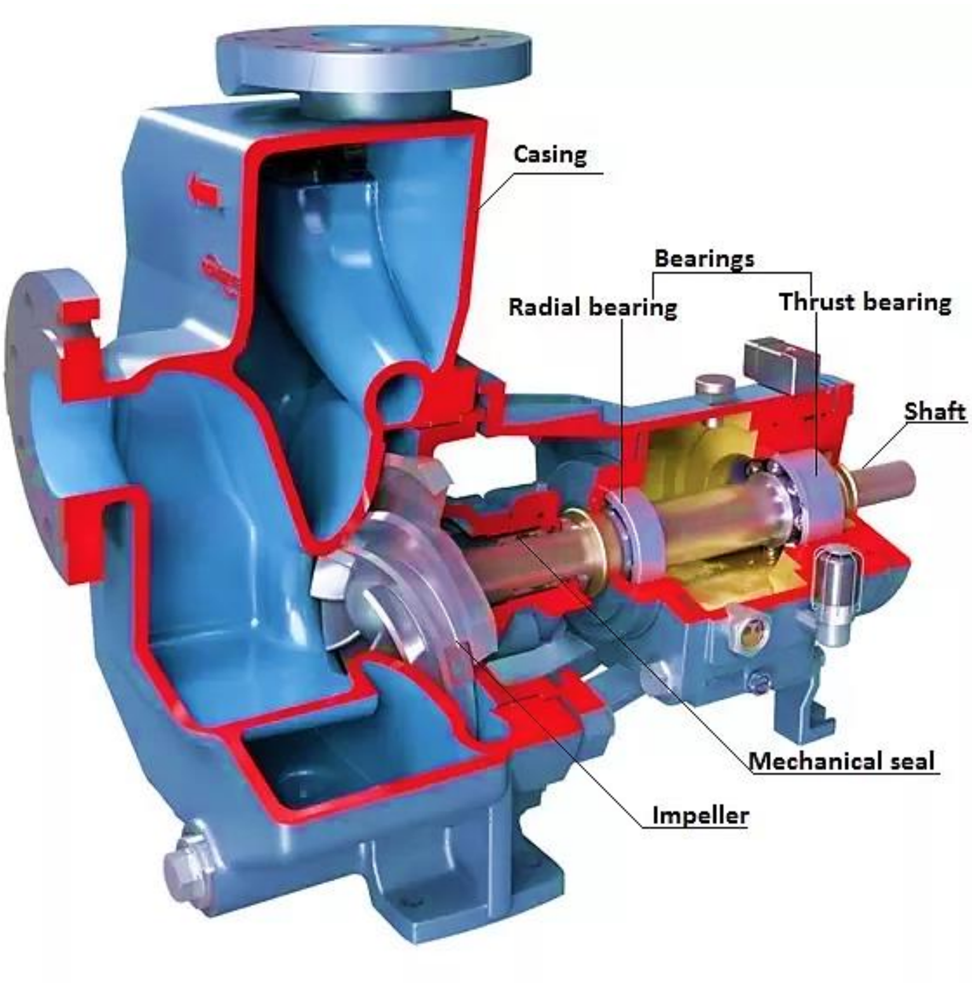
FUNDAMENTALS OF PUMPS



TYPES AND OVERVIEW

By / Mostafa Mahmoud

Contents

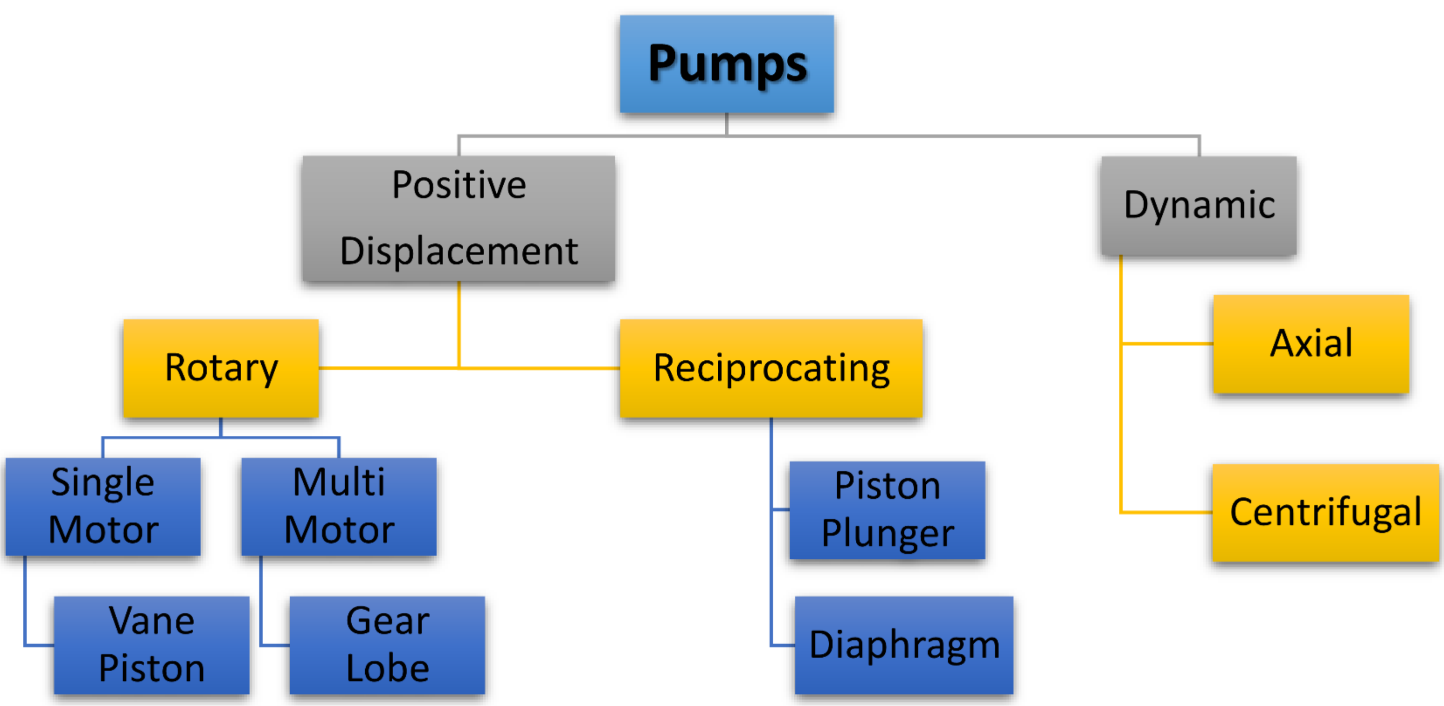
What is a pump?

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.

Applications

- Pumping oil and petroleum derivatives from production or storage site to the market.
- 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.

PUMPS TYPE



POSITIVE DISPLACEMENT Pump

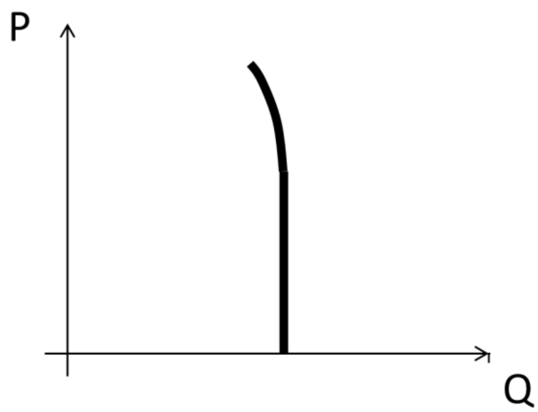
PDPs displace a fixed amount of liquid from suction side to discharge side. These pumps give very high pressures but little flow rates. So they are used in fluid power applications to pump oil in heavy duty machines (cranes, excavators, etc.).

Dynamic Head Pumps (DHP)

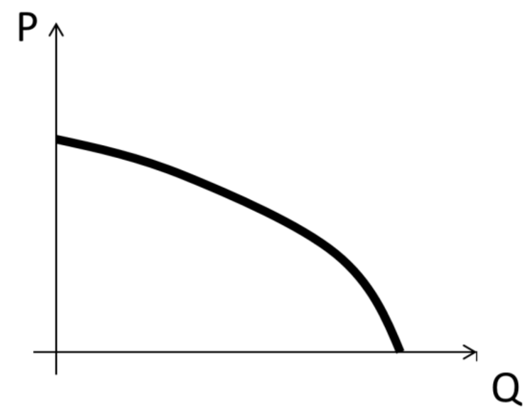
DHPs increase the kinetic energy of the flow which is then converted to pressure. These pumps give very large quantities at low pressures. So they are used in liquid transportation to pump e.g. to pump water from treatment stations to homes.

COMPARISON

POSITIVE DISPLACEMENT PUMPS (PDP)

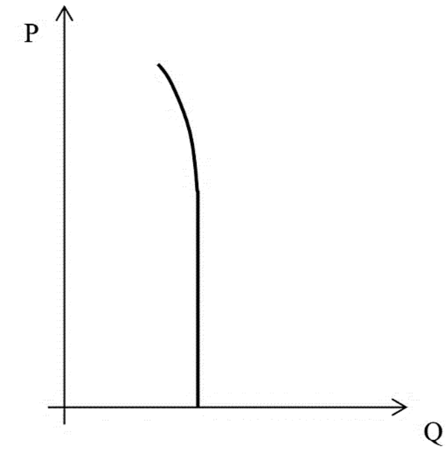


DYNAMIC HEAD PUMPS (DHP)



	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)

1. POSITIVE DISPLACEMENT PUMPS



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;

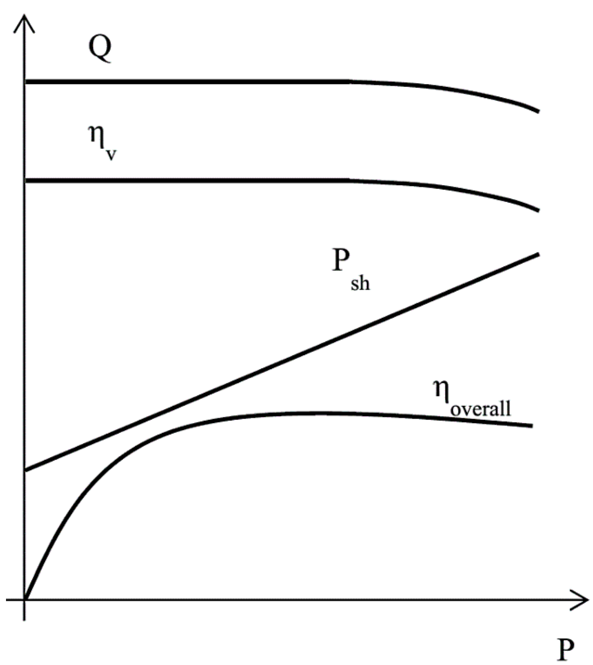
η_v = volumetric efficiency that compensates for pump leakage, slip, (=100% for zero leakage pump)

