

**FLUID POWER
TUTORIAL 4
HYDRAULIC and PNEUMATIC MOTORS**

This tutorial is set at QCF level 4 and was originally written to cover the HNC module Unit 24. It covers the principles and applications of *hydraulic and pneumatic* power systems. It introduces you to the concepts of fluid power and describes the principles, applications and types of hydraulic and pneumatic motors.

On completion of this tutorial you should be able to do the following.

- Explain the working principles of a range of hydraulic motors.
- Describe the construction of motors.
- Explain the principles of a range of semi rotary actuators
- Define the nominal displacement.
- Explain the relationship between low rate and shaft speed.
- Define fluid power and shaft power.
- Define and explain volumetric and overall efficiency.
- Solve problems involving power, torque and flow rate.
- Describe the seals and drainage used in motors.
- Recognise and draw the symbols for motors and rotary actuators.

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1. Introduction

Motors are **Rotary Actuators** and converts fluid power into rotational power of a shaft. Hydraulics use incompressible liquids and can run at high pressure so they produce a large shaft power and firm movement so the rotation is accurately linked to the flow and quantity of fluid passing through. Pneumatics use air which is very compressible and can only be used at safe low pressure. The movement is not precisely linked to the flow rate and quantity of air passing through.

2. General Theory

The purpose of a rotary motor is to convert fluid power into shaft power by forcing the shaft to rotate. Pressure is converted into torque and flow rate is converted into speed. In other words, the faster you push the fluid through the motor, the faster it goes and the harder it is to turn the shaft, the higher the pressure needed to make it go round.

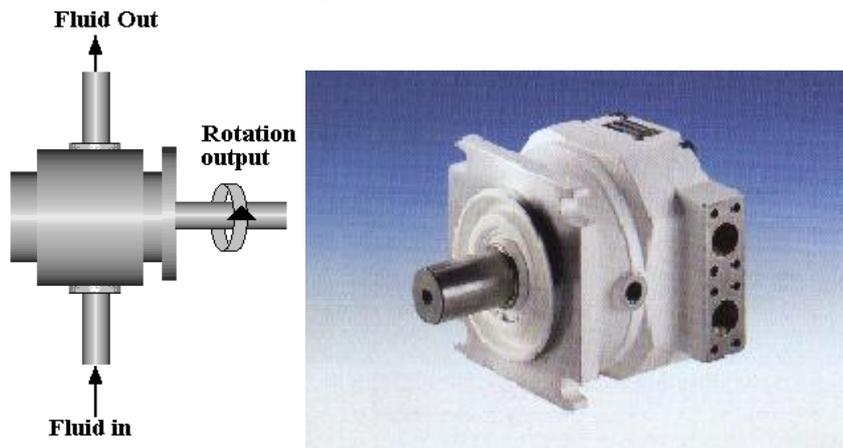


Figure 1

3. Symbols

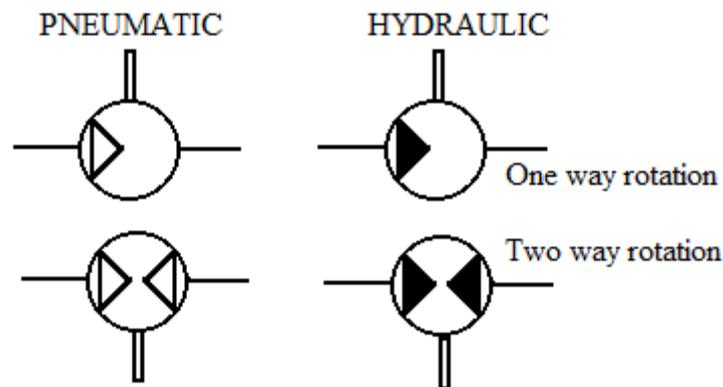


Figure 2

The basic symbol is a circle with a triangular arrow pointing inwards indicating the direction of flow.

Pneumatic symbols have white arrow and hydraulic symbols have black arrows.

4. Detailed Theory

Air is a very compressible substance and the theory for air motors is more complicated than for hydraulic motors. The volume of hydraulic fluids is considered constant in the following theory. In other words, the volume is unaffected by the pressure. The following applies to hydraulic motors.

4.1 Power and Efficiency

Fluid Power is defined as $F. P. = Q \Delta p$

Q is the flow rate in m^3/s and Δp is the difference between the inlet and outlet pressure in N/m^2 .

