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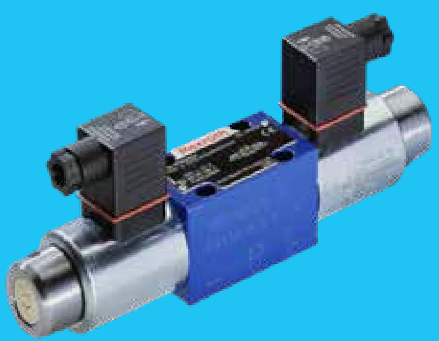
**KNOWLEDGE IN DETAIL**

# Hydraulics
# Basic Principles



Knowledge in Detail

# Hydraulics – Basic Principles

# Imprint

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# Hydraulics – Basic Principles

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www.boschrexroth.com/academy

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# 1 General information

## 1.1 Introduction to hydraulics

### 1.1.1 Definition

Hydraulics is the science of resting and flowing fluids. In technical practice, hydraulics is generally understood as the generation of forces and motion by hydraulic fluids. The term is derived from the ancient Greek words "hydor" (water) and "aulos" (pipe).

### 1.1.2 Historical development

As far back as the ancient world people were utilizing the energy of flowing water. For example, there is evidence to suggest that the first water wheels were built around 300 B.C. They are still being used today in watermills and their technical advancement can still be seen in the water turbines of power stations.

| | |
|---|---|
| **as of approx. 5000 B.C.** | People utilize the energy of flowing water. |
| **approx. 300 B.C.** | The first water wheels are created and represent a milestone in the technological history of mankind. |
| **as of approx. 1600** | Water pressure is used as drive power. |
| **1653** | French physicist Pascal (1623-1662) illustrates the hydrostatic principle using the hydraulic press as an example. |
| **1795** | British engineer Joseph Bramah (1749-1814) produces a hydraulic press using water as a hydraulic fluid for generating large forces. He is thus considered to be the developer of industrial applications in hydraulics. |
| **1851** | British industrialist William G. Armstrong (1810-1900) develops an accumulator ("weight accumulator") with which large flows can be generated. |
| **1905** | Beginning of oil hydraulics: Williams and Janney use mineral oil as a transmission medium for hydrostatic transmissions for the first time. |
| **1922** | The engineer Hans Thoma invents the radial piston pump and develops it further for industrial use. The technical field of industrial hydraulics develops and becomes increasingly important. |
| **as of approx. 1950** | Oil hydraulics becomes prevalent in all areas of industrial hydraulics. The first servo valves for industrial hydraulics come into use Proportional control valves with analog electrical control are developed on constructive basis of on/off valves and introduced to industrial applications. |
| **as of approx. 1980** | Introduction of digital electronics in continuous control valve technology and associated with the development of digital control technology. |
| **as of approx. 2015** | With "Industry 4.0", comprehensive digitalization and networking of components and functional sequences as well as complete linking with adjacent technology areas are also making their way into hydraulics. |

*Overview of the history of hydraulics*

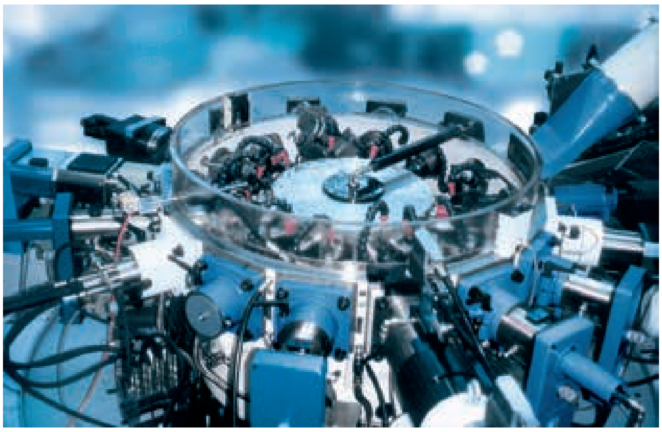
## 1.1.3 Fields of application of hydraulics

Hydraulic systems are used in the fields of power transmission and in both open and closed-loop control technology. In order to classify the variety of possible fields of application, a distinction is generally made between **industrial hydraulics** (or stationary hydraulics) and **mobile hydraulics**.

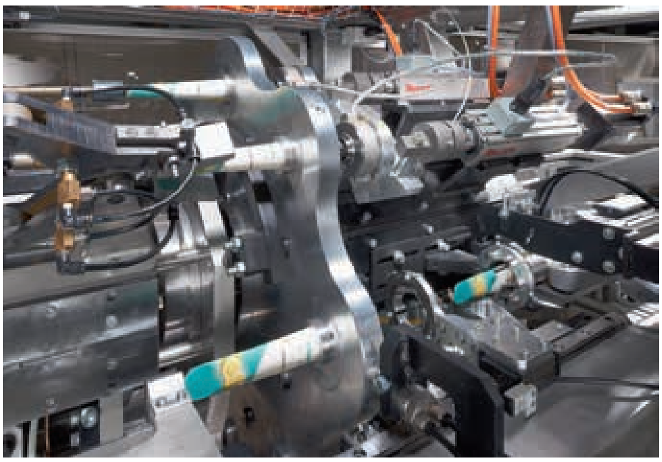
### Applications in industrial hydraulics

The term industrial hydraulics comprises applications in which hydraulic components are used in fixed installations. Examples include machine tools, plastics processing machines, presses and applications in the rolling mill industry.

