

Module

6

Actuators

# Lesson 26

## Hydraulic Actuation Systems - I: Principle and Components

## Lesson Objectives

After learning the lesson students should be able to

- Describe the principles of operation of hydraulic systems and understand its advantages
- Be familiar with basic hydraulic components and their roles in the system
- Describe the constructional and functional aspects of hydraulic pumps and motors
- Draw the graphical symbols used to depict typical hydraulic system components

## Introduction

Hydraulic Actuators, as used in industrial process control, employ hydraulic pressure to drive an output member. These are used where high speed and large forces are required. The fluid used in hydraulic actuator is highly incompressible so that pressure applied can be transmitted instantaneously to the member attached to it.

It was not, however, until the 17<sup>th</sup> century that the branch of hydraulics with which we are to be concerned first came into use. Based upon a principle discovered by the French scientist Pascal, it relates to the use of confined fluids in transmitting power, multiplying force and modifying motions.

Then, in the early stages of the industrial revolution, a British mechanic named Joseph Bramah utilized Pascal's discovery in developing a hydraulic press. Bramah decided that, if a small force on a small area would create a proportionally larger force on a larger area, the only limit to the force a machine can exert is the area to which the pressure is applied.

## Principle Used in Hydraulic Actuator System

### Pascal's Law

Pressure applied to a confined fluid at any point is transmitted undiminished and equally throughout the fluid in all directions and acts upon every part of the confining vessel at right angles to its interior surfaces.

### Amplification of Force

Since pressure  $P$  applied on an area  $A$  gives rise to a force  $F$ , given as,

$$F = P \times A$$

Thus, if a force is applied over a small area to cause a pressure  $P$  in a confined fluid, the force generated on a larger area can be made many times larger than the applied force that created the pressure. This principle is used in various hydraulic devices to such hydraulic press to generate very high forces.

## Conservation of Energy

Since energy or power is always conserved, amplification in force must result in reduction of the fluid velocity. Indeed if the resultant force is applied over a larger area then a unit displacement of the area would cause a larger volumetric displacement than a unit displacement of the small area through which the generating force is applied. Thus, what is gained in force must be sacrificed in distance or speed and power would be conserved.

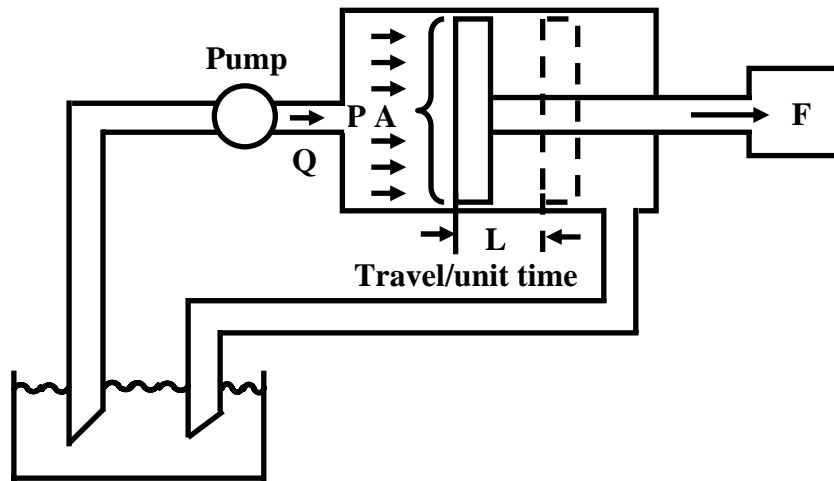


Fig. 26.1 Major hydraulic and mechanical variables

### Point to Ponder: 1

- Can you give an analogy of the force amplification in hydraulic system from an electrical system?
- Can you imagine what would happen, if the cylinder piston in Fig. 26.1 is stopped forcefully?

### Advantages of Hydraulic Actuation Systems

Hydraulics refers to the means and mechanisms of transmitting power through liquids. The original power source for the hydraulic system is a prime mover such as an electric motor or an engine which drives the pump. However, the mechanical equipment cannot be coupled directly to the prime mover because the required control over the motion, necessary for industrial operations cannot be achieved. In terms of these Hydraulic Actuation Systems offer unique advantages, as given below.

**Variable Speed and Direction:** Most large electric motors run at adjustable, but constant speeds. It is also the case for engines. The actuator (linear or rotary) of a hydraulic system, however, can be driven at speeds that vary by large amounts and fast, by varying the pump delivery or using a flow control valve. In addition, a hydraulic actuator can be reversed instantly while in full motion without damage. This is not possible for most other prime movers.

**Power-to-weight ratio:** Hydraulic components, because of their high speed and pressure capabilities, can provide high power output with very small weight and size, say, in comparison to electric system components. Note that in electric components, the size of equipment is mostly limited by the magnetic saturation limit of the iron. It is one of the reasons that hydraulic equipment finds wide usage in aircrafts, where dead-weight must be reduced to a minimum.

**Stall Condition and Overload Protection:** A hydraulic actuator can be stalled without damage when overloaded, and will start up immediately when the load is reduced. The pressure relief valve in a hydraulic system protects it from overload damage. During stall, or when the load pressure exceeds the valve setting, pump delivery is directed to tank with definite limits to torque or force output. The only loss encountered is in terms of pump energy. On the contrary, stalling an electric motor is likely to cause damage. Likewise, engines cannot be stalled without the necessity for restarting.

