Lecture 7

HYDRAULIC PUMPS

Learning Objectives

Upon completion of this chapter, the student should be able to:

- Classify the hydraulic pumps used in the industry.
- Differentiate between positive displacement and non-positive displacement pumps.
- Explain the working and construction of gear, vane and piston pumps.
- Evaluate the discharge parameters of gear, vane and piston pumps.
- Define mechanical, volumetric and overall efficiency of pumps.
- Evaluate the performance parameters of gear, vane and piston pumps.
- Differentiate between internal and external gear pumps.
- Differentiatebetween a bent-axis piston pump and a swash plate.
- State the advantage of balance vane pumps.
- Explain cavitation and various means to control it.
- Explain the importance of noise control in pumps.
- Write a computer program to evaluate the performance of the system.

1.1Introduction

The function of a pump is to convert mechanical energy into hydraulic energy. It is the heart of any hydraulic system because it generates the force necessary to move the load. Mechanical energy is delivered to the pump using a prime mover such as an electric motor.Partial vacuum is created at the inlet due to the mechanical rotation of pump shaft. Vacuum permits atmospheric pressure to force the fluid through the inlet line and into the pump. The pump then pushes the fluid mechanically into the fluid power actuated devices such as a motor or a cylinder.

Pumps are classified into three different ways and must be considered in any discussion of fluid power equipment.

1. **Classification based on displacement:**
   - Non-positive displacement pumps (hydrodynamic pumps).
   - Positive displacement pumps (hydrostatic pumps).

2. **Classification based on delivery:**
   - Constant delivery pumps.
   - Variable delivery pumps.

3. **Classification based on motion:**
   - Rotary pump.
   - Reciprocating pump.

1.2 Classification of Pumps

1.2.1Classification Based on Displacement

1.2.1.1 Non-Positive Displacement Pumps

Non-positive displacement pumps are primarily velocity-type units that have a great deal of clearance between rotating and stationary parts. Non-displacement pumps are characterized by a high slip that increases as the back pressure increases, so that the outlet may be completely closed without damage to the pump or system. Non-positive pumps do not

develop a high pressure but move a large volume of fluid at low pressures. They have essentially no suction lift. Because of large clearance space, these pumps are not self-priming. In other words, the pumping action has too much clearance space to seal against atmospheric pressure. The displacement between the inlet and the outlet is not positive. Therefore, the volume of fluid delivered by a pump depends on the speed at which the pump is operated and the resistance at the discharge side. As the resistance builds up at the discharge side, the fluid slips back into the clearance spaces, or in other words, follows the path of least resistance. When the resistance gets to a certain value, no fluid gets delivered to the system and the volumetric efficiency of the pump drops to zero for a given speed. These pumps are not used in fluid power industry as they are not capable of withstanding high pressure. Their maximum capacity is limited to 17–20 bar.These types of pumpsare primarily used for transporting fluids such as water, petroleum,etc.,from one location to another considerable apart location. Performance curves for positive and non-positive displacement pumps are shown in Fig.1.1.
Thetwo most common types of hydrodynamic pumps are the centrifugal and the axial flow propeller pumps.

Advantages and disadvantages ofnon-positive displacement pumps

The advantages are as follows:

1.Non-displacement pumps have fewer moving parts.
2.Initial and maintenance cost is low.
3. They give smooth continuous flow.
4. They are suitable for handling almost all types of fluids including slurries and sledges.
5.Their operation is simple and reliable.

The disadvantages are as follows:
1.Non-displacement pumps are not self-priming and hence they must be positioned below the fluid level.
2. Discharge is a function of output resistance.
3.Low volumetric efficiency.

1.2.1.2Positive Displacement Pumps

Positive displacement pumps, in contrast, have very little slips, are self-priming and pump against very high pressures, but their volumetric capacity is low. Positive displacement pumps have a very close clearance between rotating and stationary parts and hence are self-priming. Positive displacement pumps eject a fixed amount of fluid into the hydraulic system per revolution of the pump shaft. Such pumps are capable of overcoming the pressure resulting from mechanical loads on the system as well as the resistance of flow due to friction. This equipment must always be protected by relief valves to prevent damage to the pump or system. By far, a majority of fluid power pumps fall in this category, including gear, vane and piston pumps.Performance curves for positive and non-positive displacement pumps are shown in Fig. 1.1.

Positive displacement pumps are classified based on the following characteristics:

1. **Type of motion of pumping element:** Based on the type of motion of pumping element, positive displacement pumps are classified as follows:
- Rotary pumps, for example, gear pumps and vane pumps.
- Reciprocating pumps, for example, piston pumps.

2. **Displacement characteristics:** Based on displacement characteristics, positive displacement pumps are classified as follows:
- Fixed displacement pumps.
- Variable displacement pumps.
3. **Type of pumping element**.