*Plastic injection molding machine*



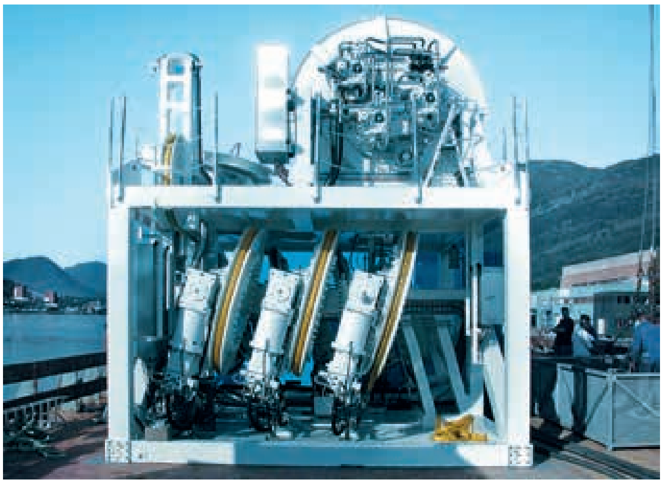
*Hydraulic axis*



*Processing machine for cardboard*

*Blank cutting line in the automotive industry*

*Tower Bridge in London*

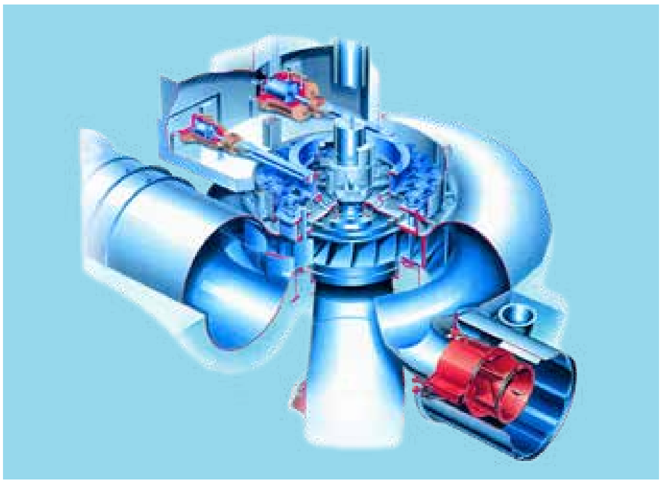


*Deep-sea winch*

*Lock in the Panama Canal*

*Offshore wind farm*

*Tunnel boring machine*



*Francis turbine*

## Applications in mobile hydraulics

Mobile hydraulics comprises applications in which hydraulic components are installed in mobile machines. For example, here hydraulics is used in hydraulic excavators, wheel loaders, road rollers, snow groomers, tractors, lift trucks, or municipal vehicles.

*Mobile excavator*

*Tractor with hoist*

*Snow groomer*

*Caterpillar crane*

*Truck mounted heavy duty crane*

*Wheel loader*

# 1.2 Drive technologies in comparison

## 1.2.1 Drive technologies

Solutions from the technological fields of hydraulics, pneumatics, electrics and mechanics come into use when designing drives:

- In hydraulic drives, motion is generated by means of hydraulic fluid. Hydraulic drives are used in many industrial fields as well as in mobile machines such as in excavators.
- In pneumatic drives, motion is generated by means of compressed air. Well-established applications include pneumatic assembly tools for screws and nuts in vehicle garages and the transportation of lightweight goods on production lines.
- Electric drive technology works mostly with electric motors, which are being increasingly controlled electronically. Electric drives are used, for example, in high-precision machine tools or in printing presses.
- Mechanical drives can generate translational or rotatory motion or curves by means of either crank drives, transmissions with a fixed transmission ratio, stepless transmissions or cam gears.

Different requirements are placed on drive technology, depending on application and use.
Differences between the drive technologies arise in particular with regard to the energy supply, the distribution of the energy, the properties of the transmission medium used and the properties of the drive (type of motion) itself.

In most applications in industry and other technical fields, several drive technologies are represented and work in interaction. This allows the advantages of each technology to be exploited and their disadvantages to be offset in the overall system design.

