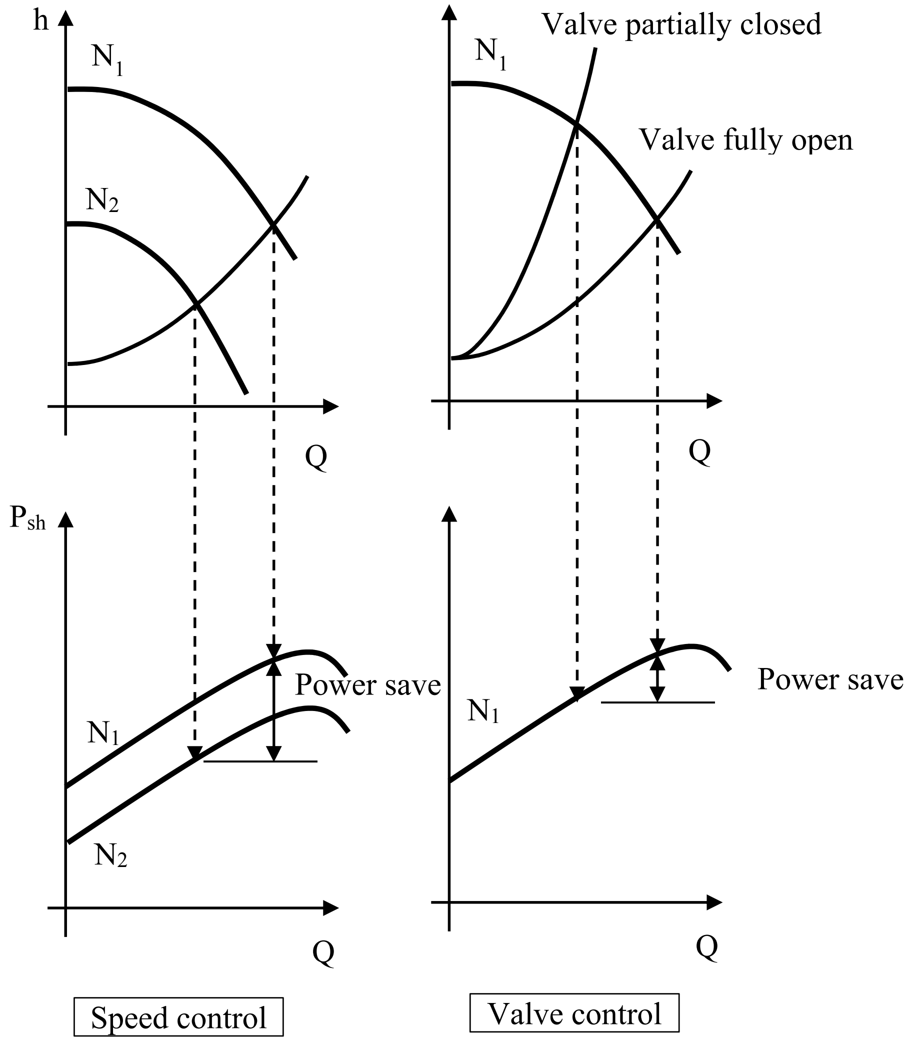
The easiest and cheapest method to control pump flow rate is the delivery valve partial closure. However, this increases the losses of the system. The most power efficient way to control flow rate is the shaft speed control. The figure shows the performance of the pump at different speeds.



It should be noted that operating the pump at a higher speed, shifts the power curve upwards. This new power curve may not be sustainable by the existing electric motor of the pump and may cause it to overheat.

7.2 Speed vs. valve control

The following figure illustrates that the speed control saves power compared with valve closure.



7.3 Impeller trimming

If the flow is to be decreased permanently, the impeller can be trimmed by lathe machine. Just as speed control, the decrease in impeller diameter causes its flow rate and head to decrease. The impeller can be trimmed down to a certain amount defined by the pump manufacturer. Exceeding this predefined amount increases leakage between impeller and pump casing.

7.4 Affinity laws

The performance curves at different speeds and impeller diameters are related to each other by the well-known affinity (similarity) laws:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}\frac{D_1}{D_2}$$

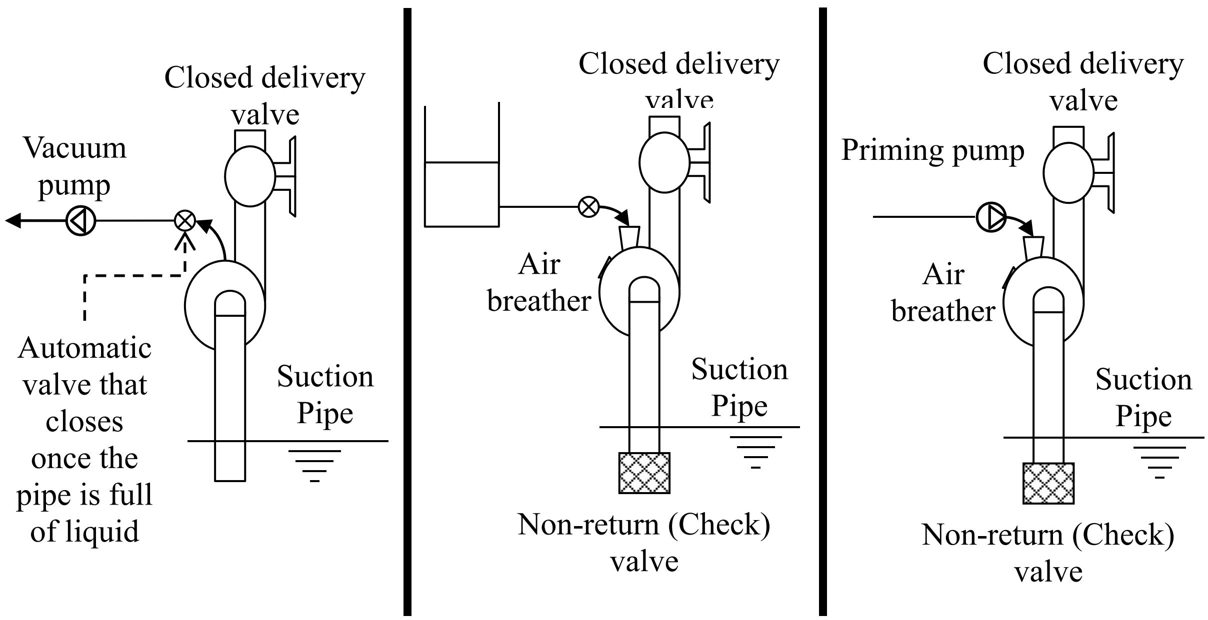
$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \left(\frac{D_1}{D_2}\right)^2$$

$$\eta_1 = \eta_2$$

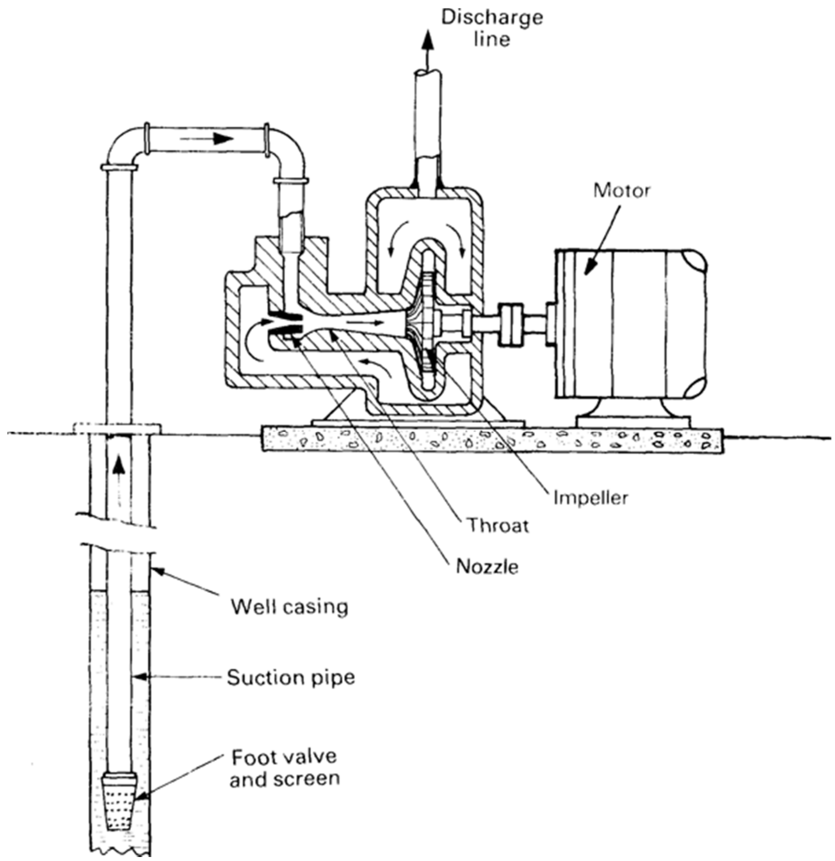
8 Priming

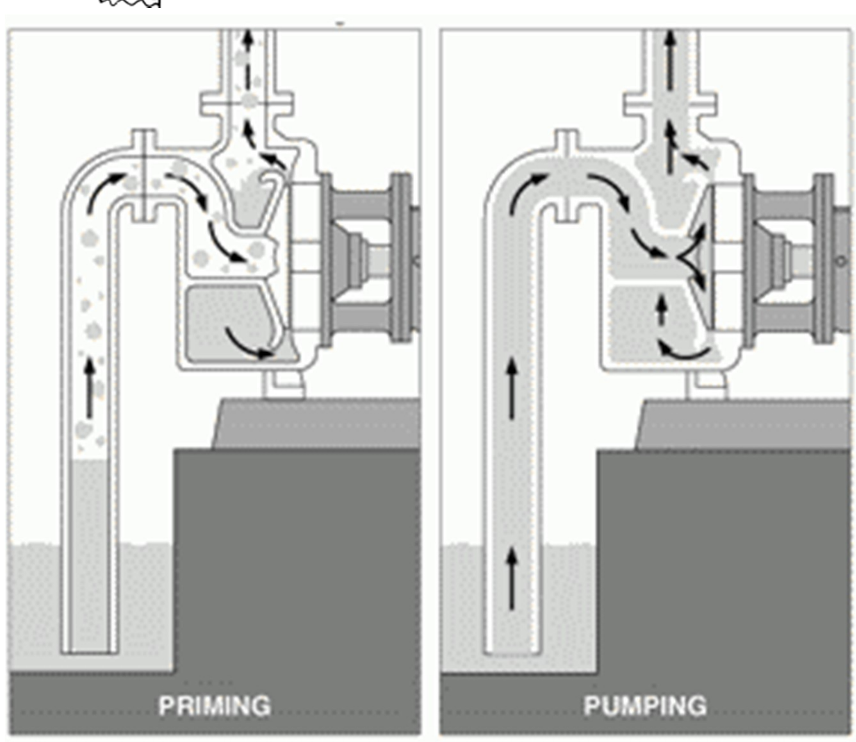
If placed above suction tank level, the DHP can't start liquid flow unless its impeller is flooded with liquid. This is because the centrifugal force depends on the density of the pumped fluid. The density of air is too low to create suction pressure that is capable of raising the heavy liquid from suction tank. To start the flow; the pump casing should first be filled with water which is called "priming".

There are many ways of priming; some of them are illustrated in figure.