The advantages of positive displacement pumps over non-positive displacement pumps are as follows:

1. They can operate at very high pressuresof up to 800 bar (used for lifting oils from very deep oil wells).
2. They can achieve a high volumetric efficiency of up to 98%.
3. They are highly efficient and almost constant throughout the designed pressure range.
4. They are a compact unit, havinga high power-to-weight ratio.
5. They can obtain a smooth and precisely controlled motion.
6. By proper application and control, they produce only the amount of flow required to move the load at the desired velocity.
7. They have a great flexibility of performance. They can be made to operate over a wide range of pressures and speeds.

1.2.2 Classification Based on Delivery

1.2.2.1 Constant Delivery Pumps
Constant volume pumps always deliver the same quantity of fluid in a given time at the operating speed and temperature. These pumps are generally used with relatively simple machines, such as saws or drill presses or where a group of machines is operated with no specific relationship among their relative speeds. Power for reciprocating actuators is most often provided by constant volume pumps.

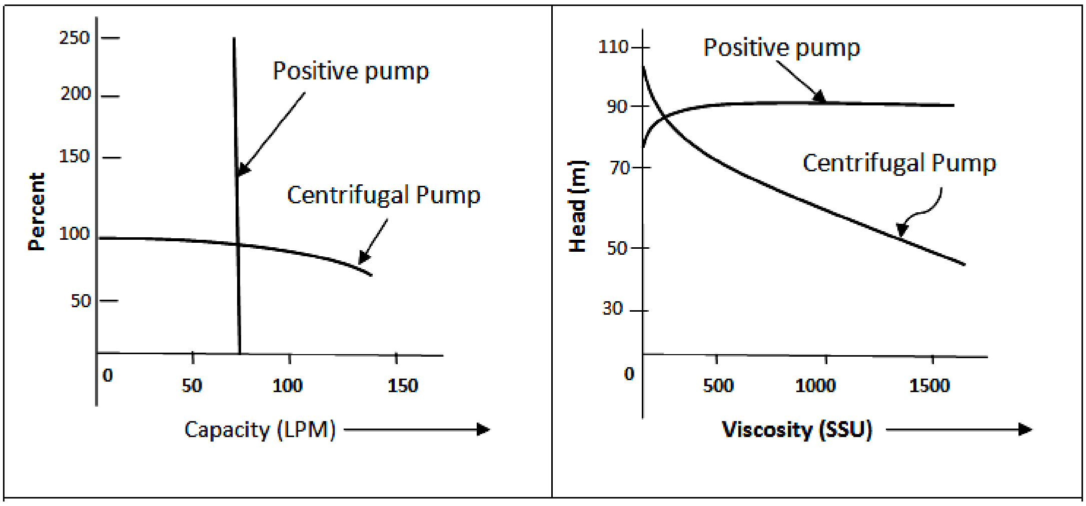
1.2.2.2Variable Delivery Pumps
The output of variable volume pumps may be varied either manually or automatically with no change in the input speed to the pump. Variable volume pumps are frequently used for rewinds, constant tension devices or where a group of separate drives has an integrated speed relationship such as a conveyor system or continuous processing equipment.

1.2.3Classification Based on Motion
This classification concerns the motion that may be either *rotary* or *reciprocating*. It was of greater importance when reciprocating pumps consisted only of a single or a few relatively large cylinders and the discharge had a large undesirable pulsation. Present-day reciprocating pumps differ very little from rotary pumps in either external appearance or the flow characteristics.

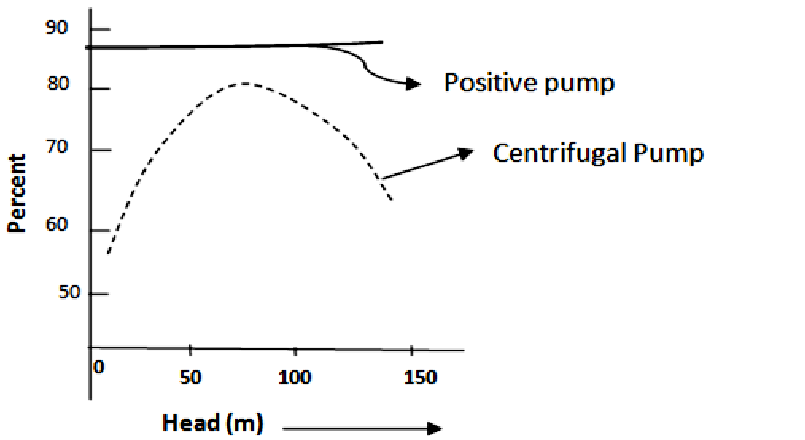
Differences between positive displacement pumps and non-positive displacement pumps are enumerated in Table 1.1.