The output power is the shaft power is given by the formula $S. P. = 2\pi NT = \omega T$

N is the speed in rev/s. T is the shaft torque in Nm and ω is the shaft speed in radian/s. The output power is reduced because of friction and internal slippage of fluid. This gives the overall efficiency for the motor and this is defined as follows.

$$\text{Overall Efficiency } \eta_o = \frac{\text{Output Power}}{\text{Input Power}} = \frac{S. P.}{F. P.}$$

It must be remembered that in the case of gas as the working fluid, the volume depends upon the pressure.

4.2 Speed - Flow Relationship

The basic relationship between flow rate and speed is

$$\text{Flow Rate} = Q = K_q \times \text{Speed}$$

K_q is the nominal displacement of the motor usually expressed in units of cm^3/rev .

4.3 Torque - Pressure Relationship

In fluid power, shaft speed is normally given in rev/min or rev/s. The formula for shaft power is given by the well known formula $SP = 2\pi NT$. If the motor is 100% efficient, the shaft power is equal to the fluid power so equating we get the following.

$$2\pi NT = Q \Delta p$$

Rearrange to make T the subject.

$$T = \frac{Q}{N} \times \frac{\Delta p}{2\pi} = K_q \frac{\Delta p}{2\pi}$$

Δp is the difference in pressure between the inlet and outlet of the motor. K_q is the nominal displacement in m^3/s . In control theory it is more usual to use radians/s for shaft speed in which case:

$$\omega T = Q \Delta p$$

Rearrange to make T the subject.

$$T = \frac{Q}{\omega} \times \Delta p = K_q \Delta p$$

K_q is the nominal displacement in $m^3/radian$. The operating characteristics of an ideal motor may be summed up by the two equations:

$$\text{Flow rate} = K_q N$$

$$T = K_q \Delta p$$

4.4 Volumetric Efficiency

It is possible for hydraulic fluid to slip forward from the high pressure port to the low pressure port through the clearance gaps around the working elements without doing anything to rotate the shaft. This is called internal slippage and it results in a flow rate larger than the theoretical.

The volumetric efficiency of the motor is defined as:

$$\eta_v = \frac{\text{Ideal Flow Rate}}{\text{Actual Flow Rate}}$$

5. Rotary Actuators

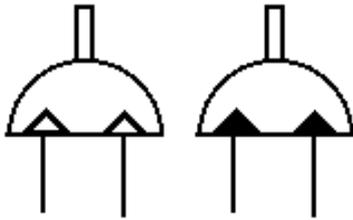


Figure 3

There is a special motor called a rotary actuator that is designed for slow rotation of less than one revolution but with a large torque. Diagrams of the various designs are shown later. The symbols are shown. These actuators are commonly used on robotic devices. Pneumatic actuators are used for simple pick and place operations and for opening and closing pipeline valves. Hydraulic actuators are typically used to swing the boom on a mobile excavator from side to side.

WORKED EXAMPLE No. 1

The pressure difference over a hydraulic motor is 80 bar and it runs at 400 rev/min. The nominal displacement is 5 cm³/rev. The overall efficiency is 85% and the volumetric efficiency is 90%. Calculate the following.

- i. The ideal flow rate.
- ii. The actual flow rate.
- iii. The fluid power.
- iv. The shaft power.
- v. The shaft torque.

SOLUTION

$$N = \frac{400}{60} \text{ rev/s} \quad K_q = 5 \times 10^{-6} \text{ m}^3/\text{rev}$$

Ideal Flow rate

$$Q_1 = K_q N = 5 \times 10^{-6} \times \frac{400}{60} = 33.33 \times 10^{-6} \text{ m}^3/\text{s}$$

Actual Flow Rate

$$Q_2 = \frac{Q_1}{\eta_v} = \frac{33.33 \times 10^{-6}}{0.9} = 37.04 \times 10^{-6} \text{ m}^3/\text{s}$$

$$\text{Fluid Power} = Q_2 \Delta p = 37.04 \times 10^{-6} \times 80 \times 10^5 = 296.3 \text{ Watts}$$

$$\text{Shaft Power} = \text{Fluid Power} \times \eta_o = 296.3 \times 0.85 = 251.85 \text{ W}$$

$$\text{Torque} = \frac{\text{S.P.}}{2\pi N} = \frac{251.85 \times 60}{2\pi \times 400} = 6.013 \text{ N m}$$