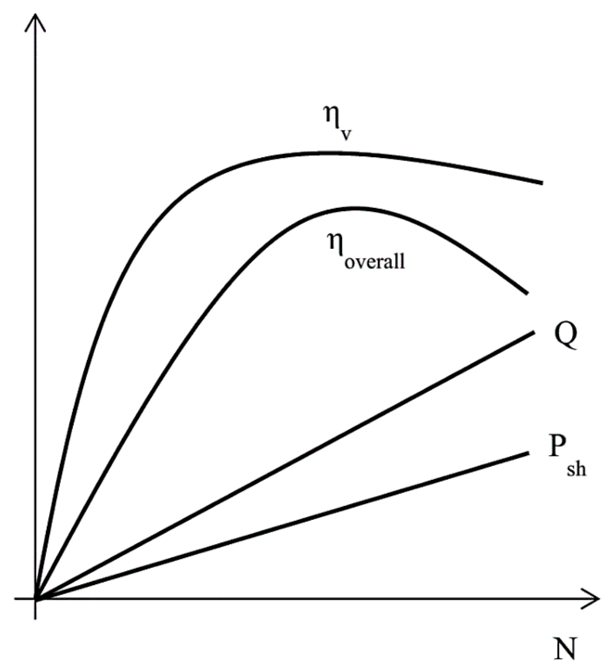
V_d= volumetric displacement of the pump (depends on the pump geometry, equals the chamber volume for piston pump and the space between teeth and casing for gear pump) (m^3)

N = pump speed (rpm)

Performance of PDPs

The figure shows the change of pump parameters (Q,η_v,$\eta_{Overall}$, Psh) with pump man-metric 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.



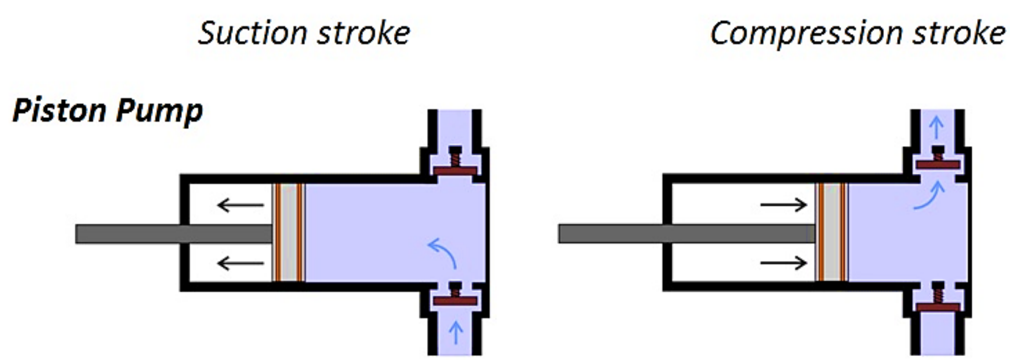


1.2 TYPE OF POSITIVE DISPLACEMENT PUMP

A. Reciprocating Pump

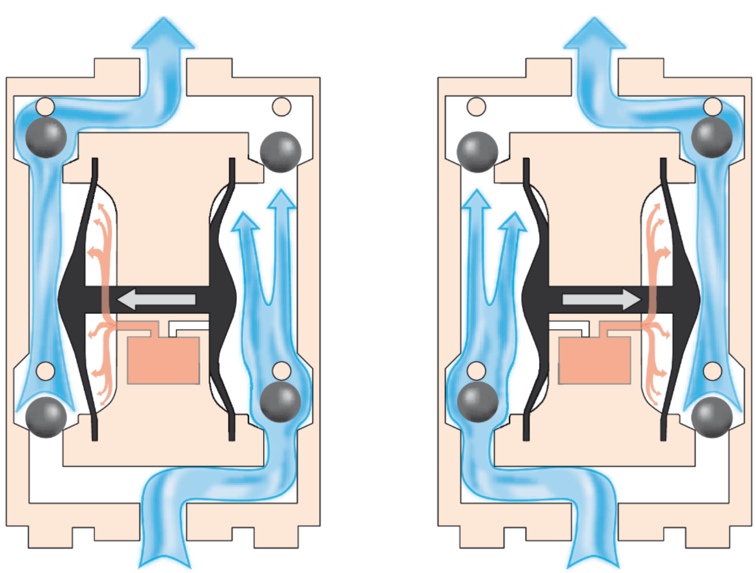
A.1 Piston Pump

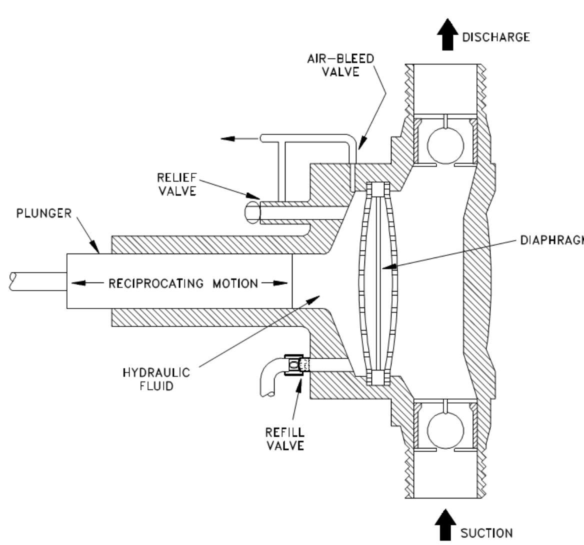
The piston pump is the simplest and may be oldest type of pumps. This pump produces very high pressures and can pump slurries and heavy liquid. It consists of a piston that reciprocates inside a cylinder. As the piston retards, the volume of the space increases and a new amount of liquid is sucked through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



A.2 Diaphragm Pump

The pump will function when a diaphragm is forced into reciprocating motion by mechanical linkage, compressed air, or fluid from a pulsating, external source. The pump construction eliminates any contact between the liquid being pumped and the source of energy. This eliminates the possibility of leakage, which is important when handling toxic or very expensive liquids. Disadvantages include limited head and capacity range, and the necessity of check valves in the suction and discharge nozzles.





B. Rotary Pump

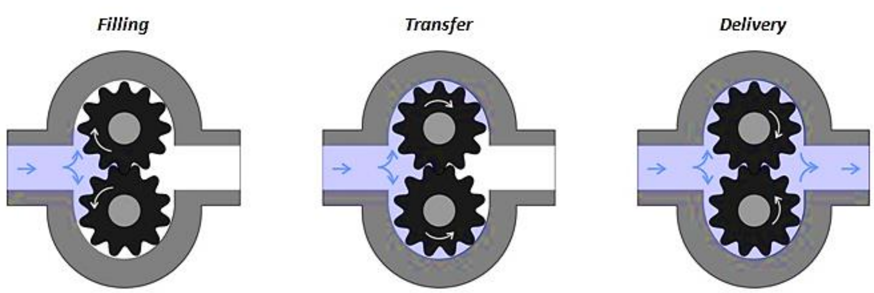
Rotary pumps operate on the principle that a rotating vane, screw, or gear traps the liquid in the suction side of the pump casing and forces it to the discharge side of the casing. These pumps are essentially self-priming due to their capability of removing air from suction lines and producing a high suction lift. In pumps designed for systems requiring high suction lift and self-priming features, it is essential that all clearances between rotating parts, and between rotating and stationary parts, be kept to a minimum in order to reduce slippage. *Slippage* is leakage of fluid from the discharge of the pump back to its suction.

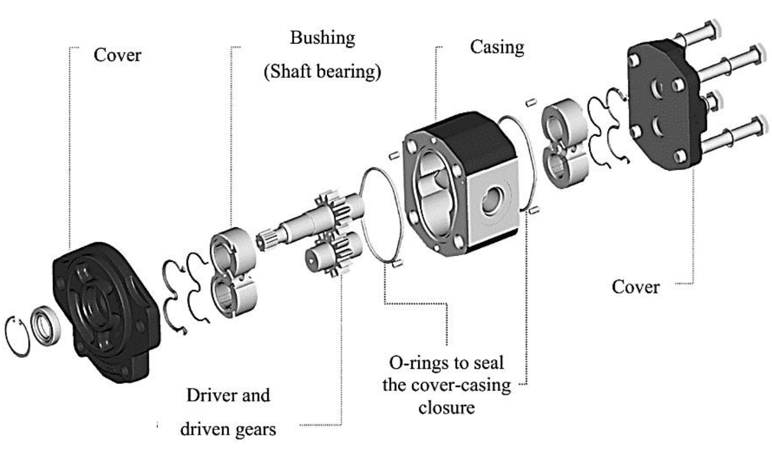
B.1 Gear Pump

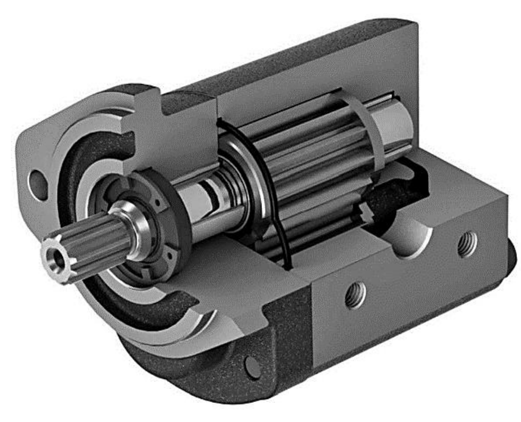
External Gear Pump: It consists of two meshing gears that rotate inside a fit casing. As the teeth separate, the space between them increases and sucks a certain amount of liquid. The trapped liquid moves with the teeth till they get in contact again and the space between them become zero. The only way the liquid has is the delivery port.

With the large number of teeth usually employed on the gears, the discharge is relatively smooth and continuous, with small quantities of liquid being delivered to the discharge line in rapid succession.

An external precision gear pump is usually limited to a maximum working pressure of 210 bars (21,000 kPa) and a maximum speed of 3,000 rpm. Some manufacturers produce gear pumps with higher working pressures and speeds but these types of pumps tend to be noisy and special precautions may have to be made.



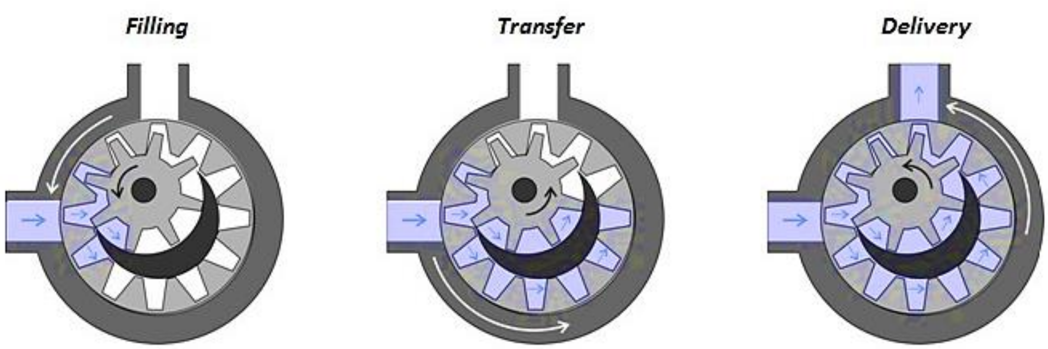




Internal Gear Pump: An internal gear pump works on a similar principle except the two linking gears sizes are different with one revolving within the other. The rotor is a larger gear and also an inner gear, and it has the teeth projecting inside.

