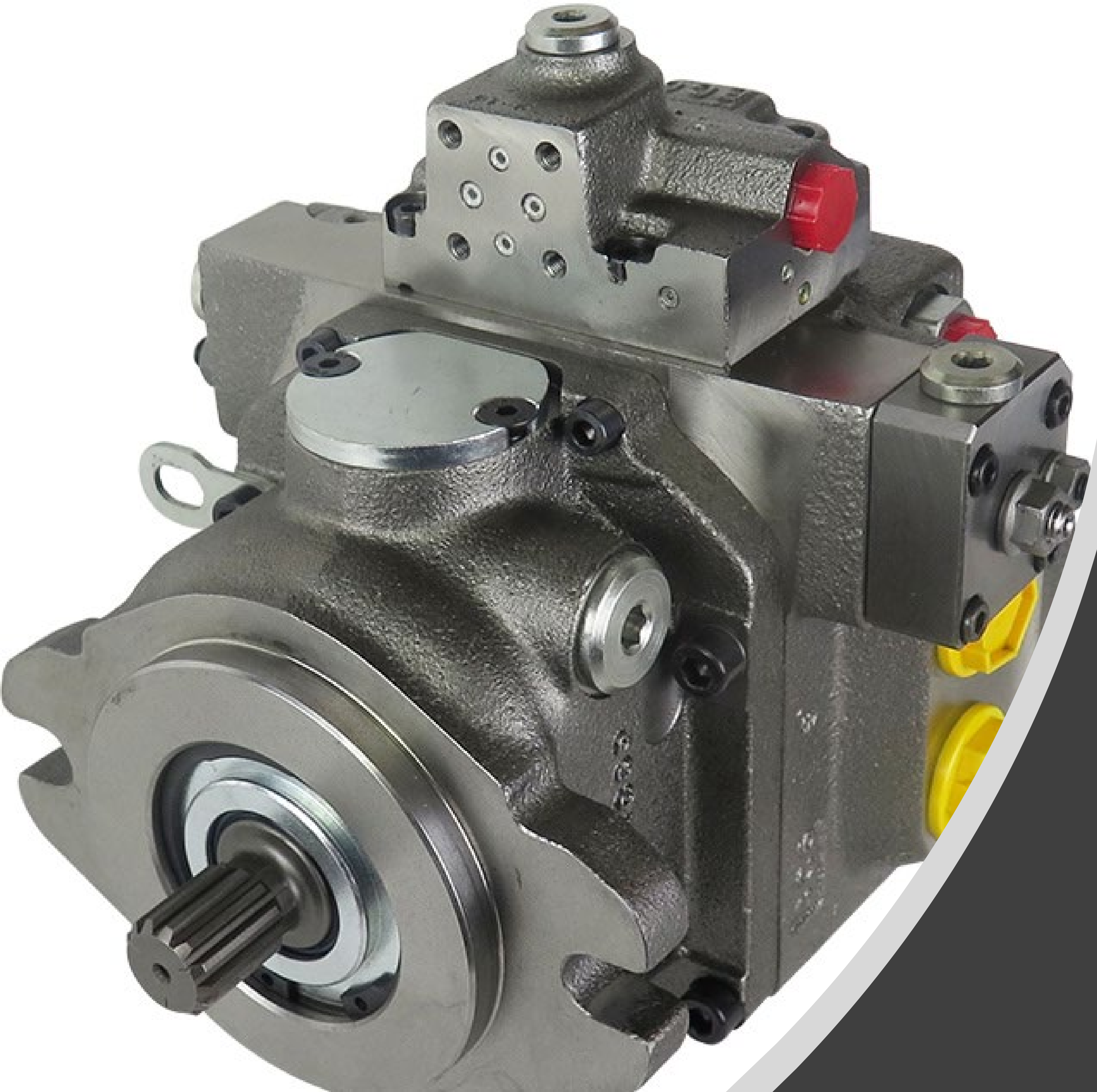


Pneumatics and hydraulics

Hydraulic Pumps

Dr. Ahmad Al-Mahasneh

Hydraulic pump: introduction

- Hydraulic pump is the heart of a hydraulic system. It converts mechanical energy into hydraulic energy.
- The mechanical energy is delivered to the pump via a prime mover such as an electric motor.
- Due to mechanical action, the pump creates a partial vacuum at its inlet.
- This permits atmospheric pressure to force the fluid through the inlet line and into the pump.
- The pump then pushes the fluid into the hydraulic system.

Hydraulic pump: classification

1- Dynamic (nonpositive displacement) pumps.

- This type is generally used for: low-pressure, high-volume flow applications.
- Because they are not capable of withstanding high pressures, they are of little use in the fluid power field.
- Normally their maximum pressure capacity is limited to 250–300 psi.
- This type of pump is primarily used for transporting fluids from one location to another.
- The two most common types of dynamic pumps are (1) the centrifugal and (2) the axial flow propeller pumps.

Hydraulic pump: classification

2- Positive displacement pumps.

- This type is universally used for fluid power systems.
- As the name implies, a positive displacement pump ejects a fixed amount of fluid into the hydraulic system per revolution of pump shaft rotation.
- Such a pump is capable of overcoming the pressure resulting from the mechanical loads on the system as well as the resistance to flow due to friction. These are two features that are desired of fluid power pumps.
- These pumps have the following advantages over nonpositive displacement pumps:
- **a.** High-pressure capability (up to 12,000 psi)
- **b.** Small, compact size
- **c.** High volumetric efficiency
- **d.** Small changes in efficiency throughout the design pressure range
- **e.** Great flexibility of performance (can operate over a wide range of pressure requirements and speed ranges).

Hydraulic pump: classification

- There are three main types of positive displacement pumps: (1) gear, (2) vane, and (3) piston.
- There are many variations exist in the design of each of these main types of pumps.
- For example, vane and piston pumps can be of either fixed or variable displacement.
- A fixed displacement pump is one in which the amount of fluid ejected per revolution (displacement) cannot be varied.
- In a variable displacement pump, the displacement can be varied by changing the physical relationships of various pump elements.
- This change in pump displacement produces a change in pump flow output even though pump speed remains constant.

Hydraulic pumps do not pump pressure

- Pumps do not pump pressure. Instead they produce fluid flow.
- The resistance to this flow, produced by the hydraulic system, is what determines the pressure.
- For example, if a positive displacement pump has its discharge line open to the atmosphere, there will be flow, but there will be no discharge pressure above atmospheric because there is essentially no resistance to flow. However, if the discharge line is blocked, then we have theoretically infinite resistance to flow.
- Hence, there is no place for the fluid to go. The pressure will therefore rise until some component breaks unless pressure relief is provided. This is the reason a pressure relief valve is needed when a positive displacement pump is used.
- When the pressure reaches a set value, the relief valve will open to allow flow back to the oil tank.
- Thus, a pressure relief valve determines the maximum pressure level that the system will experience regardless of the magnitude of the load resistance.