## Point to Ponder: 2

- A. Consider two types of variable speed drives. In the first one an electric motor with a power electronic servo drive is directly coupled to the load through a mechanism. In the second one an electric motor with a constant speed drive drives the pump in a hydraulic system which provides the variable speed drive to the load. Which one of these two is more energy efficient?
- B. Why is stalling an electric motor likely to cause damage? What can be done to prevent it?

## Components of Hydraulic Actuation Systems

### Hydraulic Fluid

Hydraulic fluid must be essentially non-compressible to be able to transmit power instantaneously from one part of the system to another. At the same time, it should lubricate the moving parts to reduce friction loss and cool the components so that the heat generated does not lead to fire hazards. It also helps in removing the contaminants to filter. The most common liquid used in hydraulic systems is petroleum oil because it is only very slightly compressible. The other desirable property of oil is its lubricating ability. Finally, often, the fluid also acts as a seal against leakage inside a hydraulic component. The degree of closeness of the mechanical fit and the oil viscosity determines leakage rate. Figure 26.2 below shows the role played by hydraulic fluid films in lubrication and sealing.

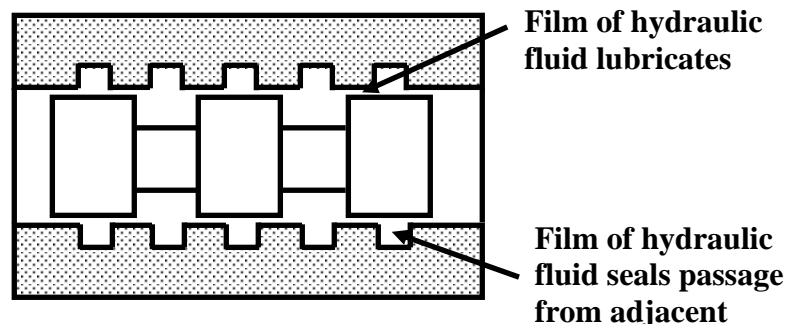


Fig. 26.2 Lubrication and Sealing by Hydraulic Fluid

## The Fluid Delivery Subsystem

It consists of the components that hold and carry the fluid from the pump to the actuator. It is made up of the following components.

### Reservoir

It holds the hydraulic fluid to be circulated and allows air entrapped in the fluid to escape. This is an important feature as the bulk modulus of the oil, which determines the stiffness of hydraulic system, deteriorates considerably in the presence of entrapped air bubbles. It also helps in dissipating heat.

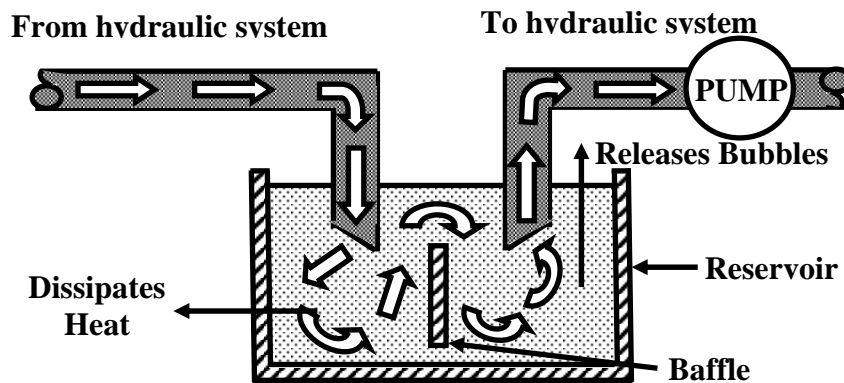


Fig. 26.3 The functions of the reservoir

### Filter

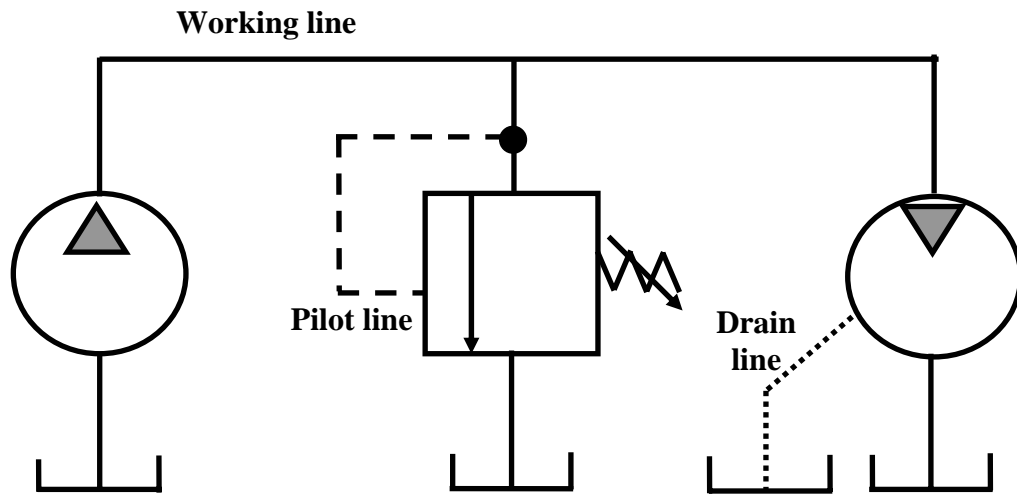
The hydraulic fluid is kept clean in the system with the help of filters and strainers. It removes minute particles from the fluid, which can cause blocking of the orifices of servo-valves or cause jamming of spools.