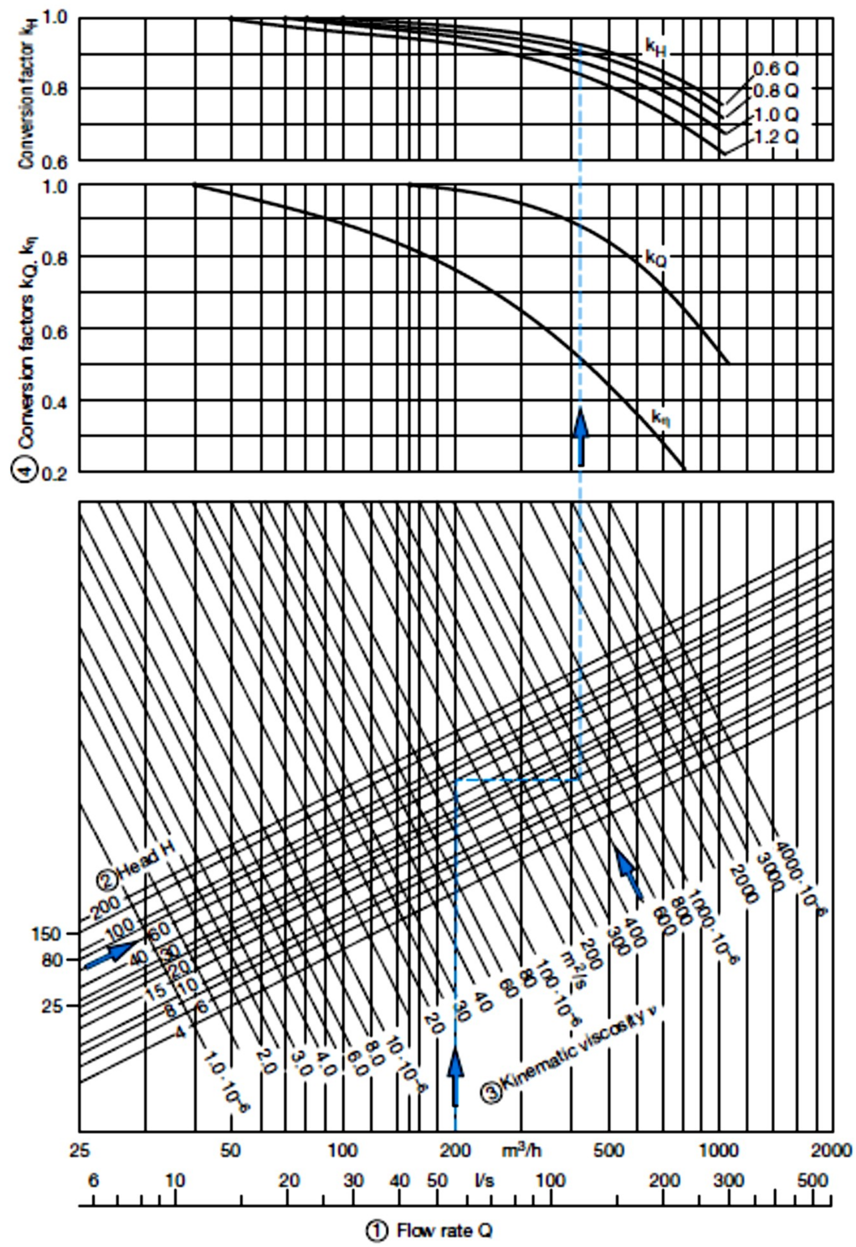
Also some pumps are designed to be "self-priming pumps".


Discharge line
Motor
Impeller
Throat
Nozzle
Well casing
Suction pipe
Foot valve and screen


PRIMING
PUMPING

9 Pumping heavy liquids

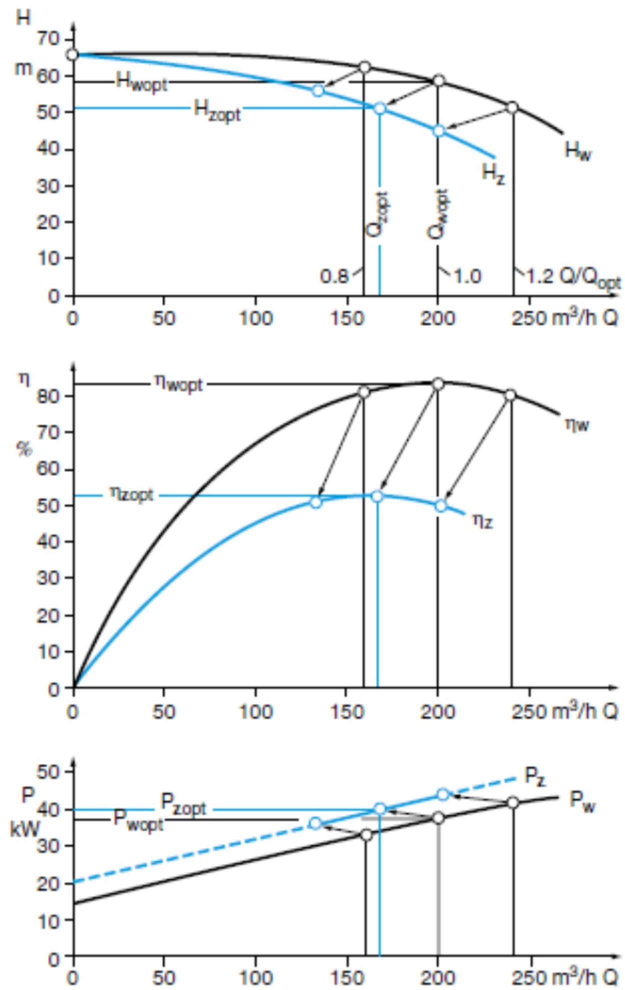
The performance curves of centrifugal pumps are usually given based on water as a pumped liquid. The performance of the pump changes if used to pump liquids of different properties. So, correction-charts are used to predict the new performance curves of the centrifugal pump.



$$Q_l = k_Q \cdot Q_w$$

$$H_l = k_H \cdot H_w$$

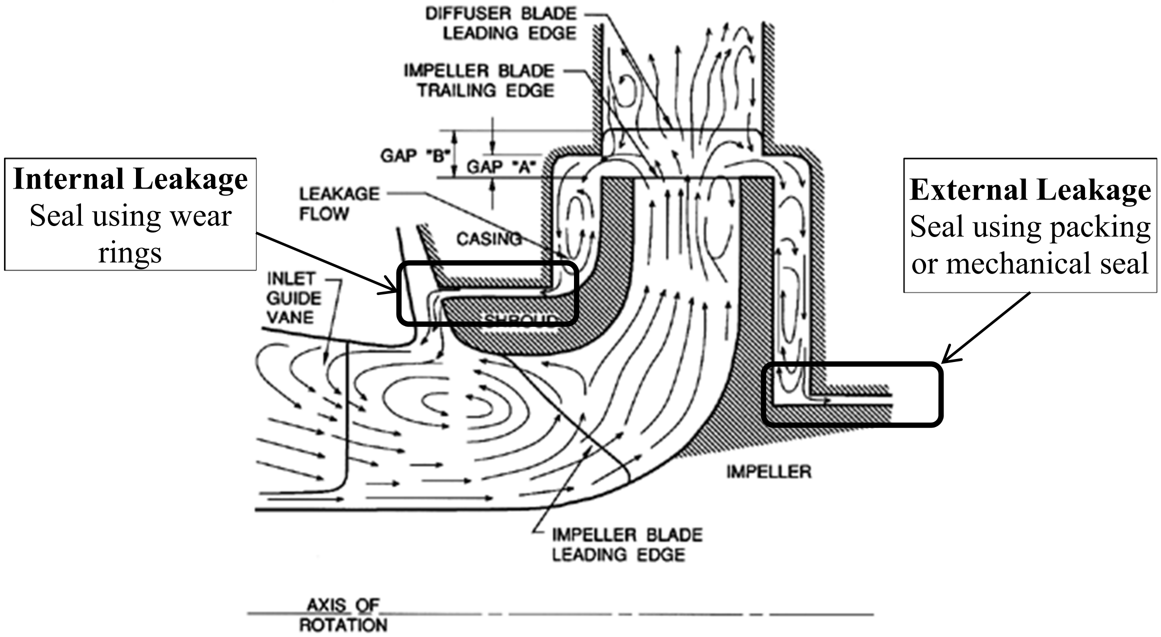
$$\eta_l = k_\eta \cdot \eta_w$$

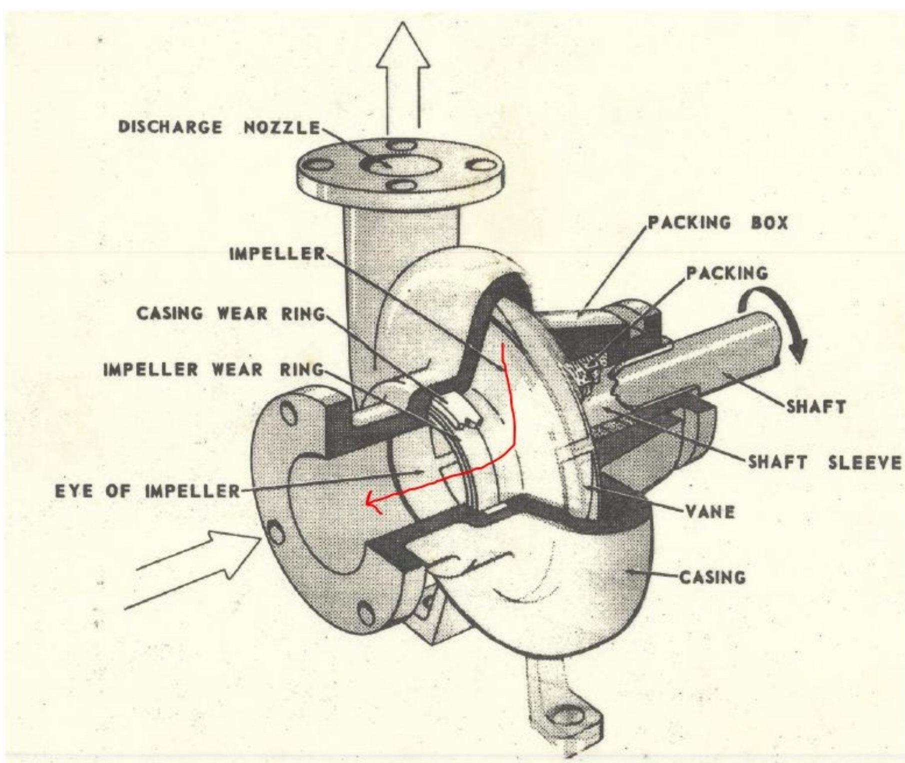


10 Seals

The pump consists of rotating components (shaft and impeller) and static components (casing), between them exists liquid under pressure. There should be some clearance between the static and rotating components, to allow rotation, through which liquid may leak. There is two types of leakage in a pump:

- Internal leakage from delivery pipe to suction pipe across the impeller. This is minimized using wear rings placed on the impeller eye.

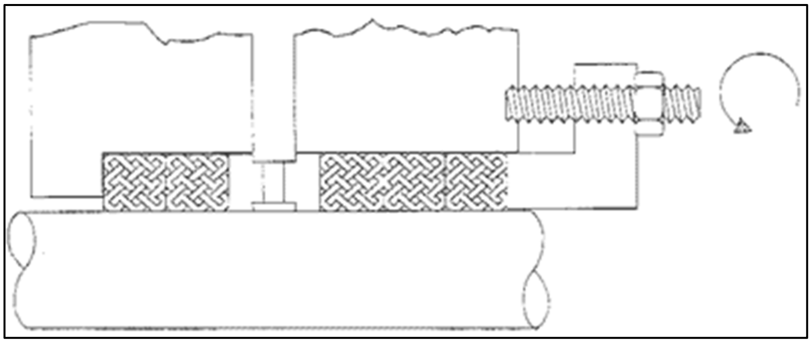


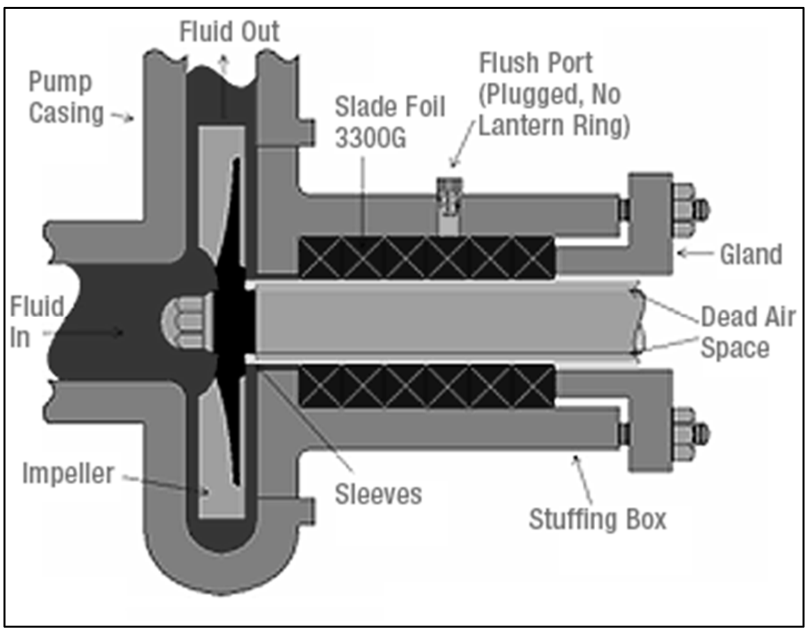


- External leakage between shaft and casing which is minimized using packing or mechanical seal which will be explained briefly in the following sections.