*Interaction of different drive technologies in modern stage technology (Krakow Opera)*

## 1.2.2 Comparison of drive technologies

The following table contains a comparison of drive technologies according to their most important technical criteria.

| Criterion | Hydraulics | Pneumatics | Electrics | Mechanics |
|---|---|---|---|---|
| **Energy carrier** | Hydraulic fluid | Air | Electrons | Motion, position, deformation |
| **Energy transmission** | Pipes, hoses, bores | Pipes, hoses, bores | Electrically conductive material | Shafts, rods, belts, chains, wheels etc. |
| **Conversion from / into mechanical energy** | Hydraulic pump, hydraulic motor, hydraulic cylinder | Compressor, pneumatic cylinder, pneumatic motor | Generator, magnet, electric motor | – |
| **Most important characteristics** | Pressure $p$, flow $q_V$ | Pressure $p$, flow $q_V$ | Voltage $U$, electric current $I$ | Force $F$, Torque $M$, Velocity $v$, Speed $n$ |
| **Storage** | Bladder-type accumulator, piston-type accumulator, diaphragm-type accumulator | Compressed air reservoir | Capacitor, battery, accumulator | Weight |
| **Power density** | Very good (high working pressures) | Good (limited by max. working pressure) | Not very good (power-weight ratio of electric motors approx. 10 times higher than that of hydraulic motors) | Good (if energy conversion is not necessary; limitations if high demands are placed on controllability) |
| **Efficiency** | Dependent on leakage and friction during energy conversion; losses during valve control (open and closed loop) | Dependent on leakage and friction during energy conversion; losses during valve control (open and closed loop) | Dependent on availability of electricity as primary energy source | Dependent on size of frictional losses |
| **Generation of linear motion** | Very easy (by means of cylinders; start-up and reversal of motion at full load possible) | Very easy (by means of cylinders) | Not very easy (by means of linear electric motor, threaded spindle etc.) | Simple (via crank drive, spindle etc.) |
| **Generation of rotational motion** | Easy (by means of hydraulic motor) | Easy (by means of compressed air motor) | Very easy (by means rotary electric motor) | Very easy (by means of transmission) |
| **Generation of curves** | Not very good | Not very good | Not very good | Very good for certain applications (bending technology) |
| **Path accuracy** | Very good (fluid is hardy compressible) | Not very good (air is compressible) | Varies: (not very good with asynchronous motors very good with synchronous and stepping motors) | Very good (by means of form and force fit) |
| **Controllability (open and closed loop), signal processing** | Very good (by means of valves and variable displacement pumps; use of servo valves in control technology; further improvements by combining with electric systems) | Very good (by means of valves) | Very good (by means of switches, relays, semiconductors, variable speed motors, variable resistors etc.) | Good (by means of transmissions, lever systems etc.) |

*Technical criteria of various drive technologies*

## 1.2.3 Differences in energy supply and conversion

The following overview illustrates the various methods and components for energy supply and energy conversion of drive technologies, divided into stationary and mobile applications.

| Drive technology | Operation | Energy supply | Energy conversion | Control | Generation of motion |
|---|---|---|---|---|---|
| **Hydraulics** | **stationary** | Mains | Electric motor + hydraulic pump | Hydraulic valve, variable displacement pumps, variable-speed pump drives or variable displacement motors, meter-out control | Hydraulic motor, hydraulic cylinder |
| | **mobile** | Fuel | Combustion engine and hydraulic pump or diesel-electric drive[1] and hydraulic pump | | |
| **Pneumatics** | **stationary** | Mains | Electric motor and compressor | Pneumatic valve | Pneumatic motor, pneumatic cylinder |
| | **mobile** | Fuel | Combustion engine and compressor or diesel-electric drive[1] and compressor | | |
| **Electrics** | **stationary** | Mains | -- | Converter, switch, relay ... | Electric motor |
| | **mobile** | Fuel | Generator, combustion engine | | |
| | | Fuel cell | -- | | |
| | | Accumulator | -- | | |
| **Mechanics** | **stationary** | Mains and electric motor | Transmission or speed adjustment | Steplessly adjustable transmission (by means of centrifugal force or lever ...) | Crank drives, transmission with fixed or stepless transmission ratio, cam gears |
| | **mobile** | Fuel | Combustion engine | | |

[1] ... diesel-electric drive consisting of diesel engine, generator and electric motor

*Energy supply and energy conversion of drive technologies*

## 1.2.4 Differences in energy distribution

Depending on the drive technology and the transmission medium used, energy distribution is determined using the following criteria:

- Range of energy transmission
- Flow velocity of the medium
- Propagation rate of waves in the medium

An economically viable energy transmission distance is limited by transmission losses which depend on the flow of the medium.

| Drive technology | Transmission medium | Range of energy transmission | Flow velocity | Wave propagation velocity |
|---|---|---|---|---|
| **Hydraulics** | Hydraulic fluid | < 100 m | 2 to 15 m/s | Approx. 1.5 - 2 km/s |
| **Pneumatics** | Compressed air | < 1000 m | 10 to 50 m/s | Approx. 0.34 km/s |
| **Electrics** | Electric charge | < 1000 km | 0.0007 m/s (electron velocity) | Approx. 300,000 km/s (in vacuum) |
| **Mechanics** | Mechanical components | Limited by mechanical stiffness | -- | -- |

*Transmission characteristics of drive technologies*

## 1.2.5 Properties of the transmission medium

Hydraulic fluid, compressed air, electric charge and mechanical components are transmission media whose properties influence the possibilities of energy storage, velocity of energy removal and environmental compatibility of the relevant drive technology.