### Point to Ponder: 3

- A. *What would happen if orifices of valves are blocked by, say, a metal chip in the hydraulic oil?*

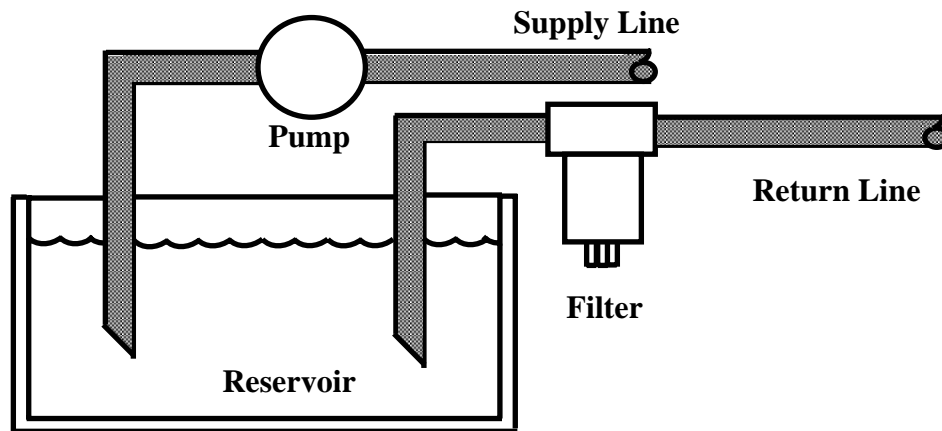
### Line

Pipe, tubes and hoses, along with the fittings or connectors, constitute the conducting lines that carry hydraulic fluid between components. Lines are one of the disadvantages of hydraulic system that we need to pay in return of higher power to weight ratio. Lines convey the fluid and also dissipate heat. In contrast, for Pneumatic Systems, no return path for the fluid, which is air, is needed, since it can be directly released into the atmosphere. There are various kinds of lines in a hydraulic system. The working lines carry the fluid that delivers the main pump power to the load. The pilot lines carry fluid that transmit controlling pressures to various directional and relief valves for remote operation or safety. Lastly there are drain lines that carry the fluid that inevitably leaks out, to the tank.

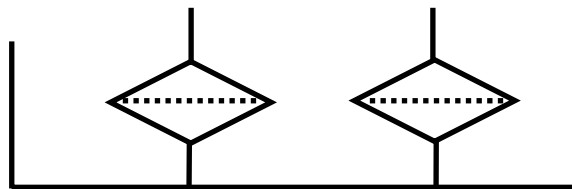


**Fig. 26.4 The various kinds of lines in a hydraulic system**

Fig 26.5 below shows a typical configuration of connecting the supply and the return lines as well as the filter to the reservoir. The graphical symbol for a Reservoir and Filters is shown in Fig. 26.6.



**Fig. 26.5 Connection Arrangement of Filter and Lines with a Reservoir**



**Fig. 26.6 The graphical symbol for Reservoirs and Filters**

## Fittings and Seals

Various additional components are needed to join pipe or tube sections, create bends and also to prevent internal and external leakage in hydraulic systems. Although some amount of internal leakage is built-in, to provide lubrication, excessive internal leakage causes loss of pump power since high pressure fluid returns to the tank, without doing useful work. External leakage, on the other hand, causes loss of fluid and can create fire hazards, as well as fluid contamination. Various kinds of sealing components are employed in hydraulic systems to prevent leakage. A typical such component, known as the O-ring is shown below in Fig. 26.7.

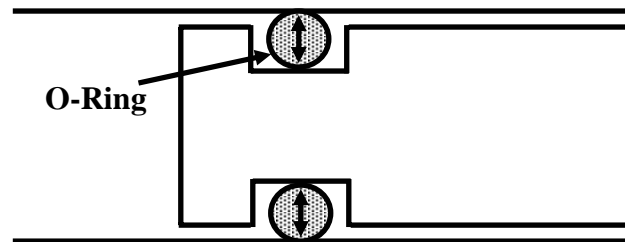


Fig. 26.7 Sealing by O-rings

## Hydraulic Pumps

The pump converts the mechanical energy of its prime-mover to hydraulic energy by delivering a given quantity of hydraulic fluid at high pressure into the system. Generically, all pumps are divided into two categories, namely, hydrodynamic or non-positive displacement and hydrostatic or positive displacement. Hydraulic systems generally employ positive displacement pumps only. The symbol for a pump, is shown in Fig. 26.8 below.

