Chapter 4

Hydraulic Pumps

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1. Introduction

The requirements of a pump may be summarised in one sentence:
Hydraulic pumps should convert mechanical energy (torque, speed) into hydraulic energy (flow, pressure).

However, in practice the requirements are much more diverse.

When choosing a pump, the following points must be taken into account:

- Operating medium
- Required range of pressure
- Expected range of speeds
- Minimum and maximum operating temperature
- Maximum and minimum viscosities
- Installation (piping, etc.)
- Type of drive (coupling, etc.)
- Expected life-time
- Maximum level of noise
- Ease of servicing
- Maximum cost

This list could be continued. The variety of requirements, however, does show that every pump cannot fulfil all the criteria to an optimum degree. Hence, a whole range of different design principles exist. One thing that all the types have in common, is that the pumps operate according to the displacement principle. This involves the existence of mechanically sealed chambers in the pumps. In these chambers, fluid is transported from the inlet of the pump (suction port) to the outlet (pressure port). As there is no direct connection between the two ports in the pump, these pumps are very suitable for operating at high system pressures. Hence they are ideal for hydraulics.

2. Basic design

The main types of hydraulic pumps, which operate to the displacement principle are outlined below:

2.1 External gear pump

Volume is created between the gears and housing.

$$V = m \cdot z \cdot b \cdot h \cdot \pi \qquad (1)$$

m = modulus

z = number of gears

b = width of gears

h = height of gears

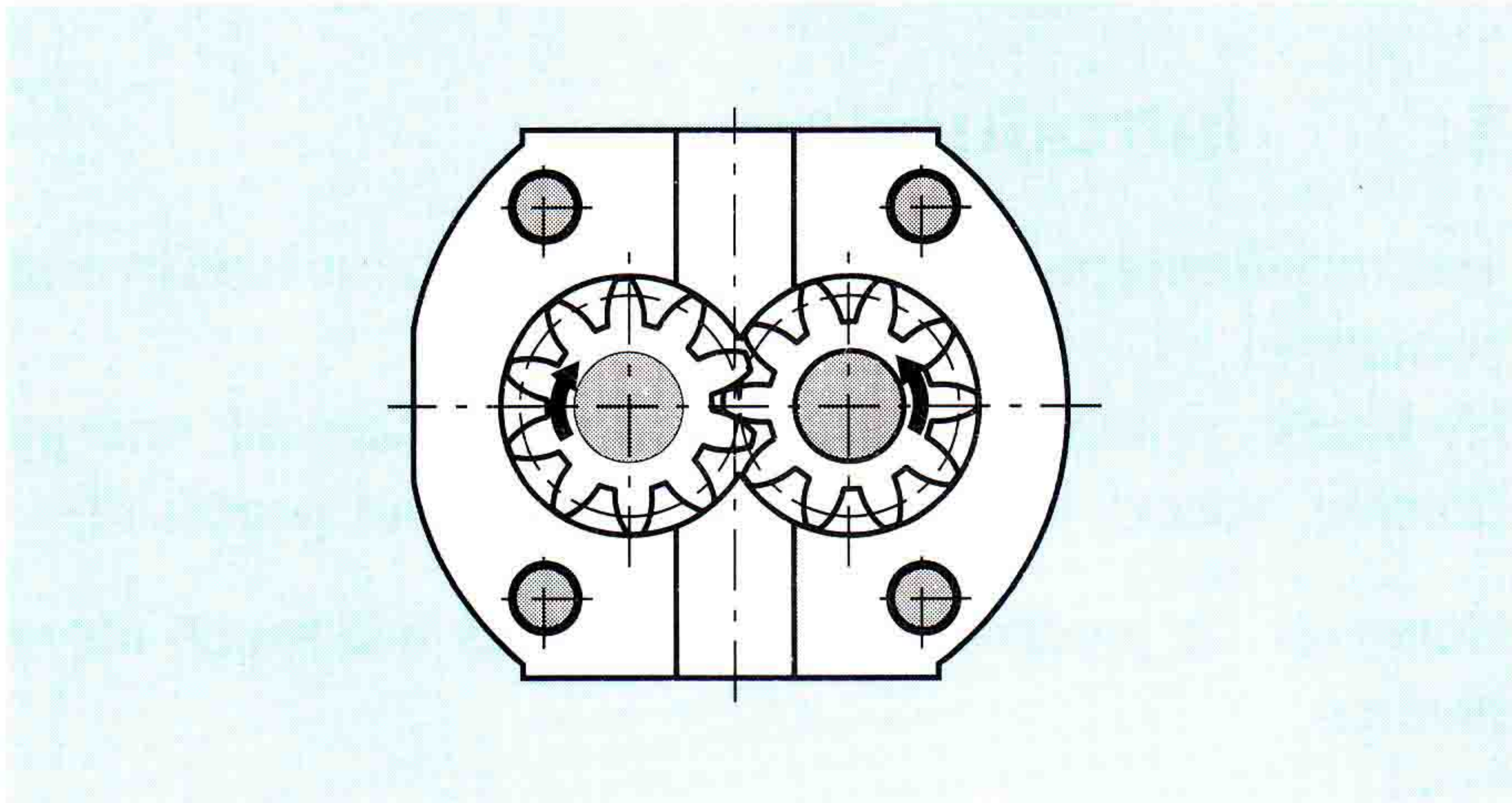


Fig. 1

2.2 Internal gear pump

Volume is created between the gears, housing and spacing/sealing element.

$$V = m \cdot z \cdot b \cdot h \cdot \pi \qquad (2)$$

m = modulus

z = number of internal gears

b = width of gears

h = height of gears

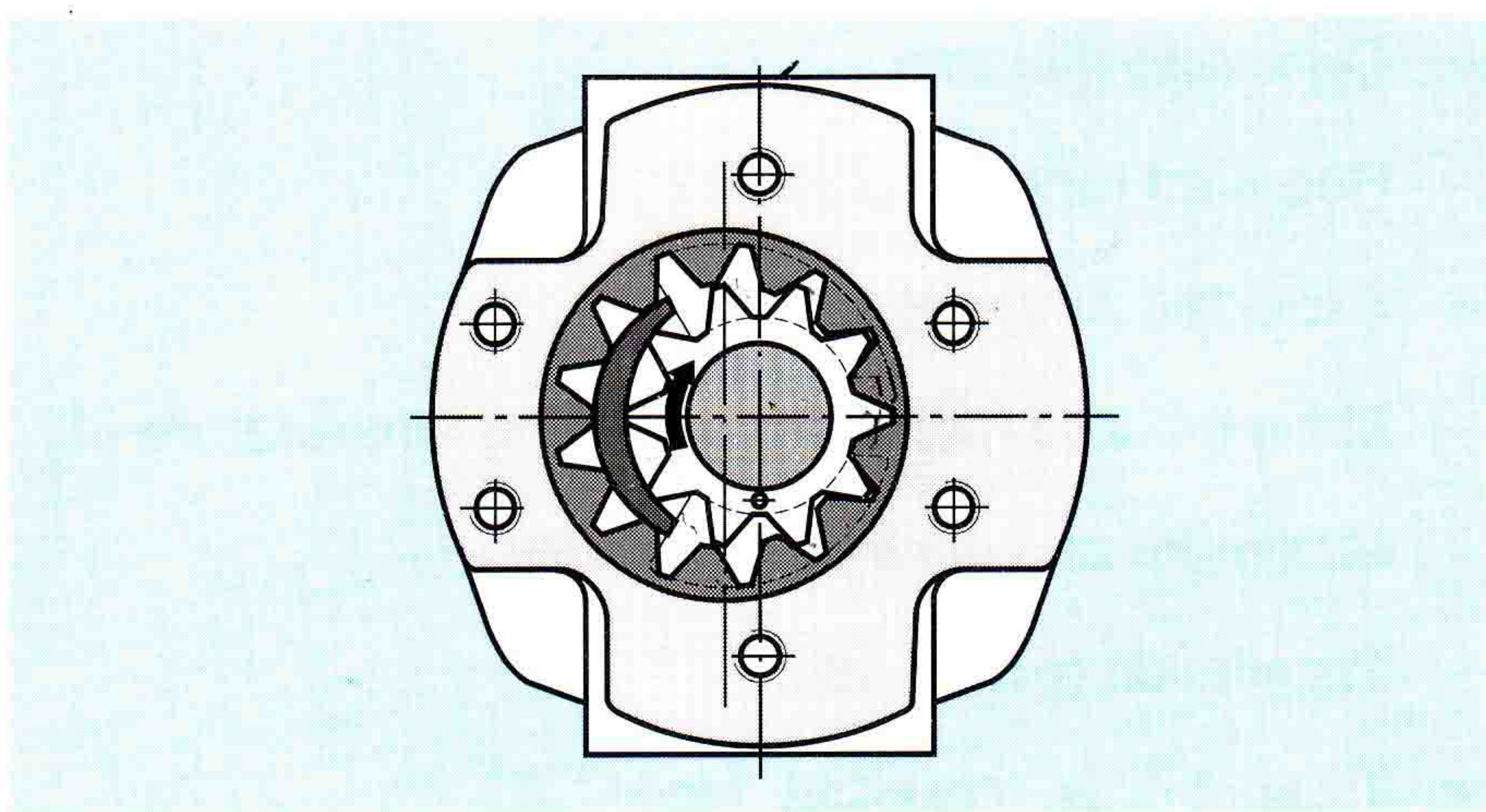


Fig. 2

2.3 Ring gear pump

The rotor has one gear less than on the internally geared stator. Planetary movement of the rotor.

$$V = z \cdot (A_{max} - A_{min}) \cdot b \qquad (3)$$

z = number of rotor gears

b = width of gears

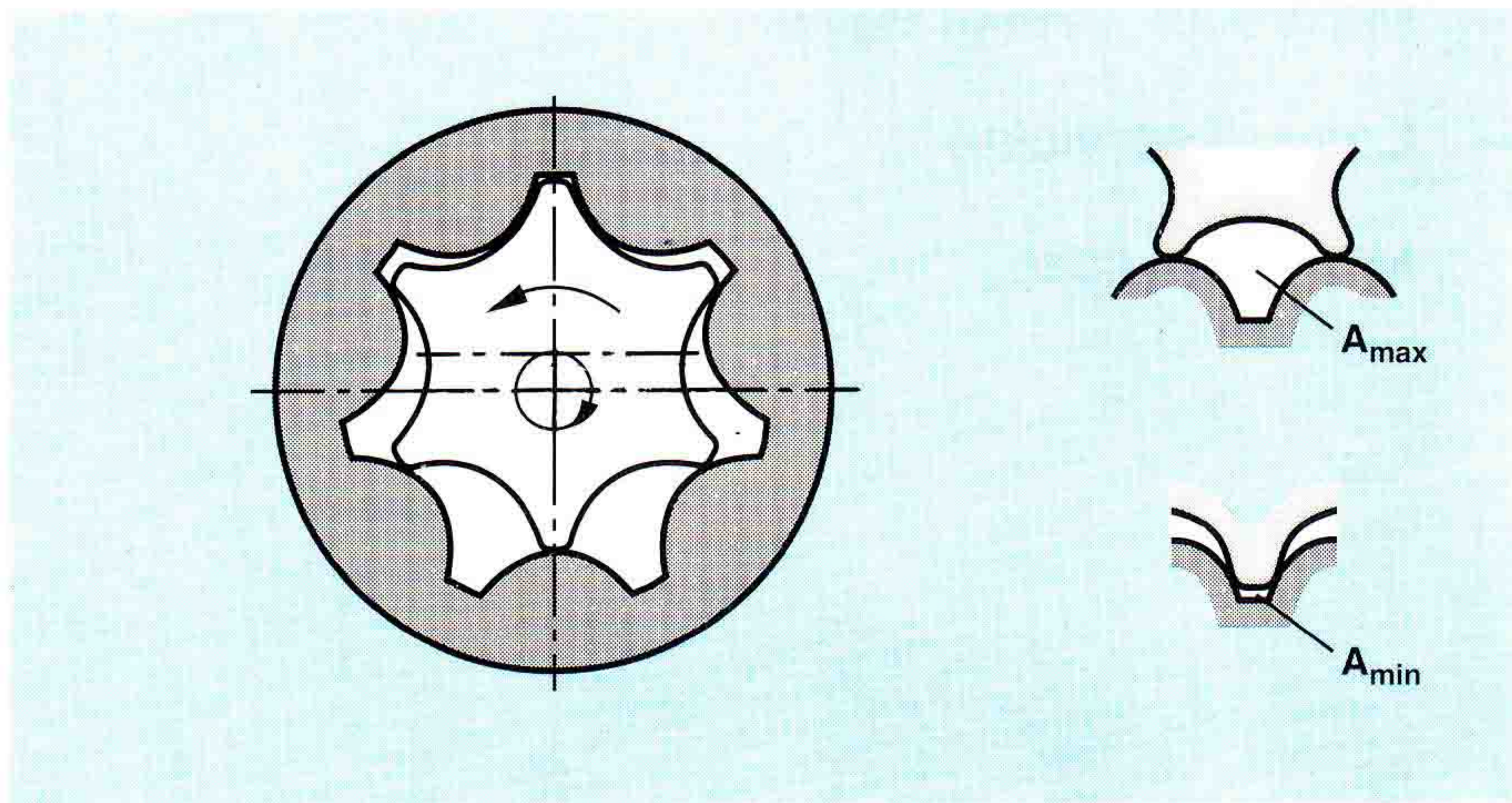


Fig. 3

2.4 Screw pump

The displacement chamber is formed between threads and housing.