Hydraulic pumps do not pump pressure

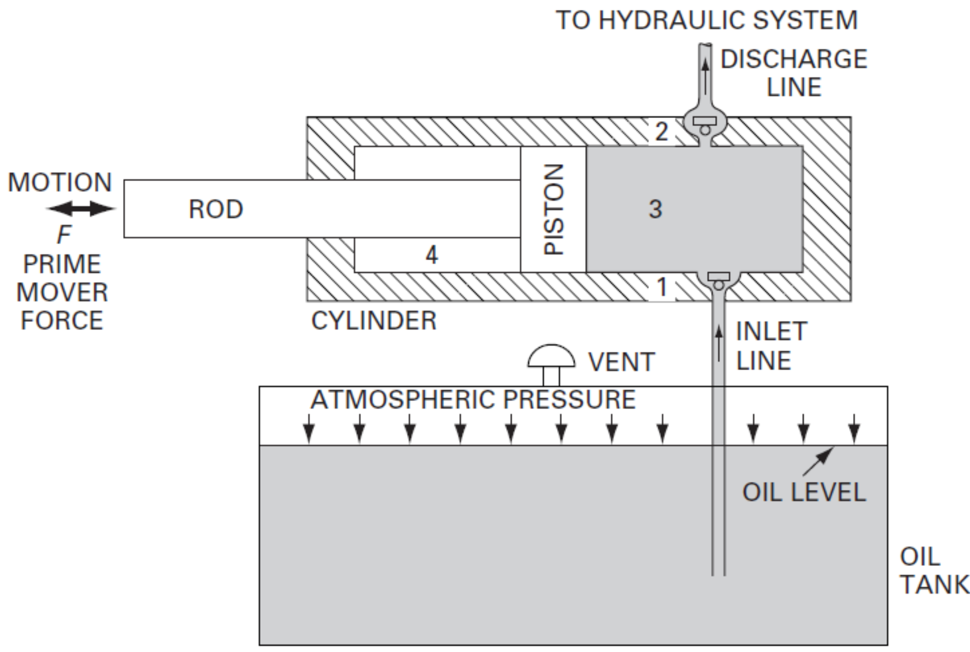
- Some pumps are made with variable displacement, pressure compensation capability.
- Such pumps are designed so that as system pressure builds up, they produce less flow.
- Finally, at some predetermined maximum pressure level, the flow output goes to zero due to zero displacement.
- This prevents any additional pressure buildup.
- Pressure relief valves are not needed when pressure-compensated pumps are used.

Pumping theory

- Pumps operate on the principle whereby a partial vacuum is created at the pump inlet due to the internal operation of the pump.
- This allows atmospheric pressure to push the fluid out of the oil tank (reservoir) and into the pump intake.
- The pump then mechanically pushes the fluid out the discharge line.

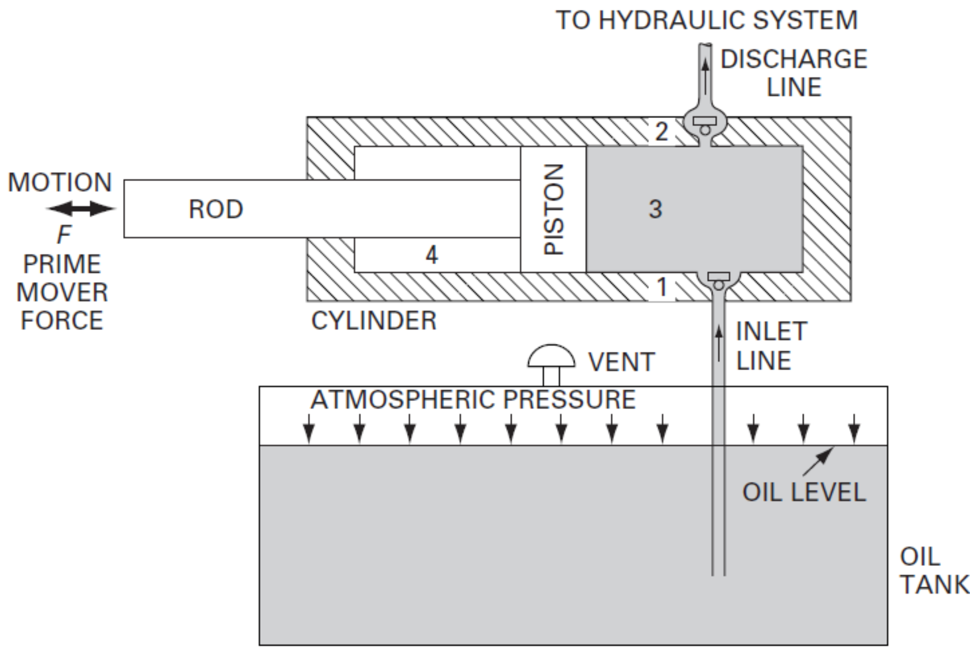
Pumping theory

- Check valve 1 is connected to the pump inlet line and allows fluid to enter the pump only at this location.
- Check valve 2 is connected to the pump discharge line and allows fluid to leave the pump only at this location.
- As the piston is pulled to the left, a partial vacuum is generated in pump cavity 3, because the close tolerance between the piston and cylinder (or the use of piston ring seals) prevents air inside cavity 4 from traveling into cavity 3.
- This flow of air, if allowed to occur, would destroy the vacuum.
- This vacuum holds the ball of check valve 2 against its seat (lower position) and allows atmospheric pressure to push fluid from the reservoir into the pump via check valve 1.
- This inlet flow occurs because the force of the fluid pushes the ball of check valve 1 off its seat.



Pumping theory

- When the piston is pushed to the right, the fluid movement closes inlet valve 1 and opens outlet valve 2.
- The quantity of fluid, displaced by the piston, is forcibly ejected out the discharge line leading to the hydraulic system.
- The volume of oil displaced by the piston during the discharge stroke is called the *displacement volume* of the pump.

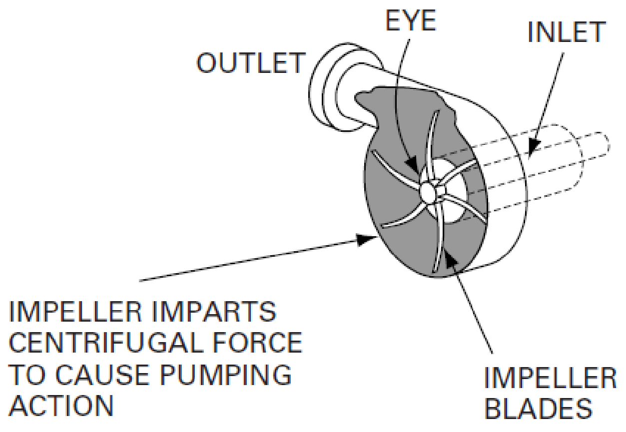


PUMP CLASSIFICATION: Dynamic pumps

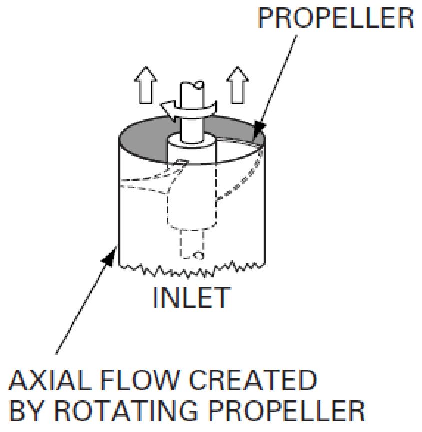
- The two most common types of dynamic pumps are the centrifugal (impeller) and axial (propeller) pumps.
- Although these pumps provide smooth continuous flow, their flow output is reduced as circuit resistance is increased and thus are rarely used in fluid power systems.
- In dynamic pumps there is a great deal of clearance between the rotating impeller or propeller and the stationary housing.
- Thus as the resistance of the external system starts to increase, some of the fluid slips back into the clearance spaces, causing a reduction in the discharge flow rate.
- This slippage is due to the fact that the fluid follows the path of least resistance.
- When the resistance of the external system becomes infinitely large (for example, a valve is closed in the outlet line), the pump will produce no flow.
- These pumps are typically used for low-pressure, high-volume flow applications.

PUMP CLASSIFICATION: Dynamic pumps

- Also, since there is a great deal of clearance between the rotating and stationary elements, dynamic pumps are not self-priming unlike positive displacement pumps.
- This is because the large clearance space does not permit a suction pressure to occur at the inlet port when the pump is first turned on.
- Thus if the fluid is being pumped from a reservoir located below the pump, priming is required.
- Priming is the prefilling of the pump housing and inlet pipe with fluid so that the pump can initially draw in the fluid and pump it efficiently.