Table 1.1 Differences between positive displacement pumps and non-positive displacement pumps

Positive Displacement Pumps	Non-positive Displacement Pumps
The flow rate does not change with head	The flow rate decreases with head
The flow rate is not much affected by the viscosity of fluid	The flow rate decreases with the viscosity
Efficiency is almost constant with head	Efficiency increases with head at first and then decreases



(a)



(b)

Figure 1.1 Performance curves for positive and non-positive displacement pumps

1.3Pumping Theory

A positive displacement hydraulic pump is a device used for converting mechanical energy into hydraulic energy.It is driven by a prime mover such as an electric motor.It basically performs twofunctions.First, it creates a partial vacuum at thepump inlet port.This vacuum enables atmospheric pressure to force the fluid from the reservoir into the pump.Second,the mechanical action of the pump traps this fluid within the pumping cavities,transports it through the pump and forces it into the hydraulic system. It is important to note that pumps create flow not pressure. Pressure is created by the resistance to flow.

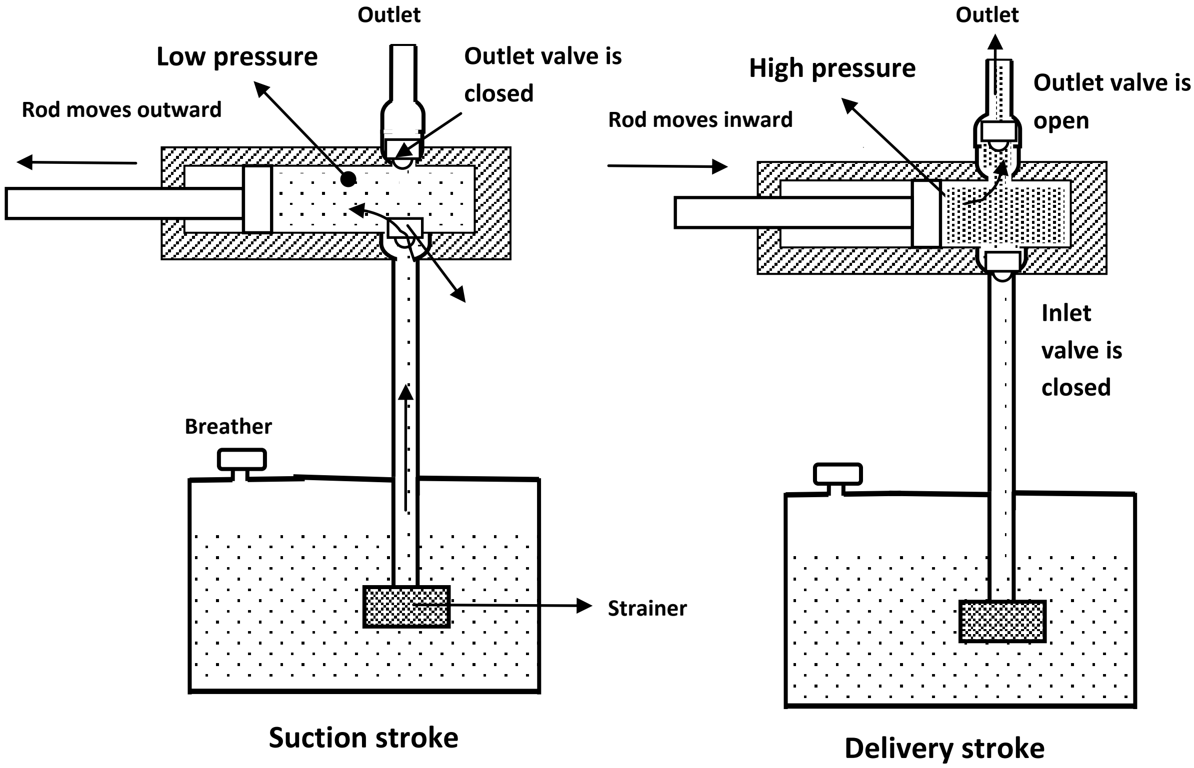


Figure 1.2 Illustration of pumping theory

All pumps operate by creating a partial vacuum at the intake, and a mechanical force at the outlet that induces flow. This action can be best described by reference to a simple piston pump shown in Fig.1.2.

1. As the piston moves to the left, a partial vacuum is created in the pump chamber thatholds the outlet valve in place against its seat and induces flow from the reservoir that is at a higher (atmospheric) pressure.As this flow is produced, the inlet valve is temporarily displaced by the force of fluid, permitting the flow into the pump chamber (suction stroke).
2. When the piston moves to the right, the resistance at the valves causes an immediate increase in the pressure that forces the inlet valve against its seat and opens the outlet valve thereby permitting the fluid to flow into the system. If the outlet port opens directly to the atmosphere, the only pressure developed is the one required to open the outlet valve(delivery stroke).

1.4Gear Pumps

Gear pumps are less expensive but limited to pressures below 140 bar.It is noisy in operation than either vane or piston pumps. Gear pumps are invariably of fixed displacement type, which means that the amount of fluid displaced for each revolution of the drive shaft is theoretically constant.