A permanent semi-circular formed divider otherwise spacer seals the void shaped through the off-center mounting location of the idler & performs like a seal among the ports like inlet & outlet. When the gears appear from the mesh on the pump's inlet side, they make an extended quantity. Fluid supplies into the cavities as well as trapped with the teeth of gear because the gears continue for rotating next to the casing of the pump. The trapped liquid can be moved from the inlet side to the discharge side in the region of the casing.

When the gears teeth become linked on the discharge surface of the pump, then the amount can be decreased & the liquid is forced out beneath force. Inner gear pump plans only utilize spur gears.



Advantages

- High speed
- High pressure
- No overhung bearing loads
- Relatively quiet operation
- Design accommodates wide variety of materials

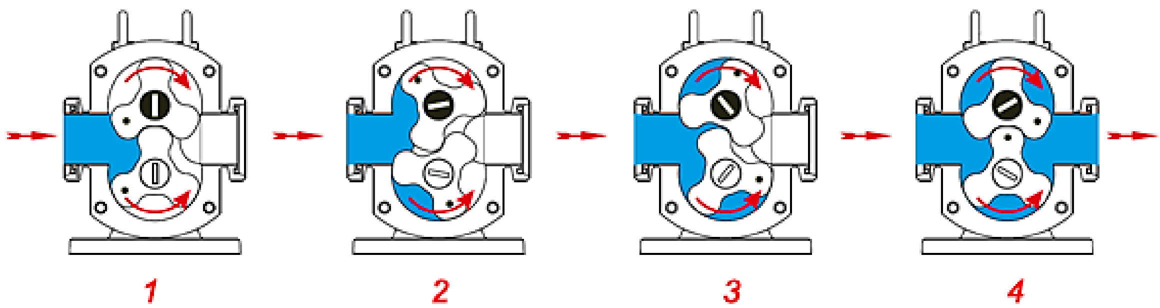
Disadvantages

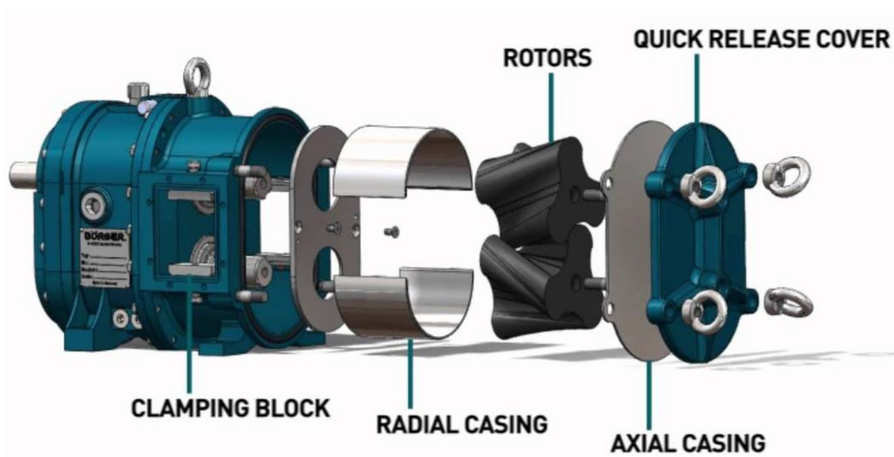
- Four bushings in liquid area
- No solids allowed
- Fixed End Clearances

Applications

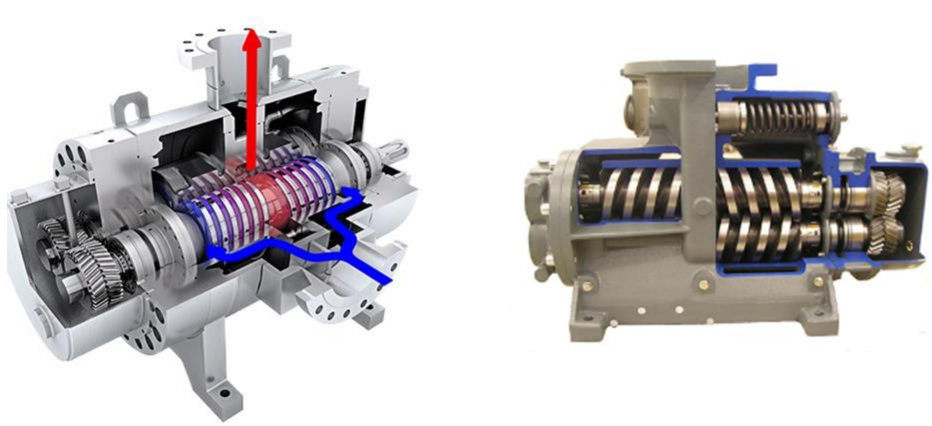
- Various fuel oils and lube oils
- Chemical additive and polymer metering
- Chemical mixing and blending (double pump)
- Industrial and mobile hydraulic applications (log splitters, lifts, etc.)
- Acids and caustic (stainless steel or composite construction)
- Low volume transfer or application.

B.2 Lope Pump Lobe pumps are similar to external gear pumps in operation in that fluid flows around the interior of the casing. Unlike external gear pumps, however, the lobes do not make contact. Lobe contact is prevented by external timing gears located in the gearbox. Pump shaft support bearings are located in the gearbox, and since the bearings are out of the pumped liquid, pressure is limited by bearing location and shaft deflection which reduces the noise levels of this pump

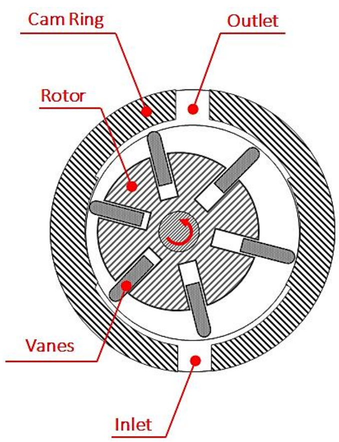


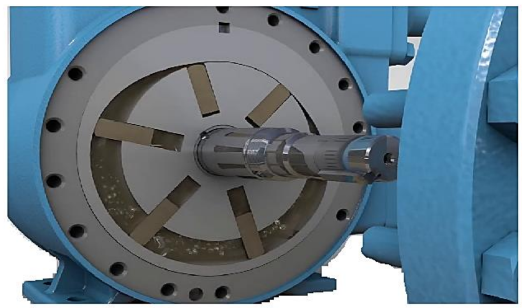


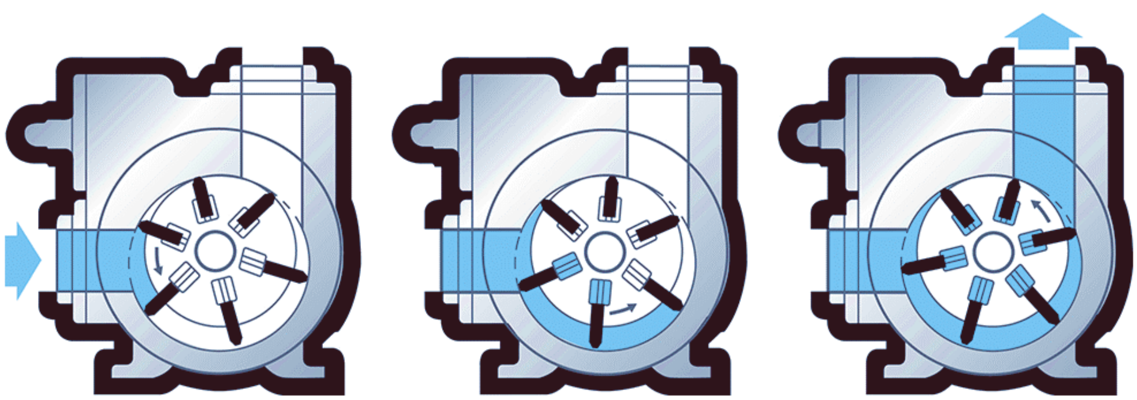
B.3 Screw Pump is equipped with screws that mesh together and rotate within a cylindrical cavity or liner. The fluid enters from the suction side of the pump and moves linearly along these intermeshing screws to the discharge side of the pump. The clearances between the screws and the liner are very small hence the fluid gains pressure while moving through the pump.



B.4 Vane Pump The pump consists of a cylindrically bored housing with a suction inlet on one side and a discharge outlet on the other. A cylindrically shaped rotor with a diameter smaller than the cylinder is driven about an axis placed above the centerline of the cylinder. The clearance between rotor and cylinder is small at the top but increases at the bottom. The rotor carries vanes that move in and out as it rotates to maintain sealed spaces between the rotor and the cylinder wall. The vanes trap liquid or gas on the suction side and carry it to the discharge side, where contraction of the space expels it through the discharge line. The vanes may swing on pivots, or they may slide in slots in the rotor.







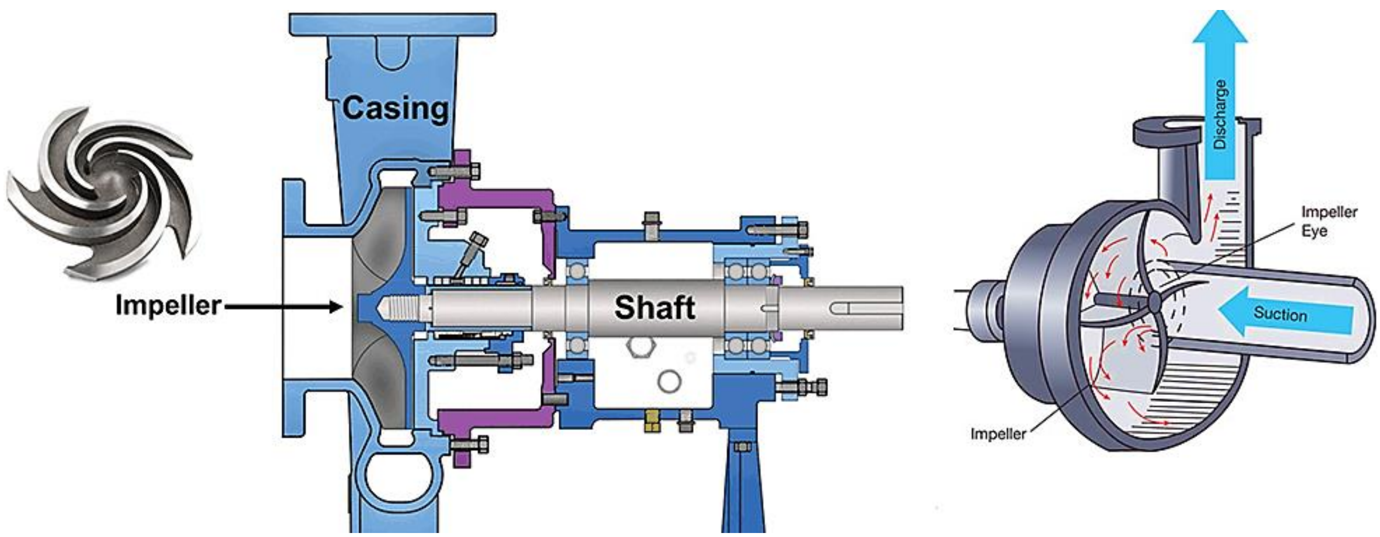
Characteristics of vane pump

- ✓ 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.