SELF ASSESSMENT EXERCISE No. 1

1. Calculate the output power of a hydraulic motor which has a flow rate of $5 \text{ dm}^3/\text{s}$ and a pressure difference of 80 bar. The overall efficiency is 75%.
(Answer 30 kW)
2. A hydraulic motor must produce an output power of 500 Watts from an oil supply at 50 barg which exhausts at 0 barg. The efficiency is 80%. Calculate the flow rate of oil required.
(Answer $125 \text{ cm}^3/\text{s}$)
3. A hydraulic motor has a flow constant of $1.2 \text{ cm}^3/\text{rad}$.
Calculate the quantity of oil needed to turn the shaft $\frac{1}{2}$ of a revolution. (3.77 cm^3)
Calculate the speed of the shaft in rev/min when oil is supplied at $20 \text{ cm}^3/\text{s}$. (159.1 rev/min)
4. The pressure difference over a hydraulic motor is 120 bar and it runs at 200 rev/min. The nominal displacement is $8 \text{ cm}^3/\text{rev}$. The overall efficiency is 80% and the volumetric efficiency is 85%. Calculate the following:
 - i. The ideal flow rate. ($26.67 \text{ cm}^3/\text{s}$)
 - ii. The actual flow rate. ($31.37 \text{ cm}^3/\text{s}$)
 - iii. The fluid power. (376.5 W)
 - iv. The shaft power. (301.2 W)
 - v. The shaft torque. (14.38 Nm)

6. Drainage and Seals

The hydraulic fluid under pressure may be forced down the shafts and would leak out from the front of the motor. In the first instance a rotary shaft seal is used to prevent leakage. However, sealing it in would result in pressurisation and the shaft seal would be blown out. To prevent this, the shaft spaces are drained to low pressure. In the case of motors with one direction of rotation, the drainage passage may be internally connected to the low pressure side. In the case of motors that rotate either way, there is no permanent low pressure side so a separate drain connection is found on the motor that must be piped back to tank.

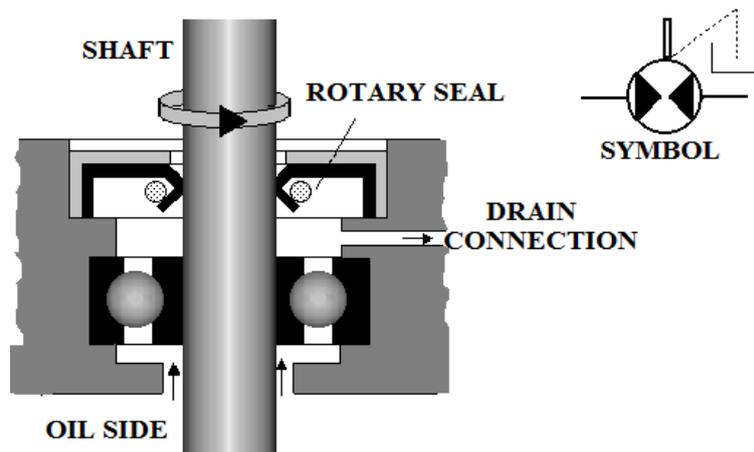


Figure 4

7. Motor Types

Hydraulic motors are used to convert hydraulic energy into mechanical energy. They are classified according to the type of internal elements that are directly actuated by the flow of fluid. Hydraulic motors are very similar in construction to hydraulic pumps. In fact many pumps may be used as motors without any modification. Like hydraulic pumps most hydraulic motors are classified as gear, vane, piston or deri sine type.

Rotary motors are generally rated in terms of *Displacement* or *Torque*. They may be fixed displacement motors or variable displacement motors.

Fixed displacement motors normally have constant torque, the speed being varied by altering the flow to the motor.

Variable displacement motors have variable torque and speed. With the input flow and operating pressure remaining constant, varying the displacement can vary the ratio between torque and speed to suit the load requirements.