1.4.1 External Gear Pumps

External gear pumps are the most popular hydraulic pumps in low-pressure ranges due to their long operating life, high efficiency and low cost. They are generally used ina simple machineThe most common form of external gear pump is shown in Figs. 1.3and 1.4 It consist of a pump housing in which a pair of preciselymachined meshing gears runs with minimal radial and axial clearance.One of the gears, called a driver,is driven by a prime mover. The driver drives another gear called a follower.As the teeth of the two gears separate, the fluid from the pump inlet gets trapped between the rotating gear cavities and pump housing.The trapped fluid is then carried around the periphery of the pump casing and delivered to outlet port. The teeth of precisely meshed gears provide almost a perfect seal between the pumpinlet and the pump outlet.When the outlet flow is resisted, pressure in the pump outlet chamber builds up rapidly and forces the gear diagonally outward against the pump inlet. When the system pressure increases, imbalance occurs. This imbalance increases mechanical friction and the bearing load of the two gears.Hence, the gear pumps are operated to the maximum pressure rating stated by the manufacturer.

It is important to note that the inlet is at the point of separation and the outlet at the point of mesh. These units are not reversible if the internal bleeds for the bearings are to be drilled to both the inlet and outlet sides.So that the manufacturer’s literature should be checked before attempting a reversed installation. If they are not drilled in this manner, the bearing may be permanently damaged as a result of inadequate lubrications.

Advantages and disadvantages of gear pumps

The advantages are as follows:

1.They are self-priming.
2.They give constant delivery for a given speed.
3. They are compact and light in weight.
4. Volumetric efficiency is high.

The disadvantages are as follows:

1. The liquid to be pumped must be clean, otherwise it will damage pump.
2. Variable speed drives are required to change the delivery.
3. If they run dry, parts can be damaged because the fluid to be pumped is used as lubricant.

Expression for the theoretical flow rate of an external gear pump

Let

D_o =the outside diameter of gear teeth

D_i= the inside diameter of gear teeth

L =the width of gear teeth

N=the speed of pump in RPM

V_D=the displacement of pump in m/rev

M= module of gear

z=number of gear teeth

α= pressure angle

Volume displacement is

$$V_D = \frac{\pi}{4}(D_o^2 - D_i^2)L$$

$$D_i = D_o - 2(\text{Addendum} + \text{Dendendum})$$

Theoretical discharge is

$$Q_T\ (\text{m}^3/\text{min}) = V_D\,(\text{m}^3/\text{rev}) \times N\ (\text{rev/min})$$

If the gear is specified by its module and number of teeth, then the theoretical discharge can be found by

$$Q_T = 2\pi L m^2 N\left[z + \left(1 + \frac{\pi^2 \cos^2 20}{12}\right)\right] \text{m}^3/\text{min}$$