2. Dynamic Head Pumps (DHP)

2.1 Centrifugal Pump

Centrifugal pumps basically consist of a stationary pump casing and an impeller mounted on a rotating shaft. The pump casing provides a pressure boundary for the pump and contains channels to properly direct the suction and discharge flow. The pump casing has suction and discharge penetrations for the main flow path of the pump and normally has small drain and vent fittings to remove gases trapped in the pump casing or to drain the pump casing for maintenance.



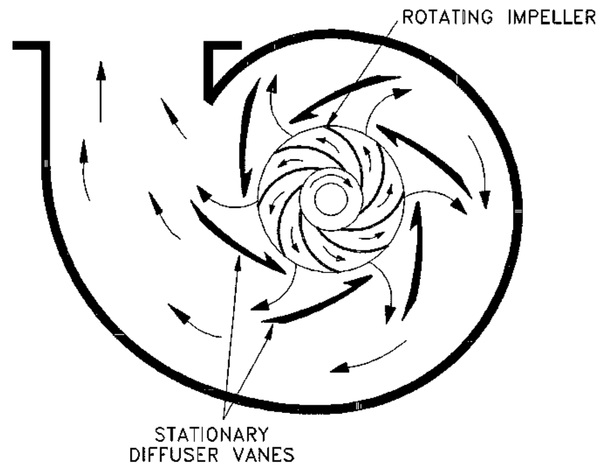
The pump casing guides the liquid from the suction connection to the center, or eye, of the impeller.

The vanes of the rotating impeller impart a radial and rotary motion to the liquid, forcing it to the outer periphery of the pump casing where it is collected in the outer part of the pump casing called the volute.

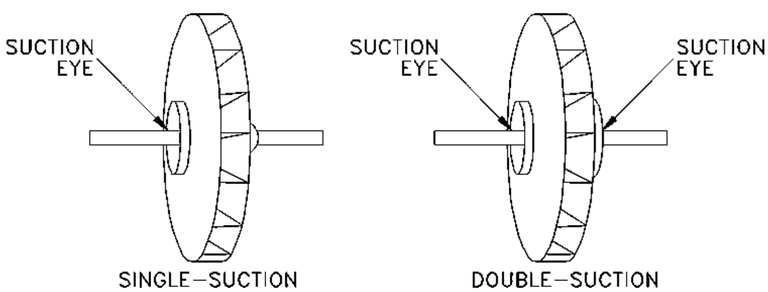
The volute is a region that expands in cross-sectional area as it wraps around the pump casing. The purpose of the volute is to collect the liquid discharged from the periphery of the impeller at high velocity and gradually cause a reduction in fluid velocity by increasing the flow area.

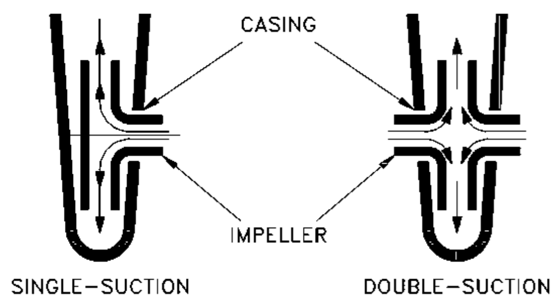
This converts the velocity head to static pressure. The fluid is then discharged from the pump through the discharge connection.

Diffuser: Some centrifugal pumps contain diffusers. A *diffuser* is a set of stationary vanes that surround the impeller. The purpose of the diffuser is to increase the efficiency of the centrifugal pump by allowing a more gradual expansion and less turbulent area for the liquid to reduce in velocity. The diffuser vanes are designed in a manner that the liquid exiting the impeller will encounter an ever-increasing flow area as it passes through the diffuser. This increase in flow area causes a reduction in flow velocity, converting kinetic energy into flow pressure.

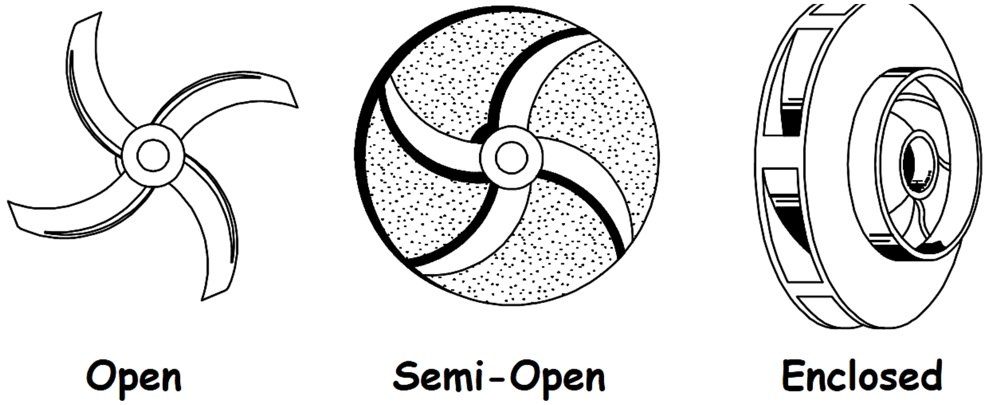


Impeller: Impellers of pumps are classified based on the number of points that the liquid can enter the impeller and also on the amount of webbing between the impeller blades. Impellers can be either single suction or double-suction. A single-suction impeller allows liquid to enter the center of the blades from only one direction. A double-suction impeller allows liquid to enter the center of the impeller blades from both sides simultaneously. Figure 4 shows simplified diagrams of single and double-suction impellers.



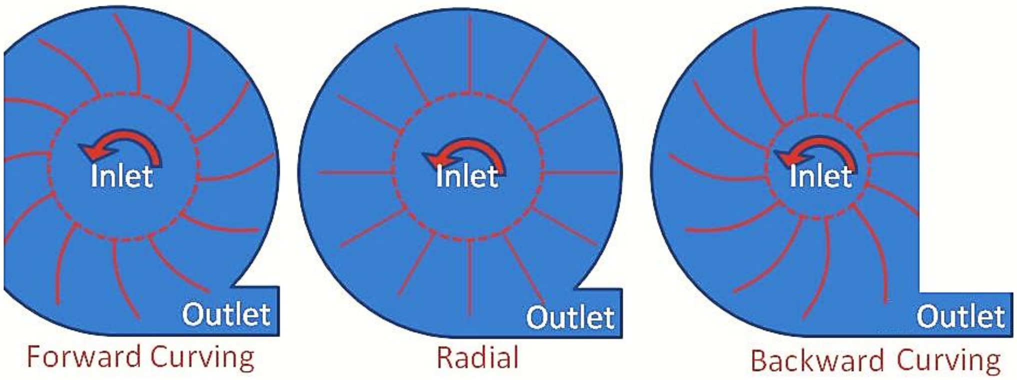


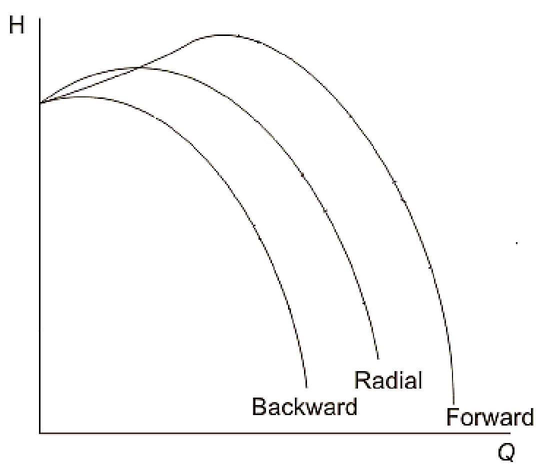
Impellers can be open, semi-open, or enclosed. The open impeller consists only of blades attached to a hub. The semi-open impeller is constructed with a circular plate (the web) attached to one side of the blades. The enclosed impeller has circular plates attached to both sides of the blades. Enclosed impellers are also referred to as shrouded impellers. Figure 5 illustrates examples of open, semi-open, and enclosed impellers.

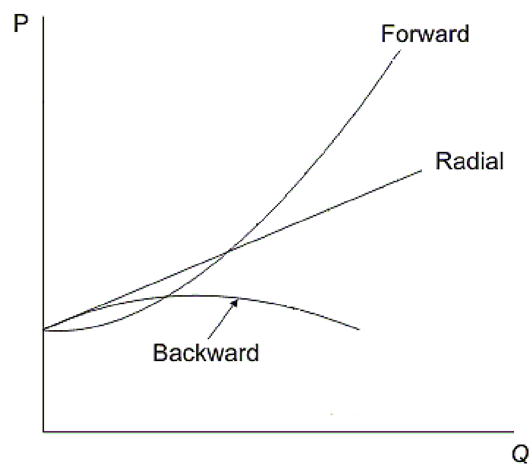


Types of Centrifugal Pump

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.