CENTRIFUGAL (IMPELLER) TYPE

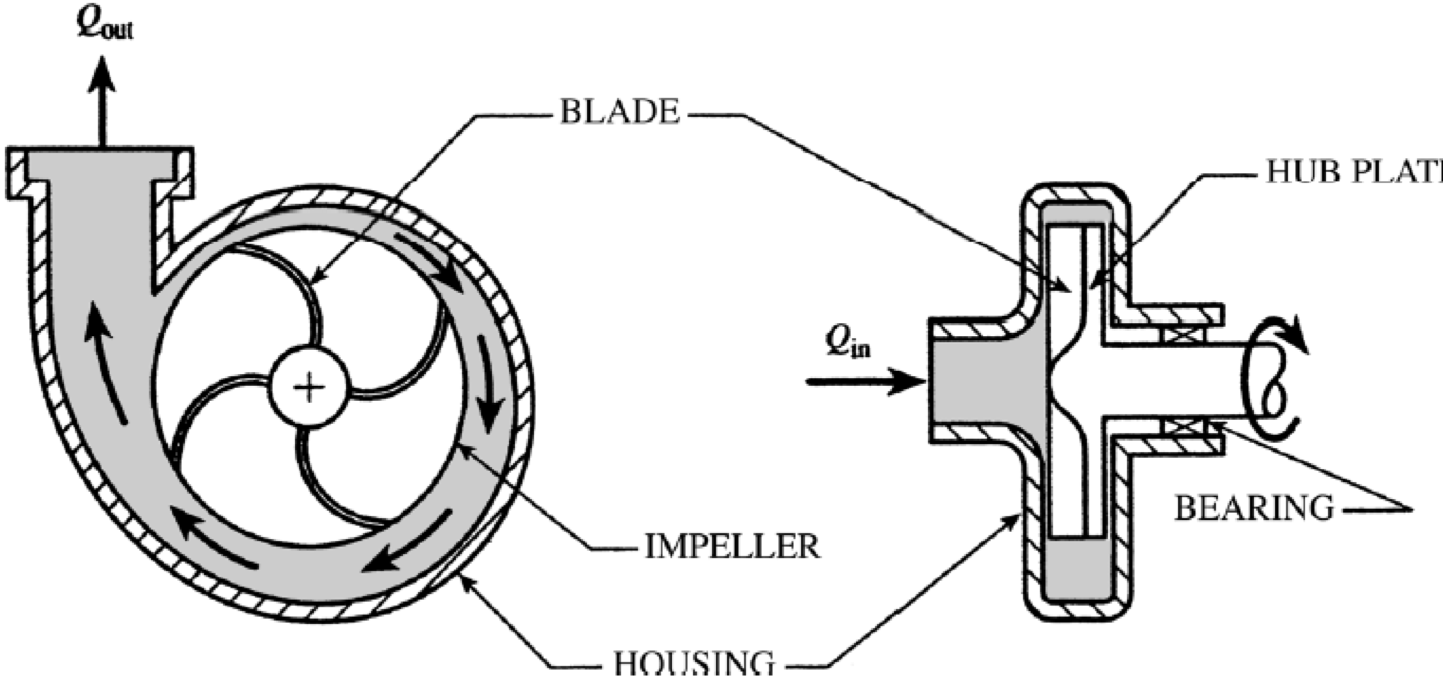


AXIAL (PROPELLER) TYPE

Centrifugal pump

The operation principle of Centrifugal pump as follows:

- The fluid enters at the center of the impeller and is picked up by the rotating impeller.
- As the fluid rotates with the impeller, the centrifugal force causes the fluid to move radially outward.
- This causes the fluid to flow through the outlet discharge port of the housing.



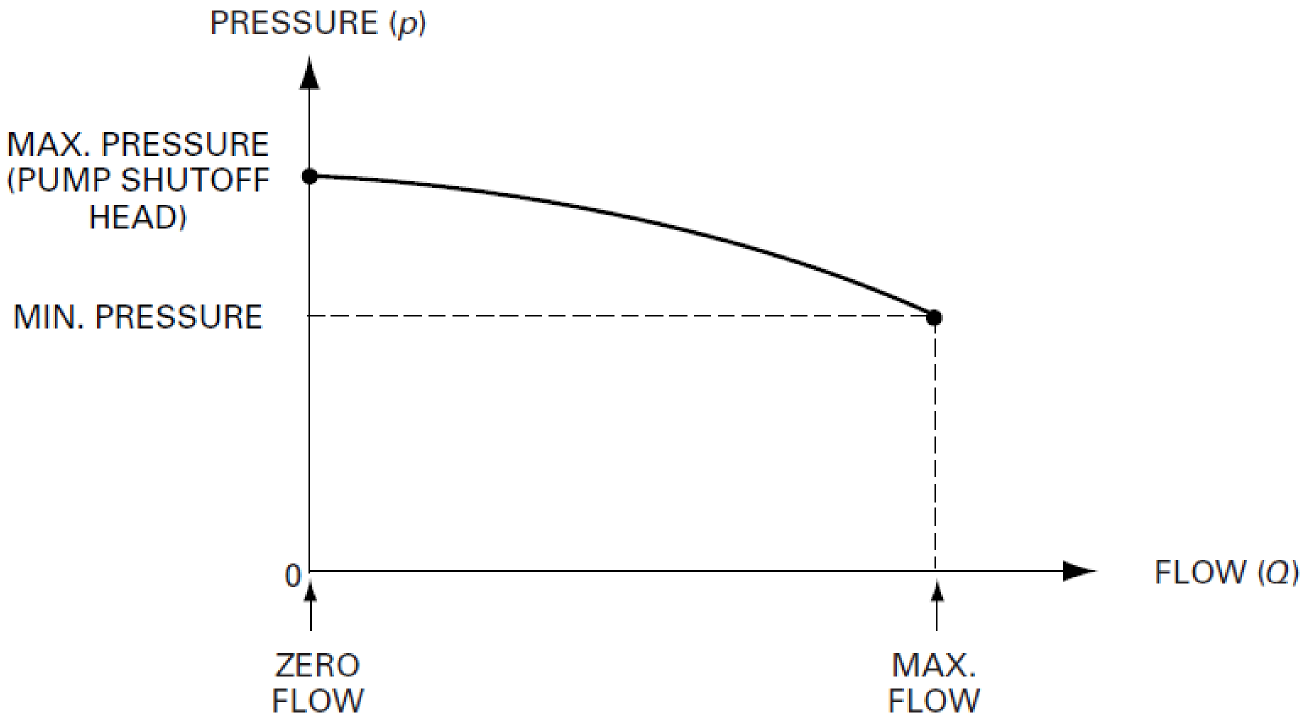
(a) Construction features.

Centrifugal pump

- One of the interesting characteristics of a centrifugal pump is its behavior when there is no demand for fluid.
- In such a case, there is no need for a pressure relief valve to prevent pump damage.
- The tips of the impeller blades merely slosh through the fluid, and the rotational speed maintains a fluid pressure corresponding to the centrifugal force established.
- The fact that there is no positive internal seal against leakage is the reason that the centrifugal pump is not forced to produce flow against no demand.
- When demand for the fluid occurs (for example, the opening of a valve), the pressure delivers the fluid to the source of the demand.
- This is why centrifugal pumps are so desirable for pumping stations used for delivering water to homes and factories.
- The demand for water may go to near zero during the evening and reach a peak sometimes during the daytime.
- The centrifugal pump can readily handle these large changes in fluid demand.

Centrifugal pump

- Although dynamic pumps provide smooth continuous flow (when a demand exists), their output flow rate is reduced as resistance to flow is increased.
- This is shown for centrifugal pumps in the figure, where pump pressure is plotted versus pump flow.
- The maximum pressure is called the *shutoff head* because an external circuit valve is closed, which shuts off the flow.
- As the external resistance decreases due to the valve being opened, the flow increases at the expense of reduced pressure.



(b) Pressure versus flow curve.

Positive Displacement Pumps

- This type of pump ejects a fixed quantity of fluid per revolution of the pump shaft.
- As a result, pump output flow, neglecting changes in the small internal leakage, is constant and not dependent on system pressure.