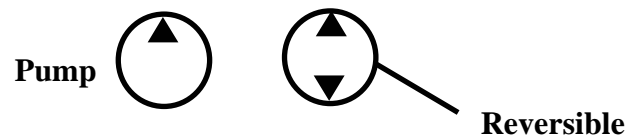


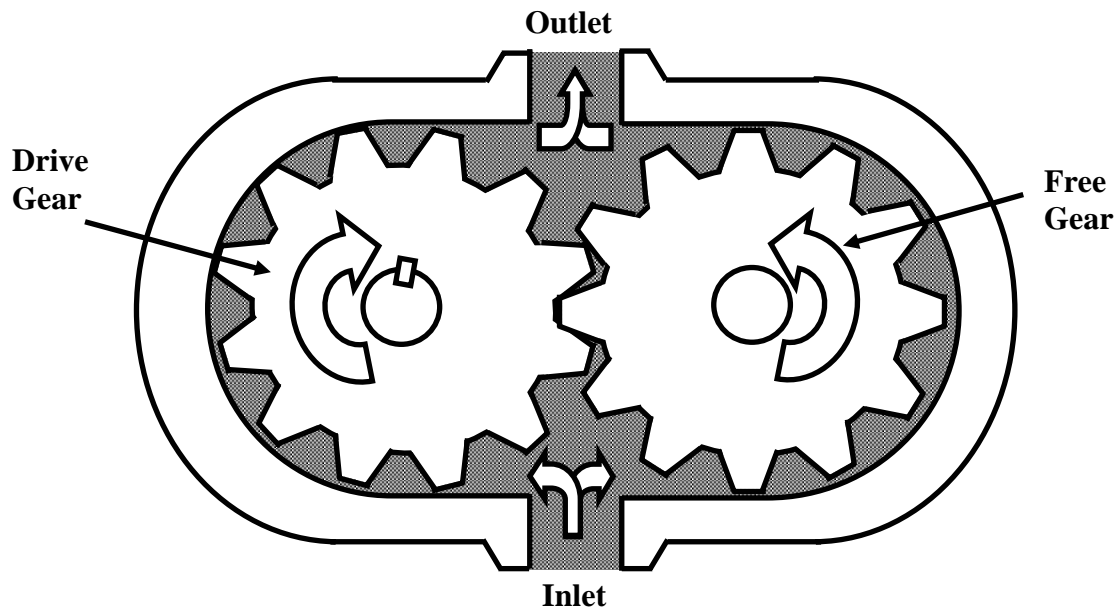
Fig. 26.8 The graphical symbol for Pumps

## Hydrostatic or Positive Displacement Pumps

These pumps deliver a given amount of fluid for each cycle of motion, that is, stroke or revolution. Their output in terms of the volume flow rate is solely dependent on the speed of the prime-mover and is independent of outlet pressure notwithstanding leakage. These pumps are generally rated by their volume flow rate output at a given drive speed and by their maximum operating pressure capability which is specified based on factors of safety and operating life considerations. In theory, a pump delivers an amount of fluid equal to its displacement each cycle or revolution. In reality, the actual output is reduced because of internal leakage or slippage which increases with operating pressure. Moreover, note that the power requirement on the prime mover theoretically increases with the pump delivery at a constant fluid pressure. If this power exceeds the power that the prime mover can handle the pump speed and the delivery rate would fall automatically. There are various types of pumps used in hydraulic systems as described below.



## Gear Pumps



**Fig. 26.9 The construction of a Gear Pump**

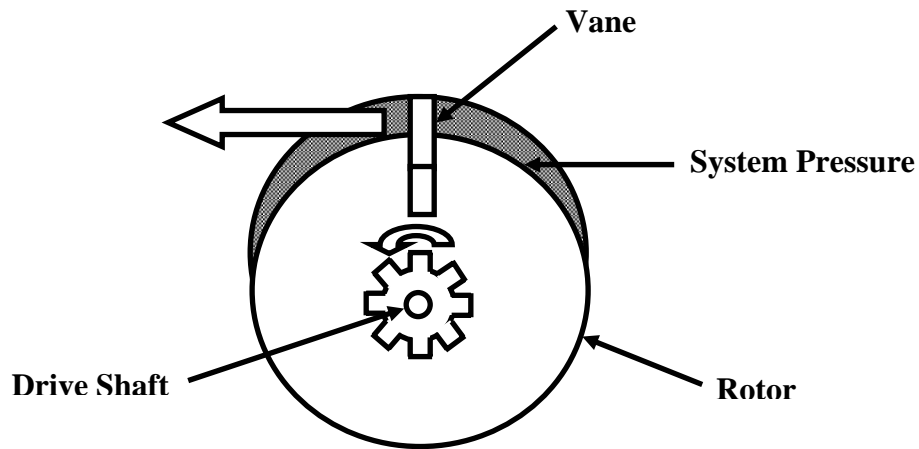
A gear pump develops flow by carrying fluid between the teeth of two meshed gears. One gear is driven by the drive shaft and turns the other, which is free. The pumping chambers formed between the gear teeth are enclosed by the pump housing and the side plates. A low pressure region is created at the inlet as the gear teeth separate. As a result, fluid flows in and is carried around by the gears. As the teeth mesh again at the outlet, high pressure is created and the fluid is forced out. Figure 26.9 shows the construction of a typical internal gears pump; Most gear type pumps are fixed displacement. They range in output from very low to high volume. They usually operate at comparatively low pressure.