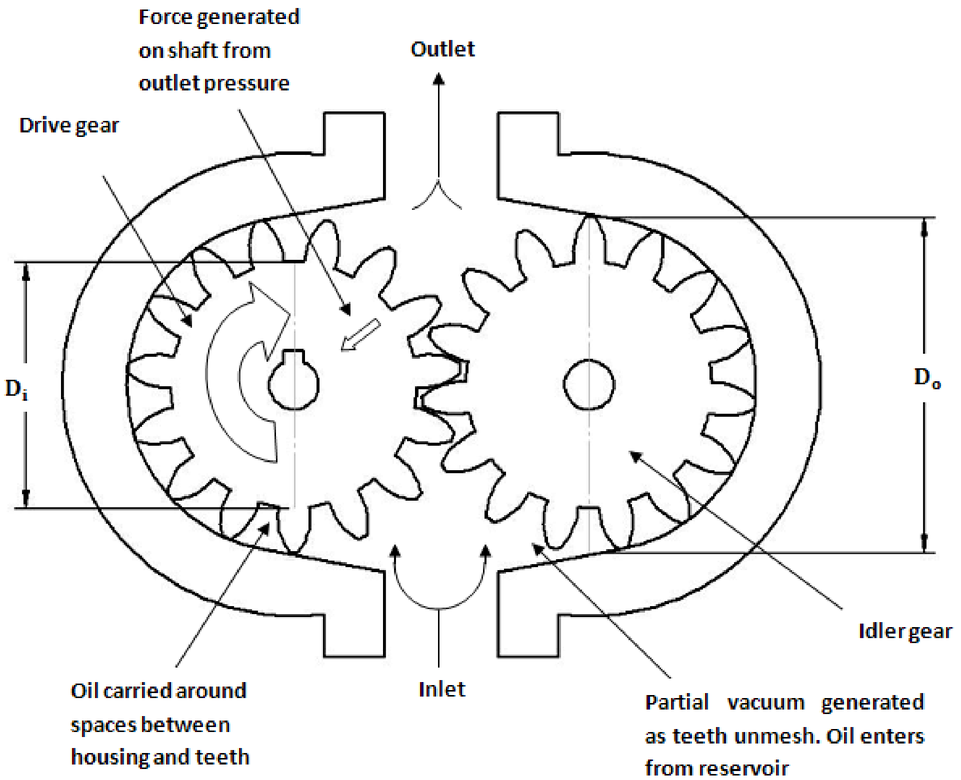


Figure 1.3 Operation of an external gear pump

1.4.2Internal Gear Pumps

Another form of gear pump is the internal gear pump, which is illustrated in Fig. 1.5. They consist of two gears:An external gear and an internal gear. The crescent placed in between these acts as a seal between the suction and discharge.(Fig.1.6) When a pump operates, the external gear drives the internal gear and both gears rotate in the same direction. The fluid fills the cavities formed by the rotating teeth and the stationary crescent. Both the gears transport the fluid through the pump. The crescent seals the low-pressure pump inlet from the high-pressure pump outlet. The fluid volume is directly proportional to the degree of separation and these units may be reversed without difficulty. The major use for this type of pump occurs when a through shaft is necessary, as in an automatic transmission. These pumps have a higher pressure capability than external gear pumps.

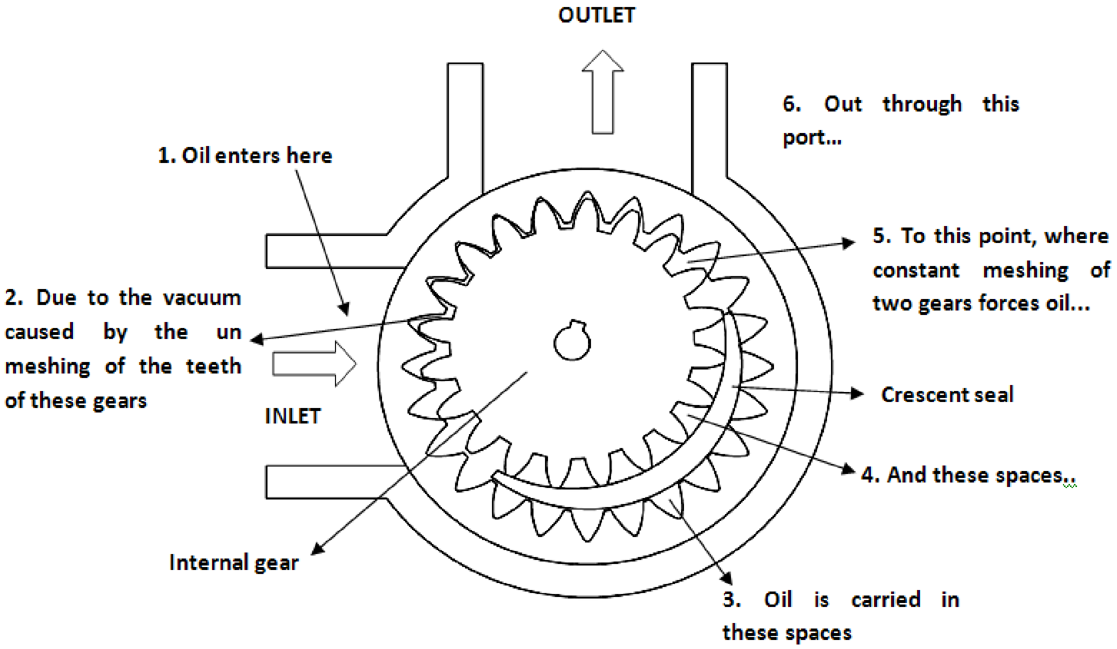


Figure 1.5 Operation of an internal gear pump

1.4.3 Gerotor Pumps

Gerotor pumps operate in the same manner as internal gear pumps. The inner gear rotor is called a gerotor element. The gerotor element is driven by a prime mover and during the operation drives outer gear rotor around as they mesh together. The gerotor has one tooth less than the outer internal idler gear. Each tooth of the gerotor is always in sliding contact with the surface of the outer element. The teeth of the two elements engage at just one place to seal the pumping chambers from each other. On the right-hand side of the pump, shown in Fig. 1.7, pockets of increasing size are formed, while on the opposite side, pockets decrease in size. The pockets of increasing size are suction pockets and those of decreasing size are discharge pockets. Therefore, the intake side of the pump is on the right and discharge side on the left.