- This makes them particularly well suited for fluid power systems.
- However, positive displacement pumps must be protected against overpressure if the resistance to flow becomes very large.

- This can happen if a valve is completely closed and there is no physical place for the fluid to go.
- The reason for this is that a positive displacement pump continues to eject fluid (even though it has no place to go), causing an extremely rapid buildup in pressure as the fluid is compressed.
- A pressure relief valve is used to protect the pump against overpressure by diverting pump flow back to the hydraulic tank, where the fluid is stored for system use.

Positive Displacement Pumps

- Positive displacement pumps can be classified by the type of motion of internal elements.
- The motion may be either rotary or reciprocating.
- Although these pumps come in a wide variety of different designs, there are essentially three basic types:

1. Gear pumps (fixed displacement only by geometrical necessity)
- External gear pumps
- Internal gear pumps
- Lobe pumps
- Screw pumps

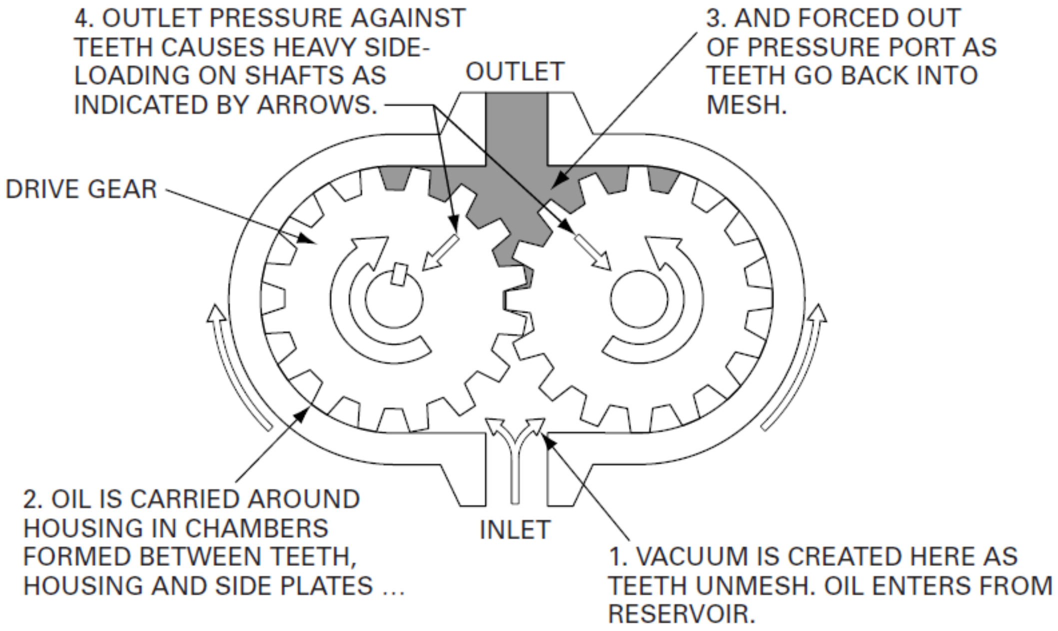
2. Vane pumps
- Unbalanced vane pumps (fixed or variable displacement)
- Balanced vane pumps (fixed displacement only)

3. Piston pumps (fixed or variable displacement)
- Axial design
- Radial design

In addition, vane pumps can be of the balanced or unbalanced design. The unbalanced design can have pressure compensation capability, which automatically protects the pump against overpressure.

External gear pump operation

- One of the gears is connected to a drive shaft connected to the prime mover.
- The second gear is driven as it meshes with the driver gear. Oil chambers are formed between the gear teeth, the pump housing, and the side wear plates.
- The suction side is where teeth come out of mesh, and it is here that the volume expands, bringing about a reduction in pressure to below atmospheric pressure.
- Fluid is pushed into this void by atmospheric pressure because the oil supply tank is vented to the atmosphere.
- The discharge side is where teeth go into mesh, and it is here that the volume decreases between mating teeth.
- Since the pump has a positive internal seal against leakage, the oil is positively ejected into the outlet port.



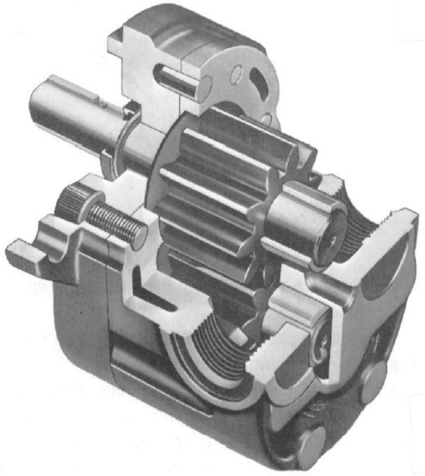


Figure 5-9. Detailed features of an external gear pump. *(Courtesy of Webster Electric Company, Inc., subsidiary of STA-RITE Industries, Inc., Racine, Wisconsin.)*

Volumetric Displacement and Theoretical Flow Rate for gear pumps

the volumetric displacement can be represented by Eq. (5-1).

$$V_D = \frac{\pi}{4}(D_o^2 - D_i^2)L \qquad \textbf{(5-1)}$$

The theoretical flow rate (in English units) is determined next:

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

Since 1 gal = 231 in^3, we have

$$Q_T(\text{gpm}) = \frac{V_D(\text{in}^3/\text{rev}) \times N(\text{rev}/\text{min})}{231} \qquad \textbf{(5-2)}$$

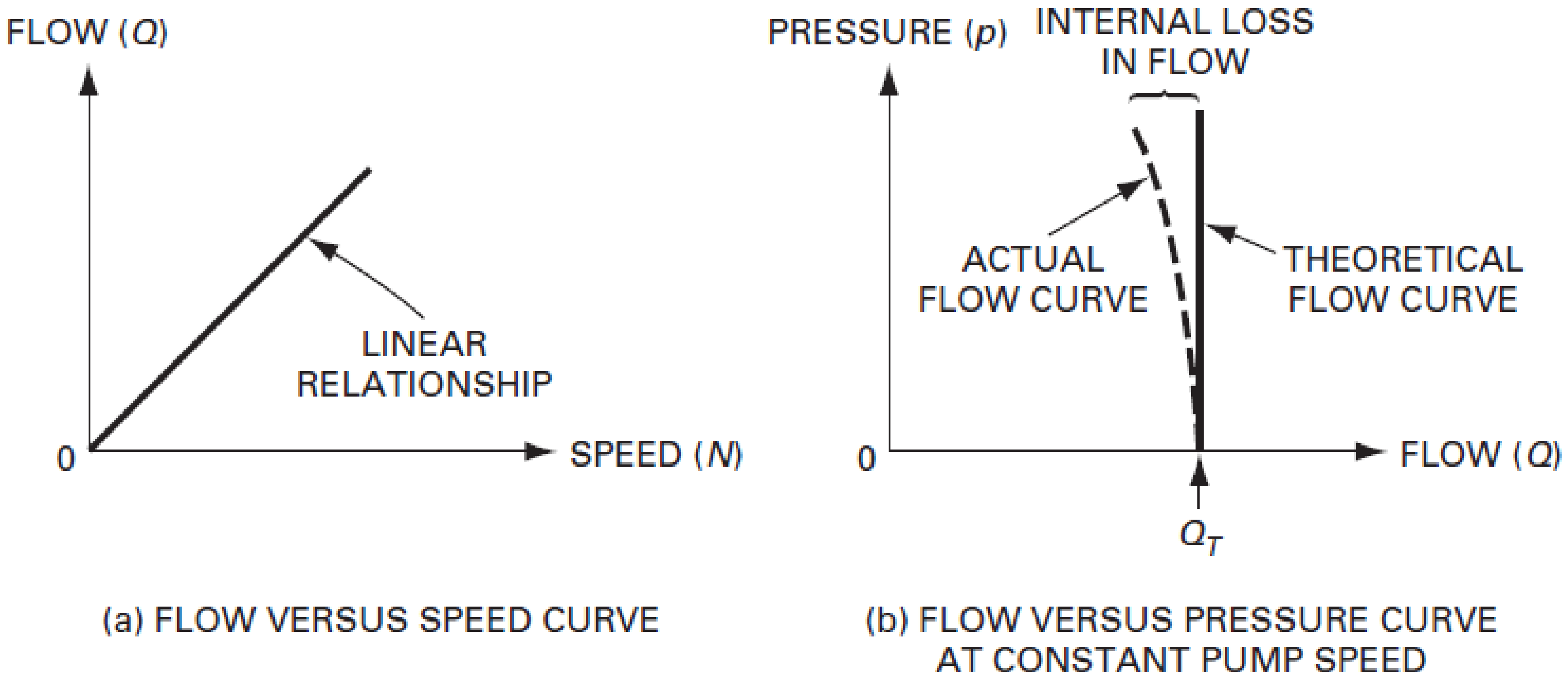
Using metric units, we have

$$Q_T(\text{m}^3/\text{min}) = V_D(\text{m}^3/\text{rev}) \times N(\text{rev}/\text{min}) \qquad \textbf{(5-2M)}$$