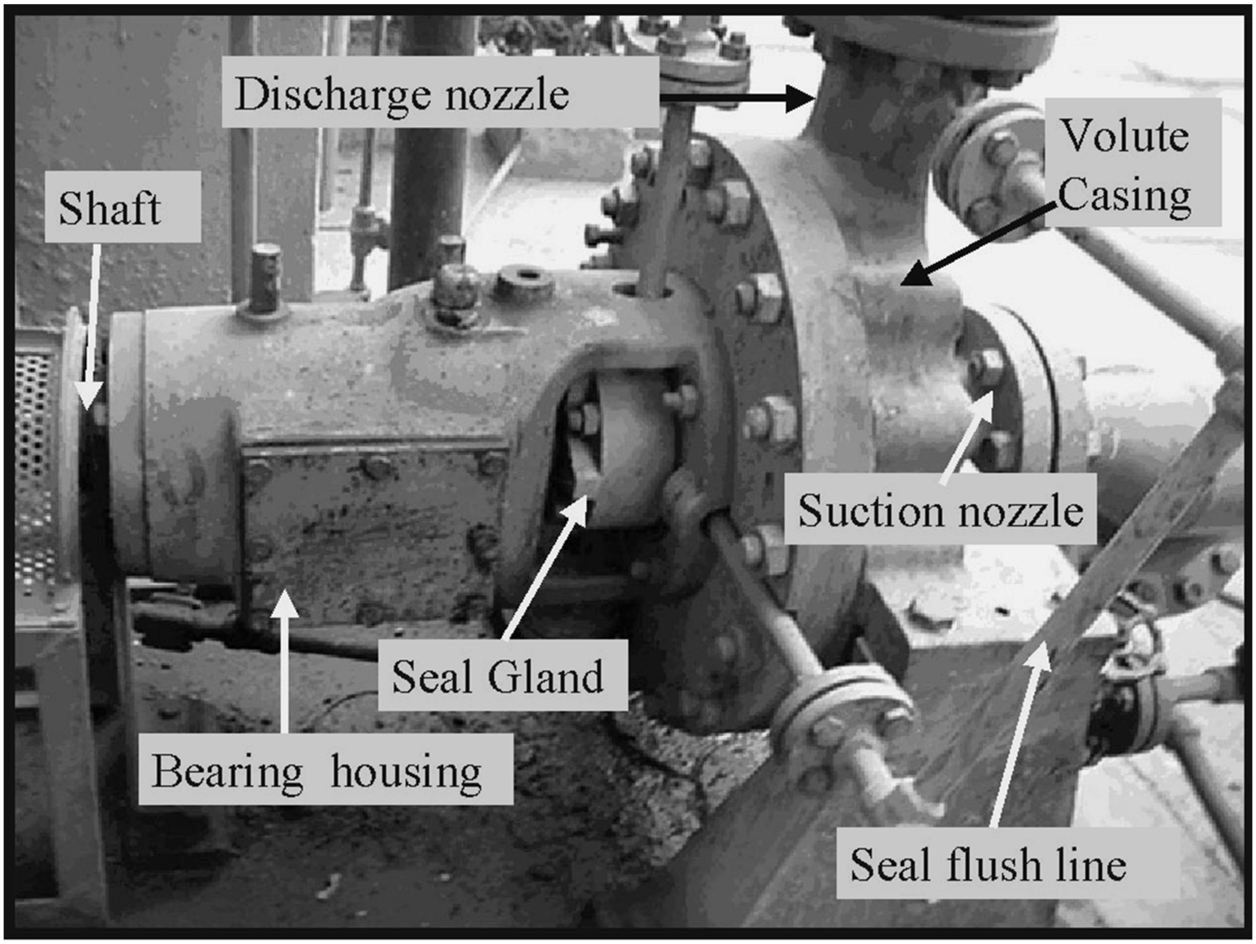
10.1 Packing seal

A group of rings of graphite, Teflon or yarns placed in a box (stuffing box) formed between shaft and casing and used to seal the pump. The seal is formed by the packing being squeezed between the inboard end of the stuffing box and the gland. A common packing installation is shown in the figure. A static seal is formed at the ends of the packing rings and at the inside diameter of the stuffing box. The dynamic seal is formed between the packing and the shaft sleeve. Load applied to the packing deforms the packing against the shaft sleeve controlling leakage.





It should be noted that some leakage should be allowed for cooling and lubrication purposes. In most cases a lantern ring is placed between the packing rings to introduce lubrication to the rings. If the pump runs dry, there is no lubrication or cooling for the seal which may cause it to overheat.



10.2 Mechanical seal

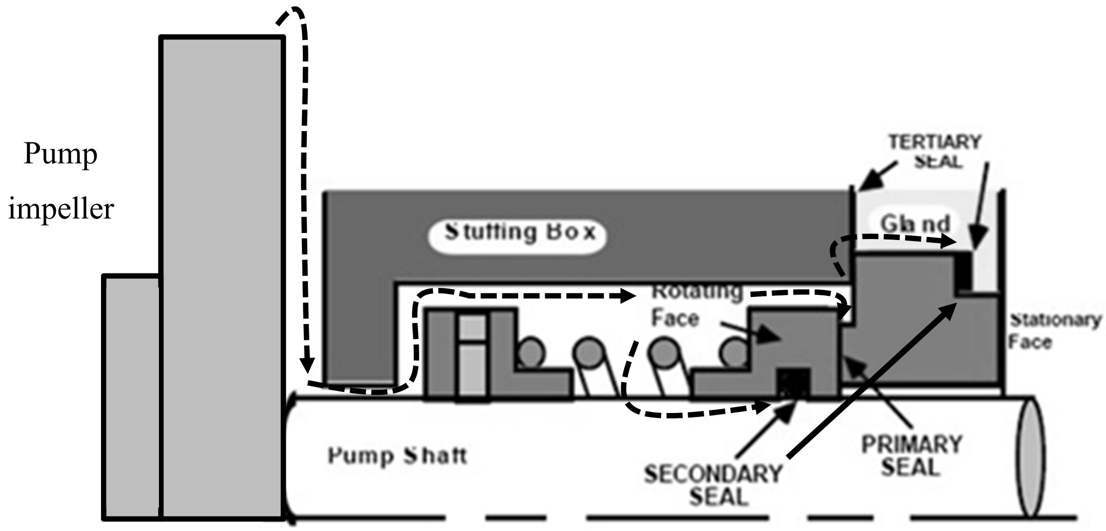
The mechanical seal is used for applications where the packing can't provide appropriate sealing for the pump such as high operating temperatures, pressures speeds, and so on.

10.3 Construction and theory of operation

The basic mechanical seal is shown in the figure below. It consists of five main parts:

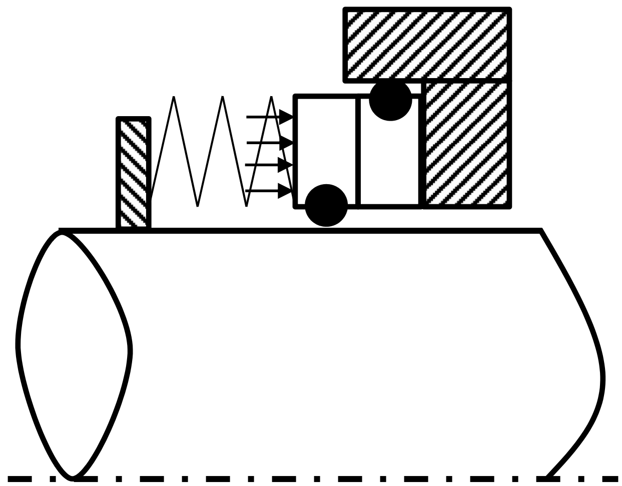
- Rotating seal face.
- Stationary seal face.
- Spring. To hold contact between the rotating and stationary faces.
- Secondary static seals (O-ring) [1]. To prevent leakage between the rotating face and pump shaft.
- Secondary static seals (O-ring) [2]. To prevent leakage between the stationary face and the stuffing box inner bore.

It should be noted that as well as the packing seal, there should be some leak through the mechanical seal to allow cooling and lubrication of the seal faces. However, the leak here is so little such that it evaporates when passes between the contact surfaces and can't be seen by the naked eye.

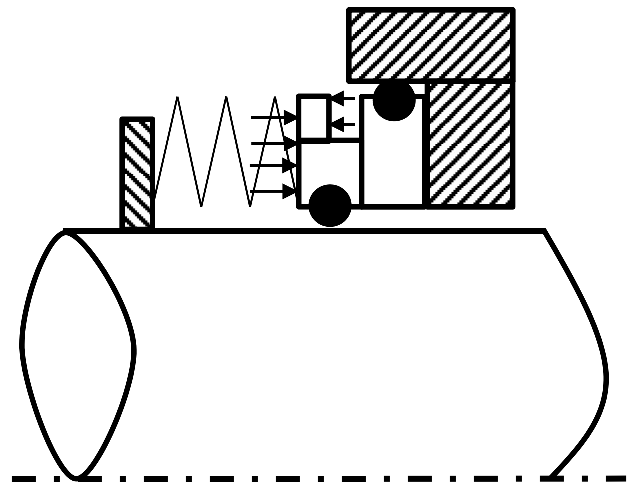


10.4 Balanced and unbalanced mechanical seal

The pump pressure acts on the back of the rotating face which helps closing the gap between the rotating and stationary faces. At high pressures, this results in increasing the friction between faces and generates excessive heat. In these cases, the "balanced mechanical seal" is used. Here, the shape of the rotating face is modified to allow the pump pressure to act on its front face as well as its back face. This reduces the closure force and the heat generated due to friction.



Unbalanced mechanical seal



Balanced mechanical seal

10.5 Seal face material

Few materials are suitable for seal faces. To keep leakage as low as possible, the seal gap must be very small. As a result, the lubricating film is very thin. Consequently, the seal face materials must be able to withstand rubbing against each other at high load and speed.

The best seal face materials have **low friction**, **high hardness**, **good corrosion resistance** and **high heat conductivity**.

- Carbon graphite
- Aluminum oxide (alumina)
- Tungsten carbide (WC)
- Silicon carbide (SiC)
- Diamond coatings

10.6 Essential requirements for proper operation of a mechanical seal

- Seal faces must be flat and polished.
- Seal faces must be installed perpendicular to the shaft.
- Spring force must be sufficient to maintain contact of the faces.