### Energy storage

Depending on the different drive technologies, energy is stored in different ways:

- **Hydraulics**
  In hydraulics, the energy storage effect is minimal due to the low compressibility of the hydraulic fluid when compared with the compressibility of gases. Energy is stored using gas, usually nitrogen, as a compression medium. Due to the high system pressure, high amounts of energy are stored. This requires special safety-related measures.

- **Pneumatics**
  Air is used as a compression medium to store pneumatic energy. Besides special pressure vessels, the entire system constitutes an energy store. For safety reasons, the system pressure must therefore be kept relatively low. The pressure range in pneumatic systems lies between 4 and 6 bar.

- **Electrics**
  Electric energy storage is associated with high energy losses. As a general rule, coils and capacitors are suitable storage media. With capacitors, the energy loss can, however, be controlled more easily than with coils. Apart from capacitors, batteries and accumulators in particular are used to store energy in electric drive technologies.

- **Mechanics**
  Mechanical energy is stored by means of spindle drives (potential energy) and braking energy by means of flywheels (kinetic energy). This enables connecting of energy during acceleration processes. Limited amounts of energy can be stored through the use of engineered springs.

### Velocity of energy removal

Energy stored in hydraulic, pneumatic and mechanical accumulators can be retrieved very quickly. Capacitors can also quickly release energy. Batteries and accumulators can store considerably more energy, though they only release it slowly.

### Environmental compatibility

The drive technologies differ considerably in terms of their environmental compatibility due to the transmission medium used in each case (hydraulic fluid, compressed air, electrical charge, ...):

- **Hydraulics**
  In hydraulic drives, undesired leakage of hydraulic fluids from the system (external leakage) constitutes a potential hazard for the environment. This hazard can be largely excluded by using biodegradable fluids or water. Collection of leaked fluids and proper disposal of used hydraulic fluids must be ensured.

- **Pneumatics**
  Pneumatic drives in modern systems (oil-free air) are very environmentally compatible, as compressed air can be directly discharged into the environment without filtration. Return of the transmission medium to a tank, as is the case with hydraulic drives, is not necessary here.

- **Electrics**
  In electric drives, electro-magnetic radiation must be taken into account and suitable countermeasures may need to be taken.

- **Mechanics**
  Mechanical drives are very environmentally friendly in fault-free operation as there is no impact on the environment (no exhaust air or external leakage of components).

### 1.2.6 Properties of drive technologies

Drive technologies differ in the conditions required and options available to generate motion. Criteria for comparison preferably include motion type (rotary, linear), structural design (direct drive, used in transmission), force density, control behavior, accuracy, efficiency and safety aspects.

The following findings are based on the comparison of application characteristics of drive technologies:

- Hydraulic and pneumatic drives are particularly suitable for **linear and rotatory motion** that can be easily generated by hydraulic cylinders or motors. Electric drives have a complex structure and are predominantly built to generate **rotational motion**. Depending on their design, mechanical drives are suitable for both linear and rotary motion as well as for producing predefined curves.

- In comparison to electric drives, the volume-related **power density** of hydraulic drives is much larger. In contrast, the power density of pneumatic drives is significantly lower.

- Hydraulic and pneumatic drives are used both as **direct drives** as well as with mechanical transmissions. Electric drives often use a transmission to adjust torque and speed. With electric drives, integration of the motor into the machine construction is only economically efficient if the highest demands are placed on dynamics and stiffness.

- The achievable **torques and forces** of hydraulic and electric drives are considerably larger than those in pneumatics. For generation of identical forces, electric drives need to be considerably larger than hydraulic drives.

- Electric motors need about three times the rated current to generate torque from standstill. This results in considerable heating of the electric motor, making **additional cooling** necessary.

- Electric and mechanical drives offer a high degree of **efficiency**. The efficiency of hydraulic and pneumatic drives is lower as there are additional losses due to flow losses and leakage. Moreover, in pneumatics, efficiency is considerably reduced by the heat generated in the compressor that is dissipated into the environment.

- In hydraulic and pneumatic drives, **overload protection** can be easily achieved by means of overload safety valves (pressure relief valves). In mechanical drives overload protection can also be achieved without any problem by predetermined breaking points. In electric drives, overload protection is more complicated, as it is difficult to dissipate resulting losses in the form of heat.

- By using isolation valves in hydraulic and pneumatic drives, it is easy to **stop motion in case of emergency**. Electric drives offer a quick emergency stop by disconnecting the energy supply. Additional braking measures should be provided to prevent the electric motor continuing to run uncontrolled.

- Pneumatic drives can be **used in explosive areas** with relatively low effort, provided the air does not contain any oil. In hydraulic systems, the use of flame-resistant hydraulic fluids is essential. When using electrically controlled valves, the components must be designed in a way which is intrinsically safe or explosion-proof. Electric drives, however, must always be encapsulated in pressure-tight housings. In mechanical drives, suitable materials must be used. For instance, use of aluminum is prohibited in mining operations (applies to all drive technologies).

### 1.2.7 Conclusion

Comparison of individual drive technologies leads to the following conclusions:

- **Hydraulics**
  Hydraulic drives offer the advantage of generating high forces yet with a very compact design.
  A disadvantage of this drive technology is the effort required to prevent hydraulic fluid from escaping and entering the environment.