### Point to Ponder: 4

A. *Why do gear pumps usually operate at comparatively low pressure?*

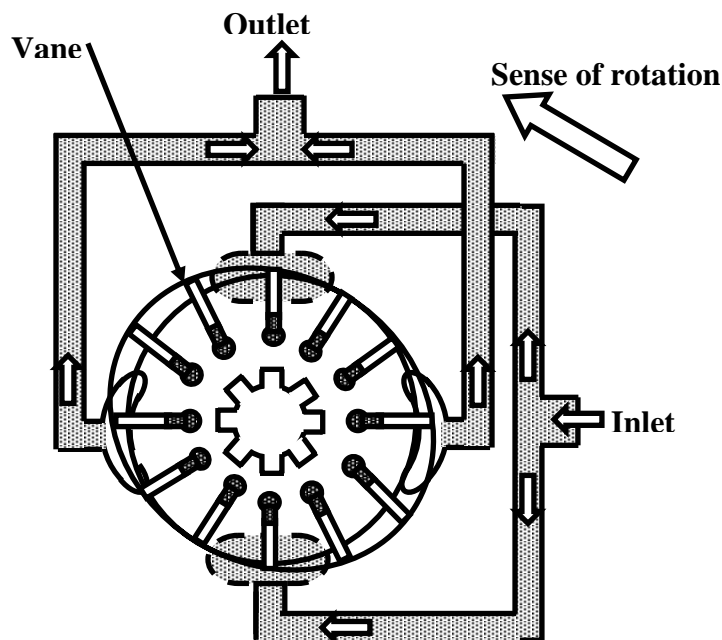
## Vane Pumps

In a vane pump a rotor is coupled to the drive shaft and turns inside a cam ring. Vanes are fitted to the rotor slots and follow the inner surface of the ring as the rotor turns (see Fig. 26.10). Centrifugal force and pressure under the vanes keep them pressed against the ring. Pumping chambers are formed between the vanes and are enclosed by the rotor, ring and two side plates. At the pump inlet, a low pressure region is created as the space between the rotor and ring increases. Oil entering here is trapped in the pumping chambers and then is pushed into the outlet as the space decreases.



**Fig. 26.10 Principle of Operation of Vane Pumps**

Most fixed displacement vane pumps today utilize the balanced design shown in Fig. 26.11. In this design, the cam ring is elliptical rather than a circle and permits two sets of internal ports. The two outlet ports are 180 degrees apart so that pressure forces on the rotor are cancelled out preventing side loading of the drive shaft and bearings



**Fig. 26.11 Construction of Balanced Vane Pumps**

## Piston Pumps

In a piston pumps, a piston reciprocating in a bore draws in fluid as it is retracted and expels it on the forward stroke. Two basic types of piston pumps are radial and axial. A radial pump has the pistons arranged radially in a cylinder block (shown in Fig. 26.12) in an axial pump the pistons are parallel to the axis of the cylinder block (shown in Fig. 26.13). The latter may be further divided into in-line (swash plate or wobble plate) and bent axis types.

## Radial Piston Pumps

In a radial pump the cylinder block rotates on a stationary pintle and inside a circular reaction ring or rotor. As the block rotates, due to centrifugal force, charging pressure or some form of mechanical action the pistons remain pressed against the inner surface of the ring which is offset from the centerline of the cylinder block. Due to the ring being off-centre, as the pistons reciprocate in their bores, they take in fluid as they move outward and discharge it as they move in.

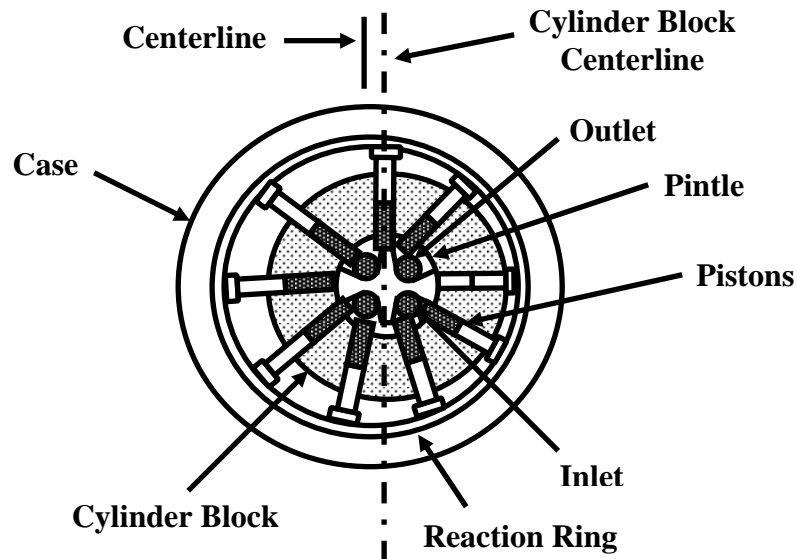


Fig. 26.12 Cross Sectional View of Radial Piston Pumps

## Swash Plate Design Inline Piston Pumps

In axial piston pumps, the cylinder block and drive shaft are co-axial and the pistons move parallel to the drive shaft. The simplest type of axial piston pump is the swash plate inline design shown in Fig. 26.13 and 26.14. The cylinder block in this pump is turned by the prime mover connected to the drive shaft. Pistons fitted to bores in the cylinder are connected to an angled swash plate. As the block turns, the piston shoes follow the swash plate, causing the pistons to reciprocate, since the distance of point of connection changes cyclically as the swash plate rotates. The fluid ports are placed in the valve plate so that the pistons pass the inlet port as they are being pulled out, so that fluid enters the cylinder cavity, and pass the outlet as they are being forced back in, delivering fluid into the system.