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

with : $\cos \alpha = \dfrac{D + d}{2D}$

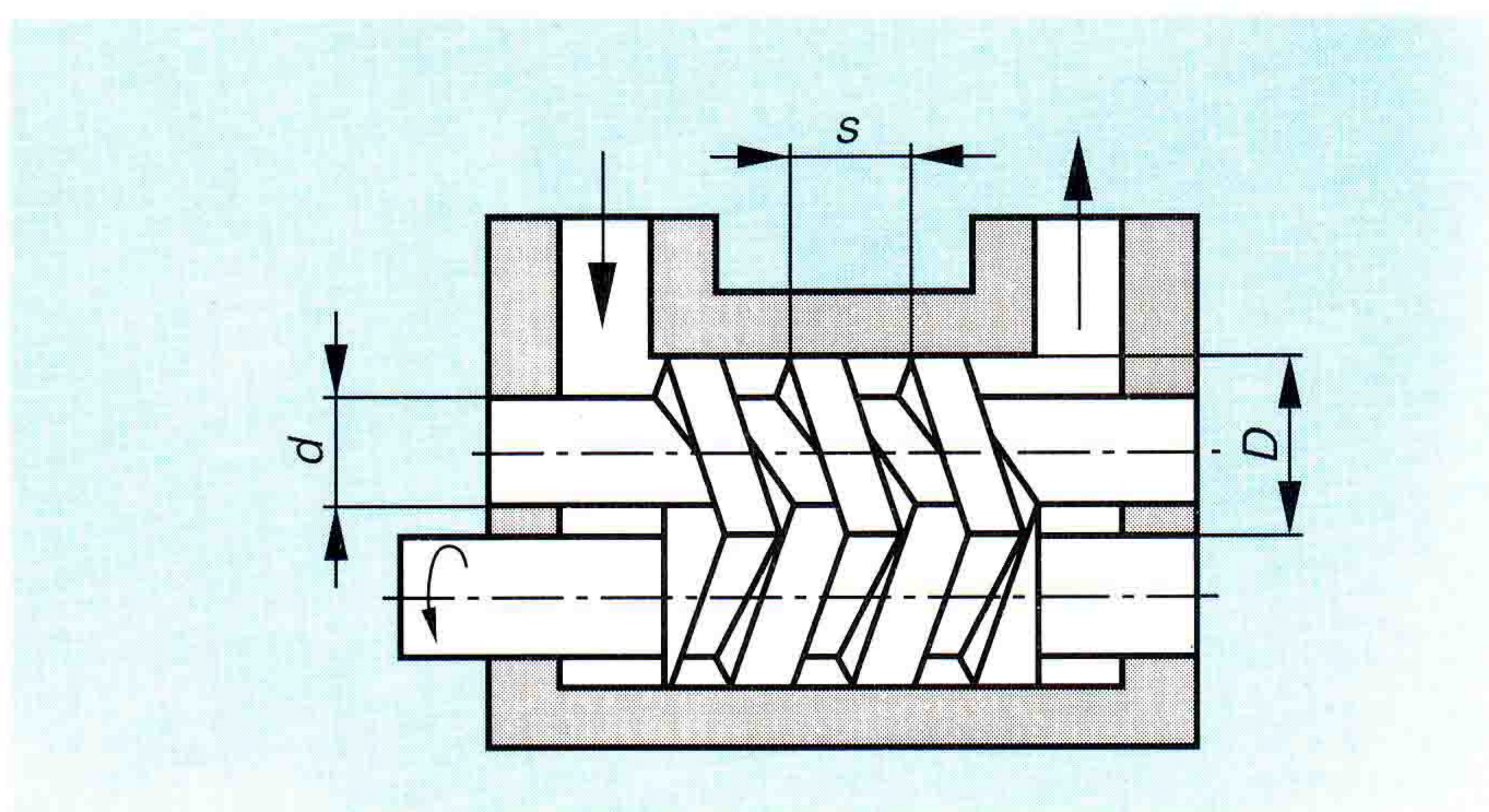


Fig. 4

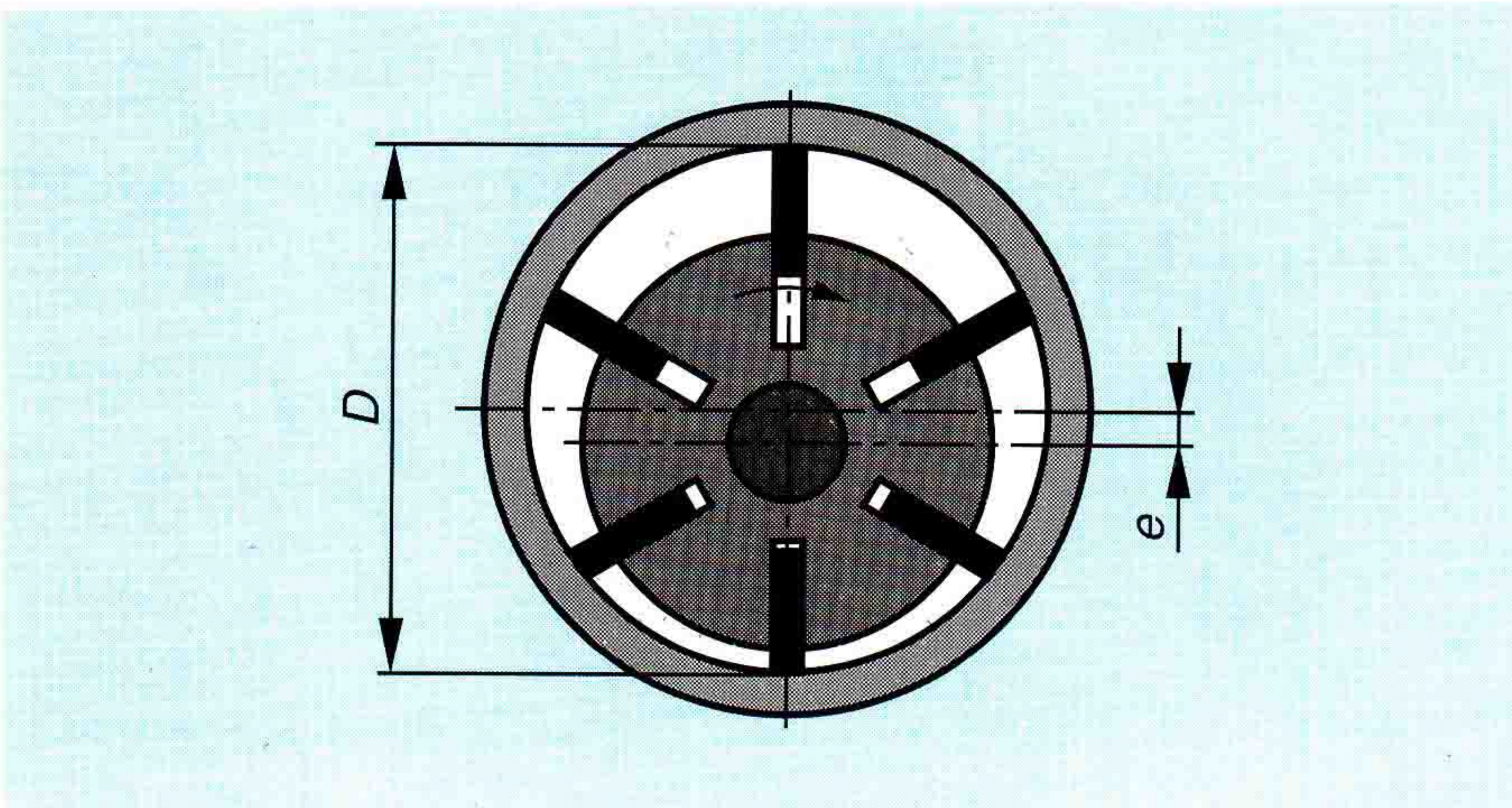


Fig. 5

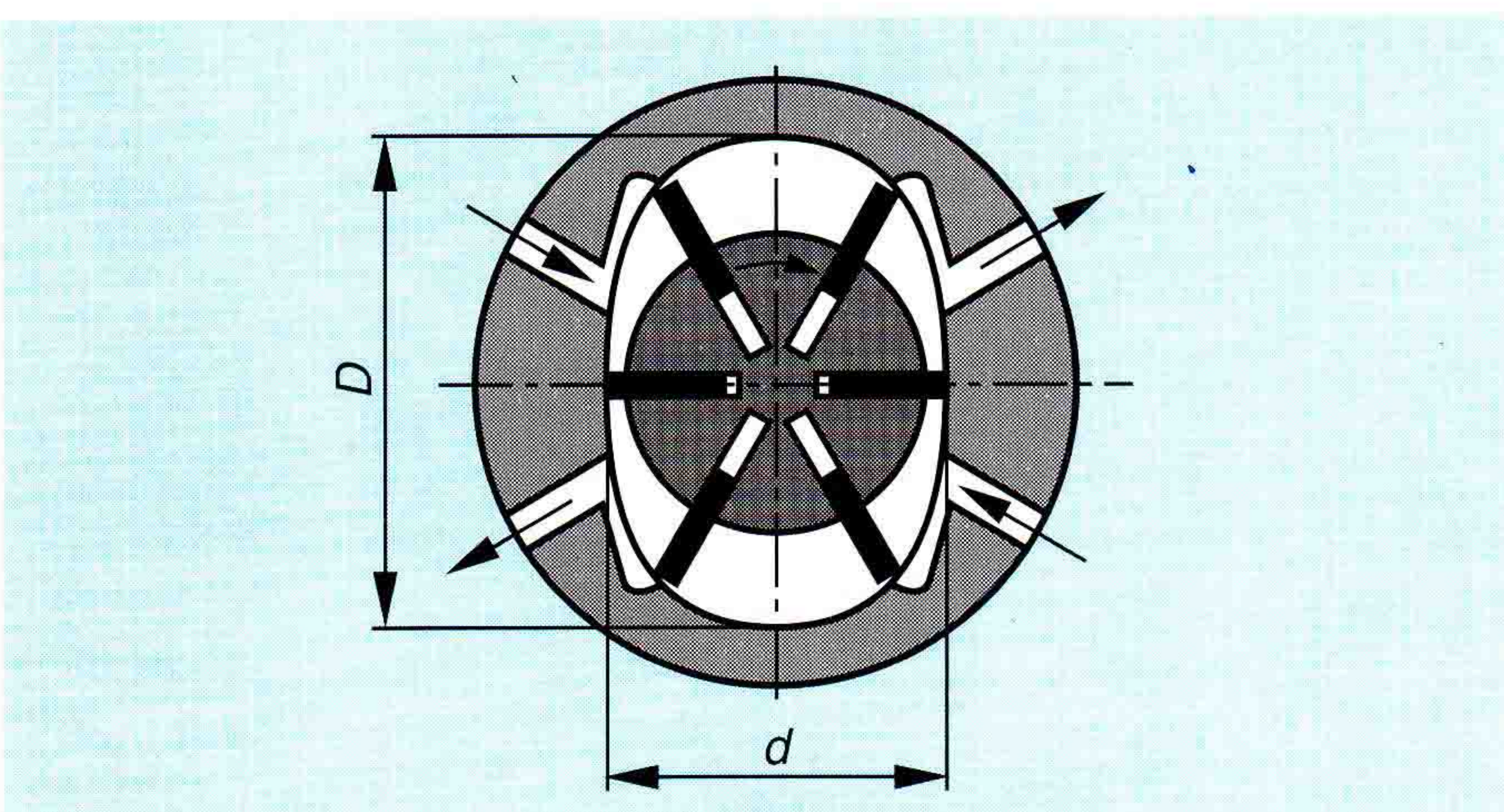


Fig. 6

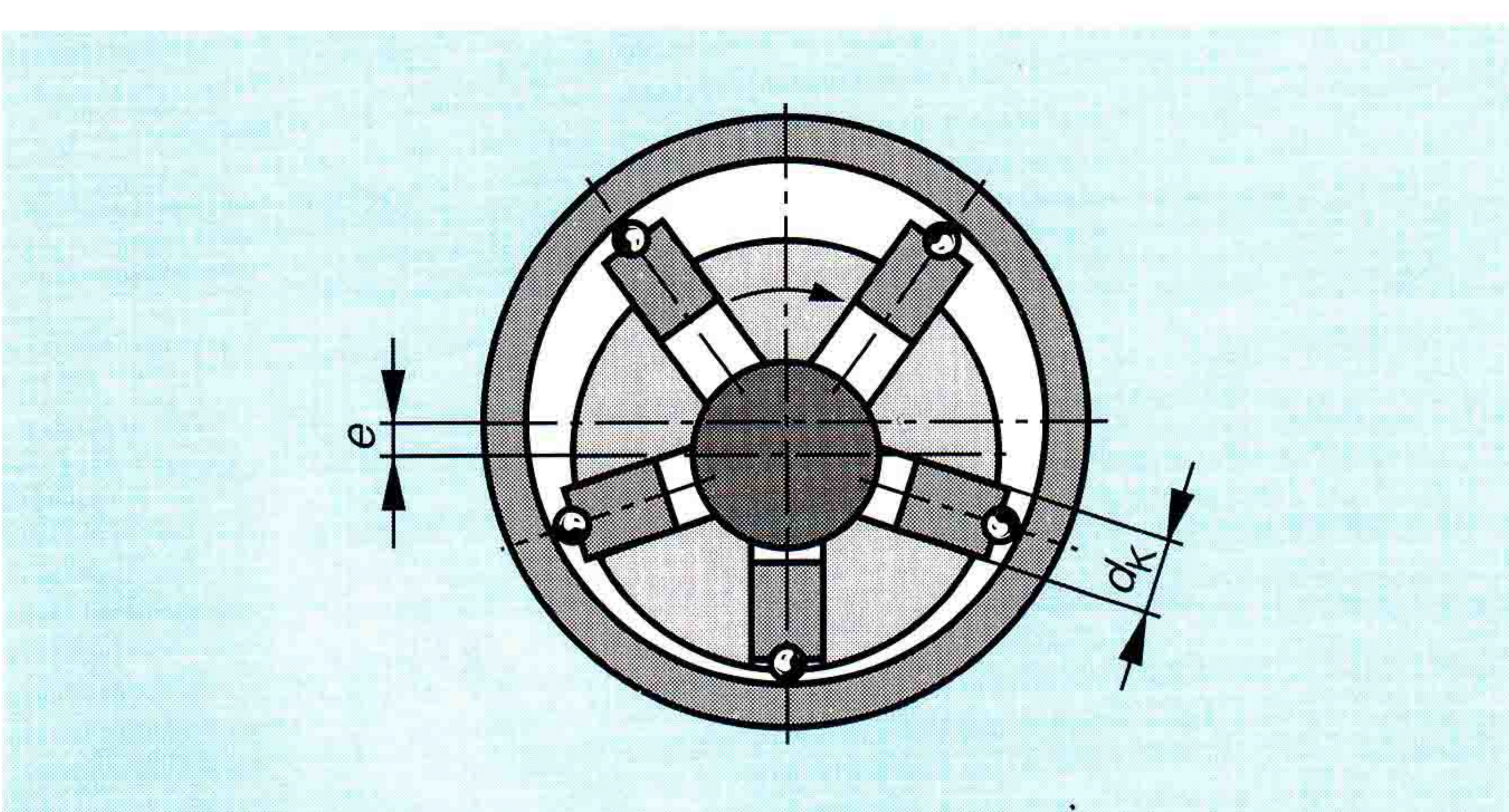


Fig. 7

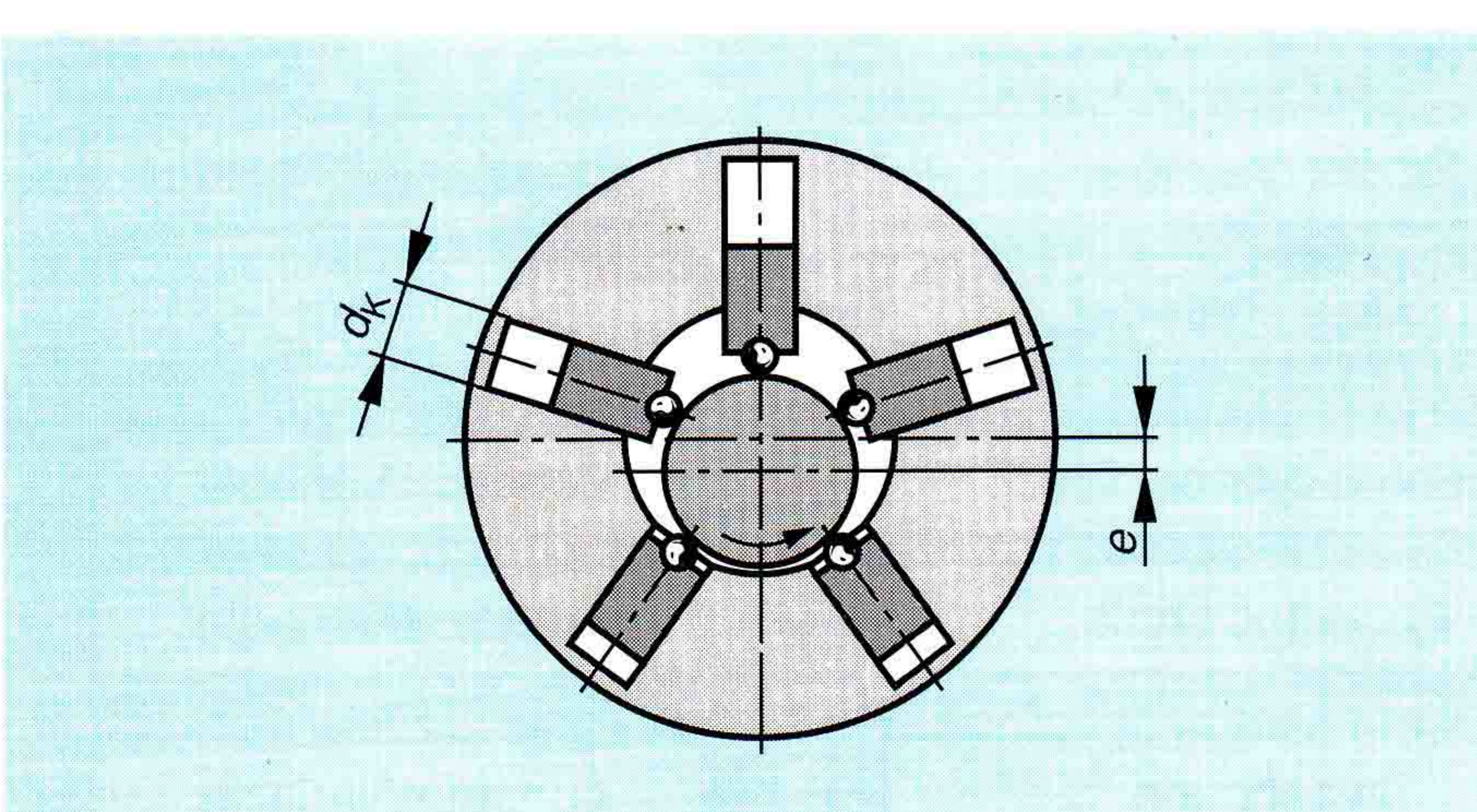


Fig. 8

2.5 Single chamber vane pump

Volume is created between the circular stator, rotor and vanes.

$$V = 2 \cdot \pi \cdot b \cdot e \cdot D \qquad (5)$$

b = vane width

2.6 Double chamber vane pump

Due to the twin cam forms of the stator, two displacement processes occur per revolution.

$$V = \left(\frac{\pi \cdot (D^2 - d^2)}{4}\right) \cdot k \cdot b \qquad (6)$$

b = vane width

k = vane stroke per revolution

2.7 Radial piston pump with eccentric cylinder block

The pistons rotate within the rigid external ring. Eccentricity "e" determines the stroke of the pistons.

$$V = \frac{d_K^2 \cdot \pi}{4} \cdot 2\, e \cdot z \qquad (7)$$