7.1. Gear Motors

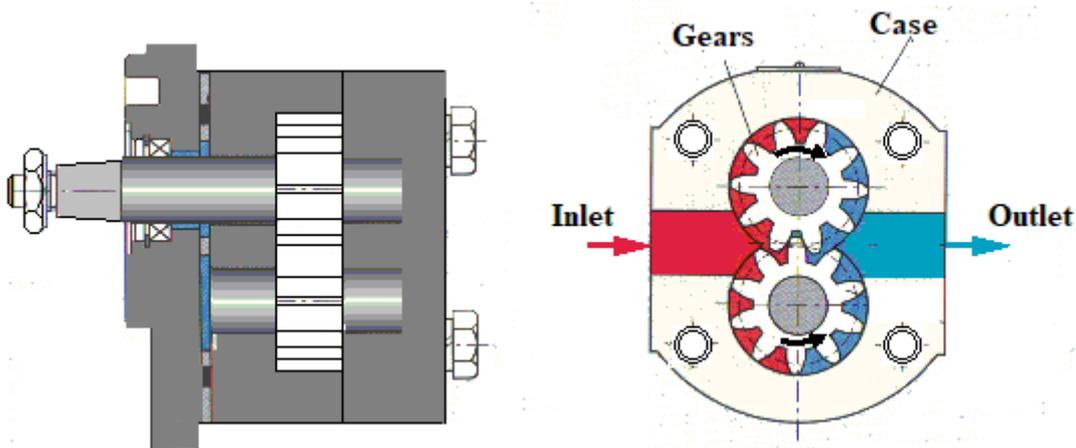


Figure 5

Fluid is pumped into the motor inlet (P) where it has two courses to follow around the outside in the space between the teeth to the exit at (T).

Like the gear pump the gears in a gear motor are closely fitted in the housing end and, for this reason, flow of fluid through the motor from the inlet to the outlet can occur only when the gears rotate. In the gear motor fluid drives both gears but only one gear is coupled to the output shaft to supply rotary mechanical motion.

Gear motors are of the fixed displacement type - this means that the output shaft speed varied only when the flow rate through the motor changes. These motors are generally two directional, the motor being reversed by direction fluid through the motor in the opposite direction.

7.2. Vane Motors

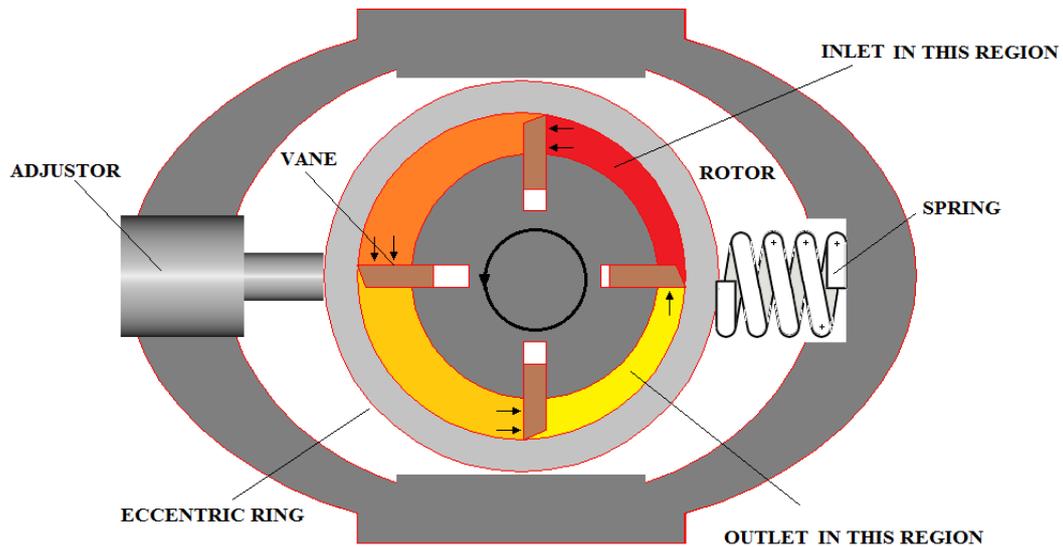


Figure 6

Flow from the pump enters the inlet, forces the rotor and vanes to rotate and passes out through the outlet. Rotation of the rotor causes the output shaft to rotate.

Since no centrifugal force exists until the rotor begins to rotate some method must be provided to initially hold the vanes against the casing contour. Springs are often used for this purpose. Springs are usually unnecessary in vane pumps because the drive shaft in these units initially supplies the centrifugal force to assure vane-to-casing contact.

Vane motors rotate in either direction but they do so only when the flow rate through the motor is reversed.