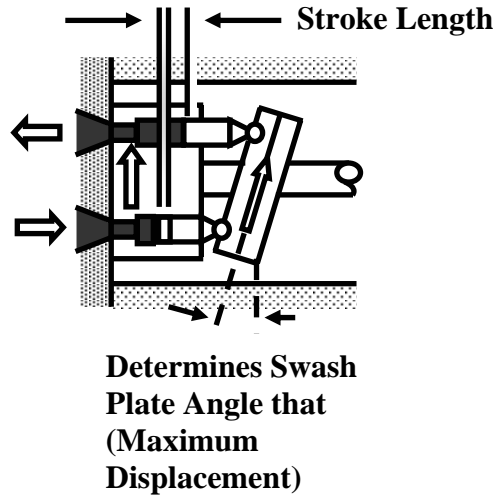


Fig. 26.13 Cross Sectional View of an Axial Piston Pump

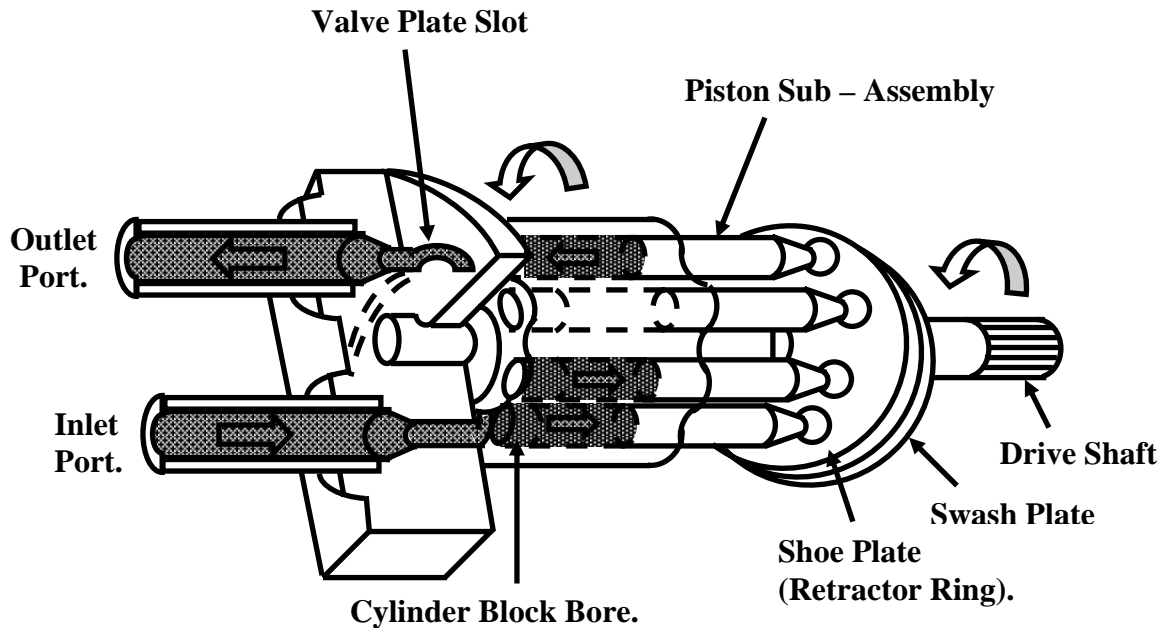


Fig. 26.14 Cut-out View of Axial Piston Pump

## Motors

Motors work exactly on the reverse principle of pumps. In motors fluid is forced into the motor from pump outlets at high pressure. This fluid pressure creates the motion of the motor shaft and finally go out through the motor outlet port and return to tank. All three variants of motors, already described for pumps, namely Gear Motors, Vane Motors and Piston motors are in use.

## Accumulators

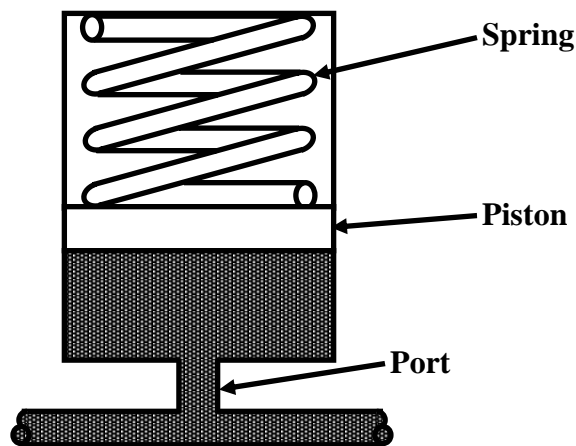
Unlike gases the fluids used in hydraulic systems cannot be compressed and stored to cater to sudden demands of high flow rates that cannot be supplied by the pump. An accumulator in a

hydraulic system provides a means of storing these incompressible fluids under pressure created either by a spring, compressed a gas. Any tendency for pressure to drop at the inlet causes the spring or the gas to force the fluid back out, supplying the demand for flow rate.

## Spring-Loaded Accumulators

In a spring loaded accumulator (Fig. 26.15), pressure is applied to the fluid by a coil spring behind the accumulator piston. The pressure is equal to the instantaneous spring force divided by the piston area. The pressure therefore is not constant since the spring force increases as fluid enters the chamber and decreases as it is discharged.

Spring loaded accumulators can be mounted in any position. The spring force, i.e., the pressure range is not easily adjusted, and where large quantities of fluid are spring size has to be very large.



**Fig. 26.15 A spring-loaded accumulator**

## Gas Charged Accumulator

The most commonly used accumulator is one in which the chamber is pre-charged with an inert gas, such as dry nitrogen. A gas charged accumulator should be pre-charged while empty of hydraulic fluid. Accumulator pressure varies in proportion to the compression of the gas, increasing as pumped in and decreasing as it is expelled.