- **Pneumatics**
  Pneumatic drives can generally be used if fast motion and little force are required. Further advantages include comparatively low capital costs and good environmental compatibility. The relatively high noise development is a disadvantage of this technology.

- **Electrics**
  Electric drives feature high control dynamics and flexibility. On the other hand, capital costs are comparatively high.

- **Mechanics**
  Mechanical drives are straightforward to construct and are easily able to generate linear and rotational motion. However, one disadvantage is the less effective controllability.

By combining various drive technologies, e.g. the combination of hydraulics and electrical engineering in variable-speed pump drives (Sytronix), the advantages of the respective technology can be optimally utilized and the disadvantages compensated as required.

## 1.3 Graphic symbols

### 1.3.1 Purpose

In hydraulics, graphical symbols (also referred to as switching symbols) are used for the abstract illustration of fluid power components and their functions, as well as to explain hydraulic circuit systems.
Graphic symbols consist of one or more basic element(s) and generally of one or more functional symbol(s) in accordance with a specific system.
They are designed in such a way that the function of the components or circuits illustrated can be quickly and easily understood.
Structural details of components are not taken into account in the symbolic illustration.
Graphic symbols are mainly used in circuit diagrams, product catalogs and operating instructions.
They are an important aid in project planning, assembly, commissioning, inspection, troubleshooting and maintenance of hydraulic systems.

### 1.3.2 Graphic symbols according to DIN ISO 1219

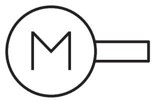
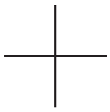
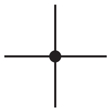
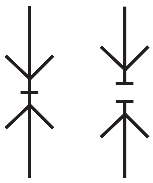
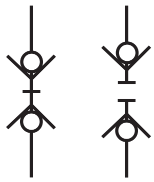
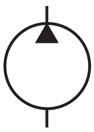
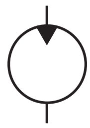
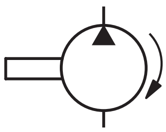
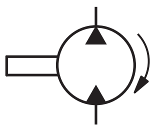
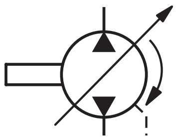
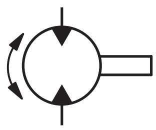
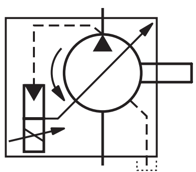
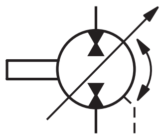
#### Scope and standard

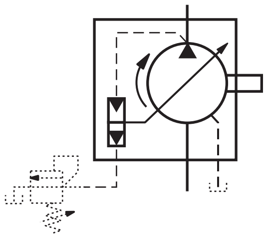
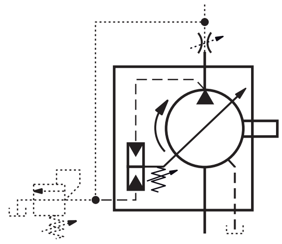
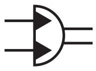
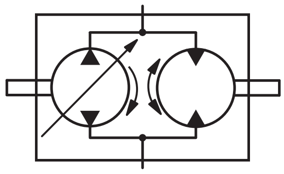
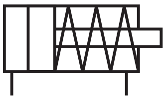
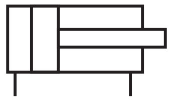
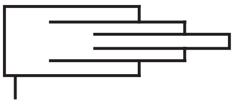
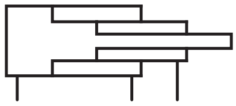
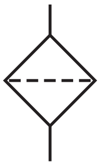
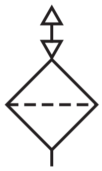
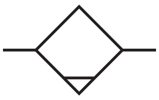
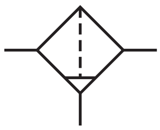
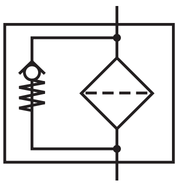
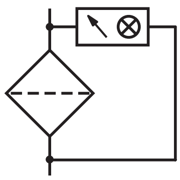
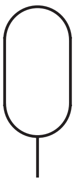
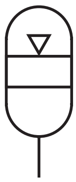
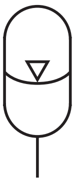
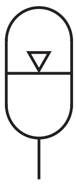
Graphic symbols for fluid technology are used worldwide and are defined in DIN ISO 1219 and standardized in an internationally binding manner.