7.3 Semi - Rotary Piston Type Actuators

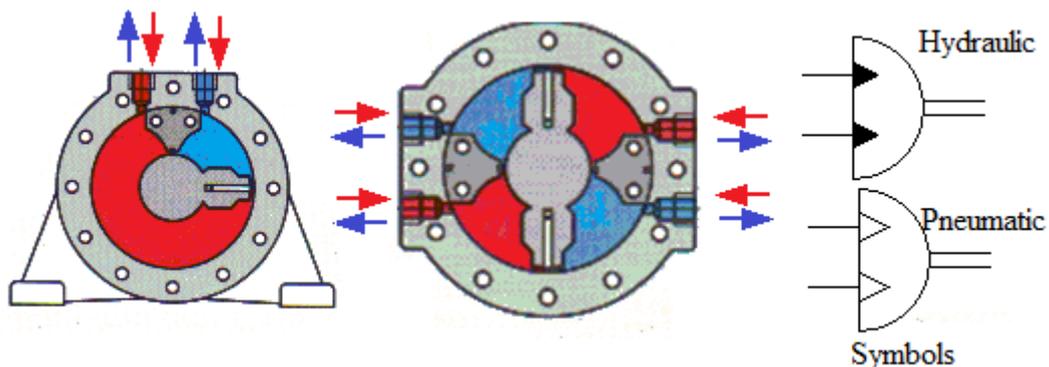
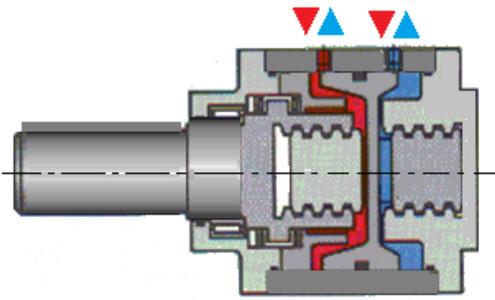


Figure 7

Torque actuators are used to give semi-rotary actuation. They produce a very large torque at low speeds. The Type on the left produces rotation of about 300° . The oil enters between the fixed and moving vanes. The pressure makes the moving vane rotate the shaft. The type on the right has two sets of vanes, which doubles the torque but reduces rotation to less than 180° .

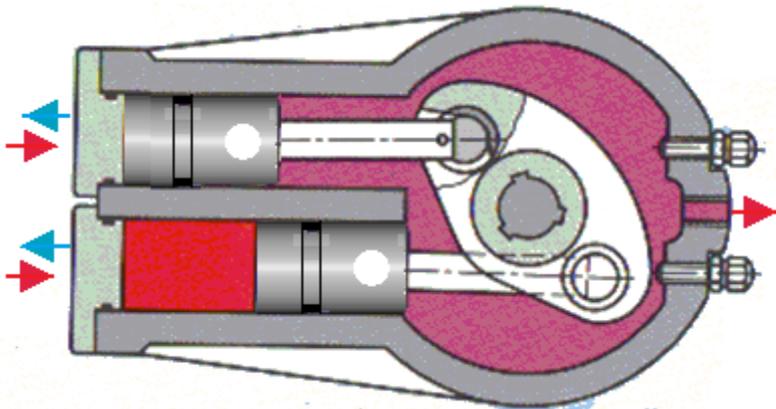
7.4 Rotary Piston Type



The oil forces the piston to move in a similar way to a hydraulic ram. The piston has studs on it with 45° splines that mate with fixed splines on one side. This makes the piston and shaft rotate as it moves.

Figure 8

7.5 Parallel Piston Type



The two pistons move parallel to each other. One piston rotates the shaft one way and the other piston rotates it the other. The rotation is about 100°. This design is commonly used for the pneumatic operation of pipe line valves.

Figure 9

7.6 Rack and Pinion Type

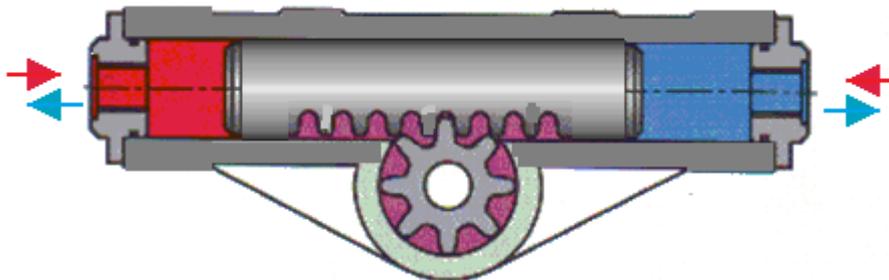


Figure 10

The construction is basically two single acting cylinders with a single connecting rod in the form of a rack. The rack engages with a pinion gear that is part of the output shaft. The pistons are moved either right to left or left to right producing clockwise or counter-clockwise rotation. Adjusting the piston stroke can set the degree of rotation. The design is typical for a pneumatic actuator.