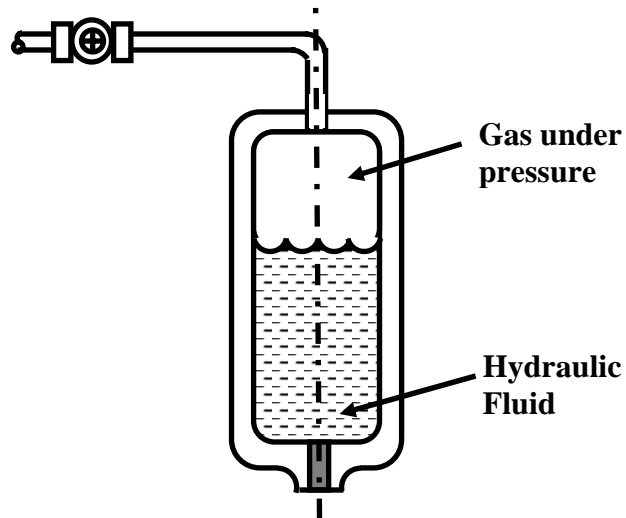


Fig. 26.16 A gas-charged accumulator

## Cylinders

Cylinders are linear actuators, that is, they produce straight-line motion and/or force. Cylinders are classified as single-or double-acting as illustrated in Figures 26.17 and 26.18 with the graphical symbol for each type.

**Single Acting Cylinder:** It has only one fluid chamber and exerts force in only one direction. When mounted vertically, they often retract by the force of gravity on the load. Ram type cylinders are used in elevators, hydraulic jacks and hoists.

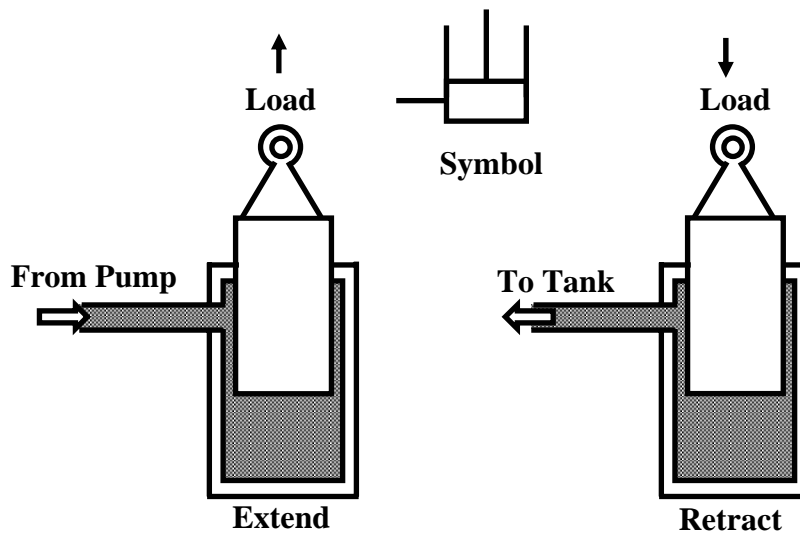
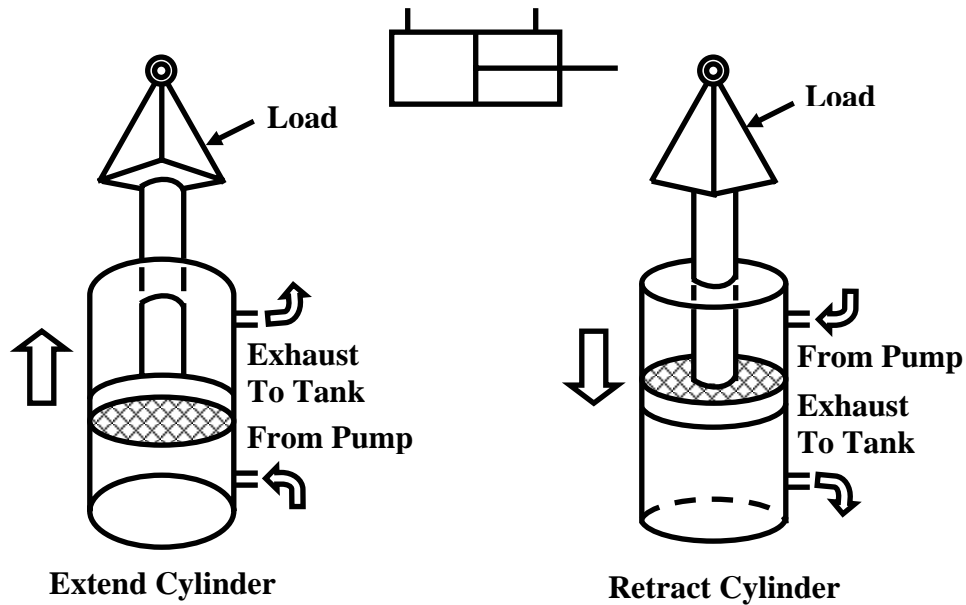


Fig. 26.17 Cross Sectional View of Single-acting Cylinder

**Double-Acting Cylinder:** The double-acting cylinder is operated by hydraulic fluid in both directions and is capable of a power stroke either way. In single rod double-acting cylinder there are unequal areas exposed to pressure during the forward and return movements due to the cross-sectional area of the rod. The extending stroke is slower, but capable of exerting a greater force than when the piston and rod are being retracted.