D_o = outside diameter of gear teeth (in, m)
D_i = inside diameter of gear teeth (in, m)

L = width of gear teeth (in, m)
V_D = displacement volume of pump (in^3/rev, m^3/rev)
N = rpm of pump
Q_T = theoretical pump flow rate

Volumetric Displacement and Theoretical Flow Rate for gear pumps



Positive displacement pump *Q* versus *N* and *p* versus *Q* curves. (a) Flow versus speed curve. (b) Flow versus pressure curve at constant pump speed.

Volumetric Efficiency

There must be a small clearance (about 0.001 in) between the teeth tip and pump housing. As a result, some of the oil at the discharge port can leak directly back toward the suction port. This means that the actual flow rate Q_A is less than the theoretical flow rate Q_T, which is based on volumetric displacement and pump speed. This internal leakage, called *pump slippage*, is identified by the term *volumetric efficiency*, η_v, which equals about 90% for positive displacement pumps, operating at design pressure:

$$\eta_v = \frac{Q_A}{Q_T} \qquad \textbf{(5-3)}$$

- The higher the discharge pressure, the lower the volumetric efficiency because internal leakage increases with pressure.
- Pump manufacturers usually specify volumetric efficiency at the pump rated pressure.
- The rated pressure of a positive displacement pump is that pressure below which no mechanical damage due to overpressure will occur to the pump and the result will be a long, reliable service life. Too high a pressure not only produces excessive leakage but also can damage a pump by distorting the casing and overloading the shaft bearings.
- This brings to mind once again the need for overpressure protection.
- High pressures occur when a high resistance to flow is encountered, such as a large actuator load or a closed valve in the pump outlet line.

Volumetric Efficiency

EXAMPLE 5-1

A gear pump has a 3-in outside diameter, a 2-in inside diameter, and a 1-in width. If the actual pump flow at 1800 rpm and rated pressure is 28 gpm, what is the volumetric efficiency?

Solution Find the displacement volume using Eq. (5-1):

$$V_D = \frac{\pi}{4}[(3)^2 - (2)^2](1) = 3.93 \text{ in}^3$$

Next, use Eq. (5-2) to find the theoretical flow rate:

$$Q_T = \frac{V_D N}{231} = \frac{(3.93)(1800)}{231} = 30.6 \text{ gpm}$$

The volumetric efficiency is then found using Eq. (5-3):

$$\eta_v = \frac{28}{30.6} = 0.913 = 91.3\%$$

Volumetric Efficiency

EXAMPLE 5-2

A gear pump has a 75-mm outside diameter, a 50-mm inside diameter, and a 25-mm width. If the volumetric efficiency is 90% at rated pressure, what is the corresponding actual flow rate? The pump speed is 1000 rpm.

Solution The volume displacement is

$$V_D = \frac{\pi}{4}[(0.075)^2 - (0.050)^2](0.025) = 0.0000614 \text{ m}^3/\text{rev}$$

Since 1 L = 0.001 m³, $V_D = 0.0614$ L.

Next, combine Eqs. (5-2M) and (5-3) to find the actual flow rate:

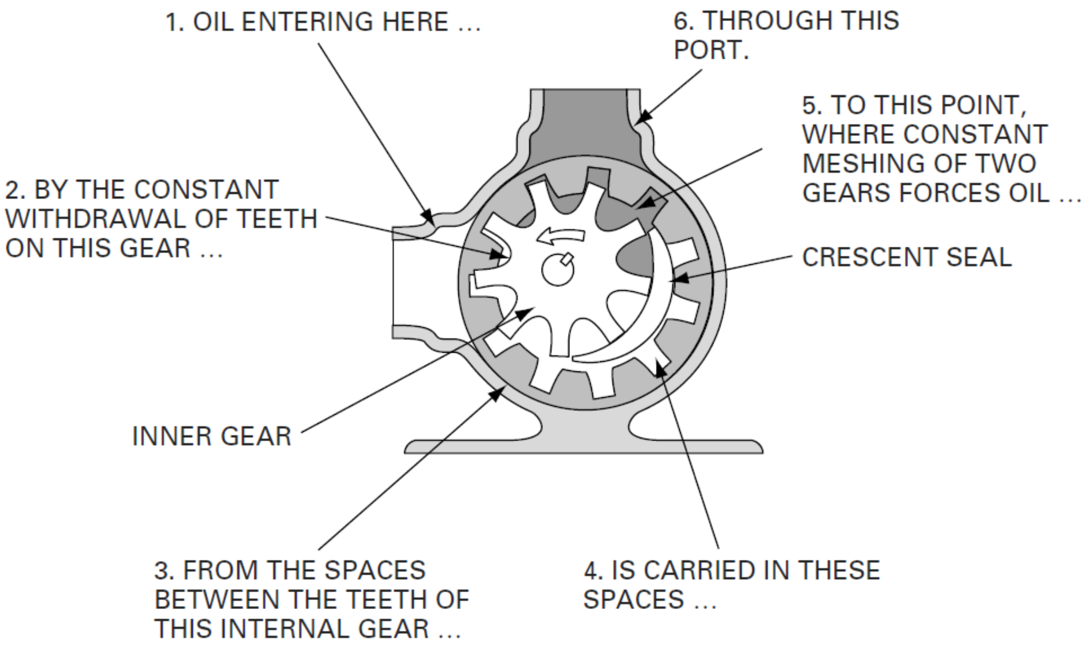
$$Q_A = \eta_v Q_T = \eta_v V_D(\text{m}^3/\text{rev}) \times N(\text{rev/min})$$
$$= 0.90 \times 0.0000614 \times 1000 = 0.0553 \text{ m}^3/\text{min}$$