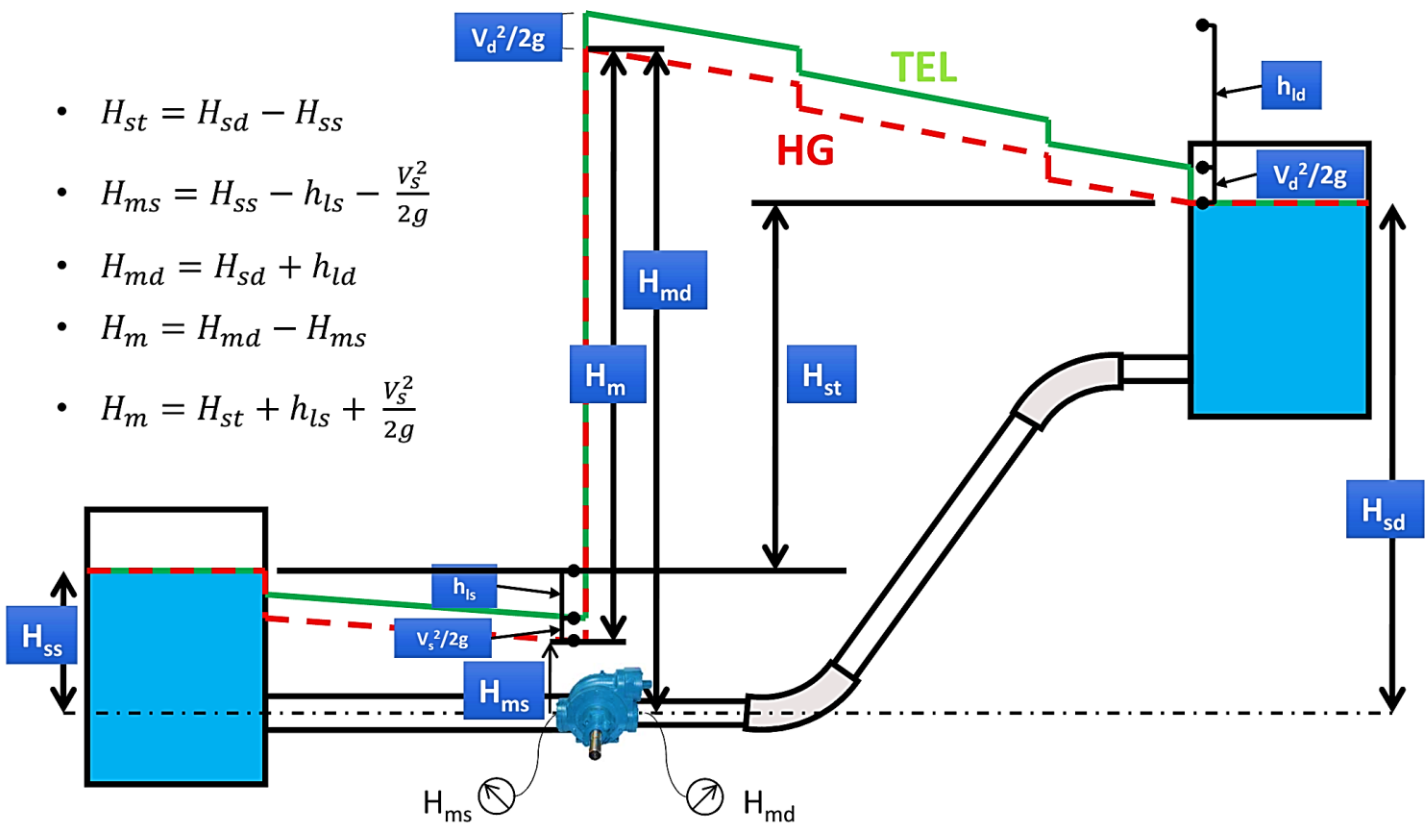


As is evident from the power-discharge characteristics of the radial and forward vane centrifugal pump, the power requirement increases monotonically with an increase in discharge. Hence, if the pump motor is rated for maximum power, then it will remain under-utilized for most of the operating time, and result in an increased cost due to its higher rating. On the other hand, if a motor is rated at the design point, and due to some reason the flow-rate exceeds the design flow rate, then the power requirement will shoot up(in case of forward and radial vanes only), causing overloading and motor failure.

However, for backward curve-vane centrifugal pumps, if the flow-rate exceeds the design flow rate (occurs quite close to the maximum of the power-discharge curve), then contrary to the earlier case, the power requirement drops down as evident from the curves. This enables the motor which is rated at the design power to handle the entire range of flow-rates without any problems. The actual design point is located corresponding to the flow-rate at which maximum efficiency occurs.

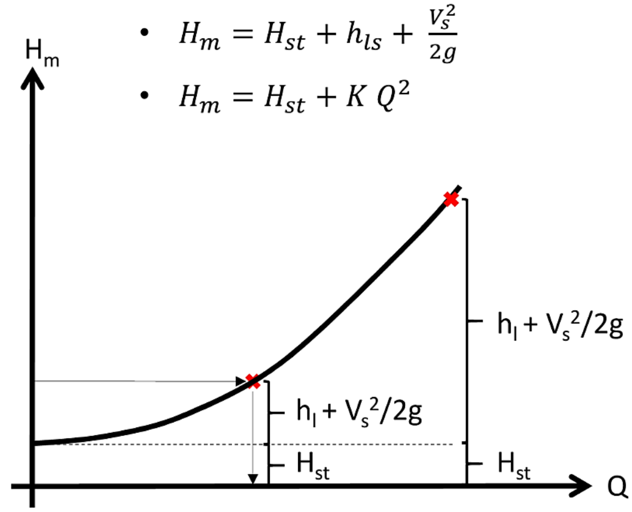
Imprtant Note

- $H_{st} = H_{sd} - H_{ss}$
- $H_{ms} = H_{ss} - h_{ls} - \frac{V_s^2}{2g}$
- $H_{md} = H_{sd} + h_{ld}$
- $H_m = H_{md} - H_{ms}$
- $H_m = H_{st} + h_{ls} + \frac{V_s^2}{2g}$



H_{st}: ***Static Head***	H_m: ***Manometric Head***	h_{ls}: ***Suction Head Losses***
H_{ss}: ***Static Suction Head***	H_{ms}: ***Manometric Suction Head***	h_{ld}: ***Delivery Head Losses***
H_{sd}: ***Static Delivery Head***	H_{md}: ***Manometric Delivery Head***	$V^2/2g$: ***Kinetic Energy***

- $H_m = H_{st} + h_{ls} + \frac{V_s^2}{2g}$
- $H_m = H_{st} + K\,Q^2$



Centrifugal Pump Performance

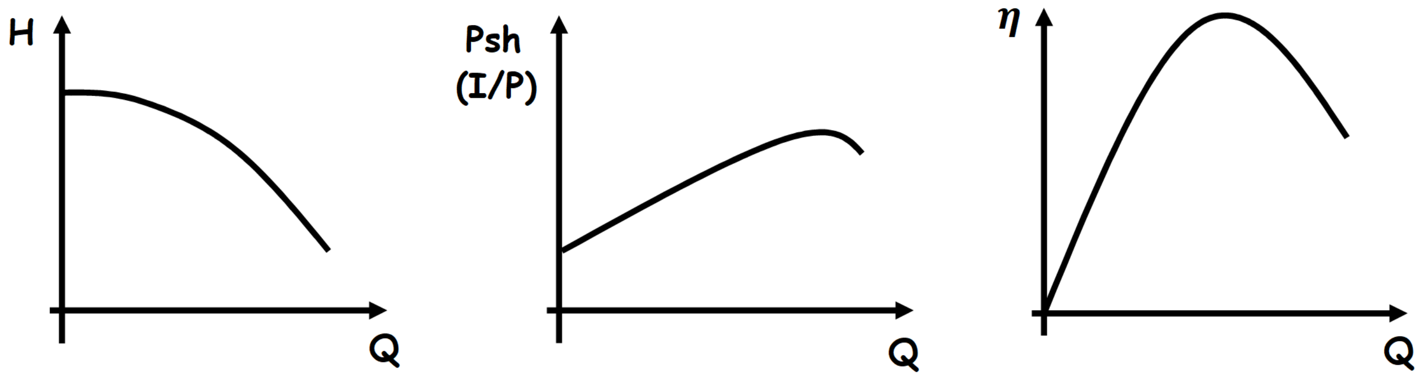
The pump performance can be obtained by testing the pump at different flow rates.

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

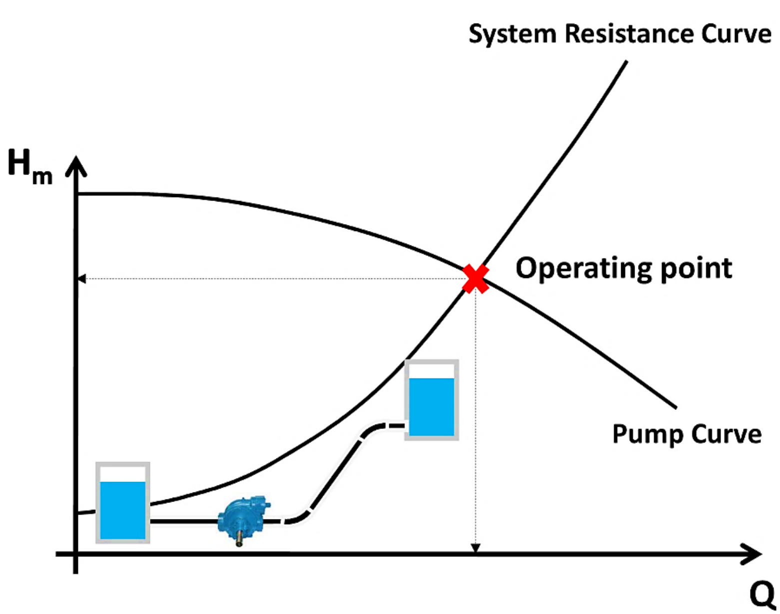
$$P_{sh} = \frac{PQ}{\eta} = \frac{\rho g h Q}{\eta}$$

Where; P = pressure difference across the pump

h = head difference across the pump (manometric head)



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.

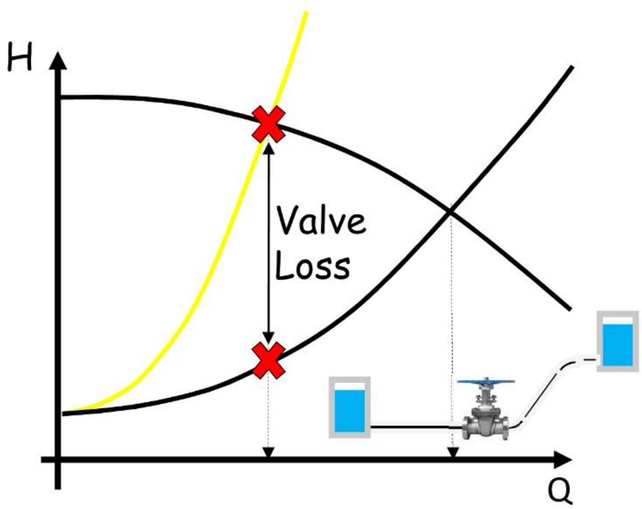


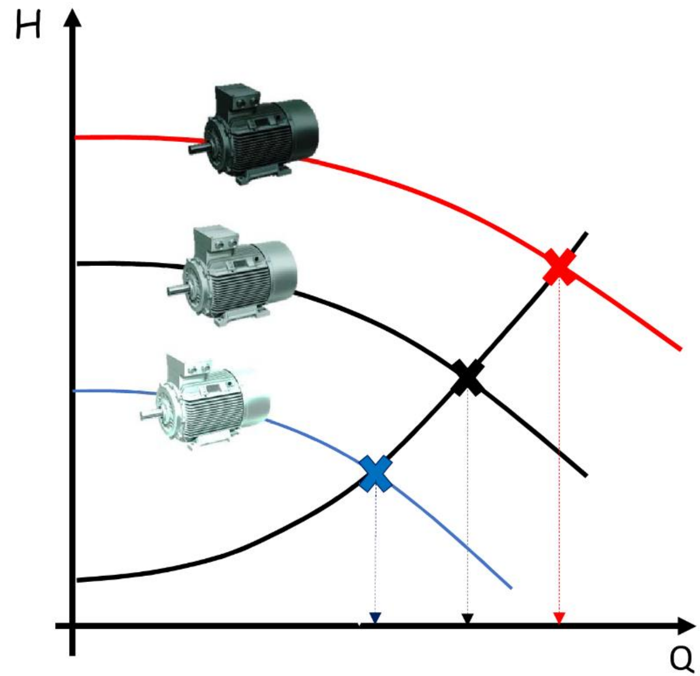
How to Control the pump flow rate?