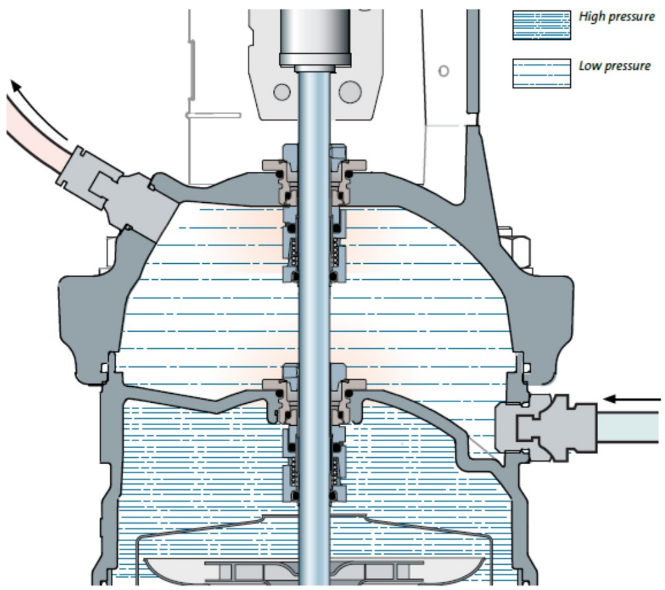
10.7 Types of mechanical seal

Besides the basic type of mechanical seal, there are other types serving special operating conditions. The most important of them are the "tandem arrangement" and the "back-to-back arrangement".

10.7.1 Tandem seal arrangement with flushing fluid

Here the high pressure pumped fluid leaks to a medium pressure fluid rather than the atmosphere. The flushing fluid is sealed by another seal connected in tandem to the pumped liquid seal. This type of arrangement gives the following advantages:

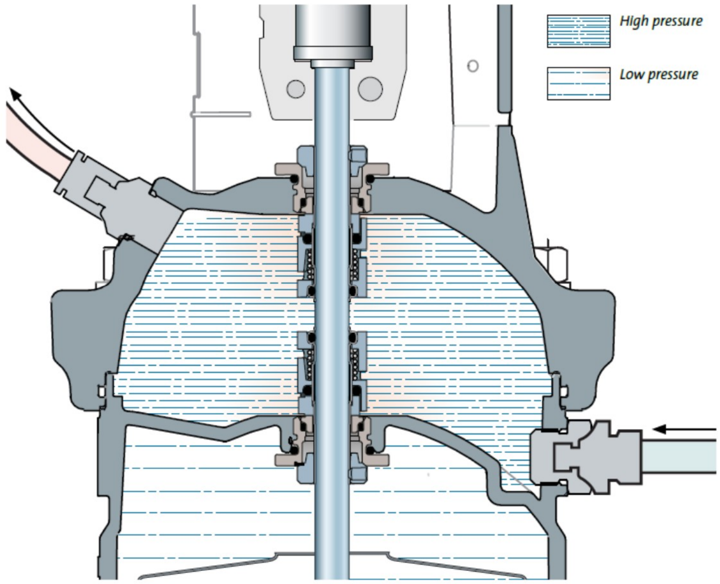
- There is no evaporation in the sealing gap. This prevents the formation of deposits as well as crystallization on the flushing fluid side.
- The flushing fluid lubricates and cools even when the pump runs dry or runs with vacuum.



10.7.2 Back-to-back arrangement with barrier fluid

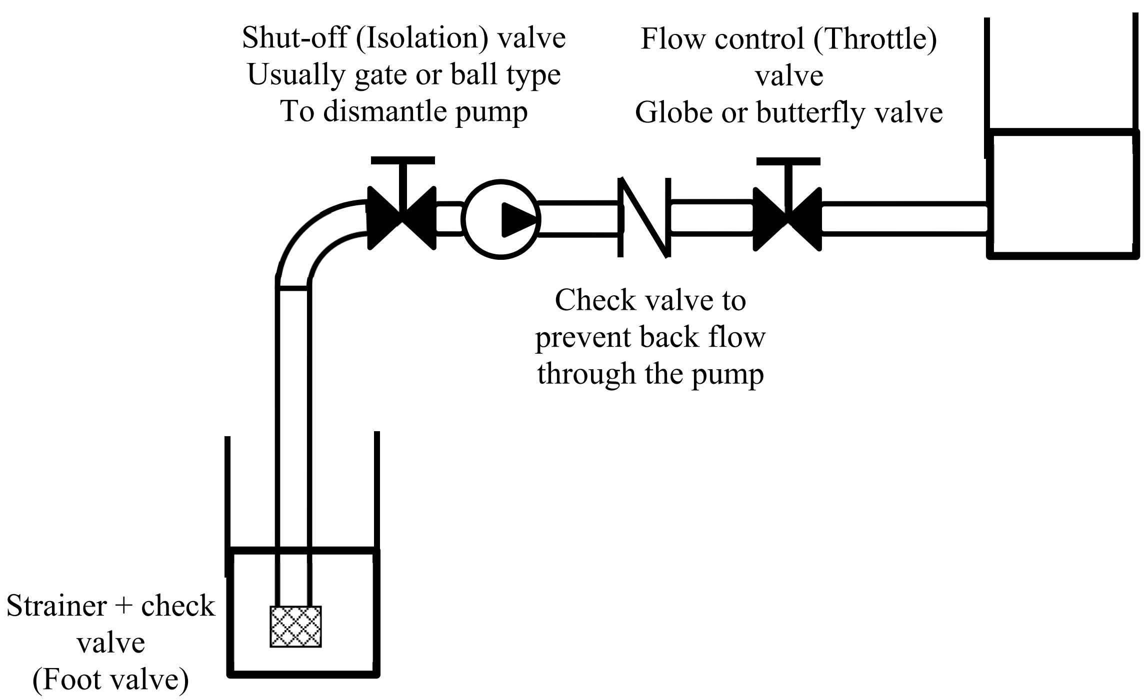
Here, the barrier fluid has a higher pressure than the pumped media. So the barrier fluid leaks to the product-side and hence the mechanical seal between them is reversed. This seal arrangement is suitable for the following cases:

- Poisonous and explosive liquids when no leakage from the pumped medium to the atmosphere can be accepted.
- Sticky media and/or liquids with many abrasive particles. The seal arrangement prevents the pumped medium from entering the seal gap and consequently prevents excessive wear.



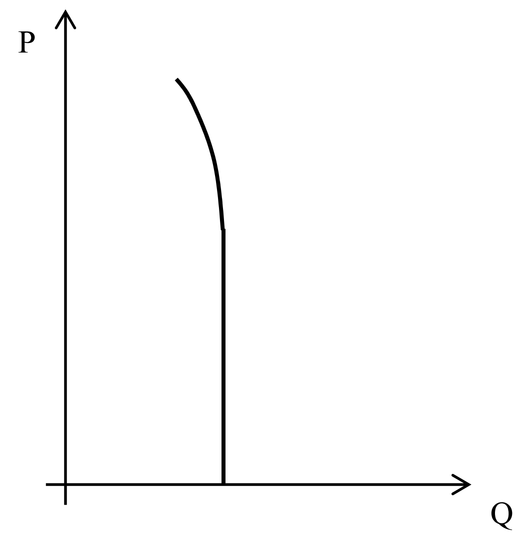
11 Centrifugal pump installation

The typical centrifugal pump installation is shown in figure.



12 Positive Displacement Pumps (PDPs)

The second family of pumps is the PDPs. Here the pump delivers a fixed amount of liquid (displacement) whatever the system pressure. The decrease of flow rate at high pressures occurs due to increased leakage.



The flow rate of any PDP can be given by the following formula:

$$Q = \eta_v V_d \frac{N}{60}$$

Where;

η_v = volumetric efficiency that compensates for pump leakage, slip, (=100% for zero leakage pump)

V_d = volumetric displacement of the pump (depends on the pump geometry, equals the chamber volume for piston pump and the space between teeth and casing for gear pump) (m^3)

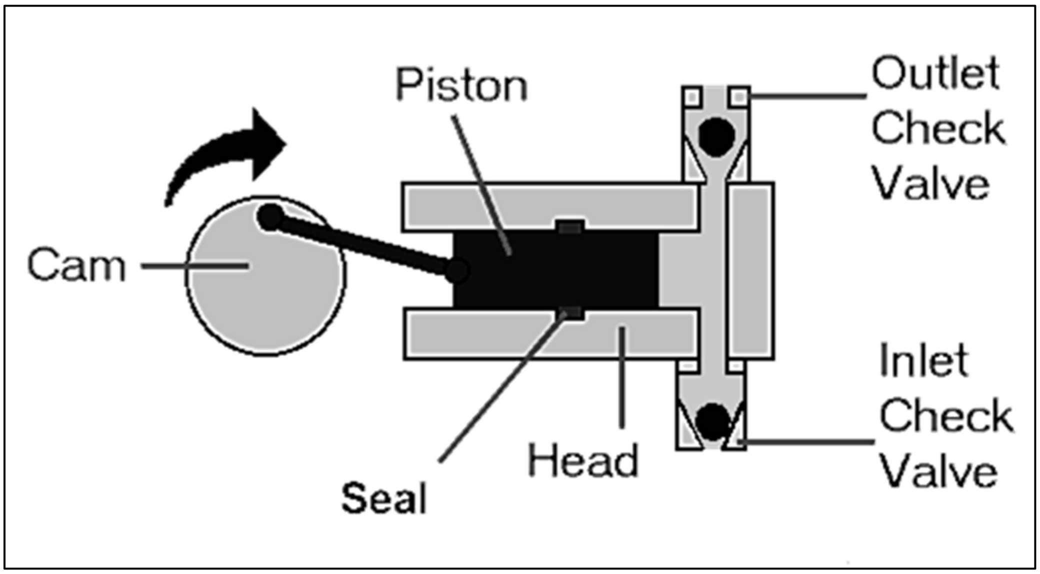
N = pump speed (rpm)

The main types of PDPs are explained briefly in the following sections.

13 PDP - reciprocating types

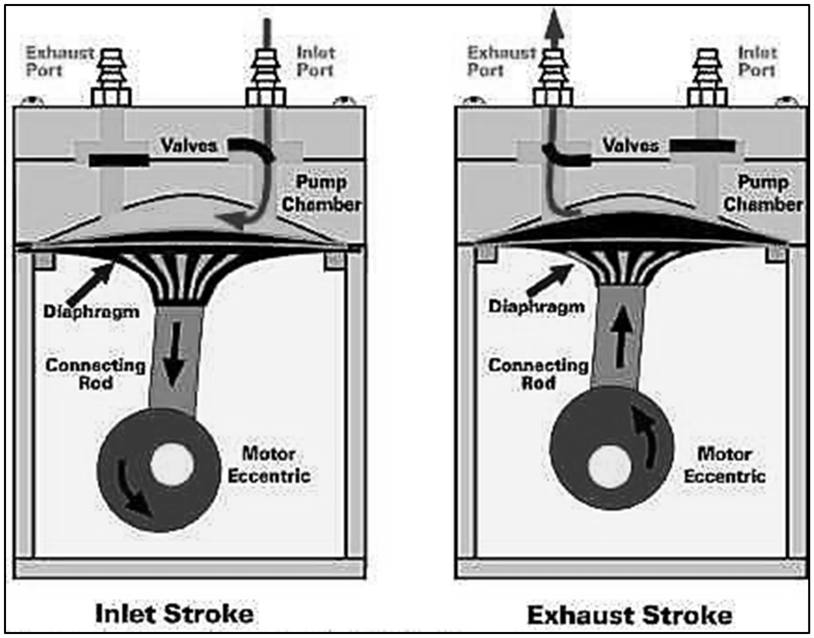
13.1 Piston pump

The piston pump is the simplest and may be oldest type of pumps. This pump produces very high pressures and can pump slurries and heavy liquid. It consists of a piston that reciprocates inside a cylinder. As the piston retards, the volume of the space increases and a new amount of liquid is sucked through inlet check valve. As the piston advances, the volume decreases and hence delivers the liquid through the outlet check valve.