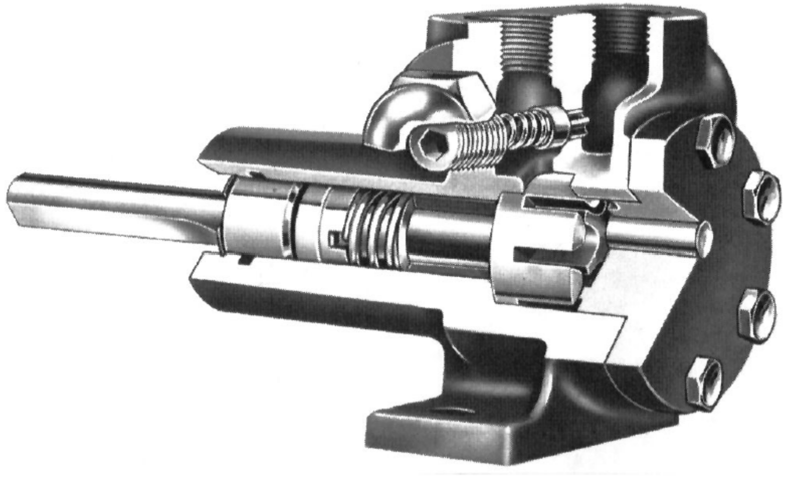
Since 1 L = 0.001 m³, we have

$$Q_A = 55.3 \text{ Lpm}$$

Internal Gear Pump

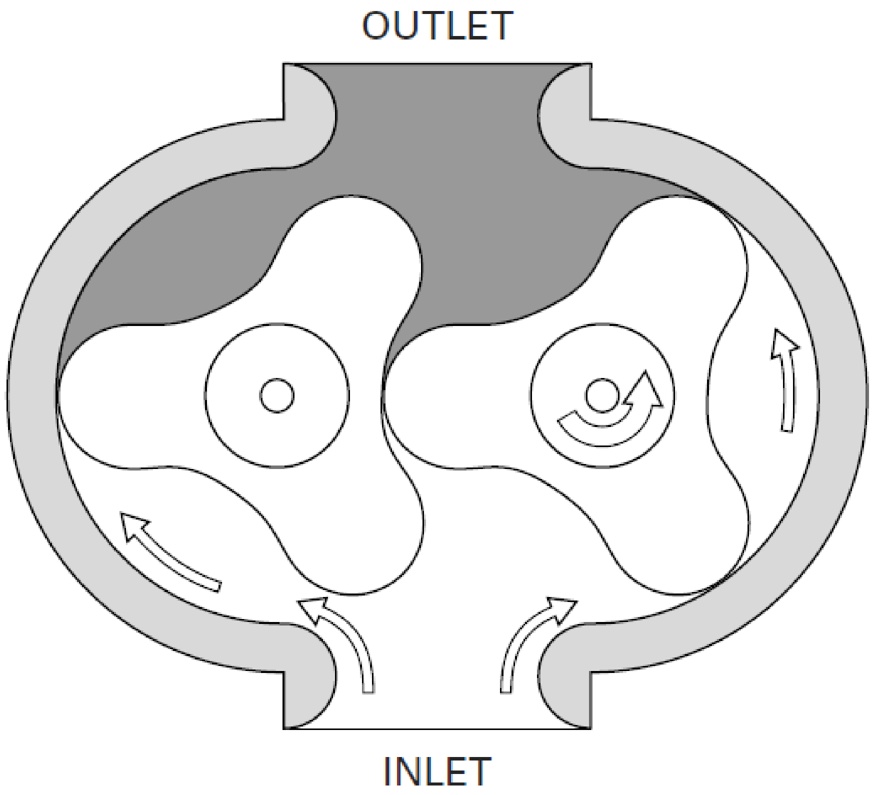
- This design consists of an internal gear, a regular spur gear, a crescent-shaped seal, and an external housing.
- As power is applied to either gear, the motion of the gears draws fluid from the reservoir and forces it around both sides of the crescent seal, which acts as a seal between the suction and discharge ports.
- When the teeth mesh on the side opposite to the crescent seal, the fluid is forced to enter the discharge port of the pump.





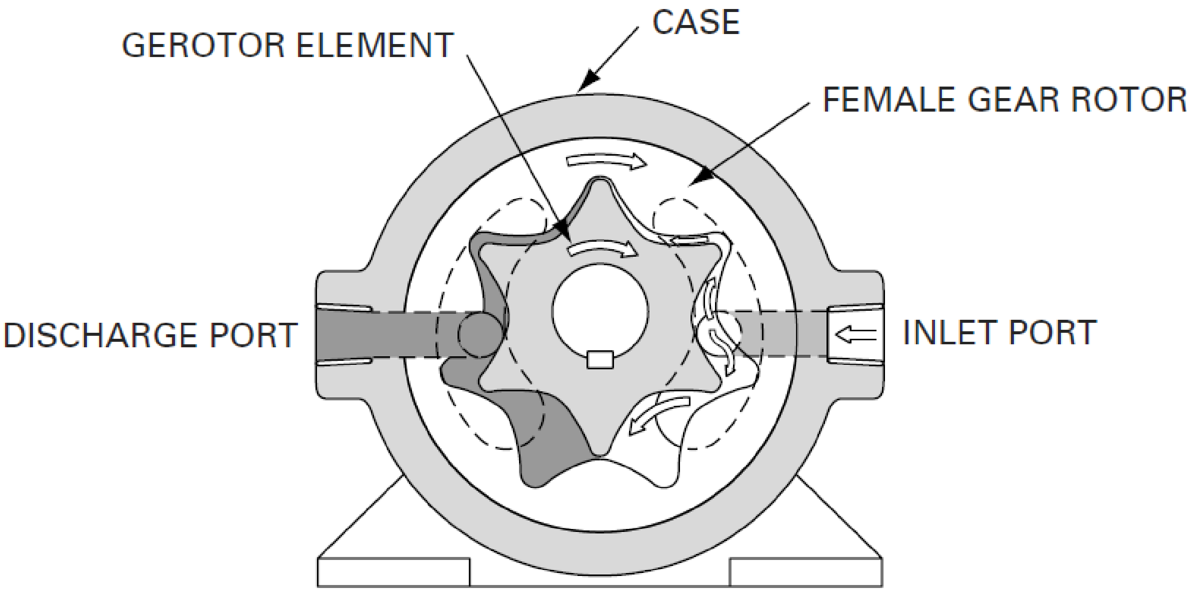
Lobe pump

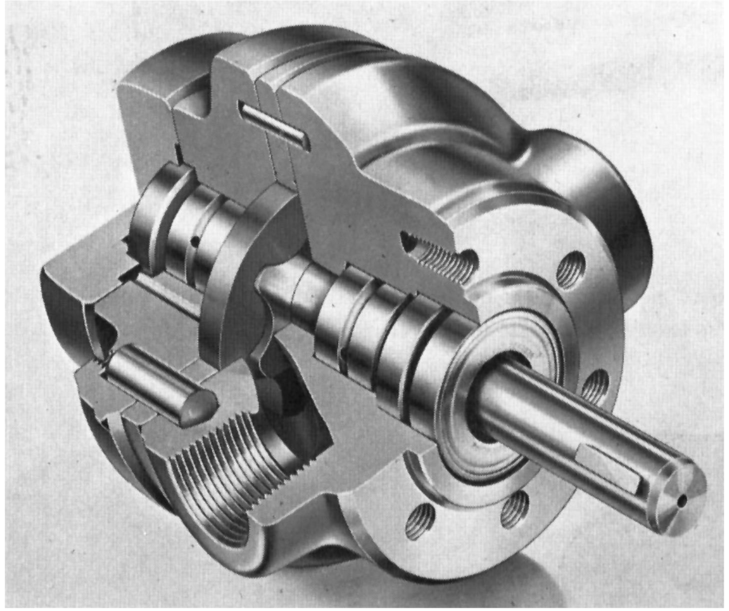
- This pump operates in a fashion similar to the external gear pump. But unlike the external gear pump, both lobes are driven externally so that they do not actually contact each other.
- Thus, they are quieter than other types of gear pumps.
- Due to the smaller number of mating elements, the lobe pump output will have a somewhat greater amount of pulsation, although its volumetric displacement is generally greater than that for other types of gear pumps.