**Fig. 26.18 Cross Sectional View of Single-acting Cylinder**

Double-rod double-acting cylinders are used where it is advantageous to couple a load to each end, or where equal displacement is needed on each end. With identical areas on either side of the piston, they can provide equal speeds and/or equal forces in either direction. Any double-acting cylinder may be used as a single-acting unit by draining the inactive end to tank.

## Lesson Summary

In this lesson we have dealt with the following topics:

- Basic Principles and Advantages of Hydraulic Control Systems:* It is seen that force can be effectively multiplied by Hydraulic Systems due to Pascal's Law. Further, there are several advantages of such systems with respect to motion control such as the ability for sudden stalling or reversal of motion under high loads.
- Hydraulic Fluids, Lines, Reservoirs, Filters and Seals :* The functions of the fluid in the system is explained along with the accessories that carry it, such as lines and reservoirs. Other accessories such as filters and seals have also been presented briefly.
- Hydraulic Pumps and Accumulators:* Various types of hydraulic pumps, namely, gear pumps, vane pumps and piston pumps have been considered and their principles of operation and construction explained. Two types of accumulators which act as temporary sources of fluids during transient high demand periods have also been presented.
- Hydraulic Motors and Cylinders:* Factories have been classified into four major categories based on the product volumes and product variety. Similarly Automation Systems are also categorized into four types and their appropriateness for the various categories of factories explained.

## Exercises

1. State Pascal's Law
2. Name several advantages of a hydraulic system
3. What makes petroleum oil suitable as a hydraulic fluid?
4. What determines the speed of an actuator?
5. How do you find the horsepower in a hydraulic system?
6. Name three kinds of working lines and tell what each does
7. Name four primary functions of the hydraulic fluid.
8. Name four quality properties of a hydraulic fluid
9. Name three functions of the reservoir?
10. What are the basic characteristics of positive displacement pumps?
11. How much oil does a vane pump rated for 5 gpm at 1200 rpm deliver at 1800 rpm?
12. What tends to limit the pressure capability of a gear pump?
13. What holds the vanes extended in a pump?
14. How can displacement be varied in a axis piston pump?
15. Name two functions of an accumulator.



## Answers, Remarks and Hints to Points to Ponder

### Point to Ponder: 1

*Can you give an analogy of the force amplification in hydraulic system from an electrical system?*

**Ans:** The electrical analog of force is voltage. Both are called *across* variables, while the electrical analog of flow rate is current, both which are called *through* variables. Note that the product of force and flow rate is power as is the product of voltage and current. Thus the analogy of force amplification is voltage amplification as can be achieved by transformers.

*A. Can you imagine what would happen, if the cylinder piston in Fig. 26.1 is stopped forcefully?*

**Ans:** If the cylinder is stopped, there cannot be any flow through the system. However, the prime mover to the pump would attempt to rotate the drive shaft and deliver fluid. Thus the operating pressure of the pump and load on the prime mover would tend to rise. Practically, this operating pressure would be contained by a relief valve which would open a low flow resistance path for the fluid to flow bypassing the cylinder (not shown in the Figure 26.1). Otherwise the load on the prime mover would be so high that it would stall. Thirdly, due to extremely high pressures fluid lines or pump may rupture.

### Point to Ponder: 2

*A. Consider two types of variable speed drives. In the first one an electric motor with a power electronic servo drive is directly coupled to the load through a mechanism. In the second one an electric motor with a constant speed drive drives the pump in a hydraulic system which provides the variable speed drive to the load. Which one of these two is more energy efficient?*

**Ans:** The first one is likely to be more efficient. This is because the overall efficiency of both the systems would include the efficiency of the motor and the efficiency of the final mechanism that connects the load with the actuator, such a gear or a ball screw. However, the hydraulic system would further involve the efficiency of the pump and cylinder as well as that of other speed control equipment such control valves. For the first system this would involve only the efficiency of the power electronic converter, which is likely to be higher. Thus the lesson is that hydraulic systems are not used for their energy efficiency, but rather for their small size, high power handling capacity and ease of control under high loads.

*B. Why is stalling an electric motor is likely to cause damage? What can be done to prevent it?*

**Ans:** Stalling an electric motor reduces the back emf in the motor to zero. Therefore very high current flows in the motor causing thermal damage. To prevent such damages, current control techniques are applied in all motor drives which sense the current and reduce the motor terminal voltage whenever the current exceeds its limit. In other cases, where such rise

of current is considered to be due to fault, over current trip mechanisms are employed that switch off supply to the motor.

### Point to Ponder: 3

A. *What would happen if orifices of valves are blocked by, say, a metal chip in the hydraulic oil?*

**Ans:** Immediately the pressure difference across the hydraulic cylinder, which moves the cylinder against load, would be neutralized. Thus the load motion would stop. At the same time the pressure difference across the jammed orifice would rise. Sometime this resulting force can dislodge or shear the chip that causes the jam.

### Point to Ponder: 4

A. *Why do gear pumps usually operate at comparatively low pressures?*

**Ans:** The load imposed by the drive shaft depends on the operating pressure. By construction, this load is unbalanced in the gear pump and therefore, considerable side loading on the drive shaft exists. To limit this loading, operating pressures have to be kept low. Note that due to the symmetry of the inlet and out let ports such forces do not arise in balanced vane pumps.

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