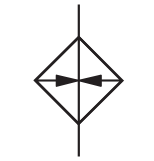
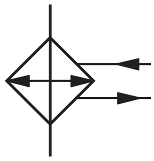
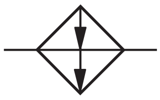
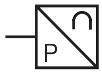
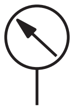
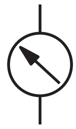
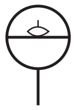
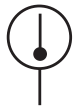
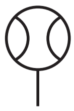
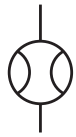
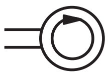
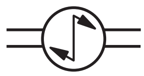
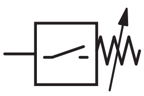
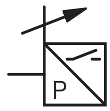
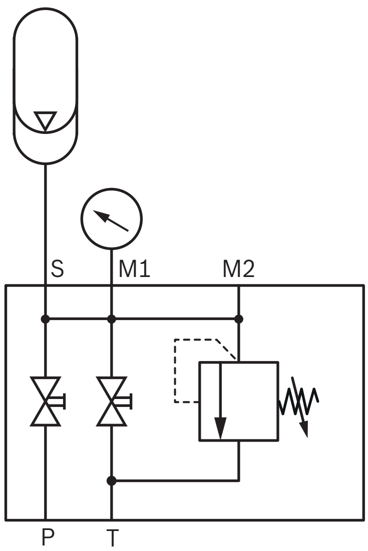
The exclusive sale of standard sheets in Germany is carried out by:
- Beuth Verlag GmbH, 10772 Berlin

The following list shows examples of graphic symbols according to the standard DIN ISO 1219 (Part1: "Graphic symbols for conventional use and data-processing applications"). This list serves as working aid for assignment of graphic symbols and reading or creating of hydraulic circuit diagrams.

## 1.3.3 Graphic symbols according to DIN ISO 1219 – Pumps, motors, cylinders, accessories

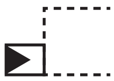
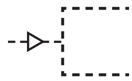
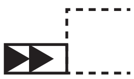
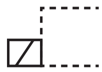
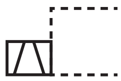
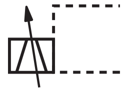
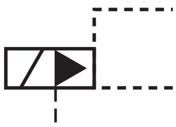
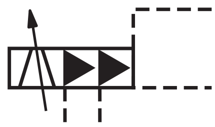
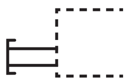
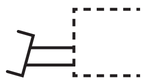
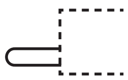
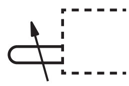
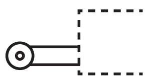
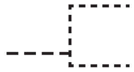
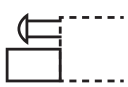
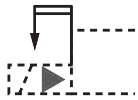
| Element description | Symbol | Element description | Symbol |
|---|---|---|---|
| Energy source, hydraulic |  | Energy source, pneumatic |  |
| Drive unit<br>(except for electric motor) |  | Electric motor |  |
| Main line (rigid)<br>Control or leakage oil line |  | Hose line (flexible) |  |
| Line crossing<br>(lines not connected) |  | Line connection |  |
| Tank |  | Tank with line |  |
| Quick-release coupling without non-return valve to be opened mechanically, coupled/uncoupled |  | Quick-release coupling with non-return valve to be opened mechanically, coupled/uncoupled |  |
| Hydraulic pump, general |  | Hydraulic motor, general |  |
| Fixed displacement pump with:<br>• 1 flow direction<br>• 1 direction of rotation |  | Fixed displacement pump/motor with:<br>• 1 flow direction<br>• 1 direction of rotation |  |
| Variable displacement pump with:<br>• 2 flow directions<br>• 1 direction of rotation<br>• drain port |  | Fixed displacement motor with:<br>• 2 flow directions<br>• 2 directions of rotation |  |
| Variable displacement pump with hydraulic servo adjustment and:<br>• 1 flow direction<br>• 1 direction of rotation<br>• drain port |  | Variable displacement pump/motor with:<br>• 2 flow directions<br>• 2 directions of rotation<br>• drain port |  |

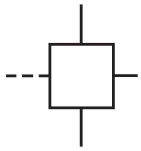
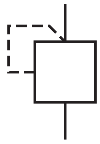
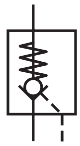
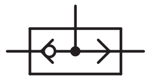
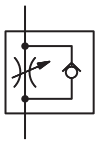
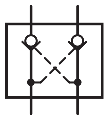
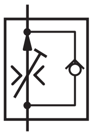
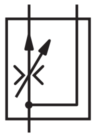
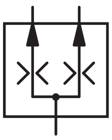
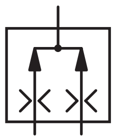
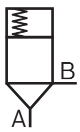
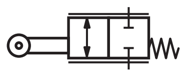
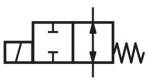
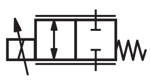
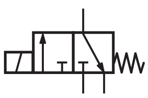
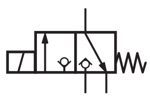
| **Element description** | **Symbol** | **Element description** | **Symbol** |
|---|---|---|---|
| Variable displacement pump with pressure controller (pilot-operated) and:<br>• 1 direction of rotation<br>• drain port |  | Variable displacement pump with combined pressure/flow controller and:<br>• 1 direction of rotation<br>• drain port |  |
| Hydraulic swivel motor |  | Compact hydro transmission |  |
| Single-acting hydraulic cylinder, with piston rod on one side, return stroke by spring force, spring chamber with port |  | Double-acting hydraulic cylinder with piston rod on one side |  |
| Single-acting telescopic hydraulic cylinder |  | Double-acting telescopic hydraulic cylinder |  |
| Filters, general |  | Breathing filter tank |  |
| Separator |  | Filter with separator |  |
| Filter with bypass valve |  | Filter with visual clogging indicator (pressure difference-based) |  |
| Accumulator, general |  | Piston-type accumulator |  |
| Bladder-type accumulator |  | Diaphragm-type accumulator |  |