Gerotor Pump

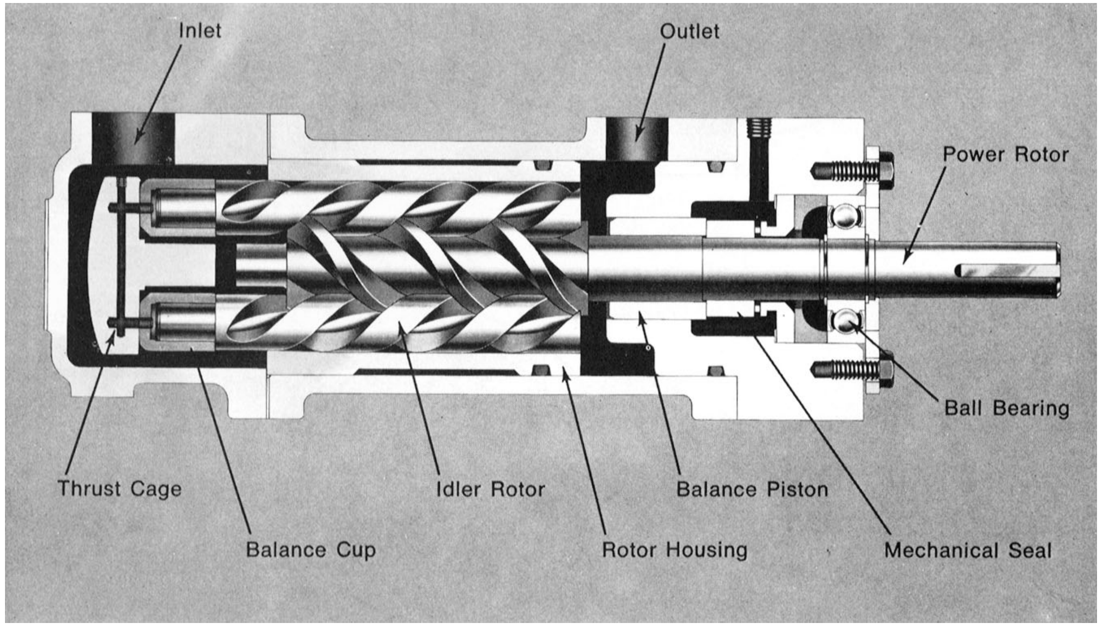
- The Gerotor pump operates very much like the internal gear pump.
- The inner gear rotor (Gerotor element) is power-driven and draws the outer gear rotor around as they mesh together.
- This forms inlet and discharge pumping chambers between the rotor lobes.
- The tips of the inner and outer rotors make contact to seal the pumping chambers from each other.
- The inner gear has one tooth less than the outer gear, and the volumetric displacement is determined by the space formed by the extra tooth in the outer rotor.

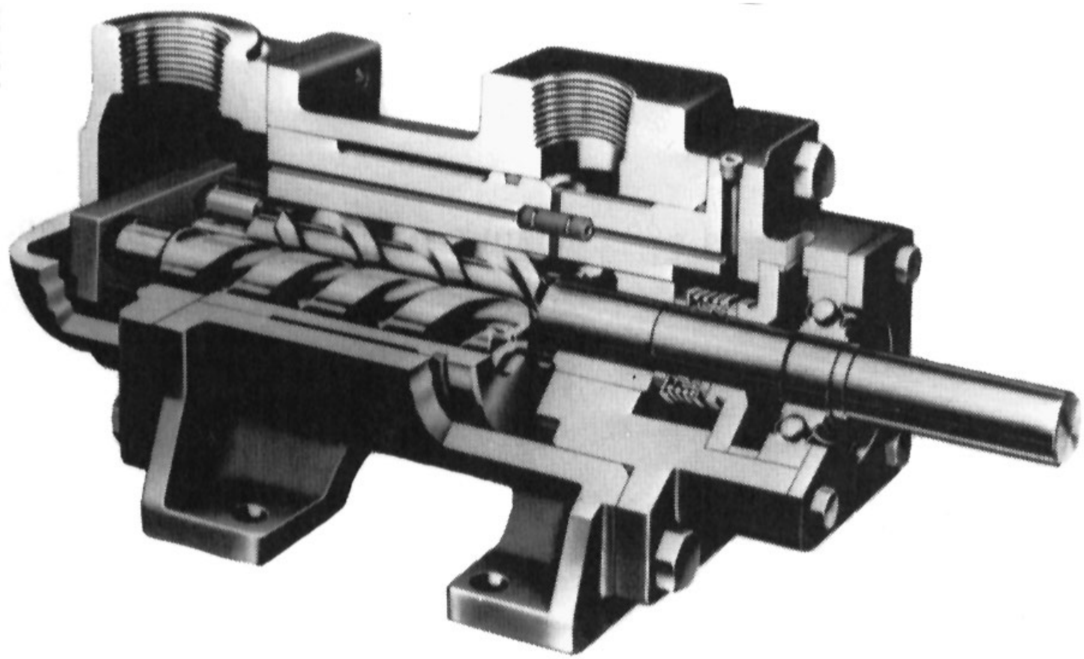




Screw Pump

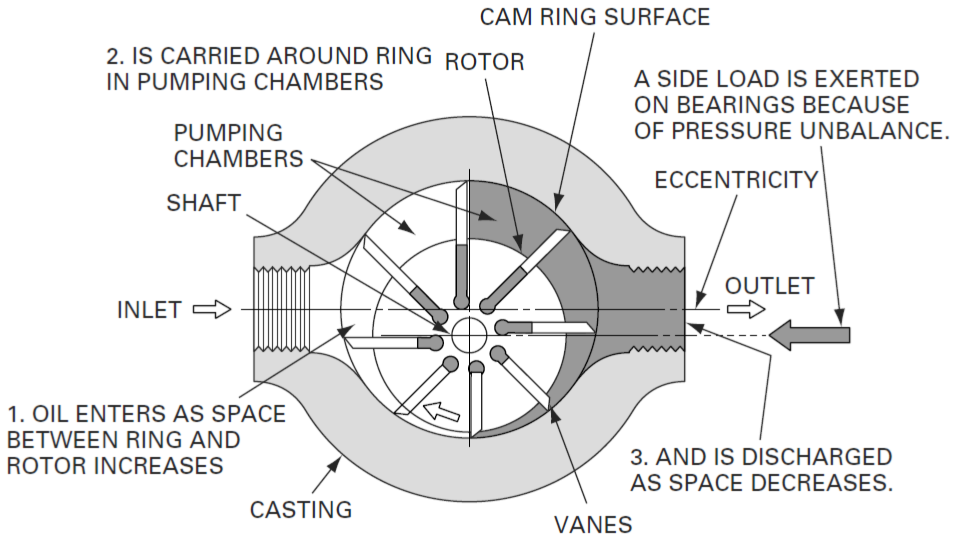
- The screw pump is an axial flow positive displacement unit.
- Three precision ground screws, meshing within a closefitting housing, deliver nonpulsating flow quietly and efficiently.
- The two symmetrically opposed idler rotors act as rotating seals, confining the fluid in a succession of closures or stages.
- The idler rotors are in rolling contact with the central power rotor and are free to float in their respective housing bores on a hydrodynamic oil film.
- There are no radial bending loads.
- Axial hydraulic forces on the rotor set are balanced, eliminating any need for thrust bearings.
- It is rated at 500 psi and can deliver up to 123 gpm.
- High-pressure designs are available for 3500-psi operation with output flow rates up to 88 gpm.





VANE PUMPS

- The rotor, which contains radial slots, is splined to the drive shaft and rotates inside a cam ring.
- Each slot contains a vane designed to mate with the surface of the cam ring as the rotor turns.
- Centrifugal force keeps the vanes out against the surface of the cam ring.
- During one-half revolution of rotor rotation, the volume increases between the rotor and cam ring.
- The resulting volume expansion causes a reduction of pressure.
- This is the suction process, which causes fluid to flow through the inlet port and fill the void.
- As the rotor rotates through the second half revolution, the surface of the cam ring pushes the vanes back into their slots, and the trapped volume is reduced.
- This positively ejects the trapped fluid through the discharge port.