z = number of pistons

2.8 Radial piston pump with eccentric shaft

The rotating eccentric shaft causes radially oscillating piston movements to be produced.

$$V = \frac{d_K^2 \cdot \pi}{4} \cdot 2\, e \cdot z \qquad (8)$$

z = number of pistons

2.9 Axial piston pump in bent axis design

Dependent on the swivel angle, the pistons move within the cylinder bores when the shaft rotates.

$$V = \frac{d_K^2 \bullet \pi}{4} \bullet 2\, r_h \bullet z \bullet \sin \alpha \qquad (9)$$

z = number of pistons

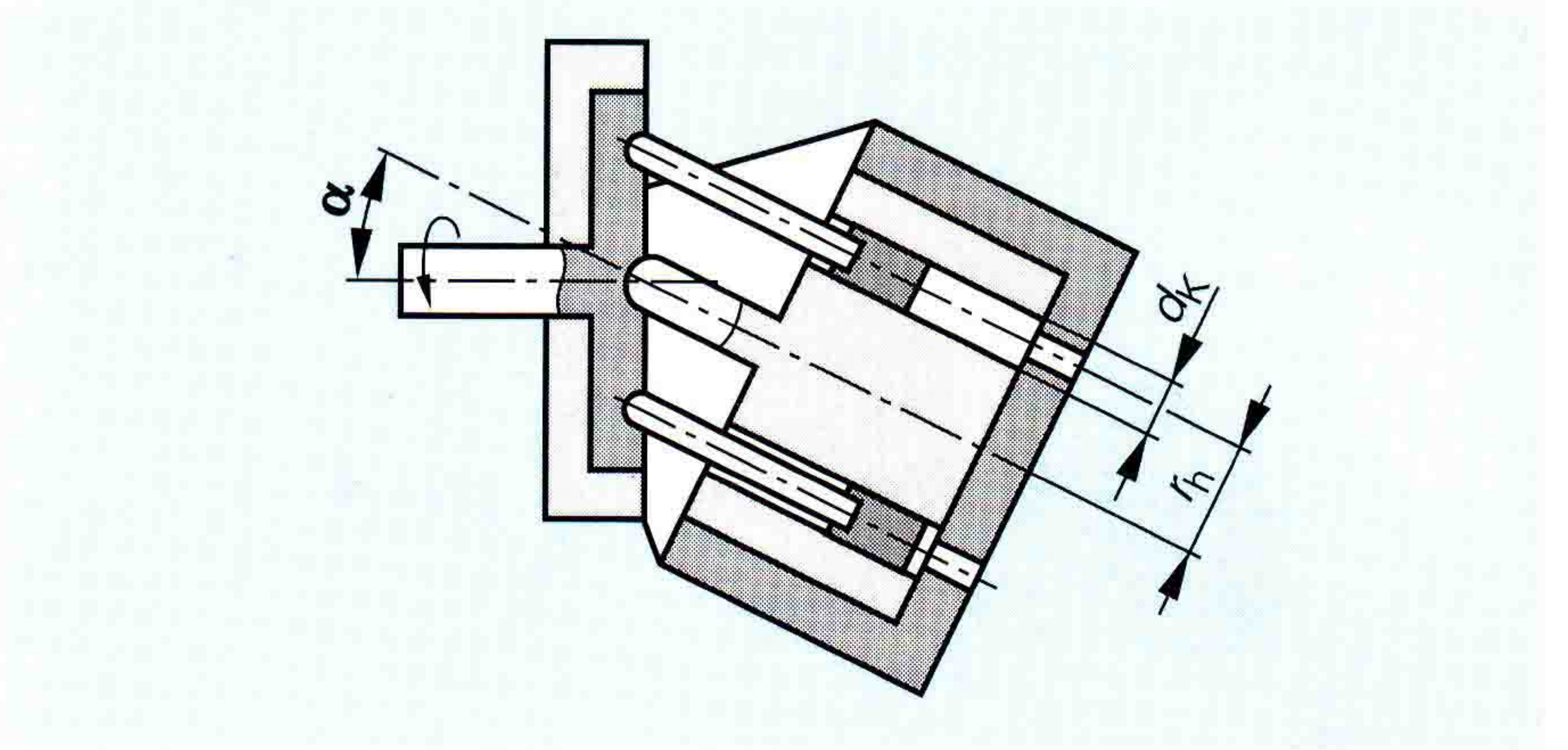


Fig. 9

2.10 Axial piston pump in swashplate design

The rotating displacement pistons are supported by a swashplate. The angle of the swashplate determines the piston stroke.

$$V = \frac{d_K^2 \bullet \pi}{4} \bullet D_K \bullet \tan \alpha \qquad (10)$$

Vane and piston pumps may operate with fixed or variable displacement volumes, but gear pumps only operated with fixed displacement volumes.