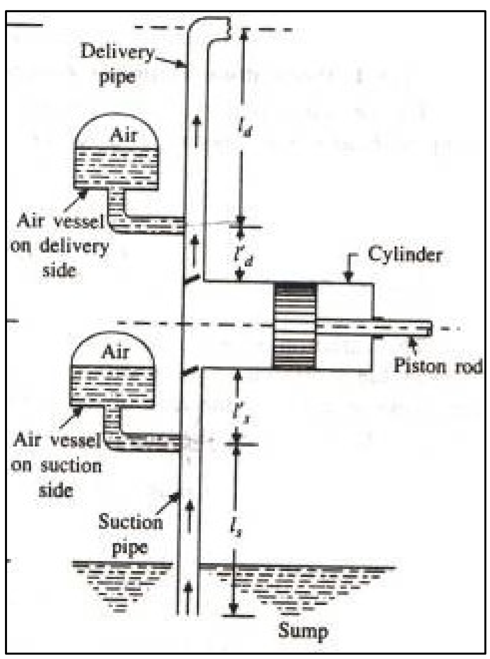
13.2 Diaphragm pump

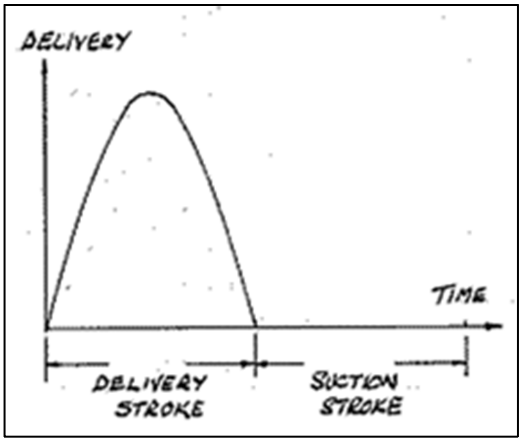
In the diaphragm pump, a reciprocating diaphragm is used instead of the piston to suck and deliver the liquid. The main advantage of this configuration is that it isolates the mechanical components from the pumped liquid and ensures zero leakage of the fluid. This is particularly important when pumping corrosive, explosive or poisonous liquids. The diaphragm pump is the usual automobile fuel pump.



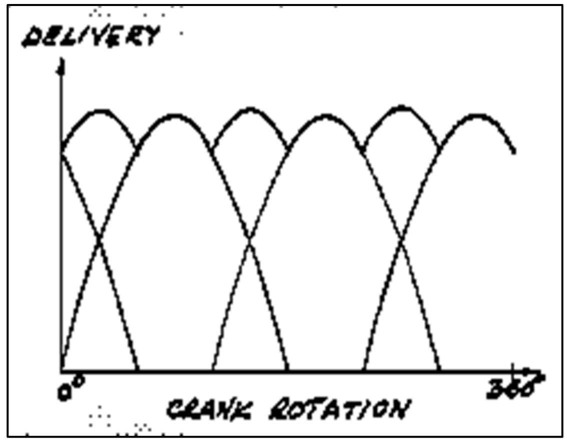
13.3 Inertia head

The reciprocating PDPs, especially the piston pump, are characterized by their pulsating flow and pressure. The pressure pulsations may cause water hummer or cavitation in the pump and hydraulic system. These pulsations can be overcome by either using air vessel(s) in the suction and/or the delivery sides or by using three cylinder pumps.





Single-cylinder piston pump



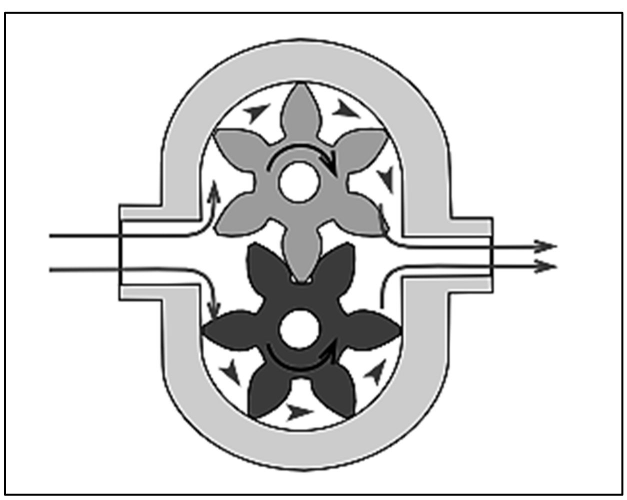
Three-cylinder piston pump

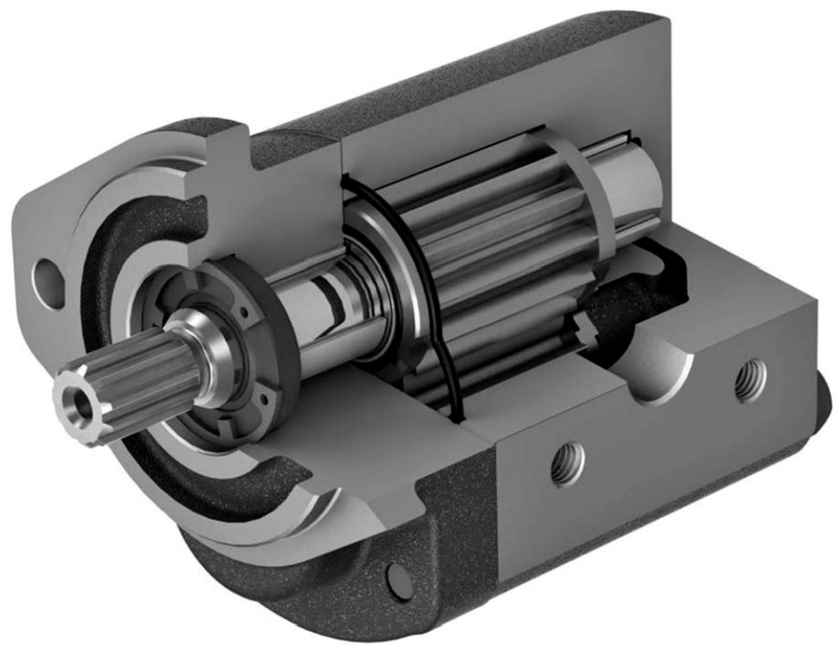
14 PDP - rotary types

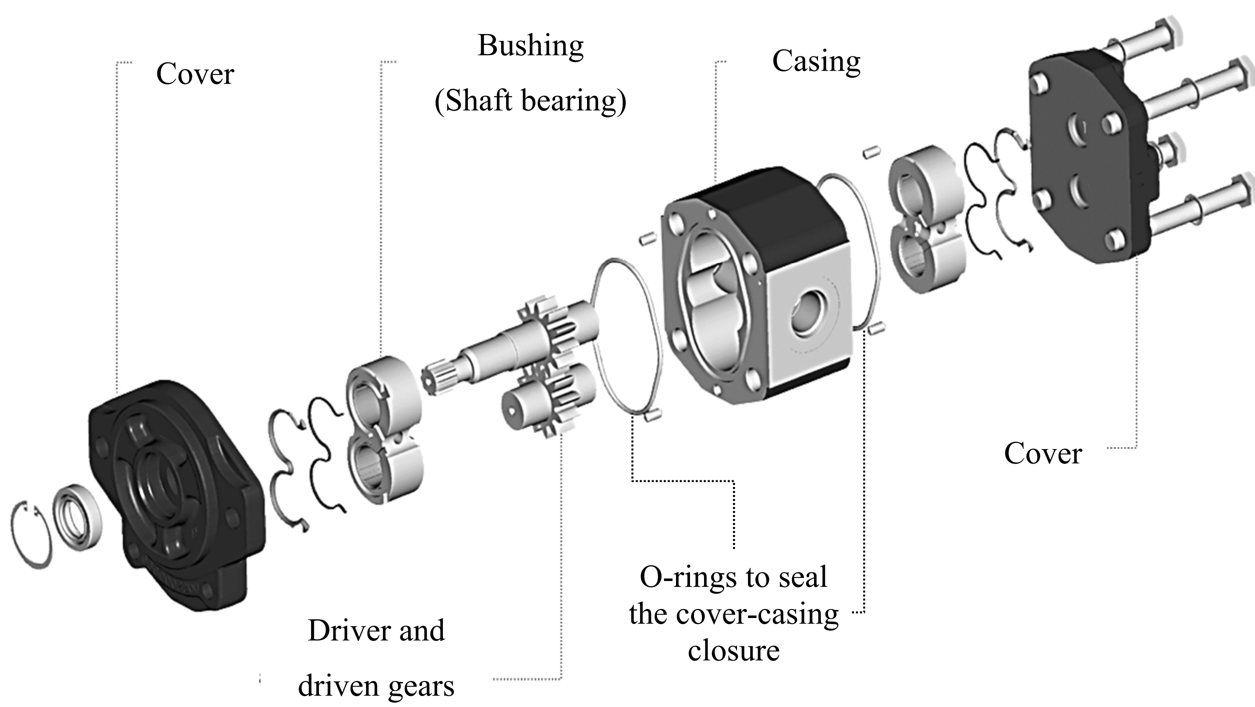
14.1 Gear pump

14.1.1 External gear pump

It consists of two meshing gears that rotate inside a fit casing. As the teeth separate, the space between them increases and sucks a certain amount of liquid. The trapped liquid moves with the teeth till they get in contact again and the space between them become zero. The only way the liquid has is the delivery port. The teeth are subjected to high pressure at the delivery side and low pressure at the suction side. This pressure unbalance causes radial force on the gears that limits the maximum pressure that can be sustained by the pump.