Pumping chambers are formed by the adjacent pair of teeth, which are constantly in contact with the outer element, except for clearance. Refer to Fig 1.7,asthe rotor is turned, its gear tips are accurately machined sothat they precisely follow the inner surface of the outer element. The expanding chambers are created as the gear teeth withdraw. The chamber reaches its maximum size when the female tooth of the outer rotor reaches the top dead center. During the second half of the revolution, the spaces collapse, displacing the fluid to the outlet port formed at the side plate. The geometric volume of the gerotor pump is given as

$$V_D = b\, Z\,(A_{max} - A_{min})$$

where b is the tooth height, Z is the number of rotor teeth, A_{max} is the maximum area between male and female gears (unmeshed – occurs at inlet) and A_{min} is the minimum area between male and female gears (meshed – occurs at outlet).

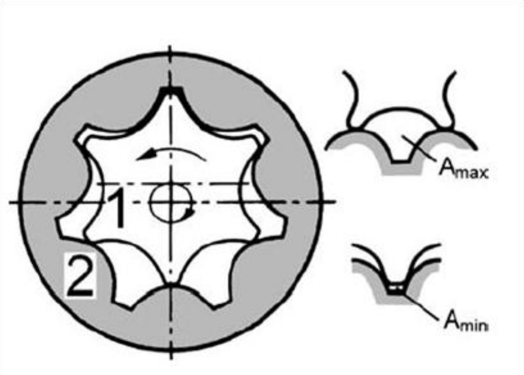


Figure 1.7 Gerotor gear pump

Example 1.1

The inlet to a hydraulic pump is 0.6 m below the top surface of an oil reservoir. If the specific gravity of the oil used is 0.86, determine the static pressure at the pump inlet.

Solution: We know that

$$\text{Pressure} = \rho g h$$

The density of water is 1 g/cm^3 or 1000 kg/m^3.

Therefore, the density of oil is $0.86 \times 1\ \text{g/cm}^3$ or $860\,\text{kg/m}^3$.

Pressure at the pump inlet is

$$P = 860 \times 0.6\,\text{kg/m}^2 = 516\,\text{kg/m}^2 = 0.0516\,\text{kg/cm}^2 = 0.0516 \times 0.981\,\text{bar}$$
$$= 0.0506\,\text{bar}$$

(Note: $1\,\text{kg/cm}^2 = 0.981\,\text{bar}$.)

Example 1.2

A hydraulic pump delivers 12 L of fluid per minute against a pressure of 200 bar. (a) Calculate the hydraulic power. (b) If the overall pump efficiency is 60%, what size of electric motor would be needed to drive the pump?

Solution:

(a) Hydraulic power is given by

$$\text{Hydraulic power (kW)} = 12\ \text{L/min} \times \frac{200\ \text{(bar)}}{600} = 4\ \text{kW}$$

(b) We have

$$\text{Electric motor power (power input)} = \frac{\text{Hydraulic power}}{\text{Overall efficiency}}$$

Substituting we get

Electric motor power (power input) $= \frac{4}{0.6} = 6.67 kW$

$$\text{Electric motor power} = \frac{4}{0.6} = 6.67\,\text{kW}$$

Example 1.3

A gear pump has an outside diameter of 80mm, inside diameter of 55mm and a width of 25mm. If the actual pump flow is 1600 RPM and the rated pressure is 95 LPM what is the volumetric displacement and theoretical discharge.

Solution: We have

Outside diameter $D_o = 80\text{ mm}$

Inside diameter $D_i = 55\text{mm}$

Width $d = 25\text{mm}$

Speed of pump N = 1600 RPM

Actual flow rate = 95 LPM

Now

$Q_A = 95\,\text{LPM} = 95 \times 10^{-3}\,\text{m}^3/\text{min}$

$V_D = \frac{\pi}{4} \times (D_o^{\,2} - D_i^{\,2}) \times L$

$V_D = \frac{\pi}{4} \times (0.080^2 - 0.055^2) \times 0.025 = 6.627 \times 10^{-5} m^3 / rev$

Theoretical flow rate

$Q_T = \frac{\pi}{4} \times (D_o^{\,2} - D_i^{\,2}) \times L \times N$

$= \frac{\pi}{4} \times (0.080^2 - 0.055^2) \times 0.025 \times 1600$

$= 0.106\,\text{m}^3/\text{min}$

Example 1.4

Calculate the theoretical delivery of a gear pump. Module of the gear teeth is 6mm and width of gear teeth is 25mm. Number of teeth on driver gear is 18 and pressure angle of the gear is 20°. Pump speed is 1000 RPM. Volumetric efficiency is 90%.

Solution: If the gear is specified by its module and number of teeth, then the theoretical discharge can be found by

$$Q_T = 2\pi L m^2 N\left[z + \left(1 + \frac{\pi^2 \cos\alpha}{12}\right)\right] \text{ m}^3/\text{min}$$

$$= 2\pi(0.025)(6\times10^{-3})^2 \times 1000 \times \left[18 + \left(1 + \frac{\pi^2 \cos^2 20}{12}\right)\right] \text{ m}^3/\text{min}$$

$$= 0.1118 \text{ m}^3/\text{min}$$

Example 1.5

Calculate the theoretical delivery of a gear pump. Module of the gear teeth is 6mm and width of gear teeth is 65mm. Number of teeth on driver gear is 16 and pressure angle of the gear is 20°. Pump speed is 1600 RPM. Outer diameter of gear is 108 mm and Dedendum circle diameter is 81 mm. Volumetric efficiency is 88%at 7 MPa.