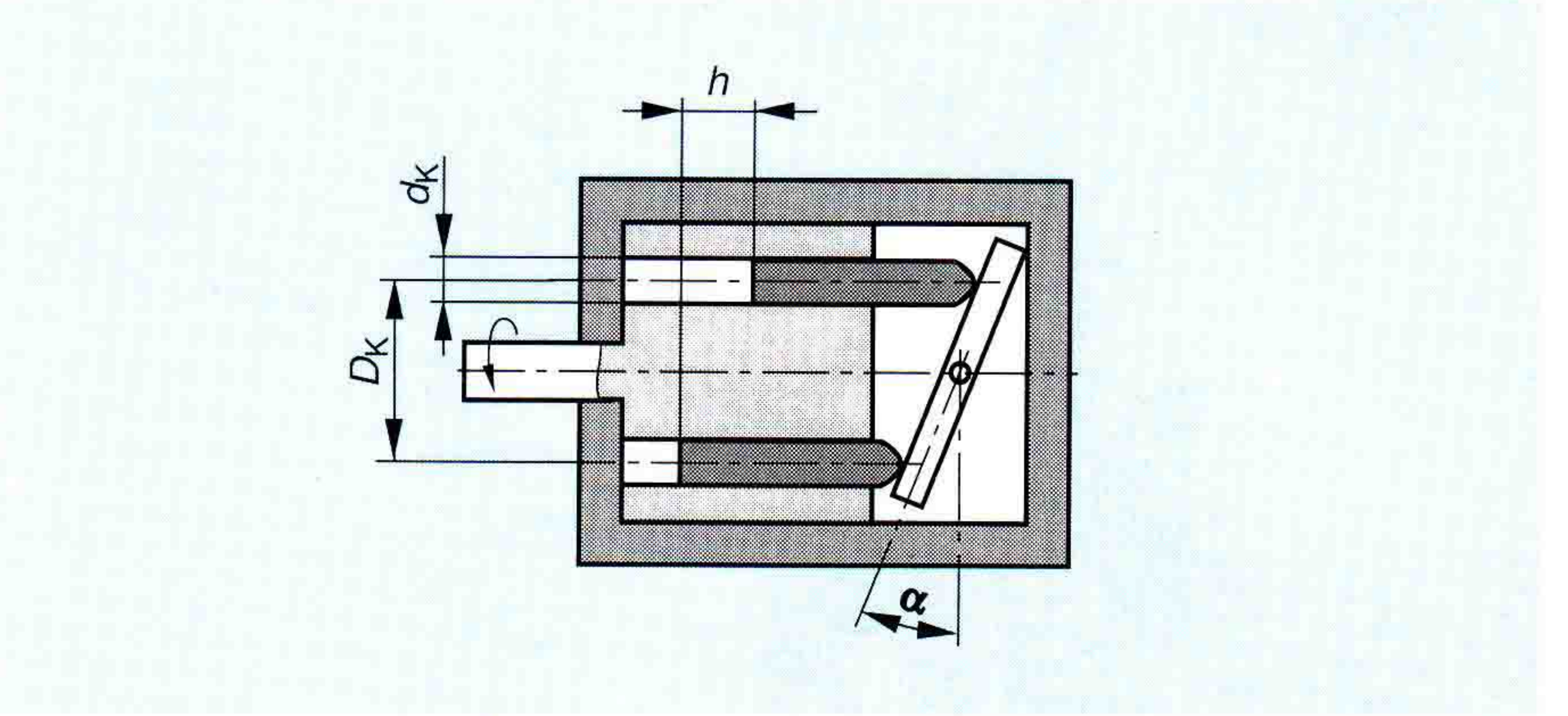


Fig. 10

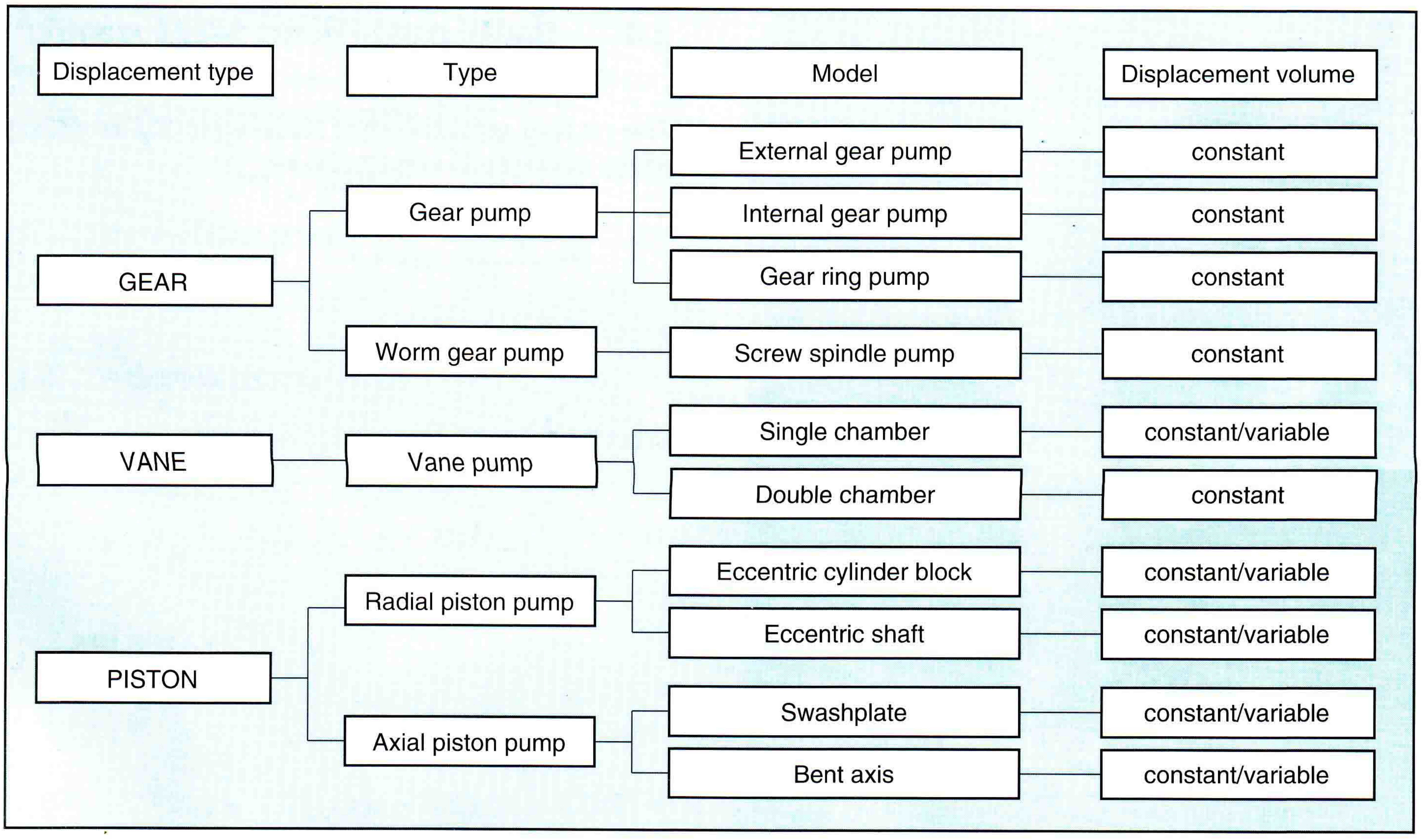


Fig. 11

3. Selection criteria

In the introduction a variety of selection criteria were mentioned for hydraulic pumps. Table 1 summarises the features of the various types of pump.

Depending on the system, a weighting is given:

1 = very good/very large

2 = good/large

3 = satisfactory

4 = poor

Criteria	Type: AZP	IZP	ZRP	SSP	FZPE	FZPD	RKPI	RKPA	AKPSA	AKPSS
Useable range of speeds	1	2	2	2	3	3	2	2	2	2
Useable range of pressures	2	2	3	3	3	3	1	1	1	1
Viscosity range	1	2	3	1	3	3	1	1	1	1
Max. noise level	4	1	2	1	2	2	3	3	3	3
Serivce life	3	2	2	1	1	1	2	2	2	2
Price	1	2	2	3	2	2	3	3	3	3

External gear pump	=	AZP
Internal gear pump	=	IZP
Gear ring pump	=	ZRP
Screw spindle pump	=	SSP
Single chamber vane pump	=	FZPE
Double chamber vane pump	=	FZPD
Radial piston pump with eccentric shaft	=	RKPI
Radial piston pump w. eccentric cylinder block	=	RKPA
Axial piston pump with bent axis	=	AKPSA
Axial piston pump with swashplate	=	AKPSS

Table 1: *Evaluation of hydraulic pumps*

The weightings for each pump must be considered in relation to the other types. As the weighting for the selection criteria depends on the application, this table may only be used as an aid in order to make comparisons when taking such features as age of noise into account.

4. Functional descriptions

4.1 Screw pumps

Screw pumps are similar to internal gear pumps in that their main characteristic is that they possess an extremely low operating noise level. They are therefore used in hydraulic systems in, for example, theatres and opera houses.

Screw pumps contain 2 or 3 worm gears within a housing.

The worm gear connected to the drive has a clock-wise thread and transmits the rotary movement to further worm gears, which each have an anti-clockwise thread.

An enclosed chamber is formed between the threads of the worm gears. This chamber moves from the suction port to the pressure port of the pump without change in volume.

This produces a constant, uniform and smooth flow and hence operation tends to be very quiet.

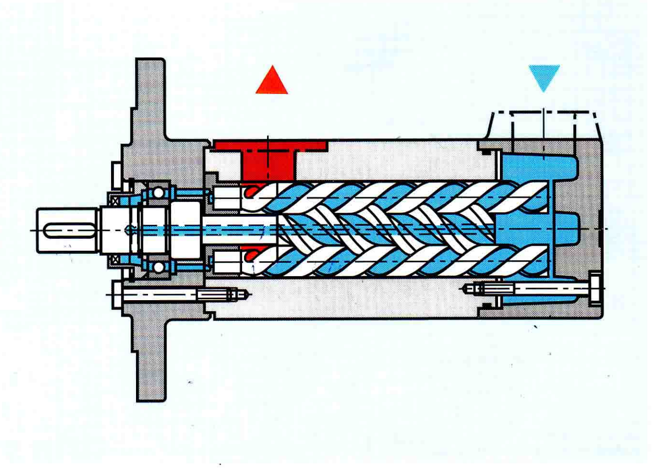


Fig. 12: *Screw pump*

Important parameters

Displacement volume	15 to 3500 cm^3
Operating pressure	up to 200 bar
Range of speeds	1000 to 3500 rpm

4.2 External gear pumps

In particular, external gear pumps are used in large numbers in mobile hydraulics.

The reason for this is the features of this design:

- Relatively high pressure for low weight
- Low cost
- Wide range of speeds
- Wide temperature/viscosity range

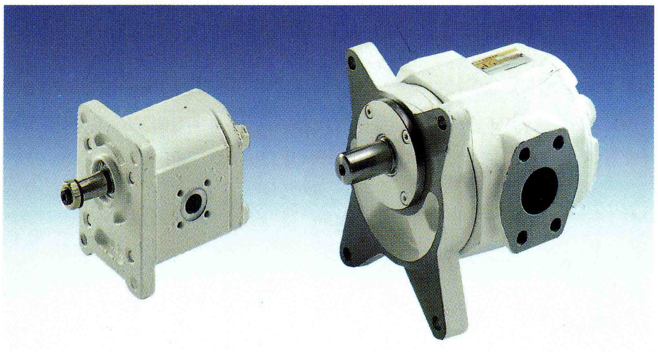
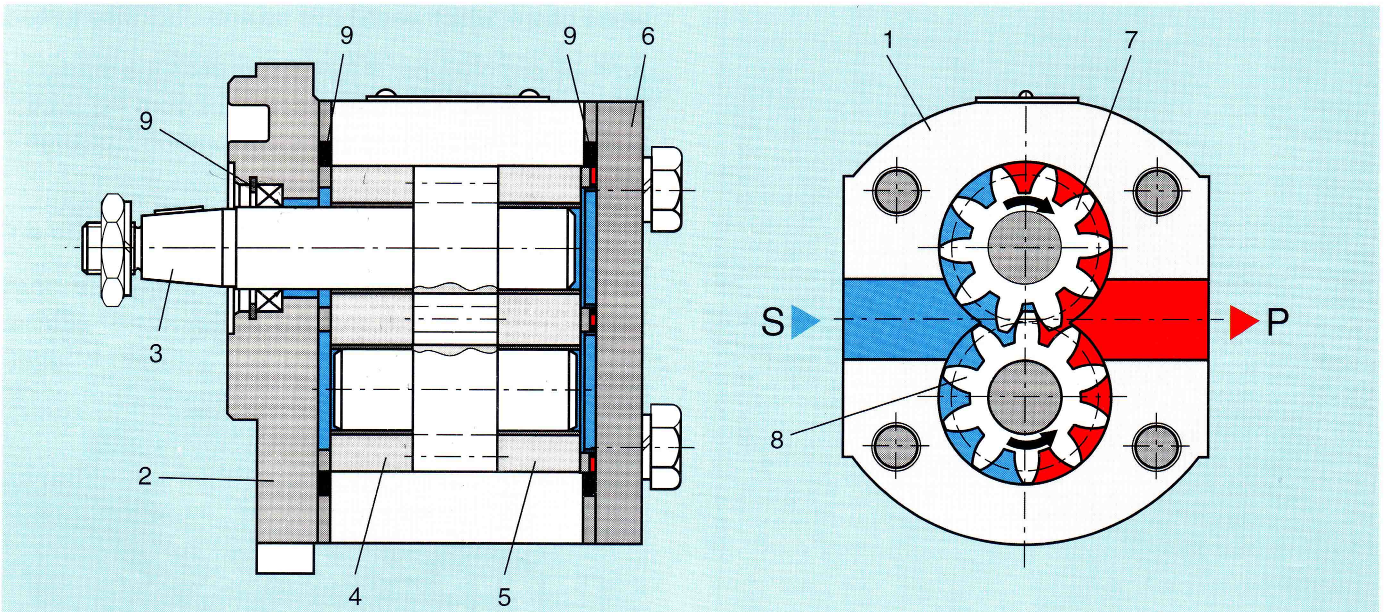


Fig. 14: *Gear pumps G2 and G4*

4.2.1 Function



1	Housing	**2**	Flange	**3**	Shaft	**4, 5**	Bearing blocks
7, 8	Gears	**9**	Seals			**6**	Cover

Fig. 13: *External gear pump*

Gear (7) is connected via a coupling with the drive (E motor, diesel engine, etc.). Gears (7) and (8) are positioned in such a way by the bearing blocks (4) and (5) that the gears mesh on rotation with the minimum clearance.

Displacement chambers are formed between the gears, internal walls of the housing and surfaces of the bearing blocks (4) and (5).

When the system is started up, first the air which is in the suction lines is transported from suction side S to pressure side P within the chamber. Hence a negative pressure is produced in the suction line. As this negative pressure increases, fluid rises from the tank into the suction line and up to the pump.

Fluid is fed into the gear chambers and via the pressure port of the pump into the hydraulic system. Hence a pre-requisite for the pump to function is that the gear chambers are sealed to such an extent that air or fluid can be transported with as little loss as possible.

External gear pumps contain clearance seals. Due to this, losses occur dependent on operating pressure from the pressure side to the suction side. So that only very little fluid manages to get through these clearances from the pressure side to the suction side as pressure increases, the rear bearing block (5) is pressed against the rear of the gears via an axial pressure field.

The actual system pressure is present in the pressure field.

Important parameters

Displacement volume	0.2 to 200 cm^3
Max. pressure	up to300 bar (size dependent)
Range of speeds	500 to 6000 rpm

4.3 Internal gear pumps

The most important feature of internal gear pumps is the very low noise level. Hence they are primarily used in industrial hydraulics (presses, machines for plastics and tools, etc.) and in vehicles which operate in an enclosed space (electric fork-lifts, etc.).