We have 2 method, by control the system resistance of pump speed.

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

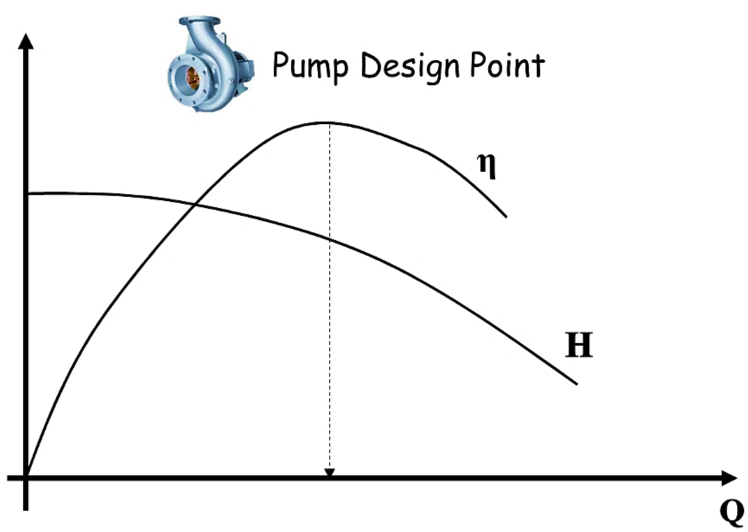
If the motor speed increased, the H-Q curve will change as shown at diagram.



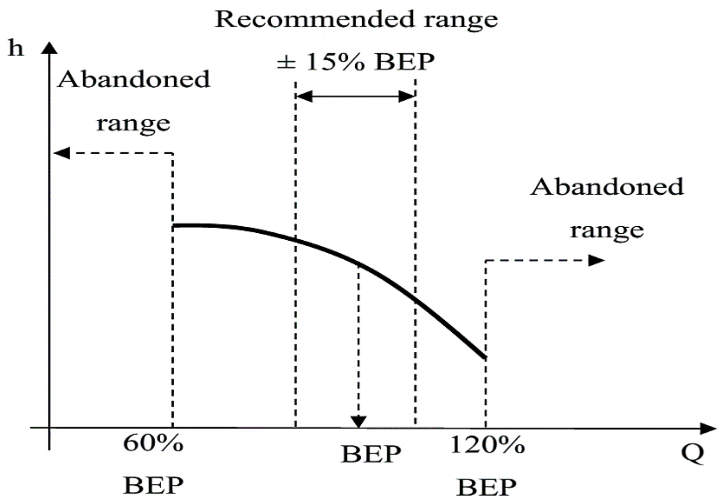


The Best Efficiency Point (BEP)

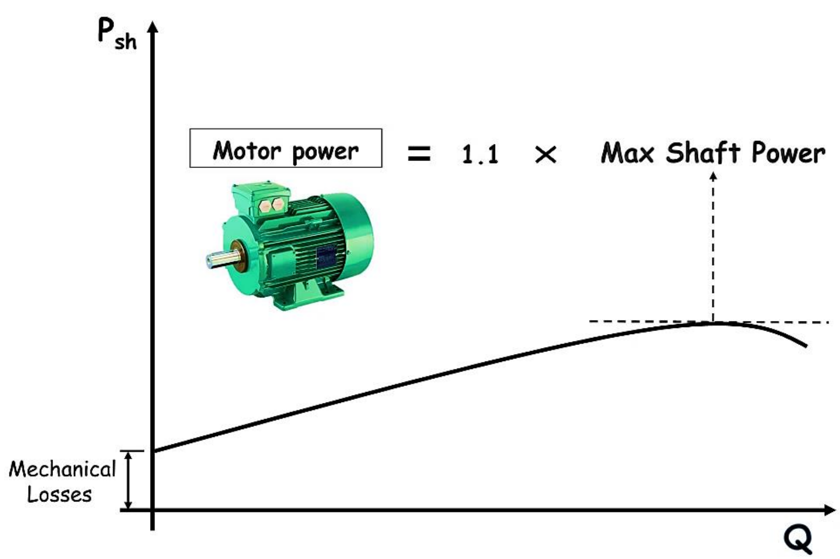
The pump design is held at a single point (flow rate and head) this point is called the Design Point. When operating the pump at this point it has the maximum efficiency. So the point is also called the Best Efficiency Point (BEP). When selecting the pump, it is normally targeted to operate the pump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



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.



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.



Cavitation

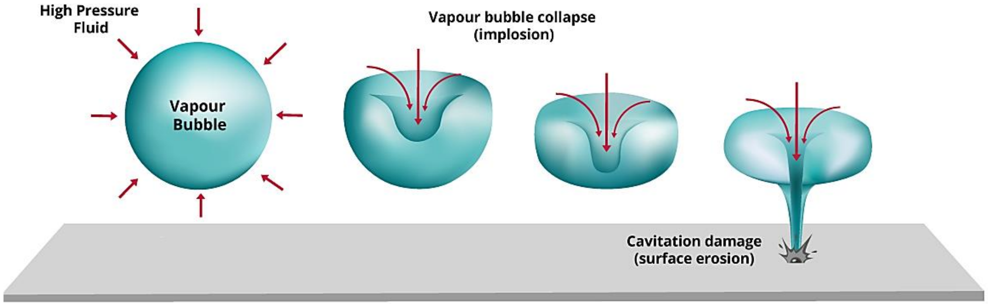
To boil any liquid, there are always two choices; increasing liquid temperature or decreasing its pressure. As the liquid temperature increases, its molecules receive more energy and at a certain temperature (boiling temperature or saturation temperature) the molecules obtain very high energy that allows 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 20o C is 0.023 bar (always absolute value).

The flow area at the eye of the pump impeller is usually smaller than either the flow area of the pump suction piping or the flow area through the impeller vanes. When the liquid being pumped enters the eye of a centrifugal pump, the decrease in flow area results in an increase in flow velocity accompanied by a decrease in pressure.

The greater the pump flow rate, the greater the pressure drop between the pump suction and the eye of the impeller. If the pressure drop is large enough, or if the temperature is high enough, the pressure drop may be sufficient to cause the liquid to flash to vapor when the local pressure falls below the saturation pressure for the fluid being pumped.

Any vapor bubbles formed by the pressure drop at the eye of the impeller are swept along the impeller vanes by the flow of the fluid. When the bubbles enter a region where local pressure is greater than saturation pressure farther out the impeller vane, the vapor bubbles abruptly collapse. This process of the formation and subsequent collapse of vapor bubbles in a pump is called cavitation.

Cavitation in a centrifugal pump has a significant effect on pump performance. Cavitation degrades the performance of a pump, resulting in a fluctuating flow rate and discharge pressure. Cavitation can also be destructive to pumps internal components. When a pump cavitates, vapor bubbles form in the low pressure region directly behind the rotating impeller vanes. These vapor bubbles then move toward the oncoming impeller vane, where they collapse and cause a physical shock to the leading edge of the impeller vane. This physical shock creates small pits on the leading edge of the impeller vane. Each individual pit is microscopic in size, but the cumulative effect of millions of these pits formed over a period of hours or days can literally destroy a pump impeller. A cavitating pump can sound like a can of marbles being shaken. Other indications that can be observed from a remote operating station are fluctuating discharge pressure, flow rate, and pump motor current.



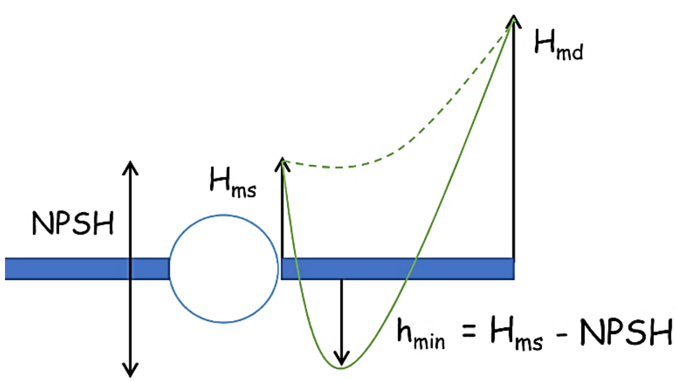
Net Positive Suction Head

To avoid cavitation in centrifugal pumps, the pressure of the fluid at all points within the pump must remain above saturation pressure. The quantity used to determine if the pressure of the liquid being pumped is adequate to avoid cavitation is the net positive suction head (NPSH).

The net positive suction head available (NPSHA) is the difference between the pressure at the suction of the pump and the saturation pressure for the liquid being pumped.

The net positive suction head required (NPSHR) is the minimum net positive suction head necessary to avoid cavitation.

The condition that must exist to avoid cavitation is that the net positive suction head available must be greater than or equal to the net positive suction head required. This requirement can be stated mathematically as shown below. NPSHA ≥ NPSHR



$$\underbrace{h_{atm} - h_{vap} + H_{ss} - h_{ls} - \frac{V_s^2}{2g}}_{\text{NPSH Available}} > \underbrace{NPSH}_{\text{NPSH Required}}$$

Preventing Cavitation

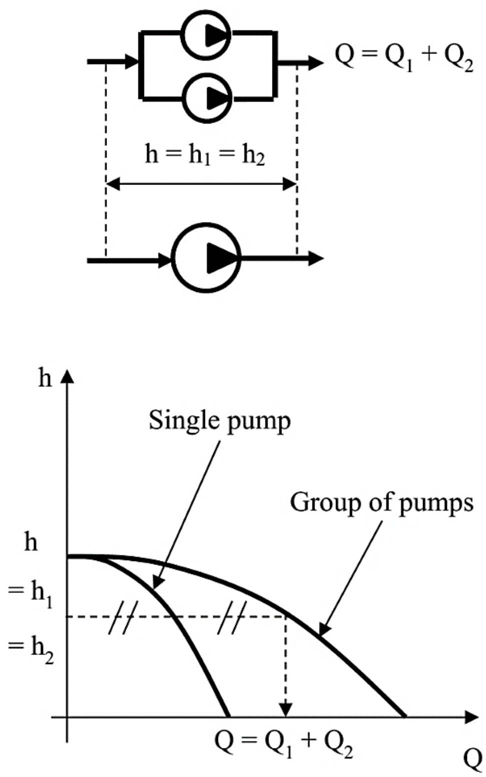
Raising the suction tank level (hss): From a rough estimation for water flow (hatm – hvap = 10 m, Vs = 2 m/s and NPSH = 4 m), we find that the suction level should not drop more than 4 m below the pump level (hss > – 4 m). Some liquids such as gasoline are volatile (hatm – hvap = 4 m). For these liquids 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.