Analysis of Volumetric Displacement

From geometry, we can find the maximum possible eccentricity:

$$e_{\max} = \frac{D_C - D_R}{2}$$

This maximum value of eccentricity produces a maximum volumetric displacement:

$$V_{D_{\max}} = \frac{\pi}{4}(D_C^2 - D_R^2)L$$

Noting that we have the difference between two squared terms yields

$$V_{D_{\max}} = \frac{\pi}{4}(D_C + D_R)(D_C - D_R)L$$

Substituting the expression for $e_{\max}$ yields

$$V_{D_{\max}} = \frac{\pi}{4}(D_C + D_R)(2e_{\max})L$$

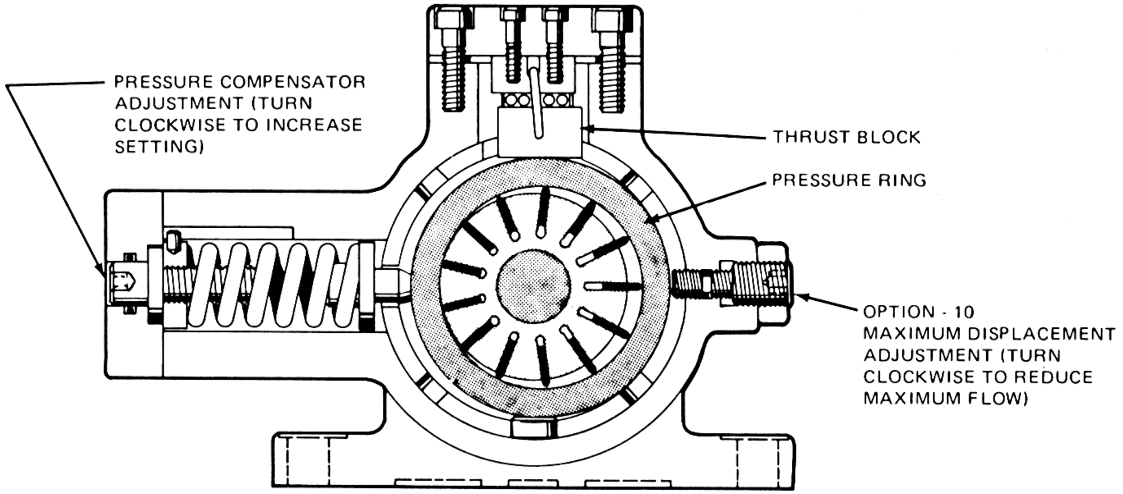
The actual volumetric displacement occurs when $e_{\max} = e$:

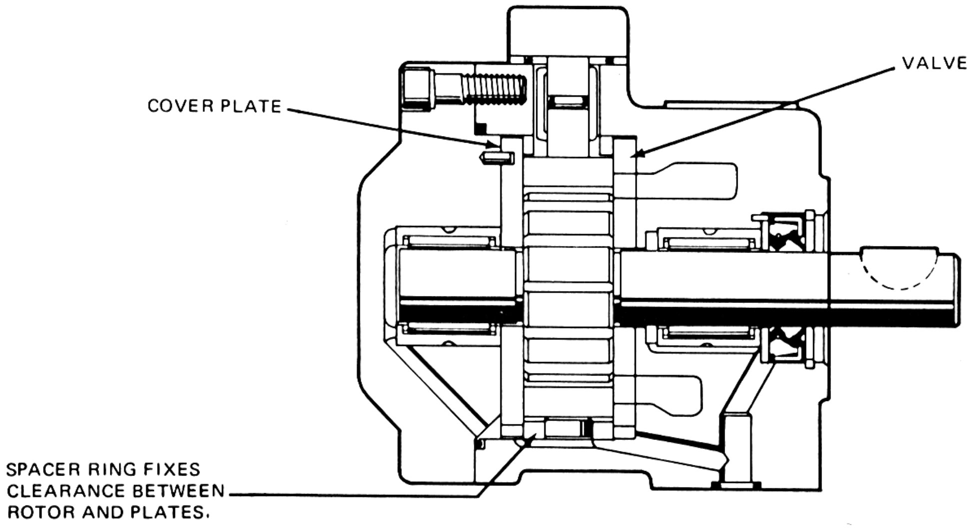
$$V_D = \frac{\pi}{2}(D_C + D_R)eL \qquad \textbf{(5-4)}$$

D_C = diameter of cam ring (in, m)
D_R = diameter of rotor (in, m)
L = width of rotor (in, m)
V_D = pump volumetric displacement (in^3, m^3)
e = eccentricity (in, m)
$e_{\max}$ = maximum possible eccentricity (in, m)
$V_{D\max}$ = maximum possible volumetric displacement (in^3, m^3)

Variable displacement vane pump

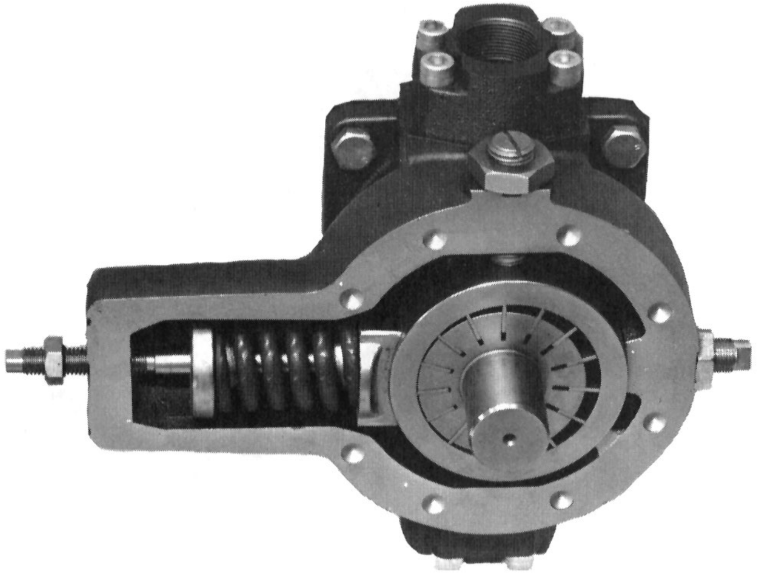
- Some vane pumps have provisions for mechanically varying the eccentricity.
- Such a design is called a *variable displacement pump.*
- A handwheel or a pressure compensator can be used to move the cam ring to change the eccentricity.
- The direction of flow through the pump can be reversed by movement of the cam ring on either side of center.

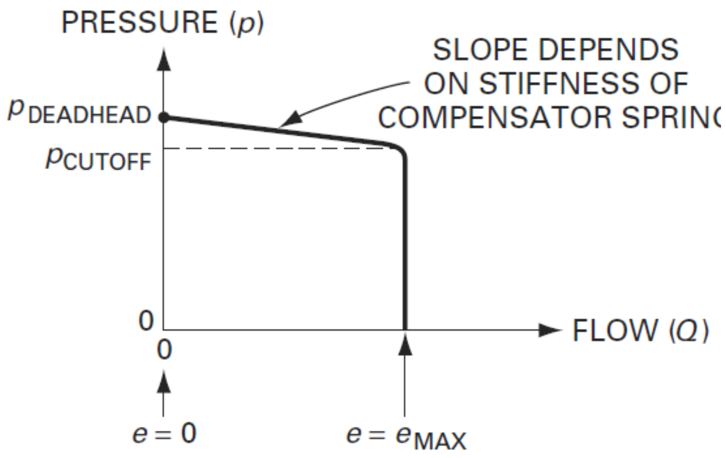




Pressure-Compensated Vane Pump

- System pressure acts directly on the cam ring via a hydraulic piston on the right.
- This forces the cam ring against the compensator spring-loaded piston on the left side of the cam ring.
- If the discharge pressure is large enough, it overcomes the compensator spring force and shifts the cam ring to the left.
- This reduces the eccentricity, which is maximum when discharge pressure is zero.
- As the discharge pressure continues to increase, zero eccentricity is finally achieved, and the pump flow becomes zero.
- Such a pump basically has its own protection against excessive pressure buildup.
- When the pressure reaches a value called p_{cutoff}, the compensator spring force equals the hydraulic piston force.
- As the pressure continues to increase, the compensator spring is compressed until zero eccentricity is achieved.
- The maximum pressure achieved is called $p_{deadhead}$, at which point the pump is protected because it produces no more flow.
- As a result, there is no power wasted and fluid heating is reduced.





Pressure versus flow for pressure compensated vane pump.