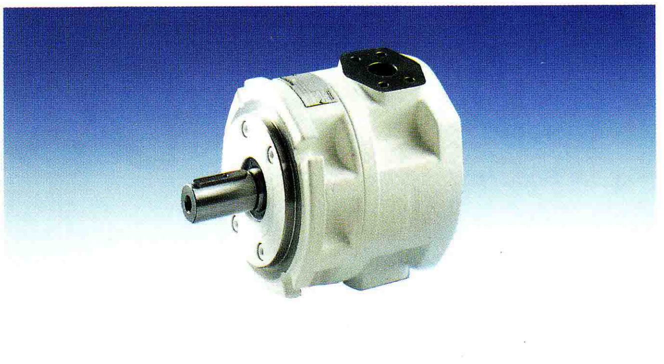
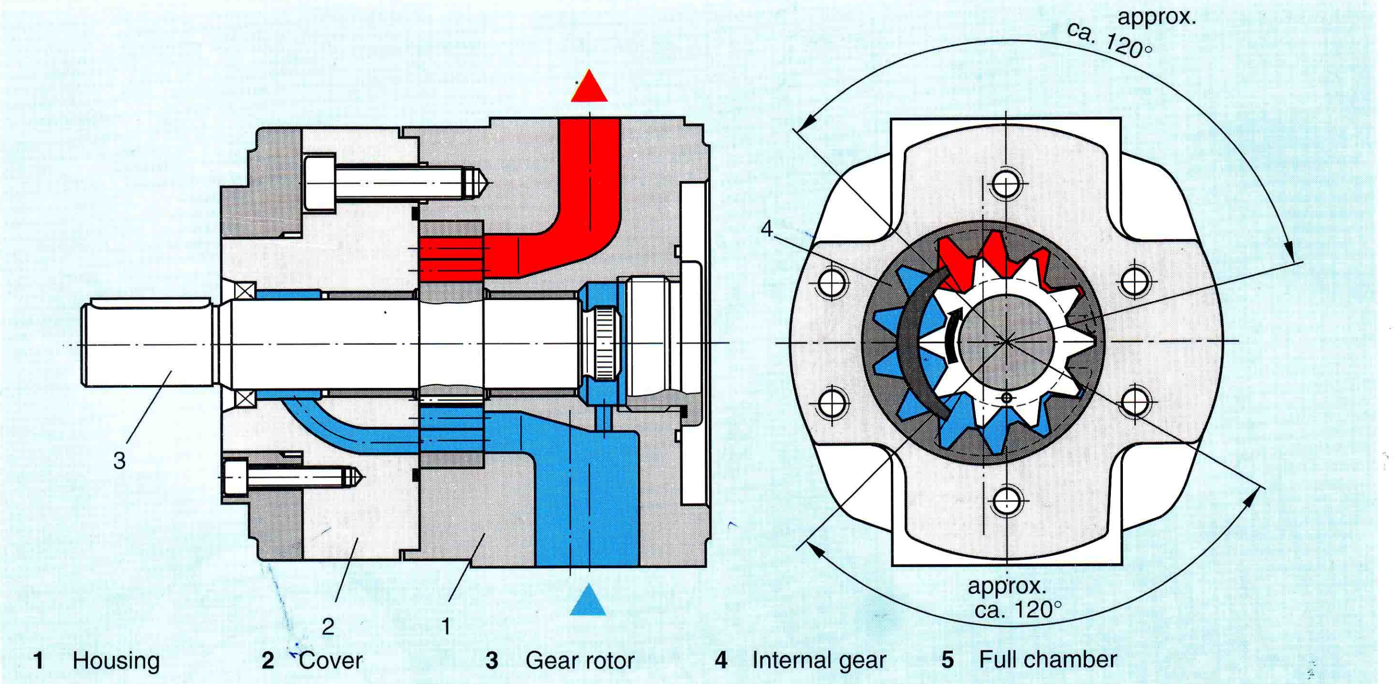


Fig. 15: *Internal gear pump GU*

4.3.1 Function



1 Housing **2** Cover **3** Gear rotor **4** Internal gear **5** Full chamber

Fig. 16: *Internal gear pump*

The gear rotor is connected to the drive. When the gear rotor and internal gear rotate, the space between the gears increases. The pump "sucks".

This increase in space occurs over an angle of rotation of about 120°C. Hence the displacement chamber is filled relatively slowly.

This causes operation to be exceptionally quiet and a very good suction characteristic to be produced.

When the chambers are full, the fluid is transported without change in volume until it reaches the pressure port.

Once a chamber is connected to the pressure port, the space decreases between the gears and the fluid is displaced.

When the gears mesh, their special shape is a positive attribute to their operation, as there is practically no dead zone between the gear rotor and internal gear (in contrast to external gear pumps).

The volume of oil in such dead regions becomes compressed and hence pressure pulses and therefore noise are produced.

Internal gear pumps as described here have practically no pressure pulses and hence are exceptionally quiet.

Important parameters

Displacement volume	3 to 250 cm^3
Operating pressure	up to 300 bar (dependent on size)
Range of speeds	500 to 3000 rpm (dependent on size)

4.4 Radial piston pumps

Radial piston pumps are used in applications involving high pressures (operating pressures above 400 bar): In presses, machines for processing plastic, in clamping hydraulics for machine tools and in many other applications, operating pressures are required of up to 700 bar. It is only radial piston pumps which satisfactorily operate at such high pressures, even under continuous operation.

A valve controlled radial piston pump with eccentric shaft operates as follows:

The drive shaft (1) is eccentric to the pump elements (2). The pump elements consist of piston (3), cylinder sleeve (4), pivot (5), compression spring (6), suction valve (7) and pressure control valve (8).

The pivot is screwed into the housing (9). The piston is positioned with the so-called slipper pad on the eccenter. The compression spring causes the slipper pad to always lie on the eccenter, when the eccentric shaft rotates and the cylinder sleeve to be supported by the pivot.

Fig. 18: *Radial piston pump R4*

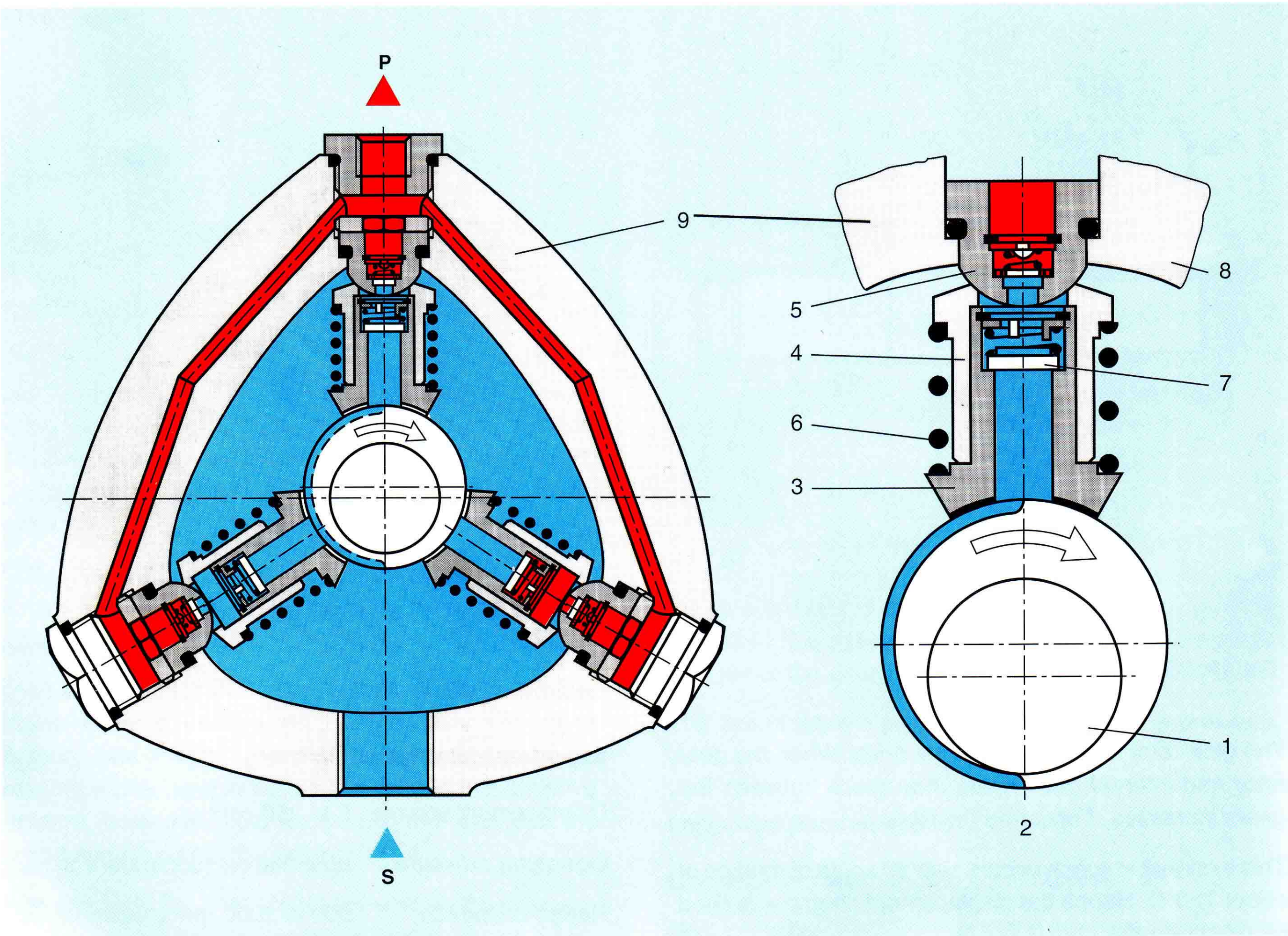


Fig. 17: *Radial piston pump with eccentric shaft*

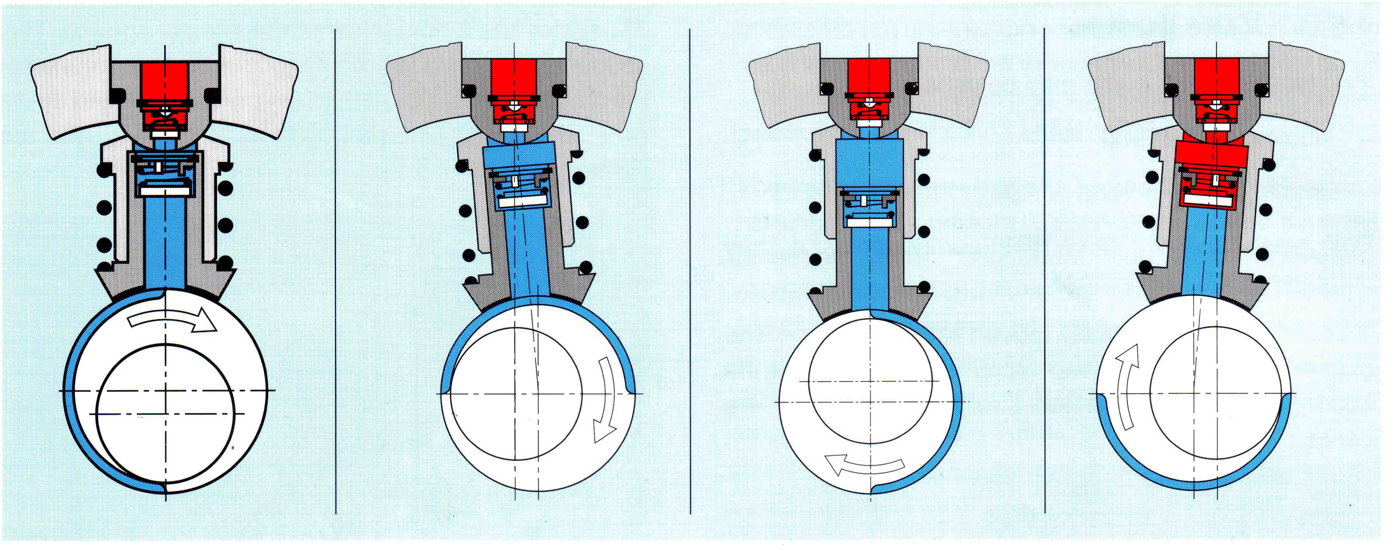


Fig. 19: *Phase 1*
The piston is at the upper idle point. The minimum volume exists in the displacement chamber. The suction valve and pressure control valve are closed.

Phase 2
As the shaft rotates, the piston moves in the direction of the centre axis of the eccentre. The displacement chamber becomes larger and the suction valve opens due to the negative pressure produced. Fluid now flows via the groove in the eccentre and bore in the piston into the displacement chamber.

Phase 3
The piston is at the lower idle point. The displacement chamber is completely full (maximum volume). Suction valve and pressure control valve are closed.

Phase 4
As the eccentre rotates, the piston is moved in the direction of the pivot. Fluid is compressed in the displacement chamber. Due to the pressure produced the pressure control valve in the pivot opens. Fluid flows into the ring channel which connects the pump elements.

In general, piston pumps have an odd number of pump elements. The reason for this is that when the flows of the individual pump elements are added together, this results in a high flow pulsation if there is an even number of elements.

Important parameters

Displacement volume	0.5 to 100 cm^3
Max. pressure	up to 700 bar (dependent on size)
Range of speeds	1000 to 3000 rpm (dependent on size)

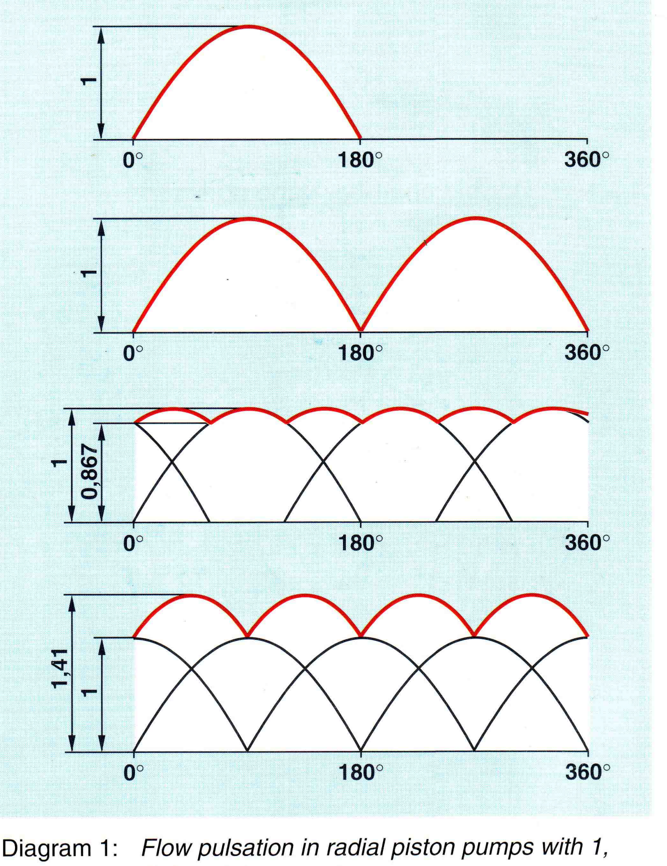


Diagram 1: *Flow pulsation in radial piston pumps with 1, 2, 3 and 4 pump elements*

4.5 Vane pumps

Two types of vane pump may be used:

- single chamber and
- double chamber vane pumps.