Solution: If the gear is specified by its module and number of teeth, then the theoretical discharge can be found by

$$Q_T = 2\pi L m^2 N\left[z + \left(1 + \frac{\pi^2 \cos^2 20}{12}\right)\right] \text{ m}^3/\text{min}$$

$$= 2\pi(0.065)(6\times10^{-3})^2 \times 1600 \times \left[16 + \left(1 + \frac{\pi^2 0.939^2}{12}\right)\right] \text{ m}^3/\text{min}$$

$$= 0.416 \text{ m}^3/\text{min}$$

Alternatively we can use

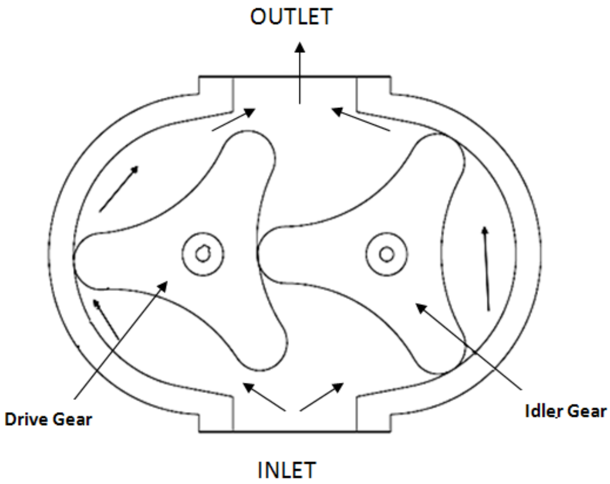
$$V_D = \frac{\pi}{4}\times(D_o{}^2 - D_i{}^2)\times L$$

$$Q_T = \frac{\pi}{4}\times(0.108^2 - 0.081^2)\times 0.065\times1600 = 0.416 \text{ m}^3/\text{rev}$$

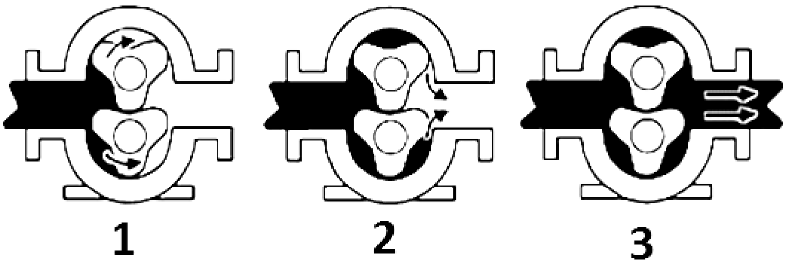
1.5Lobe Pumps

The operation of lobe pump shown in Fig.1.9 is similar to that of external gear pump, but they generally have a higher volumetric capacity per revolution. The output may be slightly greater pulsation because of the smaller number of meshing elements.

Lobe pumps, unlike external gear pumps,have both elements externally driven and neither element hasany contact with the other.For this reason, they are quieter when compared to other types of gear pumps. Lobe contact is prevented by external timing gears located in the gearbox.Pump shaft support bearings are located in the gearbox, and because the bearings are out of the pumped liquid, pressure is limited by bearing location and shaft deflection. They do not lose efficiency with use. They are similar to external gear pumps with respect to the feature of reversibility.



Stages of operation of Lobe pump



1.As the lobes come out of mesh, they create expanding volume on the inlet side of the pump.Liquid flows into the cavity and is trapped by the lobes as they rotate.

2.Liquid travels around the interior of the casing in pockets between the lobes and the casing (it does not pass between the lobes).

3.Finally, the meshing of the lobes forces the liquid through the outlet port under pressure.

Lobe pumps are frequently used in food applications because they are good at handling solids without inflicting damage to the product. Solid particle size can be much larger in lobe pumps than in other positive displacement types.Because lobes do not make contact, and clearances are not as close as in other positive displacement pumps, this design handles low-viscosity liquids with diminished performance.Loading characteristics are not as good as other designs and suction ability is low.High-viscosity liquids require reduced speeds to achieve satisfactory performance.Reductions of 25% of rated speed and lower are common with high-viscosity liquids.

1.5.1Advantages

The advantages of lobe pumps are as follows:

1. Lobe pumps can handle solids, slurries, pastes and many liquid.
2. No metal-to-metal contact.
3. Superior CIP(Cleaning in Place) /SIP(Sterilization in Place) capabilities.
4. Long-term dry run (with lubrication to seals).
5. Non-pulsating discharge.