Decreasing the losses (friction and eddy types) in the suction type: 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).

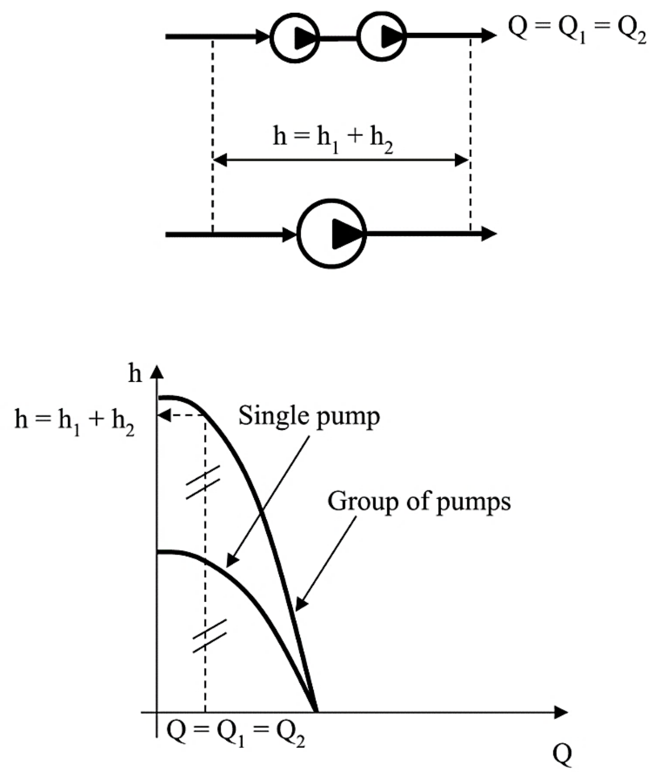
Pump Grouping

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.

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



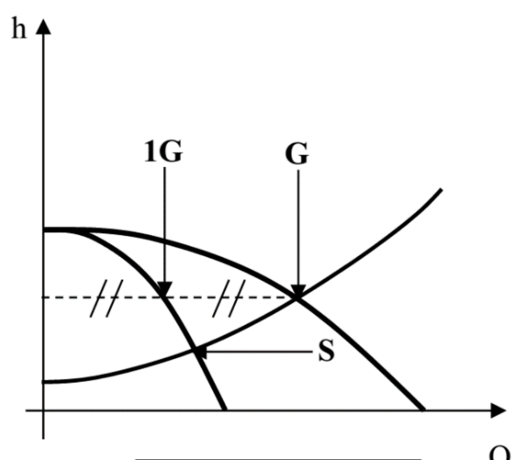
Parallel connection



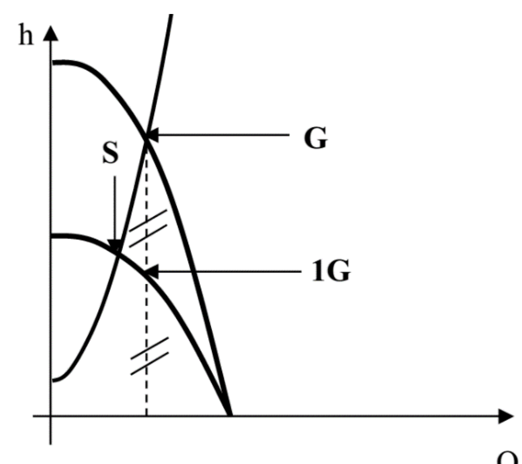
Series connection

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

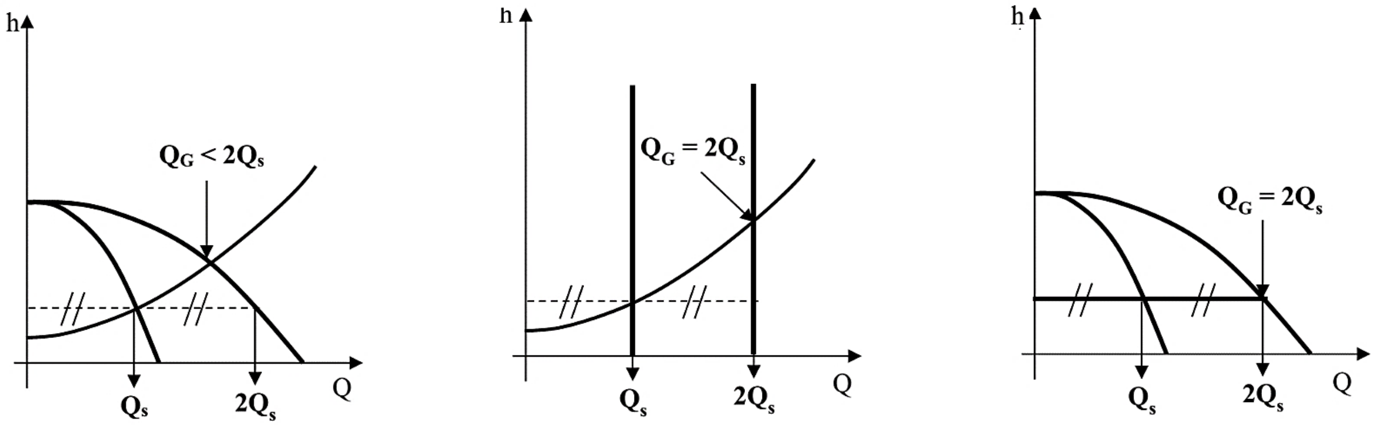


Series connection

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.

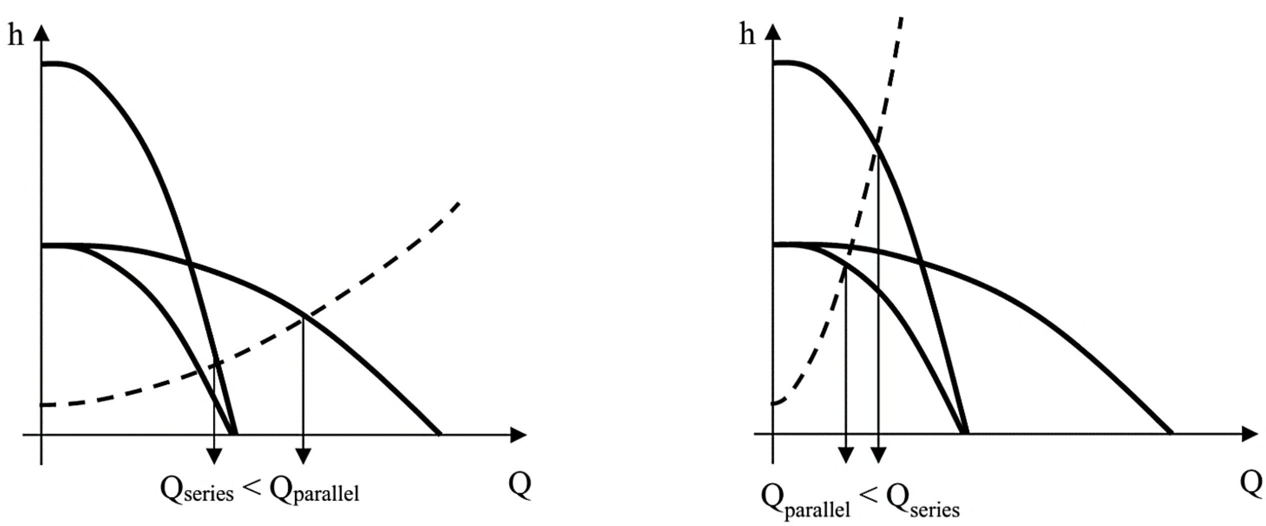


Fixed flow pump (PDP)

Flat system

Which connection gives more flow rate?

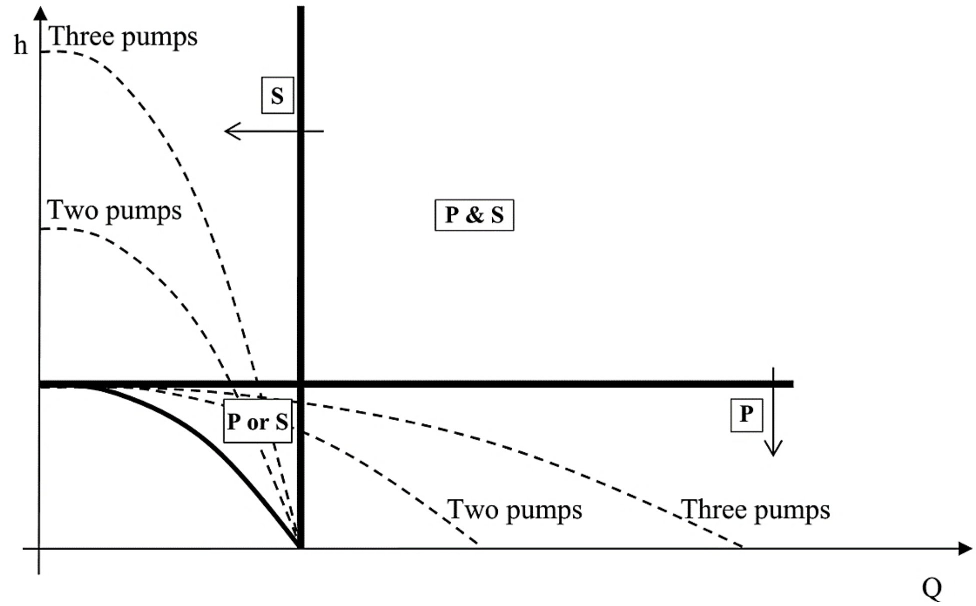
Assume two hydraulic systems as the shown in figure. For both systems, connect two identical in parallel at one time and in series at another time.



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.