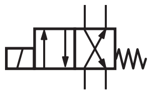
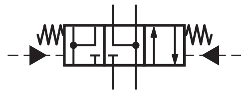
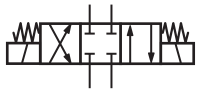
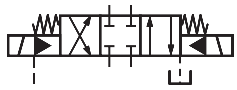
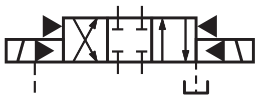
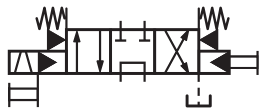
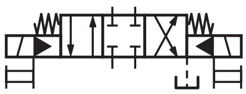
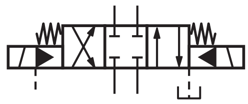
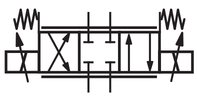
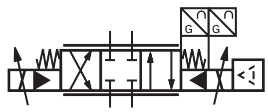
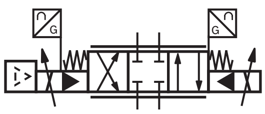
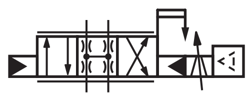
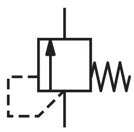
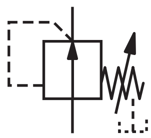
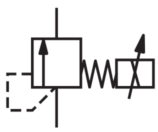
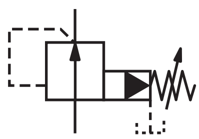
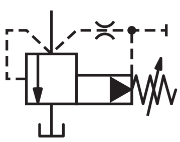
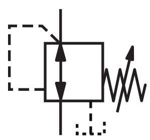
| Element description | Symbol | Element description | Symbol |
|---|---|---|---|
| Heater |  | Cooler with cooling fluid |  |
| Thermostat |  | Pressure sensor, output signal analog |  |
| Pressure measuring instrument (manometer) |  | Pressure differential gauge |  |
| Fluid level indicator (sight glass) |  | Thermometer |  |
| Flow indicator |  | Flow meter |  |
| Tachometer |  | Torque measuring instrument |  |
| Pressure switch, electro-mechanical, adjustable |  | Pressure switch, electronically adjustable, output signal switching |  |
| Accumulator with accumulator shut-off block<br><br>Accumulator shut-off block with:<br>• system-shut-off valve<br>• pressure relief valve (safety valve)<br>• manual relief<br>• pressure measuring instrument (manometer) |  | | |

*Selection of symbols from the fields of pumps, motors, cylinders, accumulators and accessories*

## 1.3.4 Graphic symbols according to DIN ISO 1219 – Hydraulic valves

| Element description | Symbol | Element description | Symbol |
|---|---|---|---|
| Hydraulic operation (single-stage) |  | Pneumatic operation (single-stage) |  |
| Hydraulic operation (two-stage) |  | Operation by means of solenoid coil with one winding |  |
| Operation by means of solenoid coil with two counteracting windings |  | Operation by means of solenoid coil with two counteracting windings, continuously adjustable |  |
| Electrical operation (solenoid coil with one winding), hydraulic pilot control with external pilot oil supply |  | Electrical operation (solenoid coil with two counteracting windings, continuously adjustable), two-stage hydraulic pilot control with external pilot oil supply |  |
| Operation by pushbutton |  | Operation by pedal |  |
| Operation by fulcrum |  | Operation by lever |  |
| Operation by plunger |  | Operation by plunger with adjustable stroke limitation |  |
| Operation by roller plunger |  | Operation by spring force |  |
| Operation by hydraulic pressurization (by the use of pilot oil) or pressure relief, directly acting on the operating element |  | Operation by hydraulic pressurization (by the use of pilot oil) or pressure relief by means of different-sized, opposing control areas |  |
| Two operations acting in parallel |  | Mechanical feedback |  |

| Element description | Symbol | Element description | Symbol |
| --- | --- | --- | --- |
| External pilot oil line |  | Internal pilot oil channel |  |
| Throttle valve, adjustable |  | Non-return valve |  |
| Non-return valve with spring |  | Pilot-operated double non-return valve with spring, valve is opened by pilot pressure |  |
| Shut-off valve |  | Shuttle valve (OR function) |  |
| Throttle/non-return valve, adjustable |  | Double non-return valve, pilot-operated |  |
| 2-way flow control valve, permanently adjusted, with bypass non-return valve |  | 3-way flow control valve, adjustable |  |
| Flow divider |  | Flow totalizer |  |
| Pressure control valve and directional control valve installation kit, poppet design |   | Throttle valve, operation with roller plunger, spring return |  |
| 2/2 directional control valve, normally open, solenoid operation, spring return |  | 2/2 proportional directional control valve, normally closed, solenoid operation, spring return |  |
| 3/2 directional control valve, normally closed, solenoid operation, spring return |  | 3/2 directional poppet valve, normally closed, solenoid operation, spring return |  |