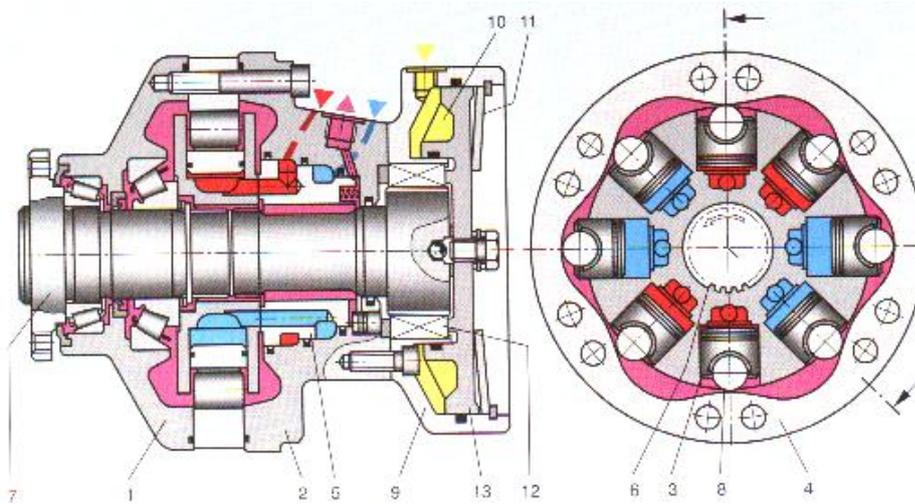
7.7 Radial Piston Motors



There are many designs for radial piston motors. They are typically used for applications requiring a large torque and slow speed such as with winches. The design is common for hydraulic and pneumatic motors. The diagram shows a design with radial cylinders each in a separate block. The pistons are connected to the shaft by a crank or some other mechanism. Suitable valve designs allow the oil into the cylinders and force the pistons to reciprocate and turn the shaft. These produce high power and torque.

Figure 11

This design uses a central piston block. The oil pressure forces the pistons out against a cam. The



force acting on the side of the cam produces rotation of the piston block and shaft. The cam has several lobes and so the pistons make several strokes in one revolution. They are typically used to rotate large drums.

Figure 12

7.8 Axial Piston Motors



These motors can be either fixed or variable displacement and are usually two directional. Typical designs are the cam type (fixed) or swash plate (fixed or variable).

Figure 13

7.9 Cam Type

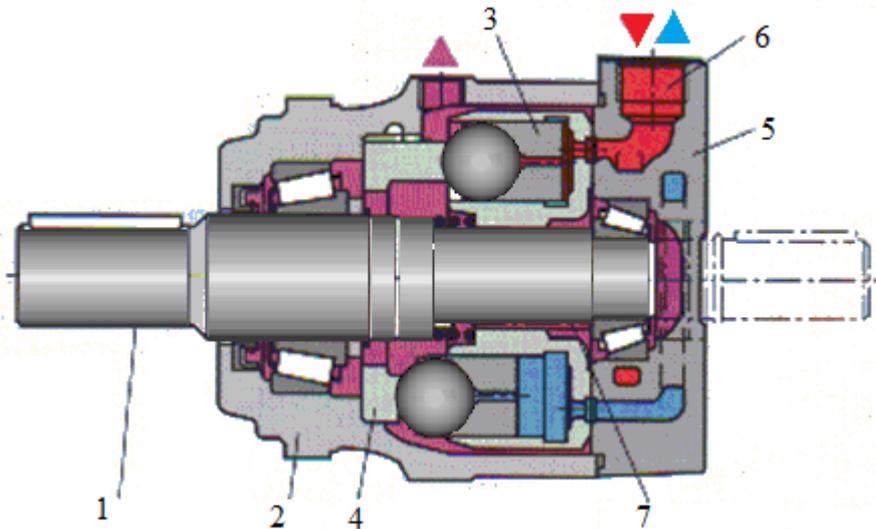


Figure 14

Flow enters the motor at the inlet (6) and is directed to piston and ball (3), which pushes forward against a ring cam (4). The ball engages on the slope of the cam and produces rotation. The cam is fixed but the cylinder block is splined to the shaft (7). The cylinder block and shaft rotates. When the block rotates the cam pushes the piston back. At this point the piston connects to the low pressure exhaust port (Blue). By using cams with several lobes and several inlet and outlet ports in the rear block (7) the piston is made to do several strokes during each revolution. They are typically used to rotate the drums on dustbin lorries (garbage trucks).