Both types have the same main components, i.e. they comprise a rotor and vanes.

The vanes may be radially moved within the rotor. The difference between the two types is in the form of the stator ring, which limits the stroke movement of the vanes.

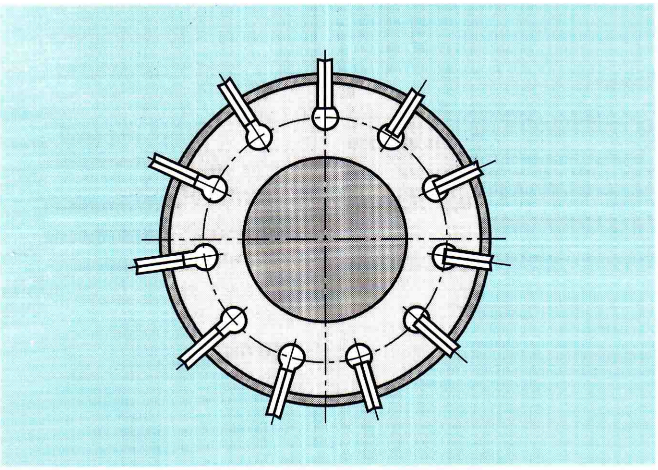


Fig. 20: *Main assembly of vane pump with rotor and vanes*

4.5.1 Double chamber vane pump

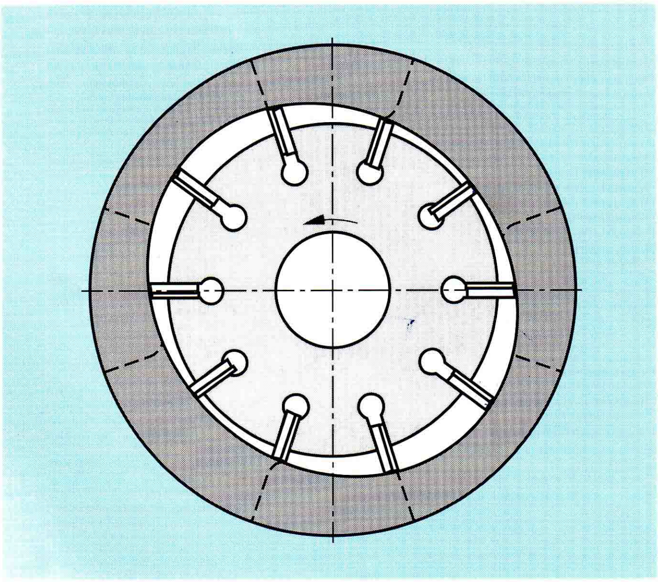


Fig. 21

The stator has a double cam form internal surface. This causes each vane to carry out two strokes per rotation of the shaft. The displacement chambers are created by the rotor, two vanes, internal surface of the ring and the control plate on one side.

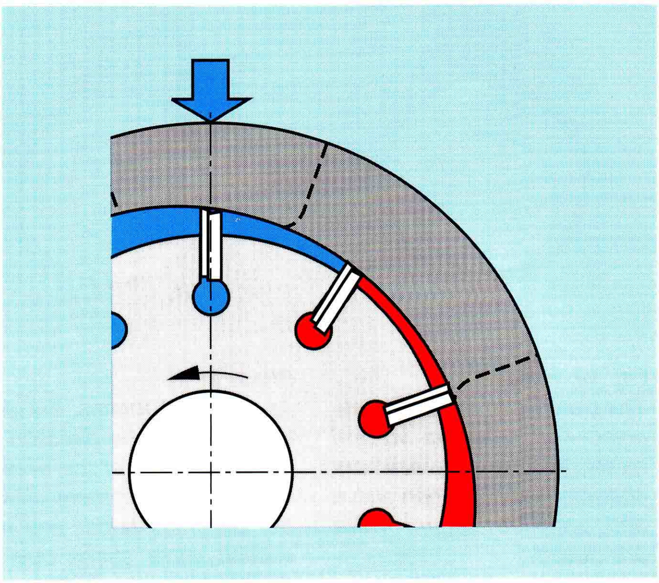


Fig. 22

In the range where the minimum distance between the rotor and ring occurs, the volume in the displacement chambers is also at a minimum. As the rotor rotates, the volume in the displacement chamber increases. As the vanes follow the contour of the ring, every chamber is fairly tightly sealed. A negative pressure is produced. The displacement chamber is connected to the suction side via control slits at the side. As a result of the negative pressure, fluid flows into the displacement chamber.

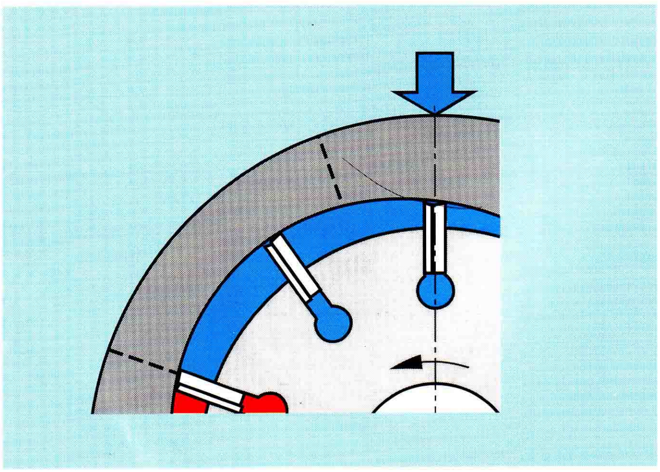


Fig. 23

The maximum volume in the displacement chamber occurs (*Fig. 23*). The connection to the suction side is then interrupted.

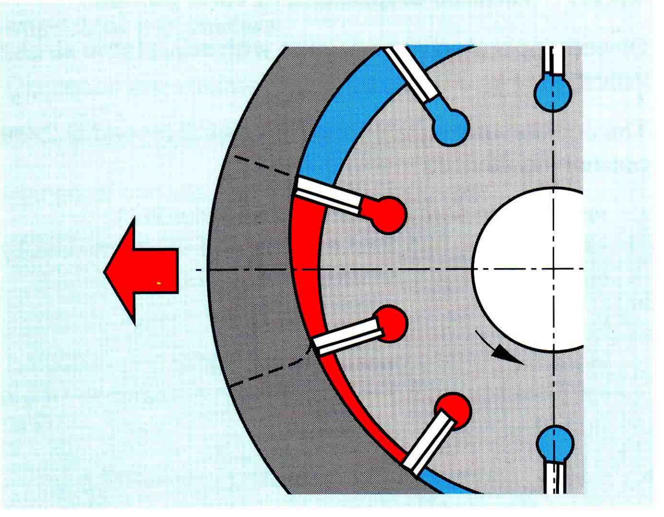


Fig. 24

As the rotor rotates further, the volume in the displacement chamber decreases (*Fig. 24*). Slits in the control disc on the side let the fluid flow via a channel to the pressure port of the pump.

This process is carried out twice per rotation of the shaft.

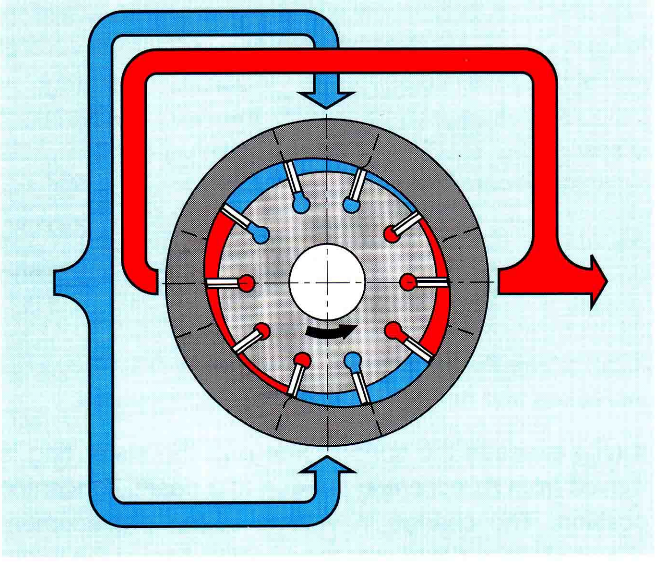


Fig. 25: *Double chamber vane pump*

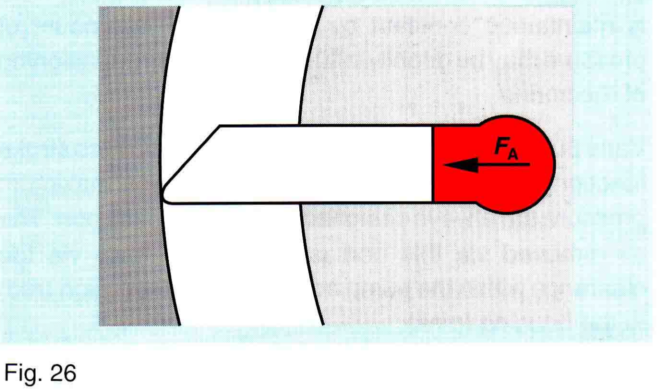


Fig. 26

In order to ensure that the vanes lie correctly on the ring, the chamber behind the vanes must be supplied with oil. This means, that in the pressure range, the total system pressure is behind the vanes.

The vanes are therefore pressed on the ring with a force resulting from pressure x vane area. Above a certain pressure and dependent on the lubrication characteristics of the fluid, the lubricating film between the ring and vanes may be torn away. This leads to wear. In order to reduce the pressing force, vane pumps used at operating pressures of approx. above 150 bar are designed with double vanes.

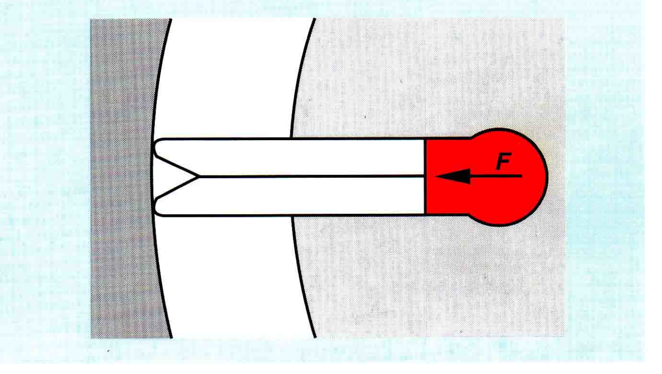


Fig. 27

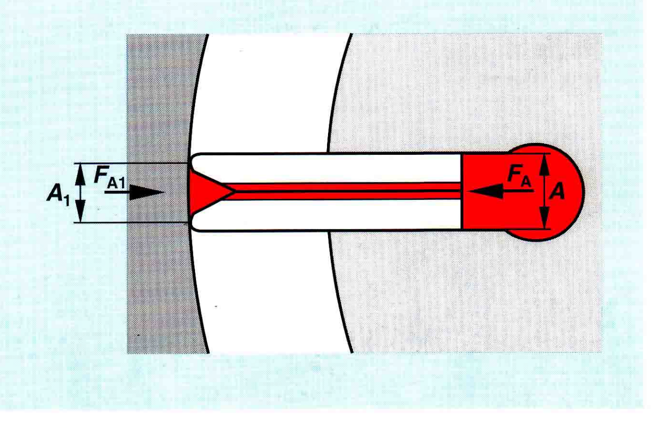


Fig. 28

The fluid under pressure is fed to the chamber between the tips of the vanes via a chamfer or groove. F_{A1} is less than F_A due to the smaller effective area.

The pressing force is hence compensated for to a large extent.

4.5.2 Single chamber vane pumps

The stroke movement of the vanes is limited by a ring with a circular internal form. Due to the off-centre position of the ring with respect to the rotor, the volume is changed within the displacement chambers. The process of filling the chambers (suction) and emptying is in principle the same as for double chamber vane pumps.