1.5.2Disadvantages

The disadvantages of lobe pumps are as follows:

1. Require timing gears.
2. Require two seals.
3. Reduced lift with thin liquids.

1.5.3Applications

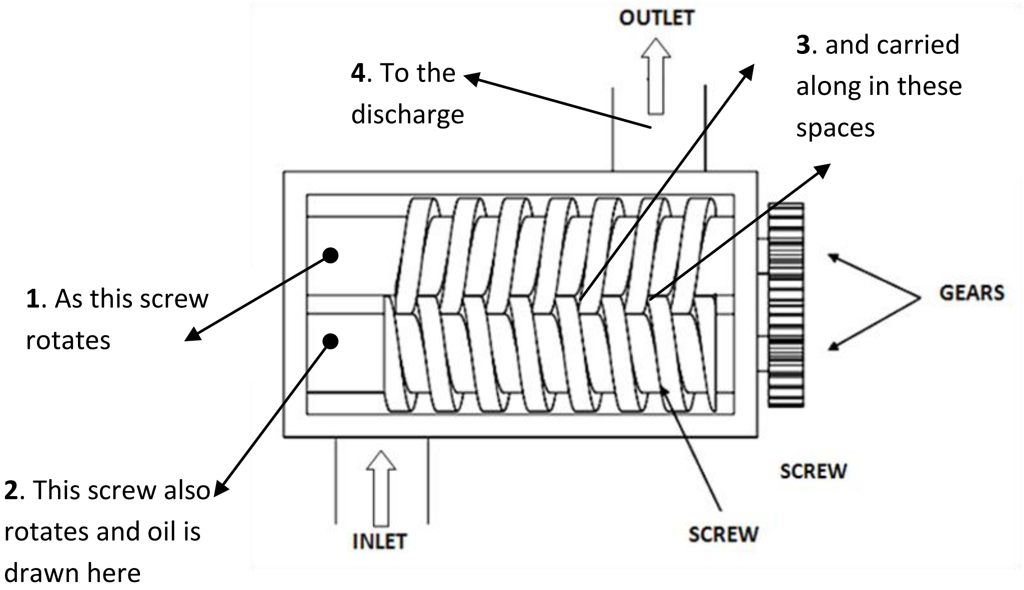
Common rotary lobe pump applications include, but are not limited to, the following:

1. Polymers.
2. Paper coatings.
3. Soaps and surfactants.
4. Paints and dyes.
5. Rubber and adhesives.
6. Pharmaceuticals.
7. Food applications.

1.6Screw Pumps

These pumps have two or more gear-driven helical meshing screws in a closefitting caseto develop the desired pressure. These screws mesh to form a fluid-type seal between the screws and casing.

A schematic diagram of a screw pump is shown in Fig 1.10. A two-screw pump consists of two parallel rotors with inter-meshing threads rotating in a closely machined casing. The driving screw and driven screw are connected by means of timing gears. When the screws turn, the space between the threads is divided into compartments. As the screws rotate, the inlet side of the pump is flooded with hydraulic fluid because of partial vacuum.When the screws turn in normal rotation, the fluid contained in these compartments is pushed uniformly along the axis toward the center of the pump, where the compartments discharge the fluid. Here the fluid does not rotate but moves linearly as a nut on threads. Thus, there are no pulsations at a higher speed; it is a very quiet operating pump.



Ina screw pump, a chamber is formed between thread and housing as shown in Fig.1.11. The following expression gives the volumetric displacement

$$V_{\mathrm{D}} = \frac{\pi}{4}(D^2 - d^2)s - D^2\left\{\frac{\alpha}{2} - \frac{\sin 2\alpha}{2}\right\}s$$

Heres is the stroke length and $\cos(\alpha) = \dfrac{D+d}{2D}$

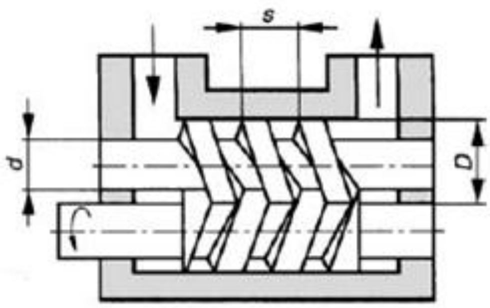


Figure 1.11 Volumetric displacement of a screw pump

Advantages and disadvantages of screw pump

Theadvantages are as follows:

1.They are self-priming and more reliable.
2. They are quiet due to rolling action of screw spindles.
3.They can handle liquids containing gases and vapor.
4. They have long service life.

The disadvantages are as follows:

1.They are bulky and heavy.
2.They are sensitive to viscosity changes of the fluid.
3. They have low volumetric and mechanical efficiencies.
4. Manufacturing cost of precision screw is high.