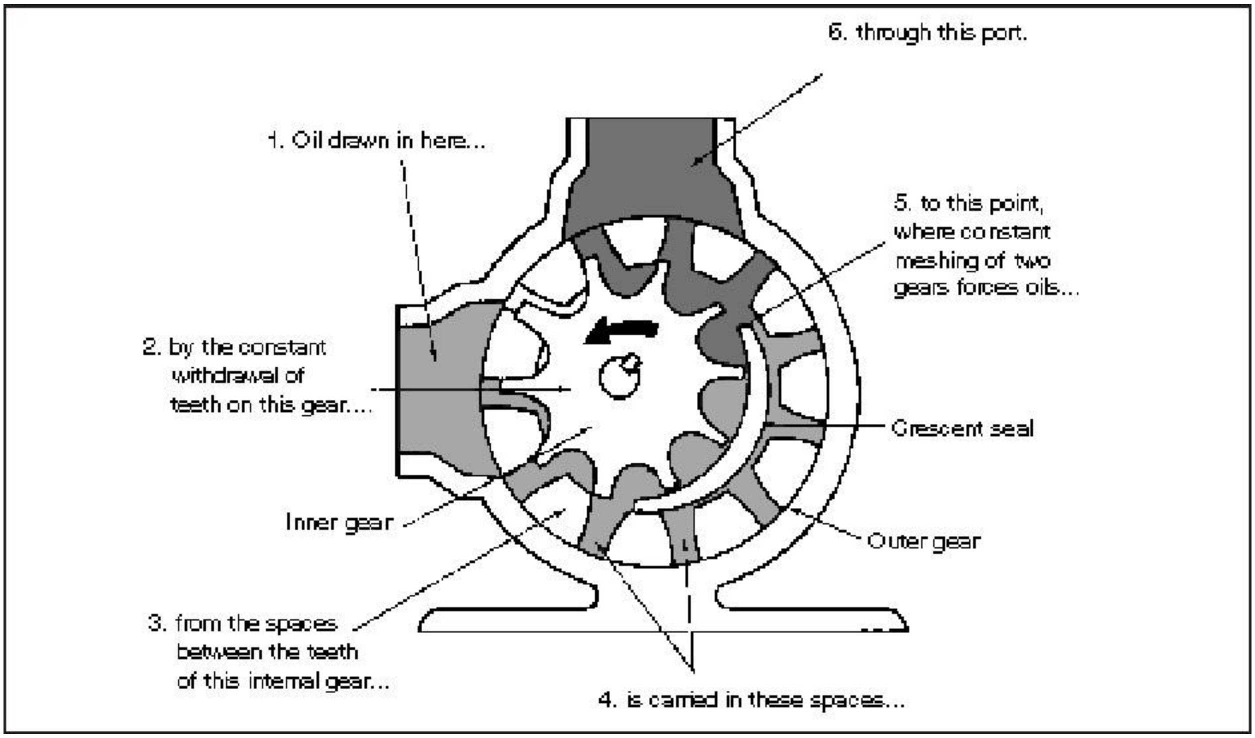


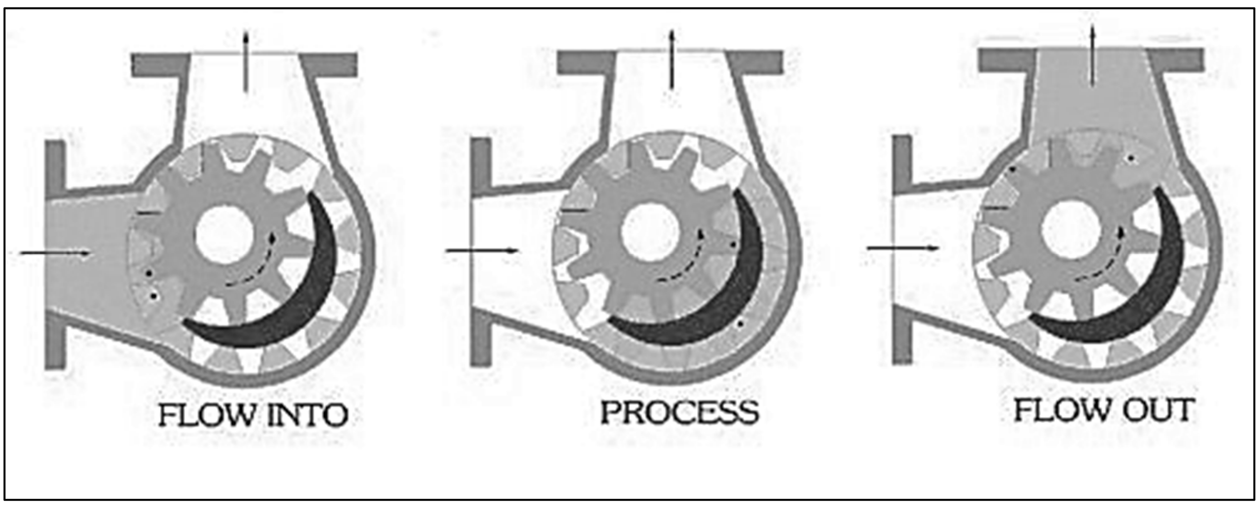




14.1.2 Internal gear pump

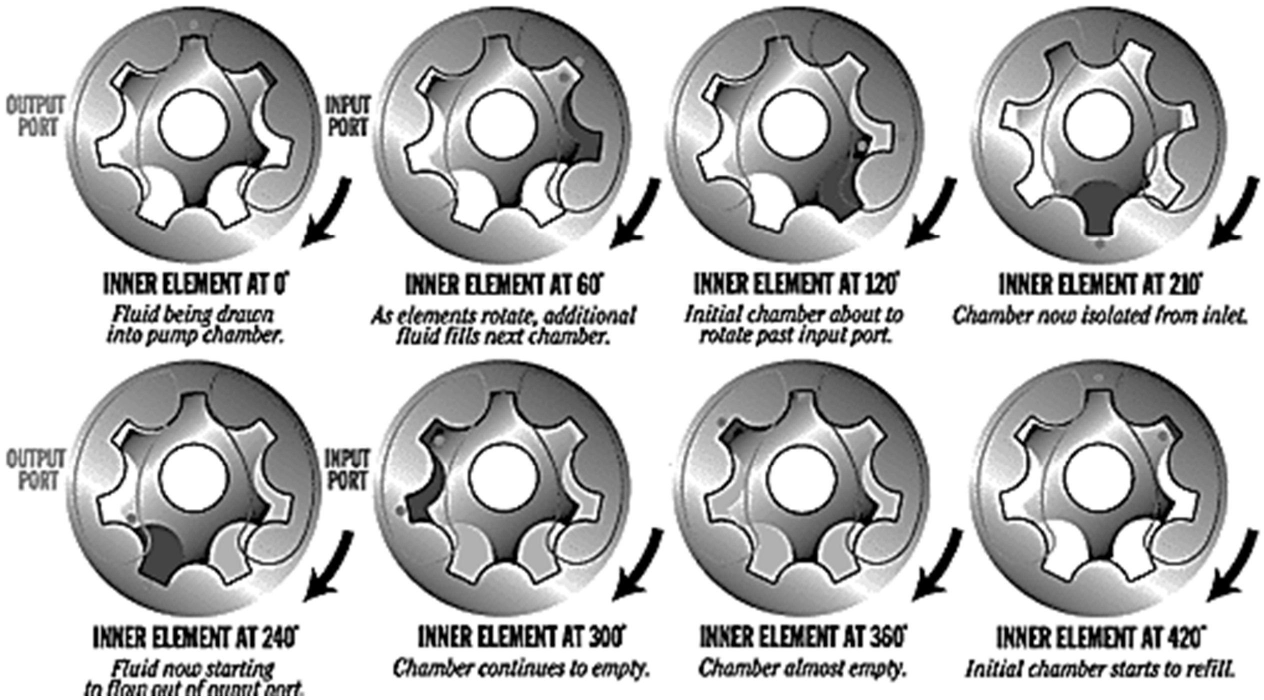
The crescent is used to seal the space between the inner outer gears and prevent leakage from the delivery side to the suction side. Unlike the external gear pump, higher pressures can be attained due to pressure force support by the outer gear.





14.1.3 Gerotor pump

Here the crescent is removed and the inner gear has one teeth less than the outer gear.

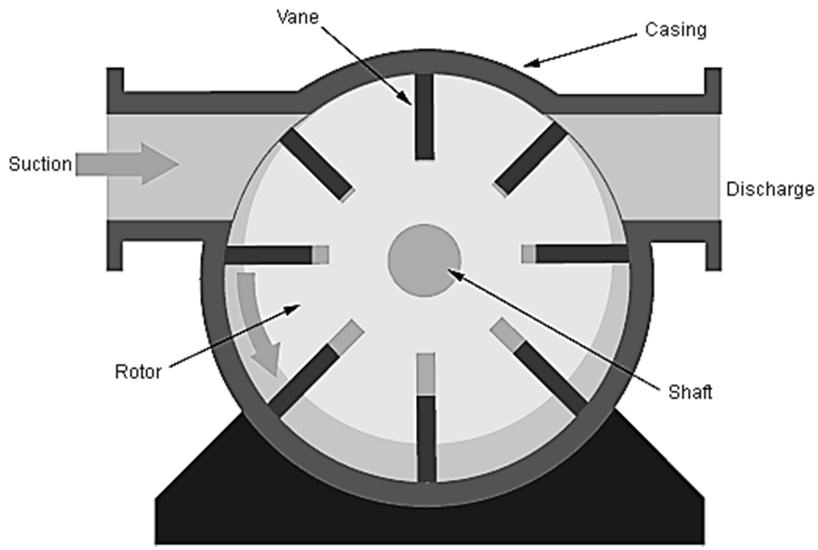


14.1.4 Characteristics of gear pump

- Widely used, simply designed, compact.
- Can operate at relatively high pressures (300 bar).
- Applications:
  - Usual car's oil pump.
  - Industrial and mobile hydraulic applications.
  - Metering applications (gear pumps are good at controlling volume flow rate).
- Low efficiency (90%).
- Slip depends on clearance space, pressure difference and liquid viscosity.
- Can’t tolerate dirt.
- Not efficient in pumping low-viscosity liquids.
- Moderate noise.

14.2 Sliding vane pump

Consists of a rotor with radial slots where the vanes can move back and forth. As shown in figure, the rotor is placed eccentric with the cam. As the rotor rotates, the centrifugal force obliges the vanes to slide along the cam ring. The space between the rotor and cam holds the pumped fluid. In one half this space increases which sucks a new amount of liquid into the pump (suction). While in the second half the space decreases pushing the liquid out of the pump (delivery).

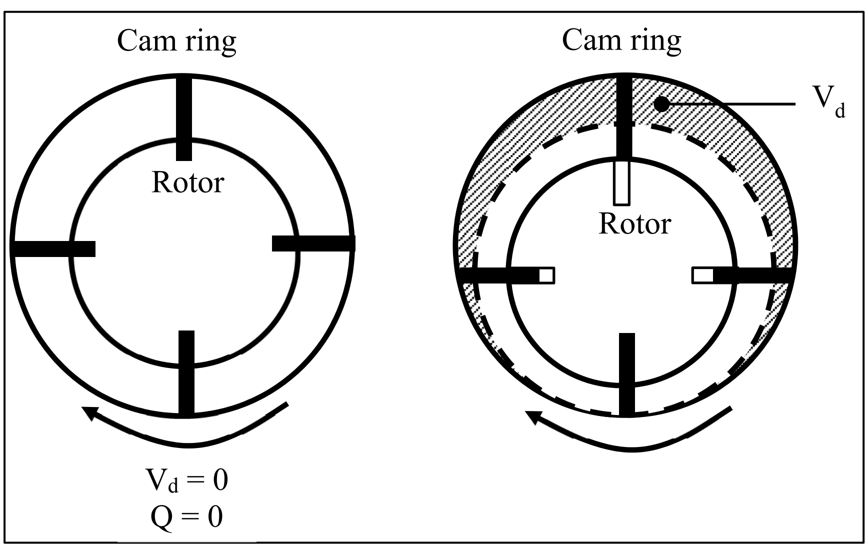


The displacement of is given by the equation:

$$V_d = \frac{\pi}{2}(D_C + D_R)eL$$

Where;

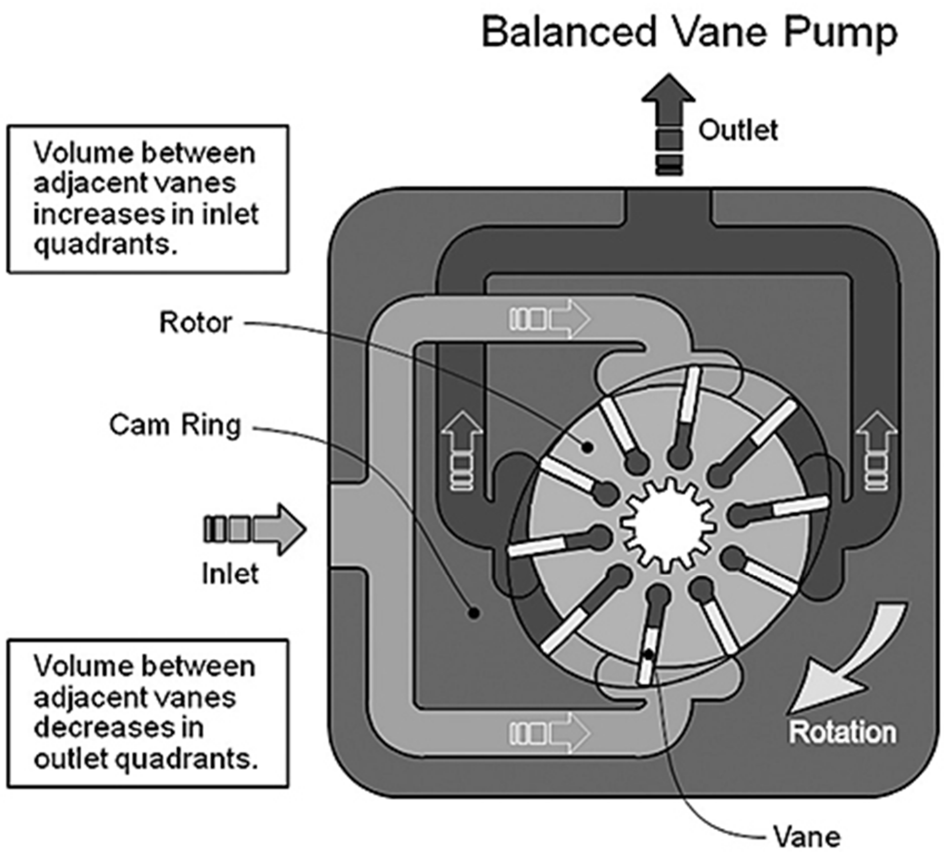
D_C	=	cam diameter
D_R	=	rotor diameter
e	=	eccentricity
L	=	rotor width



The pump rotor is subjected to thrust due to the pressure difference between the suction and delivery sides, hence this basis design in named “unbalanced vane pump”. As the pressure increases, the thrust increases which limits the maximum pressure that can be sustained by this type of pumps.