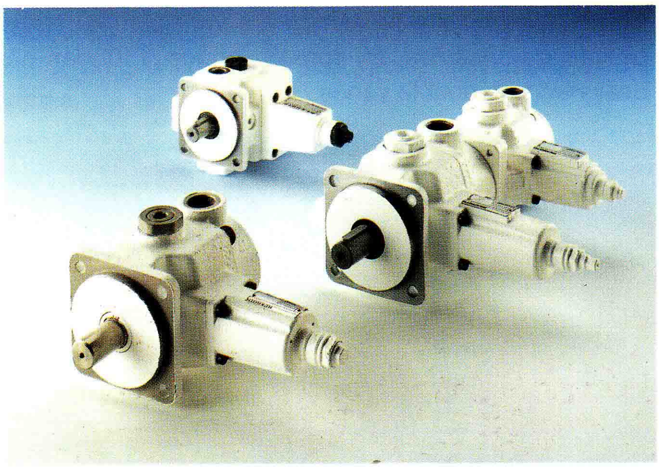


Fig. 29: *Vane pumps V5 and V3*

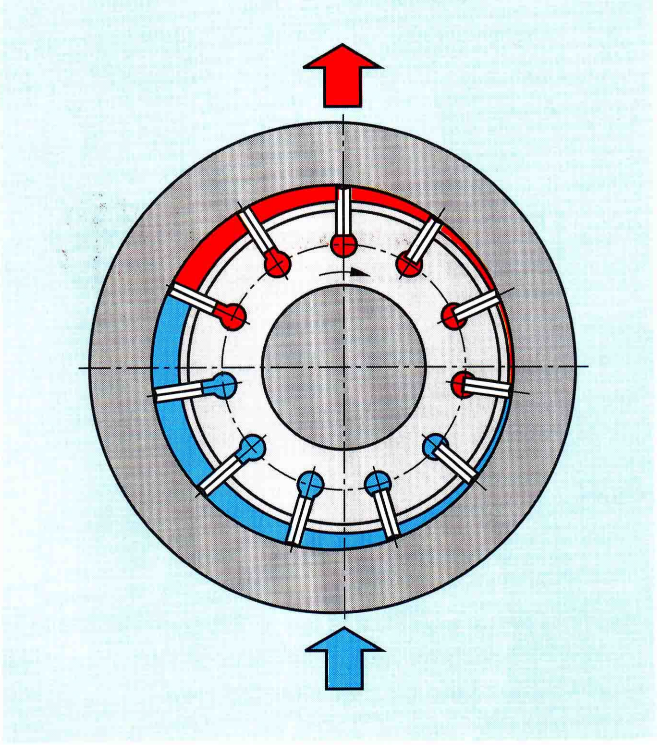


Fig. 30: *Single stroke vane pump*

4.5.2.1 Variable displacement vane pumps

Directly operated vane pumps with adjustable stroke volumes (*Fig. 31*)

The position of the stator ring may be influenced at three positioning devices in this pump:

- Adjustment screw for the stroke volume (1)
  The distance between the ring and the rotor directly determines the feed volume from the pump.
- Height adjustment screw (2)
  Here the vertical position of the stator ring is altered (directly effects noise and dynamic response of the pump).
- Setting screw for max. operating pressure (3)
  The amount of the spring pre-tensioning determines the max. operating pressure.

The pumping action of this pump has already been described under 4.5.2.

Dependent on the resistance in a hydraulic system, a pressure is produced. This pressure is present in the pump in the region marked in red and acts on the internal surface of the ring.

The pressure force in this region may be represented by force vector (F_p). If this force vector is split into its vertical and horizontal components, a large force (F_v) is produced which is removed by the height adjustment screw and a small force (F_h) is produced which acts against the compression spring.

As long as the force of the compression spring (F_f) is greater than the force (F_h) the ring remains in the position shown.

If the pressure increases in the system, the force (F_p) increases and hence (F_v) and (F_h) also increase.

If (F_h) exceeds the spring force (F_f), the ststor ring is moved from its eccentric position to a nearly concentric position. The change in volume in the displacement chambers is reduced until the effective flow at the pump outlet is zero. The pump now feeds only as much oil as required to make up leakage which occurs in the internal clearances within the pump. The pressure in the system is maintained constant by the pump. The amount of pressure may be directly influenced by the pre-tensioning of the spring.

Vane pumps with variable displacements and zero stroke functions (Q = zero) on reaching the set maximum pressure are always designed with a drain case port. The oil removed via this port is that which flows via the clearance within the pump from the pressure region (red) to the housing (pink).

Heat due to friction is removed via the leakage oil and during zero stroke operation the lubrication of internal parts is ensured by this oil.

Important parameters

Displacement volume	5 to 100 cm^3
Operating pressure	up to 100 bar
Range of speeds	1000 to 2000 rpm

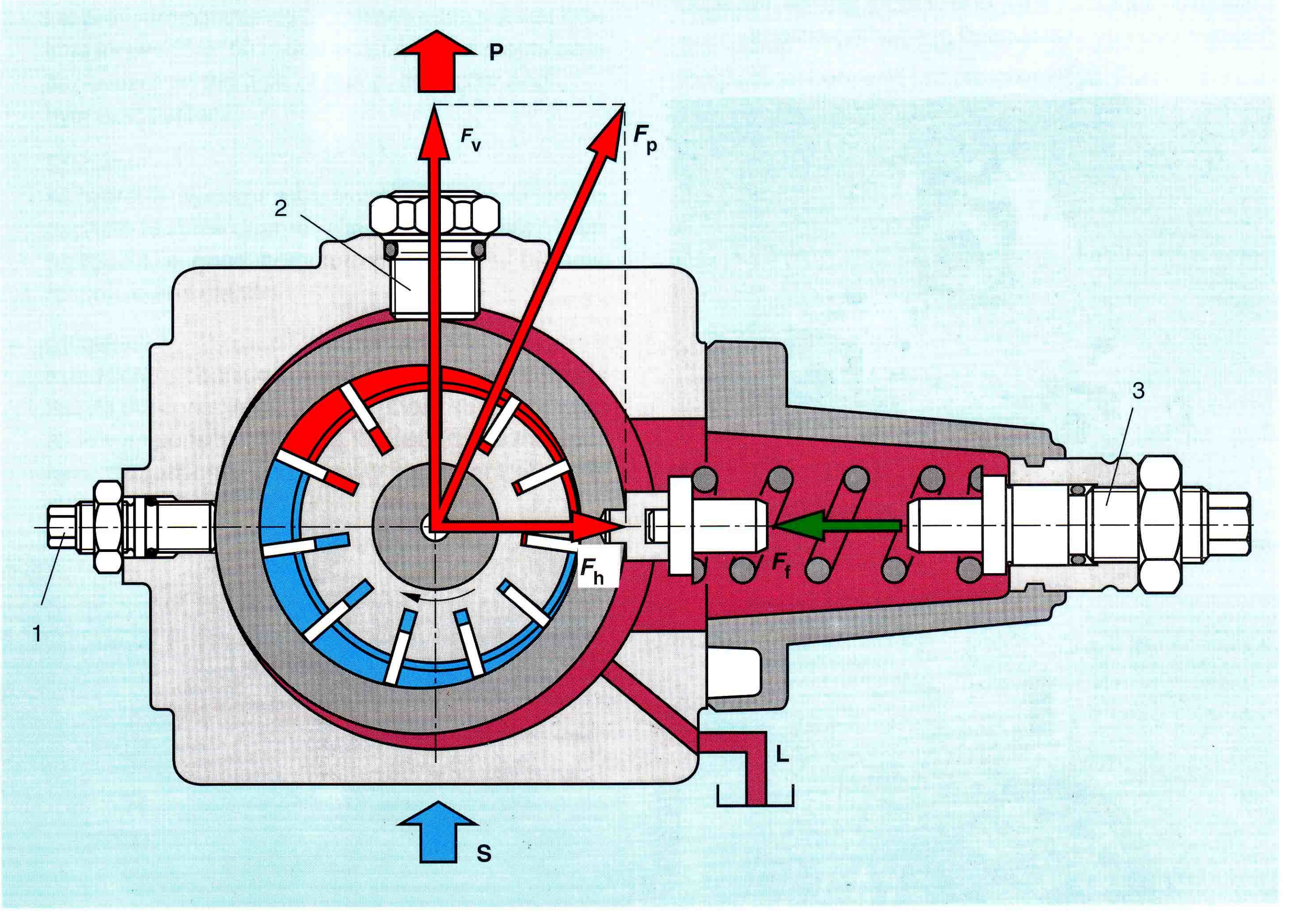


Fig. 31: *Directly operated vane pumps*

Pilot operated vane pumps with adjustable stroke volumes

The basic principle of this pump is very similar to that of the directly operated vane pump. The difference is in the adjustment devices for the stator ring.

Instead of being moved by one or more springs, the stator ring is moved by pressurised positioning pistons.

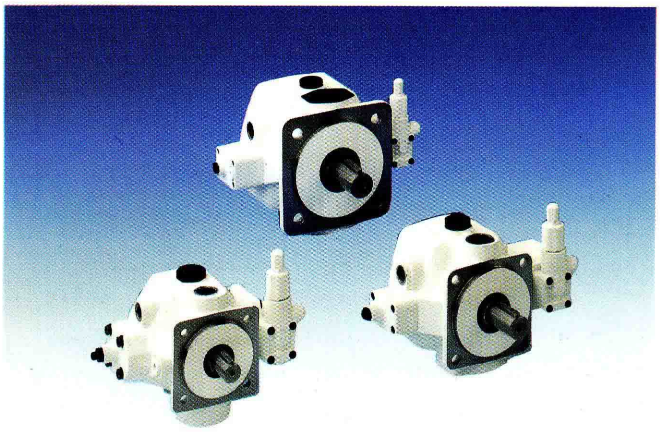


Fig. 32: *Vane pump V7*

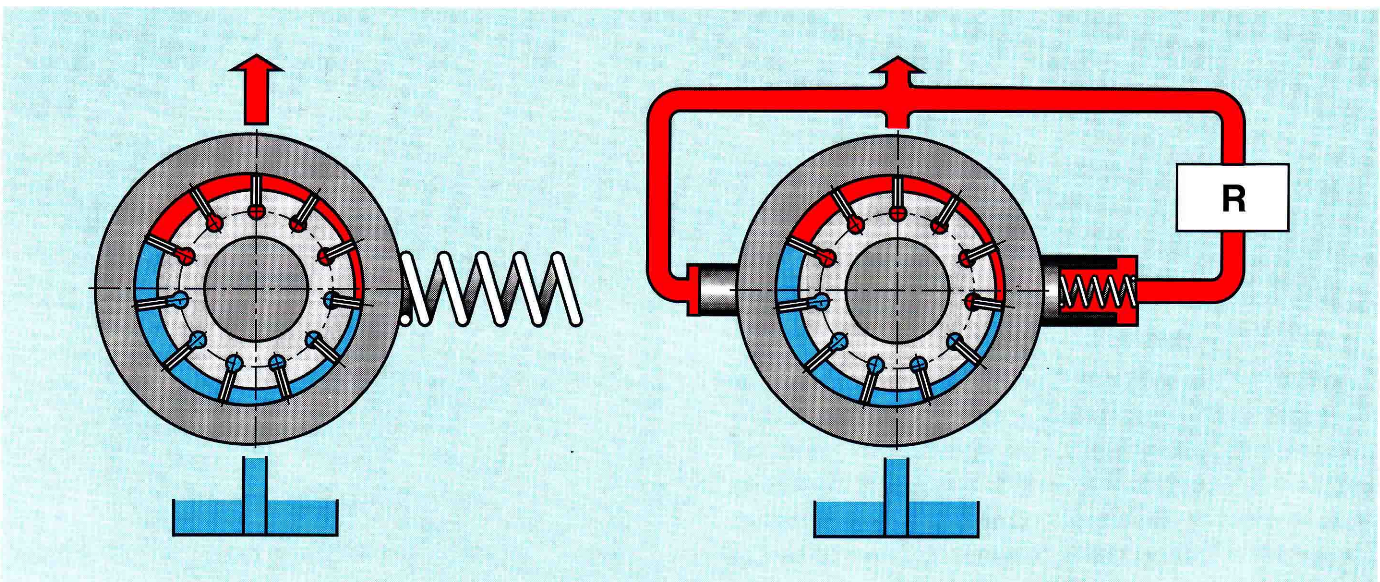


Fig. 33: *Directly operated (left) and pilot operated (right) vane pumps*

The two positioning pistons have different diameters (ratio of areas is approx. 2:1).

Behind the positioning piston with the larger diameter is a compression spring. This spring ensures that the stator ring is in its eccentric position when the pump is started.

The pressure which is formed in the hydraulic system is led via internal channels behind the smaller positioning piston to the controller R and further on to the larger positioning piston.

If the pressures behind both positioning pistons are the same, the stroke ring remains in the position shown due to the difference in areas of the positioning pistons.

4.5.3 Function of pressure controller

The pressure controller determines the maximum system pressure.

Requirements of the pressure controller are as follows:

- High dynamic response
  i.e. pressure controlling processes must take as little time as possible (50 to 500 ms). Dynamic response is dependent on the type of pump, controller and hydraulic system.
- Stability
  All hydraulic systems with controlled pressure tend to oscillate to some degree. The controller must hence represent a good compromise between dynamic response and stability.
- Efficiency
  In the control position a certain amount of pump flow is fed via the controller to tank. This loss should be kept as low as possible, but also it must ensure that the dynamic response and stability of the controller are sufficiently maintained.

4.5.4 Design of pressure controller

The pressure controller comprises a control spool (1), housing (2), spring (3) and adjustment device (4).

In the output position the spring pushes the control spool into the position shown in the controller housing.

Hydraulic fluid reaches the control spool via channels in the pump. The control spool is designed with a longitudinal bore and two cross drillings. Furthermore an orifice limits the flow through the control spool. In the position shown, fluid under pressure flows via the longitudinal bore and the cross drilling to the large positioning piston.

The connection to tank is closed by the control spool.

The actual pressure in the hydraulic system acts against the top surface of the control spool. As long as the force F_p resulting from the pressure is less than the opposing force of the spring F_f, the pump remains in the position shown. The same pressure exists behind both positioning pistons.