7.10 Swash Plate Types

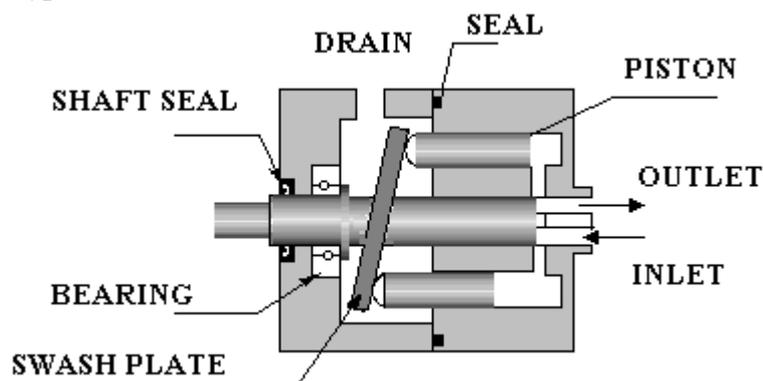


Figure 15

These are similar to the cam in principle but the cam ring is replaced by a swash plate. Because of the angle of the plate, the piston pushing against it produces rotation.

In some designs the swash plate is fixed and the cylinder block rotates. In other designs the piston block is fixed and the cam plate rotates. The speed of the motor at a given flow rate may be changes by altering the angle of the swash plate. Sometimes the piston block is cranked to make a fixed angle with the swash plate.

The motors can run at high speed and the speed can be varied by changing the angle of the swash plate. Large powerful versions are used in heavy vehicle transmission systems and the gear ratio to te wheels is varied by varying the swash plate angle.

7.11 Deri -Sine Motors

These motors are of the fixed displacement type and are suitable for two directional rotations.

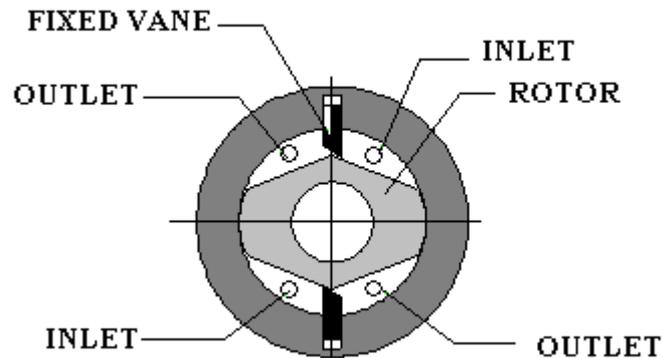


Figure 16

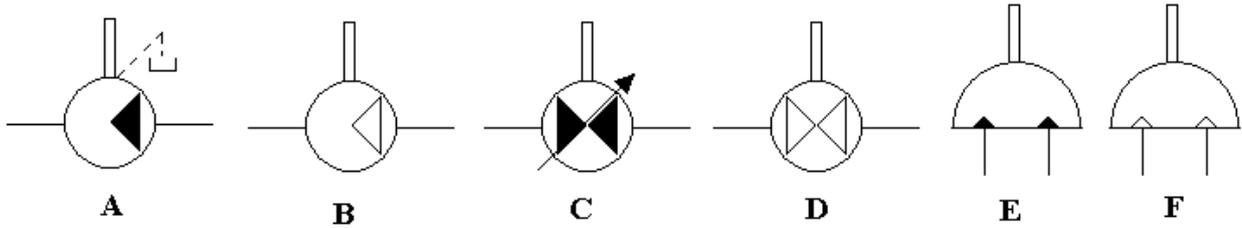
Fluid enters the motor and is directed to two ports that allow the fluid to enter the rotor chamber. Pressure acting on the rotors forces them to rotate. The vanes follow the cam shaped contours of the rotor and prevent fluid passing directly to the outlet ports.

Because of the shape of the rotors the space at the inlet increases as the fluid enters which causes the rotor to turn, then as the rotor approaches the outlet the space begins to decrease and the fluid is discharged from the outlet. Reversing the direction of flow through the motor reverses the motor.