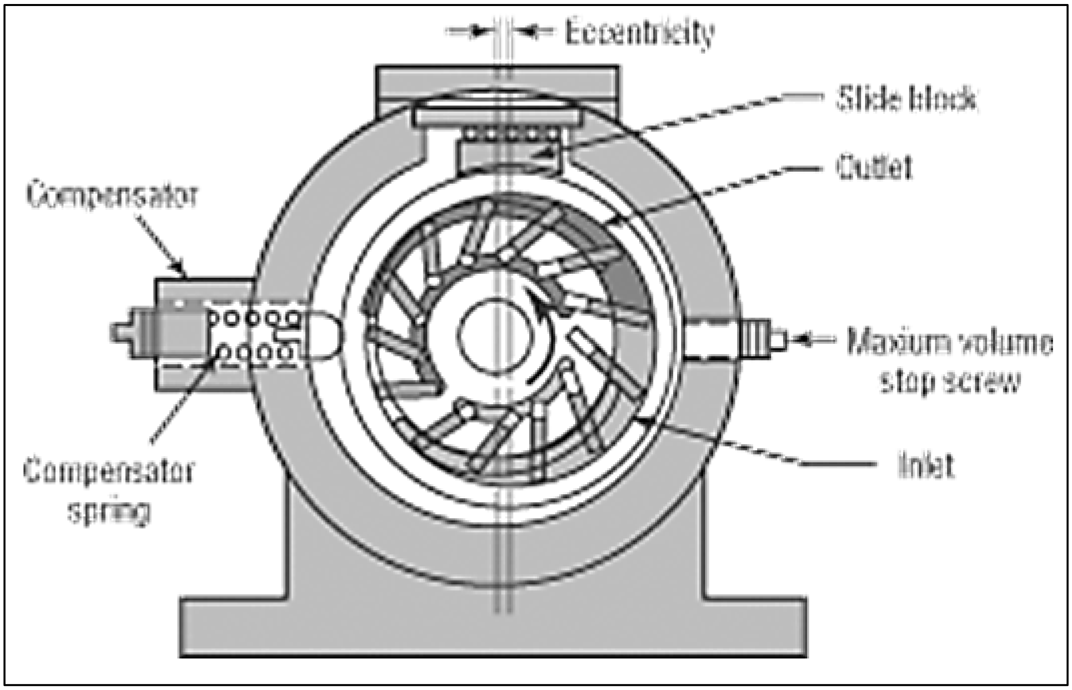
14.2.1 Balanced vane pump

In this design, the rotor and cam are concentric but the cam is oval. The space, between the rotor and cam, increases and decreases twice which forms two high and low pressure regions. Thus the rotor is balanced under pressure forces. This allows sustaining higher pressures.



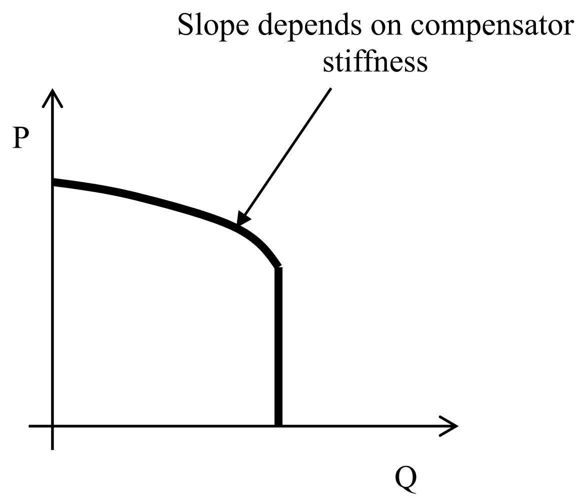
14.2.2 Variable displacement vane pump

If the cam ring can be displaced radially, the eccentricity between the cam and rotor can be varied and consequently the pump displacement and flow rate can be controlled.



14.2.3 Pressure compensated vane pump

In this type of vane pumps, the adjusting piston is controlled via a bypass line from the high pressure delivery side. So if the system pressure (delivery pressure) exceeds a predefined limit, the adjusting piston starts displacing the cam ring. Then, the eccentricity decreases, and consequently the flow rate. When reaching the set pressure, the eccentricity, flow rate, becomes zero. The pressure compensating mechanism acts as a relief (safety) valve.



14.2.4 Characteristics of vane pump

- Polished hardened vanes and cam ring.

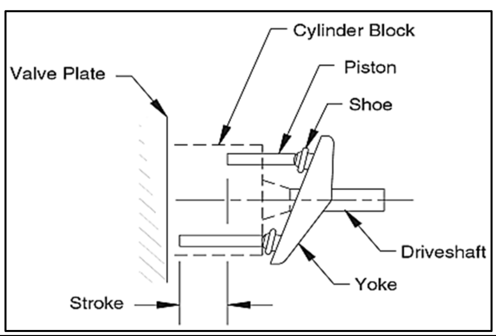
- High efficiency (95%) even for low viscosity liquids.
- Automatic wear compensation.
- Low pressures (200 bar).
- Low noise at low speed.
- Widely used in mobile equipment.
- Used for high speed services or springs are needed to hold the vanes out against the ring.
- Tolerate dirt.

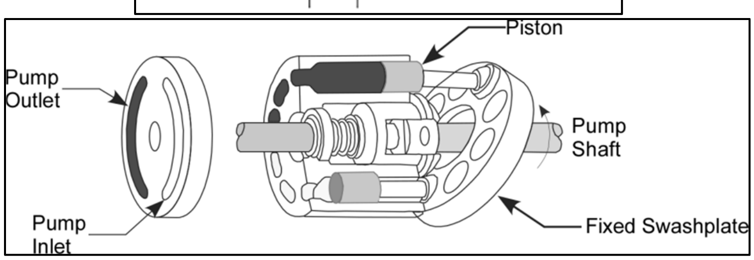
14.3 Axial piston pump

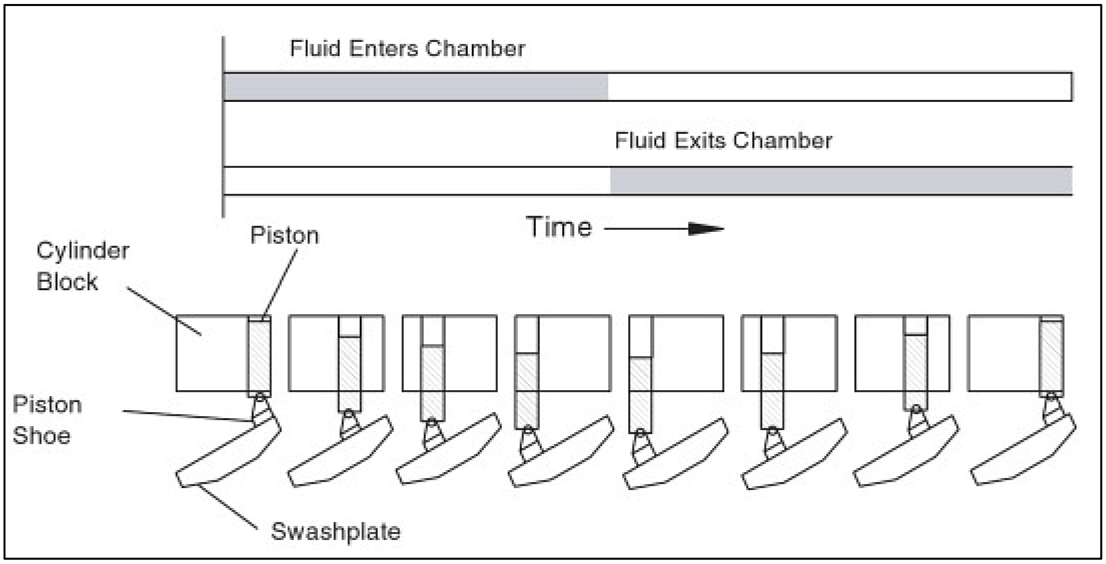
The axial piston pump consists of a cylinder block that has circular longwise holes distributed over a pitch circle. Through the circular holes, small pistons slide back and forth to make the pumping action. There are three main designs of axial piston pump.

14.3.1 In-line axial piston pump

Here, the cylinder block rotates with the pistons. The shoes of the pistons slide over an inclined fixed swash plate. Thus the pistons have two kinds of motion; rotating motion and reciprocating motion. The latter produces the pumping action. A fixed valve plate containing two kidney-like ports is placed in front of the cylinder block, such that the inlet valve faces the suction part of the piston stroke while the outlet valve faces the delivery part of the piston stroke.







As the angle of the swash plate increases, the stroke of the pistons increases and hence the displacement. The displacement of the pump is given by:

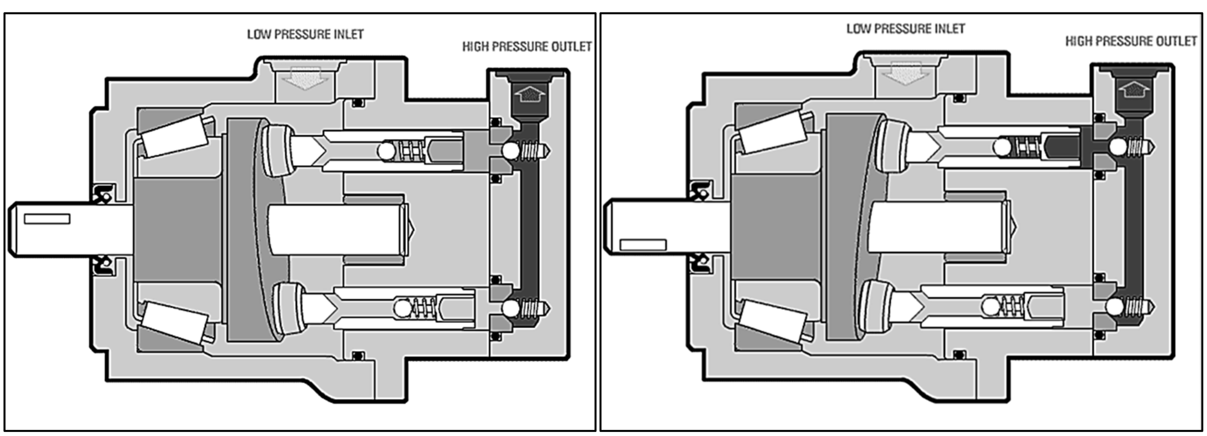
$$V_d = \frac{\pi}{4} d^2 Z D_C \tan\alpha$$

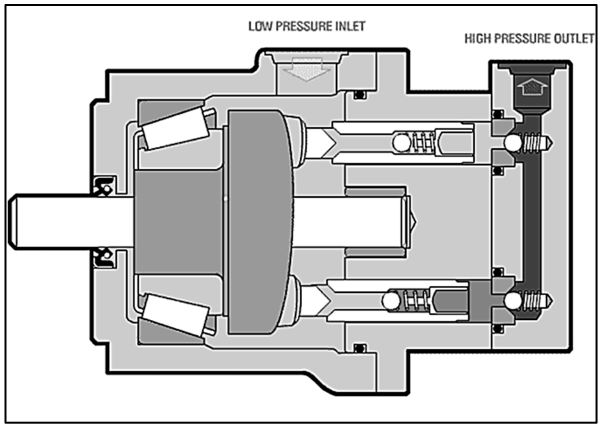
Where;

d	=	hole (small cylinder) diameter
Z	=	number of cylinders
D_c	=	pitch circle diameter
α	=	inclination angle of the swash plate

14.3.2 Wobble plate axial piston pump

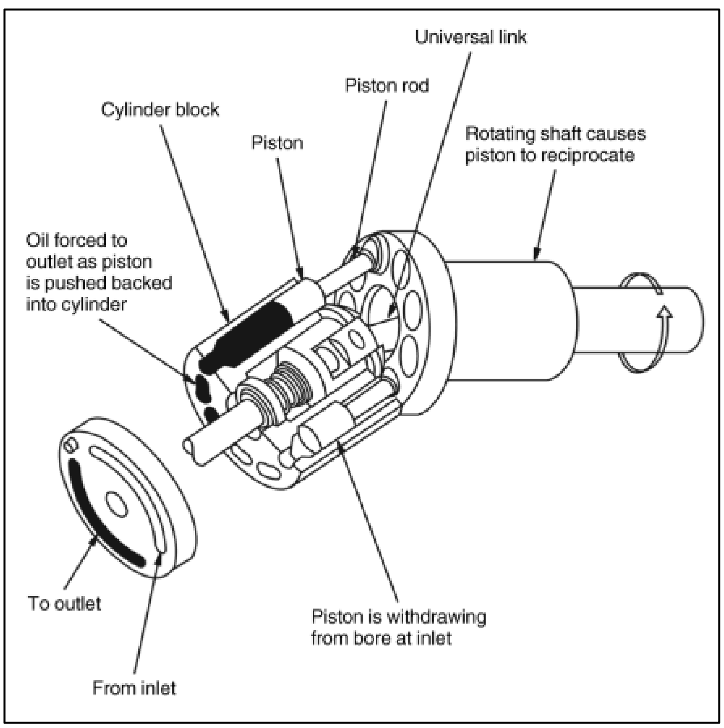
In this design, the cylinder block and pistons are fixed but the swash plate rotates in a "wobble" motion that makes each piston moves in a reciprocating motion without rotation. Here the piston faces the same ports all the time, hence two check valves are needed at the inlet and outlet ports.