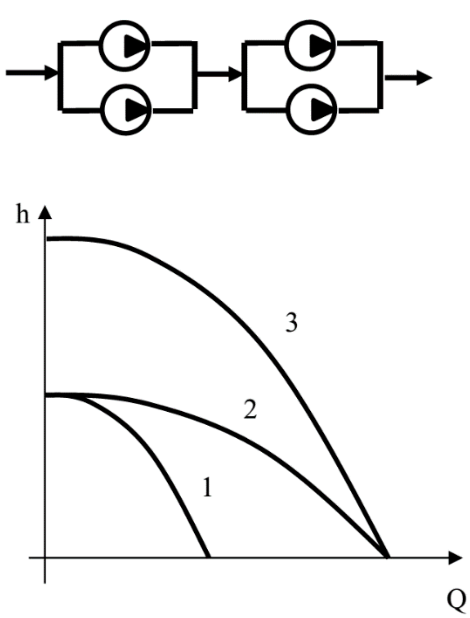
Series or parallel

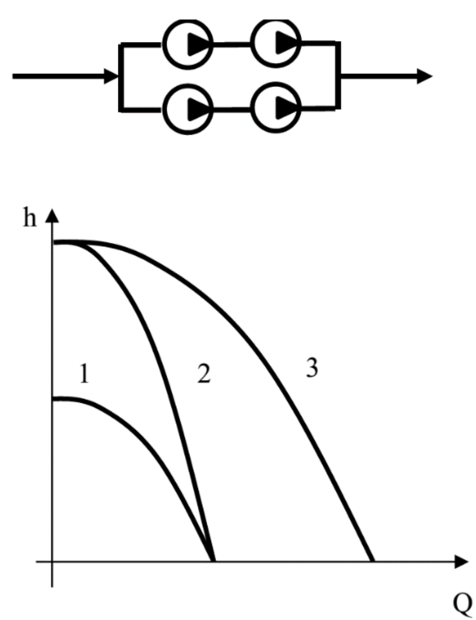
The following graph shows the zones of operation of each type of connection.



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.





Motor selection and cavitation probability

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.

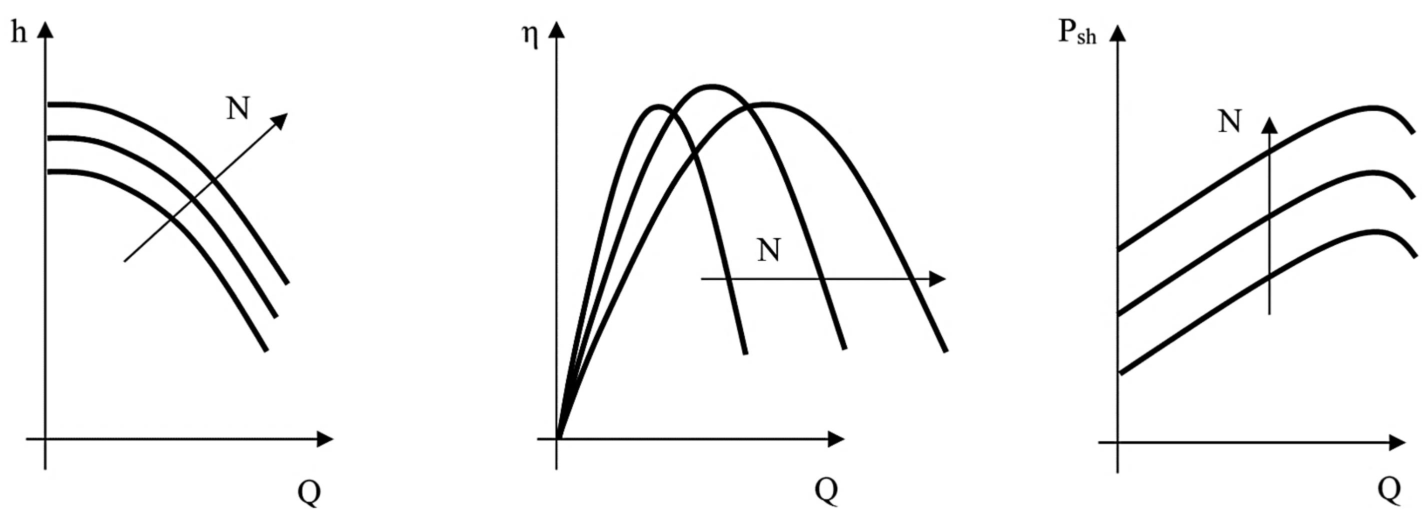
But it is known that the pump power consumption increases as the flow rate increases.

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.

On the other hand, connecting pumps in series increases the flow rate which makes cavitation more probable. Hence, when connecting pumps in series, cavitation must be checked for the pumps in the group connection. Besides, if the two pumps are not identical, the larger pump has a larger NPSH and it is, therefore, recommended to connect the larger pump downstream the smaller pump.

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.

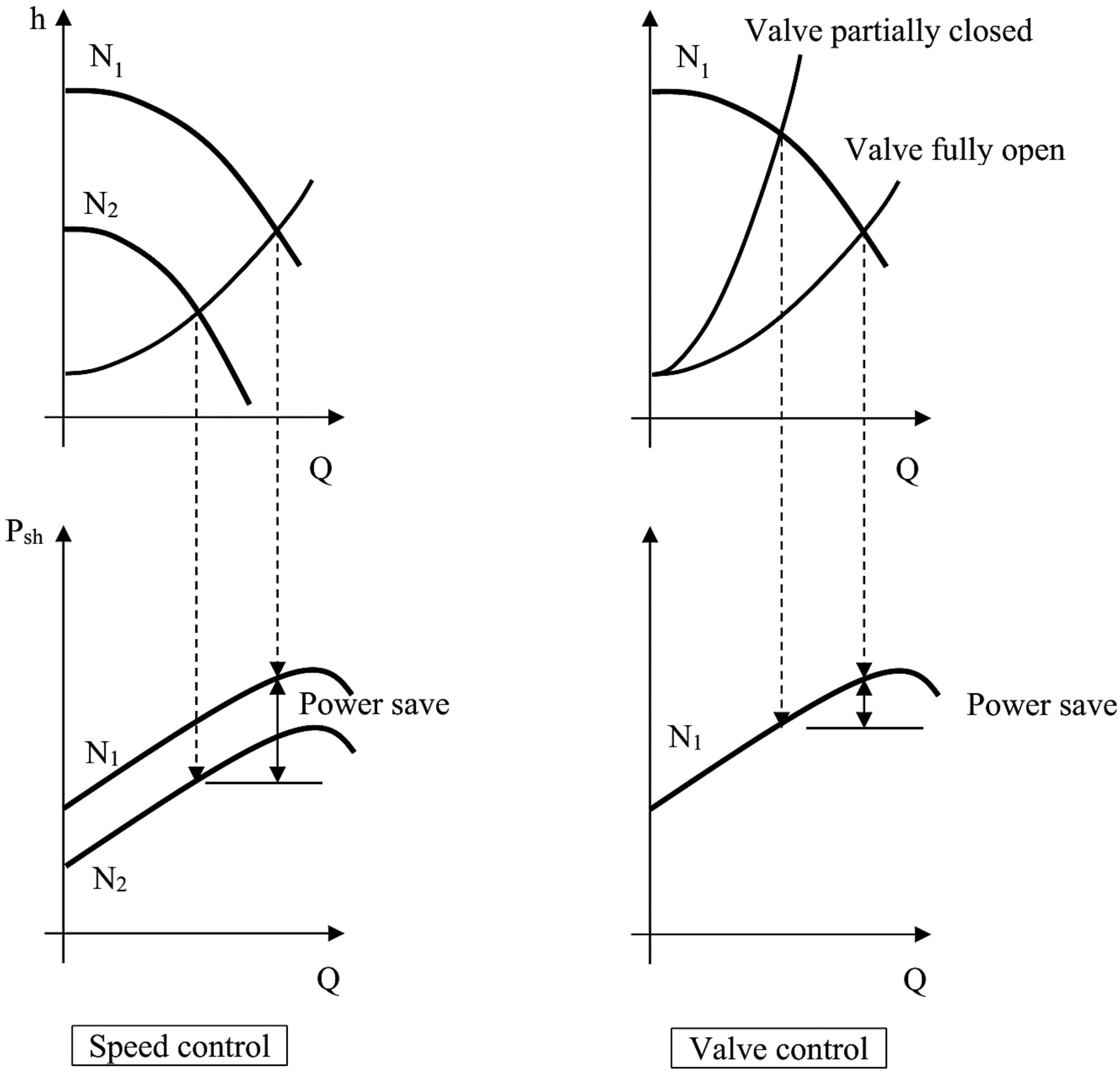
The figure shows the performance of the pump at different speeds.



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.

Speed vs. valve control

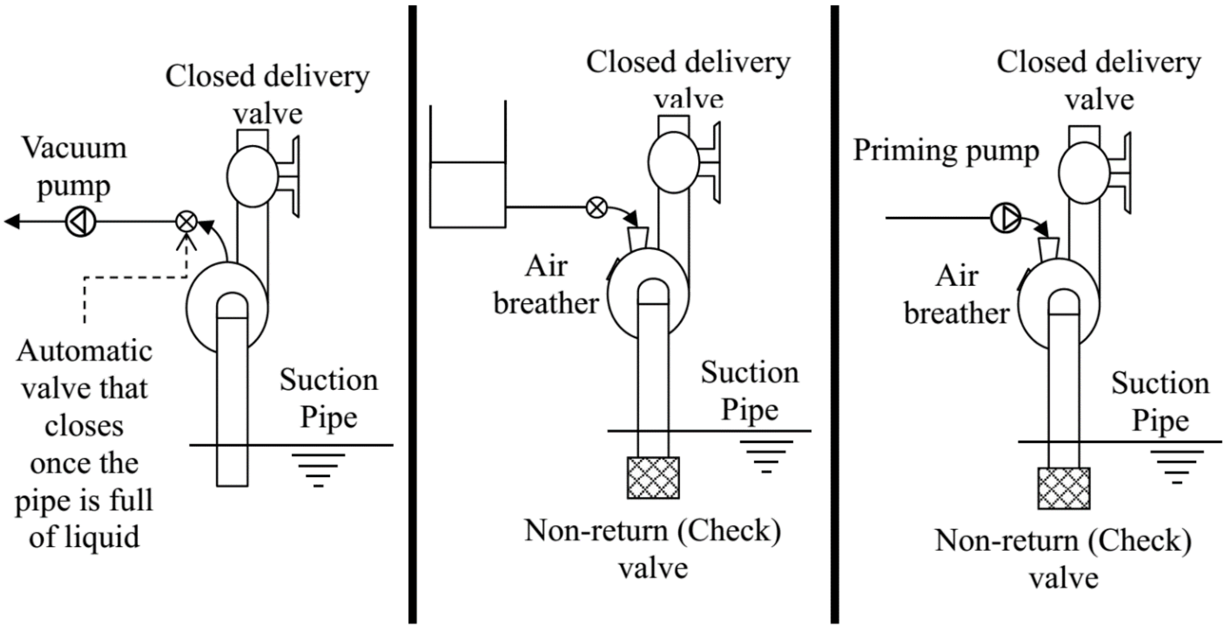
The following figure illustrates that the speed control saves power compared with valve closure.



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".



Centrifugal pump installation