These motors are very quiet and smooth running. They are compact and easily fit inside robotic devices.

SELF ASSESSMENT EXERCISE No.2

1. Describe accurately and fully the type of motor represented by each symbol A to F.



A. _____

B. _____

C. _____

D. _____

E. _____

F. _____

This is a good point to do the Worksheet

WORKSHEET

HYDRAULIC PUMPS AND MOTORS

PART 1 - PUMP CHARACTERISTICS

The simple circuit shown is to enable a pump to be tested by measuring the flow rate and pressure.

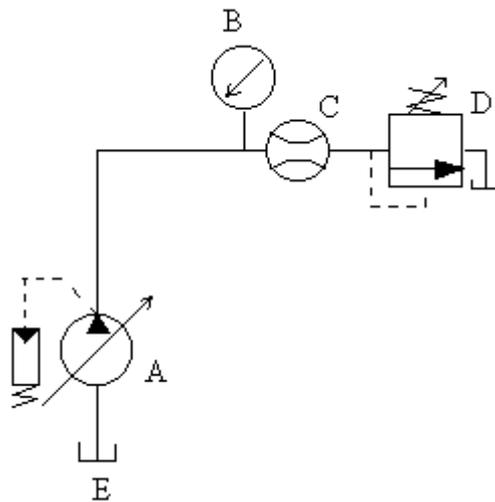
A flow meter is connected in series with the pump and the flow from the pump will be controlled by a pressure relief valve as shown.

Identify by name the item represented by each symbol.

A _____ B. _____

C _____ D. _____

E _____



The results of the test are given below. Plot a graph with Flow vertically and pressure horizontally.

Flow l/min	6	5	4	3	2	1	0
p bar	10	40	50	50	50	50	50

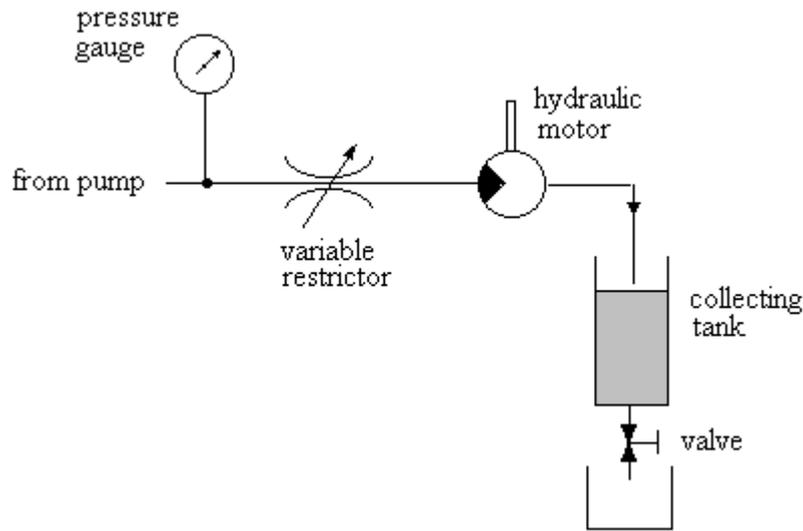
Explain why the flow suddenly falls away at a certain pressure.

The speed of the pump is 1420 rev/min. Calculate the nominal displacement based on the flow rate at low pressure.

PART 2 - HYDRAULIC MOTORS

SPEED - FLOW RATE CHARACTERISTIC

Set up the following circuit to measure the flow of oil through a motor.



- *Control the speed of the motor with the variable restrictor.*
- *For each speed, collect a known volume of oil and time the collection with a stop watch.*
- *Calculate the flow rate in cm³/min for each result.*
- *Calculate the nominal displacement for each result.*
- *Plot the results on a sheet of graph paper with flow rate vertically and speed horizontally.*

Speed rev/min	100	200	300	400	500	600	700	800	900	1000	1200
Volume litres											
Volume cm ³											
Time taken seconds											
Flow cm ³ /min											
Nominal displacement cm ³ /rev											

On a separate sheet of paper, explain the following.

1. *How did you calculate the nominal displacement? Show the formula and a sample calculation.*
2. *What is the name of the instrument used to measure the speed?*
3. *Explain the basic principle of the instrument?*
4. *Your graph should be a straight line going through the origin. If this is the case, how would you describe the relationship between flow rate and speed?*
5. *If the motor was forced to work and needed high pressure to force it to go round, the flow rate would not be as high as that measured. Explain why.*