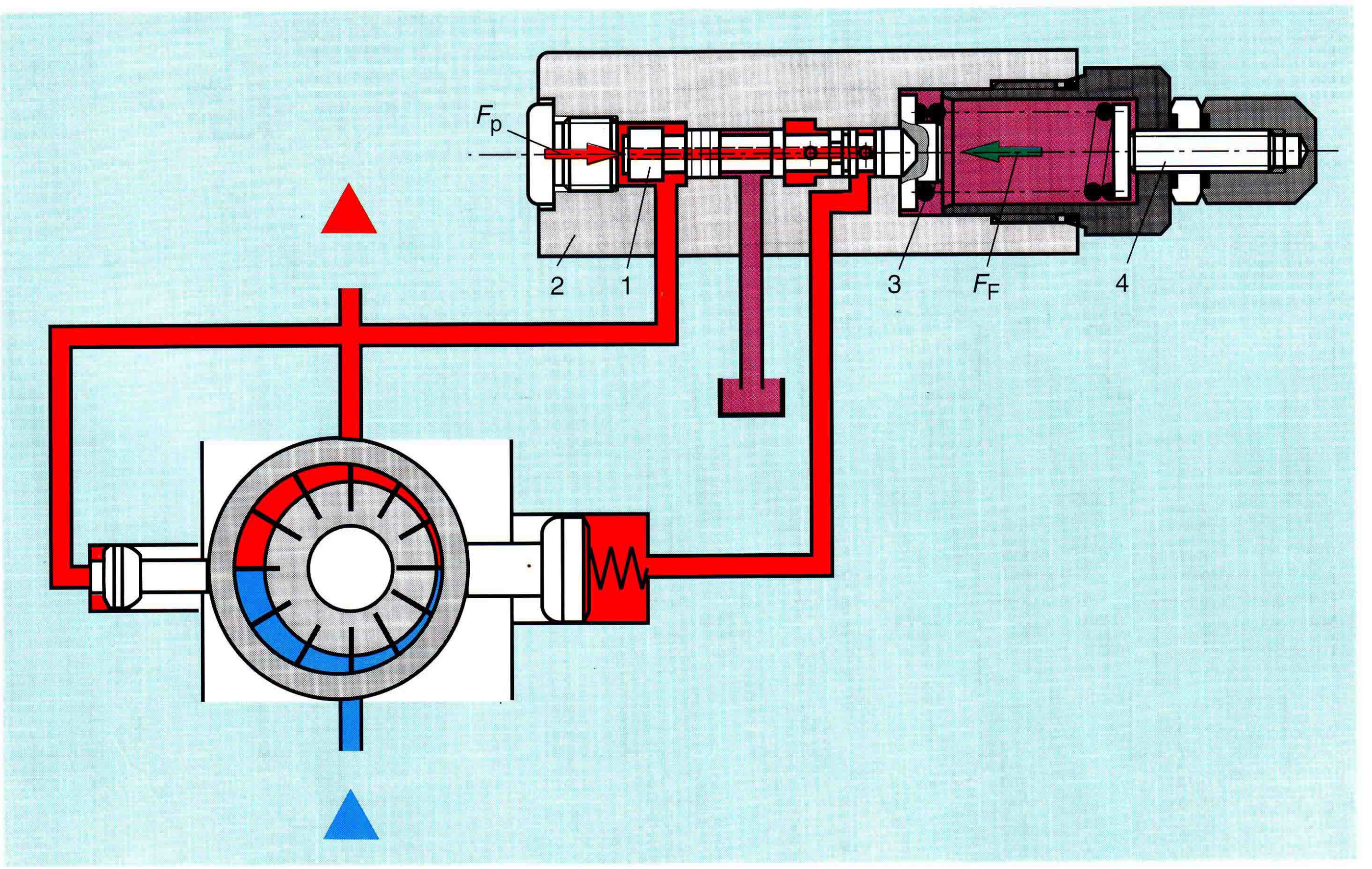


Fig. 34: *Pressure controller, pump delivering fluid. The operating pressure is less than the maximum pressure set at the pressure controller.*

When the force F_p increases as the pressure in the hydraulic system increases, the control spool is pushed against the spring.

The connection to tank in the controller is opened. The fluid flowing away here causes the pressure to decrease behind the large positioning piston. The small positioning piston is still under system pressure and hence pushes the stator ring against the large positioning piston (under reduced pressure) until the ring is nearly in mid-position.

Forces become balanced:
Small positioning piston area x high pressure =
large positioning piston x low pressure

The flow returns to zero, and the system pressure is maintained constant.

Due to this behaviour the power lost in the system is low when the maximum pressure is reached. The fluid does not heat up so much and energy consumption is minimal.

If the pressure decreases in the hydraulic system, the spring in the pressure controller moves the control spool. The connection to tank is hence closed and the complete system pressure builds up behind the large positioning spool.

The forces of the positioning pistons become unbalanced and the large positioning piston pushes the stroke ring back to the eccentric position.

The pump once again delivers fluid to the hydraulic system.

Variable displacement pumps, which operate in this manner, may be designed with any of a series of other control devices, e.g.

- flow controller
- pressure/flow controller
- power controller

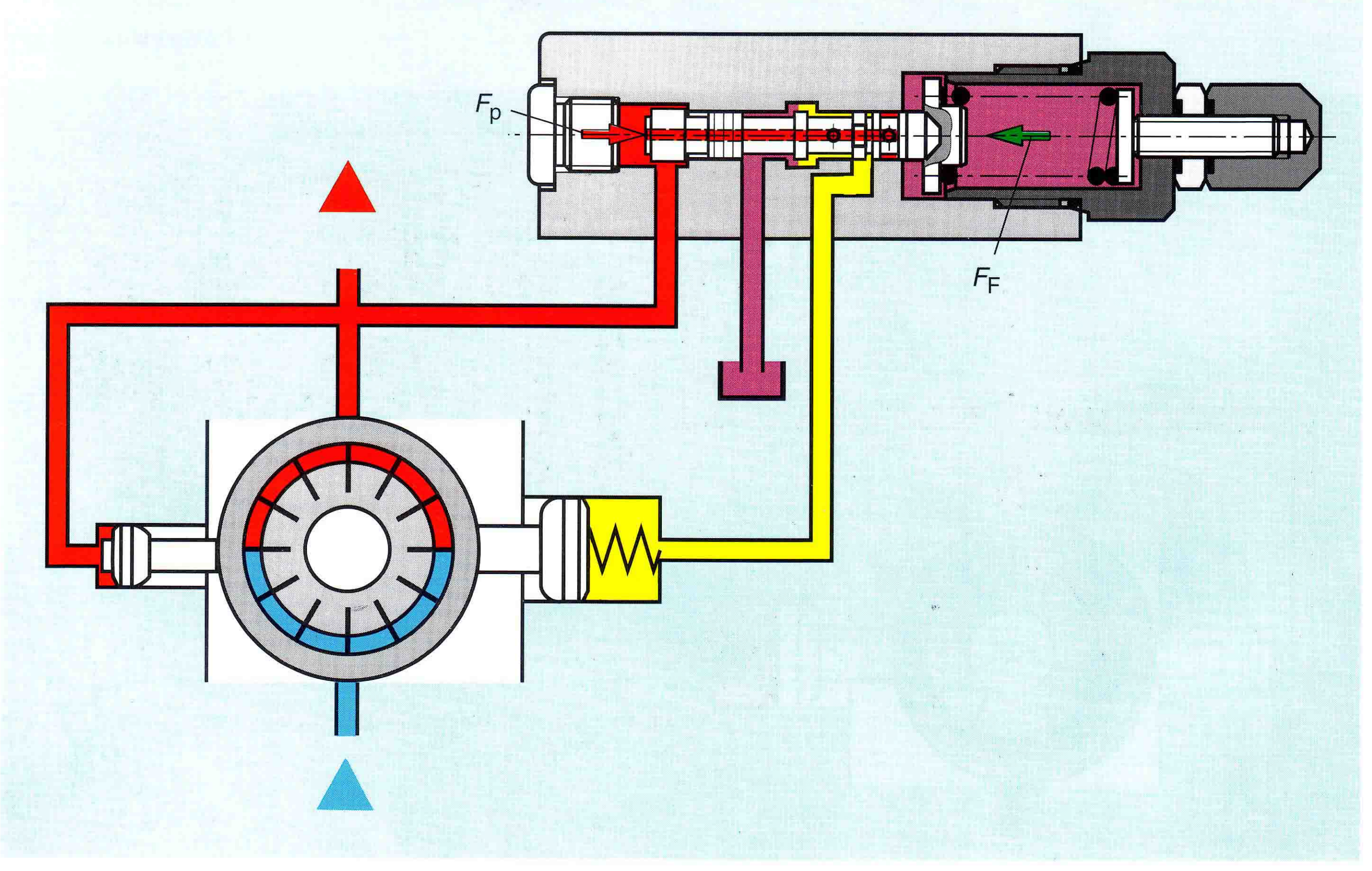


Fig. 35

4.5.5 Flow controller

With flow control the displacement of the pump is matched to a specified value. In order to achieve this, flow is passed through a measuring orifice (throttle, proportional directional valve etc.). The pressure drop at the measuring orifice is taken as the control parameter.

The pressure from the measuring orifice is fed to the top surface to the control spool. This pressure also exists behind the small positioning piston.

The pressure down-stream of the measuring orifice (which is lower than up-stream of the measuring orifice) is fed via a line to the spring chamber of the controller.

At the control spool the forces are balanced. The forces are also balanced at the pistons.

In the position shown, the pressure drop at the measuring orifice is equal to the spring force in the controller.

Pilot oil continually flows away via a control land (X) at the controller, so that a specific pressure is set behind the large positioning piston.

The ring is kept in a stable position.

If (for example) the area of the measuring orifice is increased, the pressure drop is then reduced.

Hence the spring moves the control spool. The opening at the control land is reduced and hence the pressure increases behind the large positioning piston.

The ring is moved in the direction of greater eccentricity and the feed volume of the pump is increased.

Due to the larger feed volume, Δp at the measuring orifice is increased until a stable state is once more achieved.

(Δp at the measuring orifice $\triangleq$ spring force at the controller)

Pressure and flow controllers may be controlled and adjusted by various means (mechanical, hydraulic, electrical).

The combination of flow and pressure controller permits very economic hydraulic drives to be designed (see e.g. load sensing).

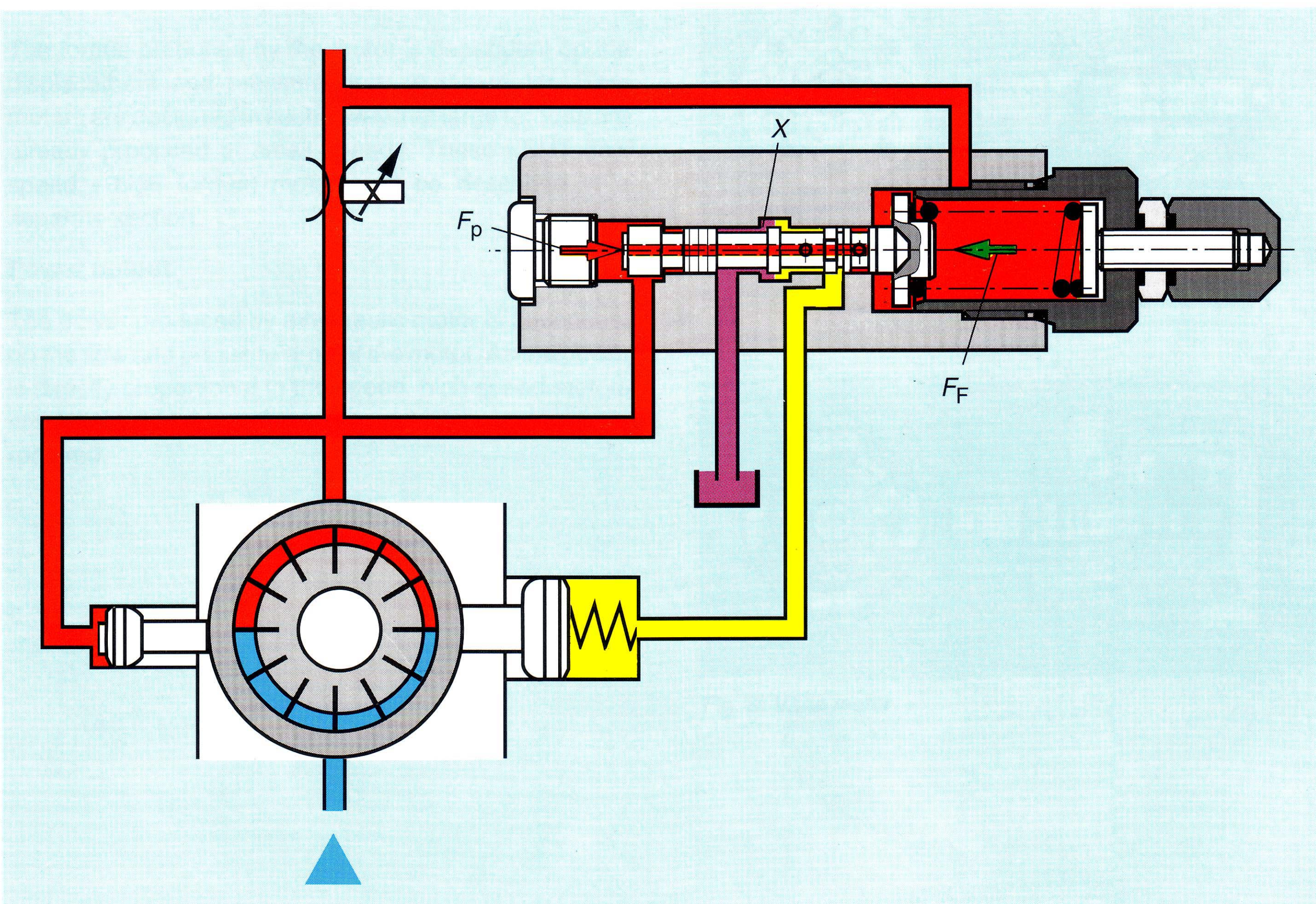


Fig. 36