14.3.3 Bent-axis axial piston pump

The difference between the bent-axis and in-line designs is that in the bent-axis design, the pistons are fixed in the swash plate which rotates around an inclined axis. The timing between the swash plate and cylinder block is attained via bevel gears fixed on each of them or via universal joints.



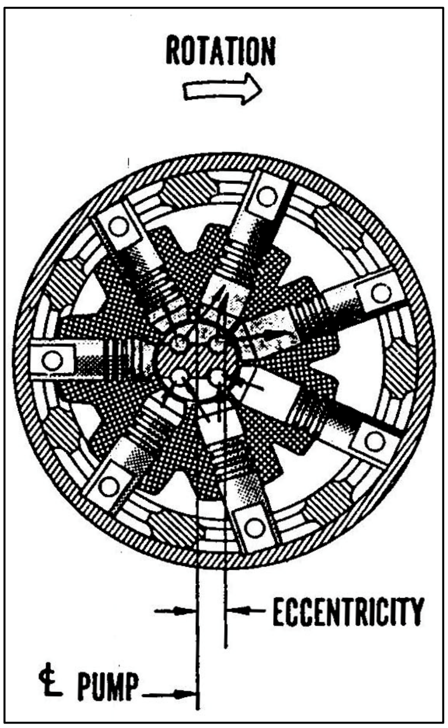
14.3.4 Characteristics of axial piston pump

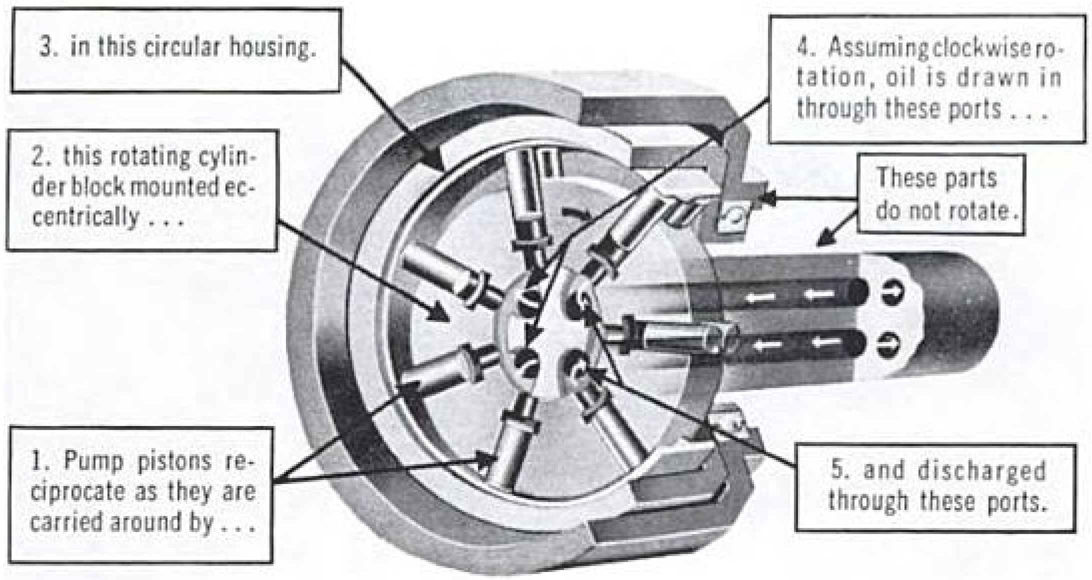
- In capacity, piston pumps range from low to very high capacities.
- Pressures are as high as 350-700 bars.
- Drive speeds are medium to high.

- Efficiency is high.
- Pumps generally have excellent durability.
- Pulsations in delivery are small and of medium frequency.
- The pumps are quiet in operation but may have a growl or whine, depending on condition.
- Except for in-line pumps, which are compact in size, piston pumps are heavy and bulky.

14.4 Radial piston pump

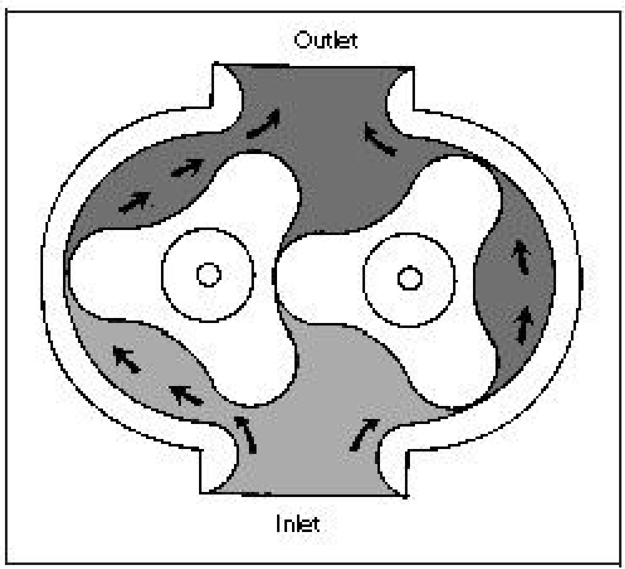
The radial piston pump consists of a rotor placed eccentric to a cam ring. The rotor has radial cylindrical holes where small pistons can slide radially back and forth. Due to centrifugal force, the shoes of the piston slide over the cam ring surface. A fixed cylinder (pintle) with intake and delivery ports is fixed at the hollow center of the rotor. The ports are grooved such that the piston faces the inlet port during suction stroke and the outlet port during delivery stroke.





14.5 Lobe pump

It looks like the external gear pump but with the gears replaced by lobes.

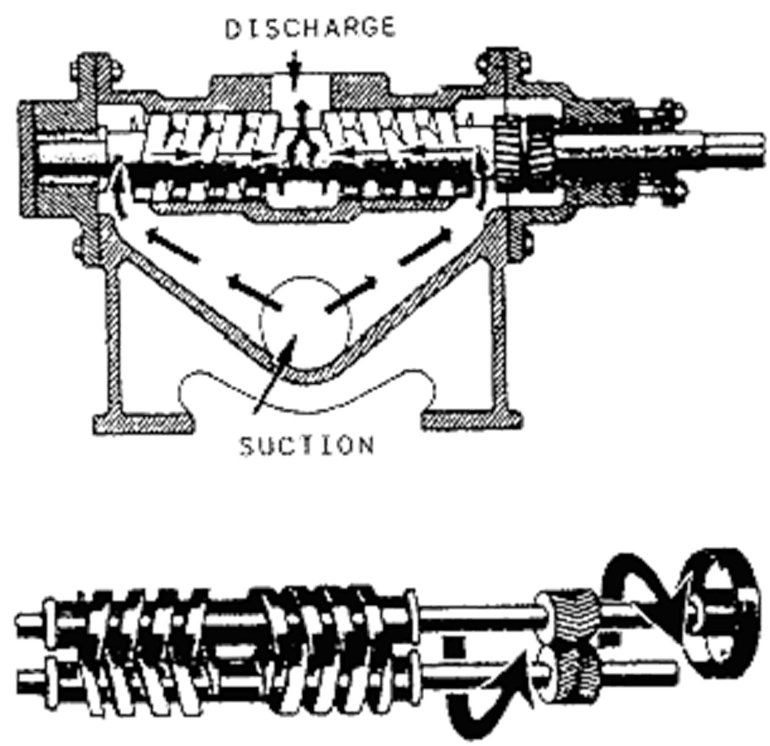


14.5.1 Characteristics of lobe pump

- The lobes don’t contact.
- External timing gears are needed to rotate the lobes.
- Not efficient in pumping low-viscosity liquids.
- Used to pump slurries and pastes.
- Can handle solids without damage.

14.6 Screw pump

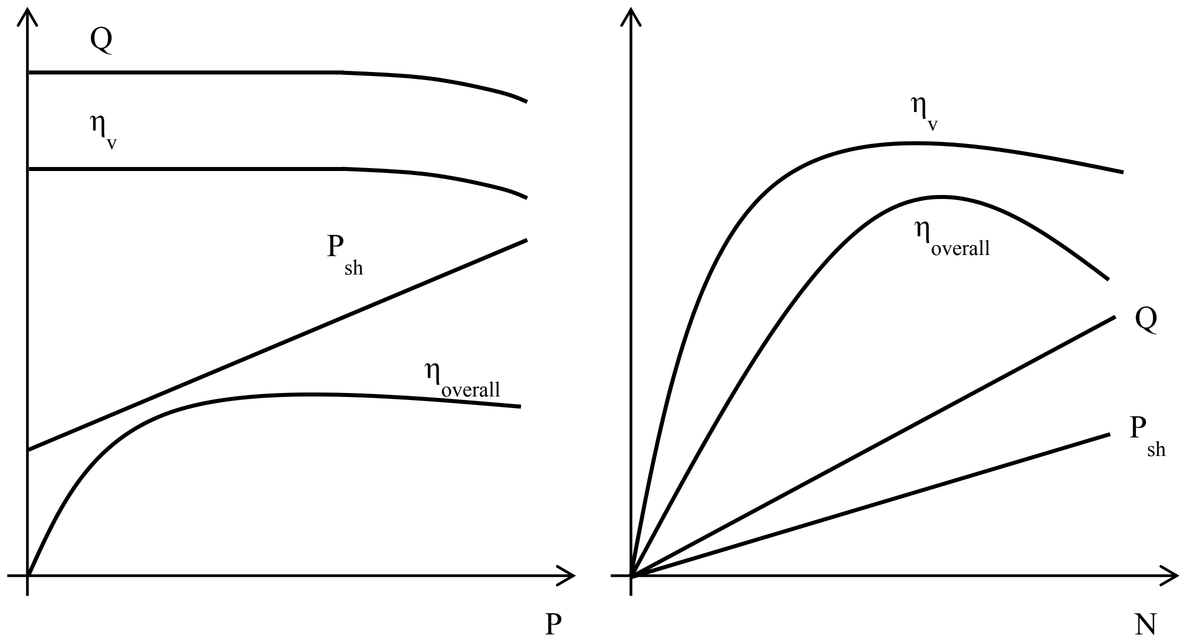
It uses a screw or a number of screws for pumping liquid. The screw pump is usually used for pumping fuels and lubricating oils.



Double-screw, low-pitch pump.

15 Performance of PDPs

The figure shows the change of pump parameters (Q, η_v, $\eta_{overall}$, P_{sh}) with pump manometric pressure and speed. The volumetric efficiency decreases as the pressure difference increases. This is due to increase of leakage through pump clearances at high pressures. Also, as the pump speed increases the liquid can be displaced by minimum leakage i.e. the volumetric efficiency increases.


Q
η_v
P_{sh}
$\eta_{overall}$
P
η_v
$\eta_{overall}$
Q
P_{sh}
N