| Element description | Symbol | Element description | Symbol |
|---|---|---|---|
| 4/2 directional control valve, solenoid operation, spring return |  | 4/3 directional control valve, hydraulic operation, spring centering |  |
| 4/3 directional control valve, direct solenoid operation, spring centering of center position |  | 4/3 directional control valve, pilot-operated, electro-hydraulic operation, spring centering of center position, external pilot oil supply and pilot oil return |  |
| 4/3 directional control valve, two-stage, electro-hydraulic operation, pressure centering of center position, external pilot oil return |  | 4/3 directional control valve, two-stage, electro-hydraulic operation, spring centering of center position, main control spool with additional pressure centering, with emergency operation, external pilot oil return |  |
| 4/3 directional control valve, pilot-operated, electro-hydraulic operation, spring centering of center position, with emergency operation, external pilot oil return |  | 4/3 directional control valve, pilot-operated, electrical operation of the pilot control stage and hydraulic operation of the main stage, without emergency operation, spring centering of center position, external pilot oil supply and pilot oil return |  |
| 4/3 proportional directional control valve, direct solenoid operation, spring centering of center position |  | 4/3 proportional directional control valve, pilot-operated, with position control of main and pilot control stages, with integrated electronics |  |
| 4/3 proportional directional control valve, pilot-operated, with actuating solenoid, with position control of the main and pilot control stages, with integrated electronics |  | 4/3-way servo valve, pilot-operated, pilot control stage with electrical operation, with mechanical feedback of the control spool position, with integrated electronics |  |
| Pressure relief valve, direct-operated, internal pilot oil supply |  | 2-way pressure reducing valve, direct-operated, adjustable, internal pilot oil supply, external pilot oil return |  |
| Proportional pressure relief valve, direct-operated, solenoid acts via spring on valve poppet, internal pilot oil supply |  | 2-way pressure reducing valve, pilot-operated, internal pilot oil supply, external pilot oil return |  |
| Pressure relief valve, pilot-operated, internal pilot oil supply and return |  | 3-way pressure reducing valve, direct-operated, internal pilot oil supply, external pilot oil return |  |

*Selection of symbols from the field of hydraulic valves*

# 2 Basic principles of physics

## 2.1 Basic principles of hydraulics

### 2.1.1 Hydrostatics – Pascal's Law

#### Short description

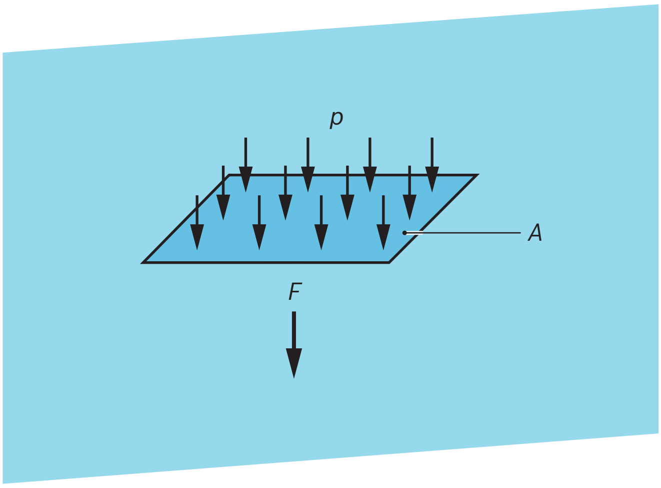
Hydrostatics describe the state of resting fluids. In this respect, Pascal's Law is of major significance. This law of physics describes the effect of pressure on resting fluids – the pressure propagates evenly in all directions.

#### Pascal's Law

##### Definition of pressure

Pressure is a basic physical parameter in hydrostatics. Pressure *p* is defined as the vertically acting force *F* on the area *A*.

$$p = \frac{F}{A} \quad \Rightarrow \quad F = p \cdot A$$




*Pressure p on area A creates force F*

##### Physical measurement units of pressure

**Physical unit of pressure as per definition**

According to the International System of Units (SI), the physical unit of pressure is the **Pascal (Pa)**:

$$1\,\text{Pa} = 1\,\frac{\text{N}}{\text{m}^2}$$

In hydraulics, a pressure of 1 Pa is an extremely low and impractical value. Relevant specified pressures could start at approx. 10000 Pa and could reach values with up to seven digits.
Therefore, to avoid massive numerical values, the unit megapascal (MPa) is used:

$$1\,\text{MPa} = 10^6\,\text{Pa} = 1\,\frac{\text{N}}{\text{mm}^2}$$

**Physical unit of pressure in practice**

In hydraulics, according to the EU directive, the unit "bar" (bar) is also permitted in addition to the SI unit and is widely used in practice:
- 1 bar = 10 N/cm$^2$
- 1 bar = $10^5$ Pa
- 1 bar = 0.1 MPa

In the US, however, the unit **pound-force per square inch (psi)** is commonly used:
- 1 psi = 6894.757293168 Pa

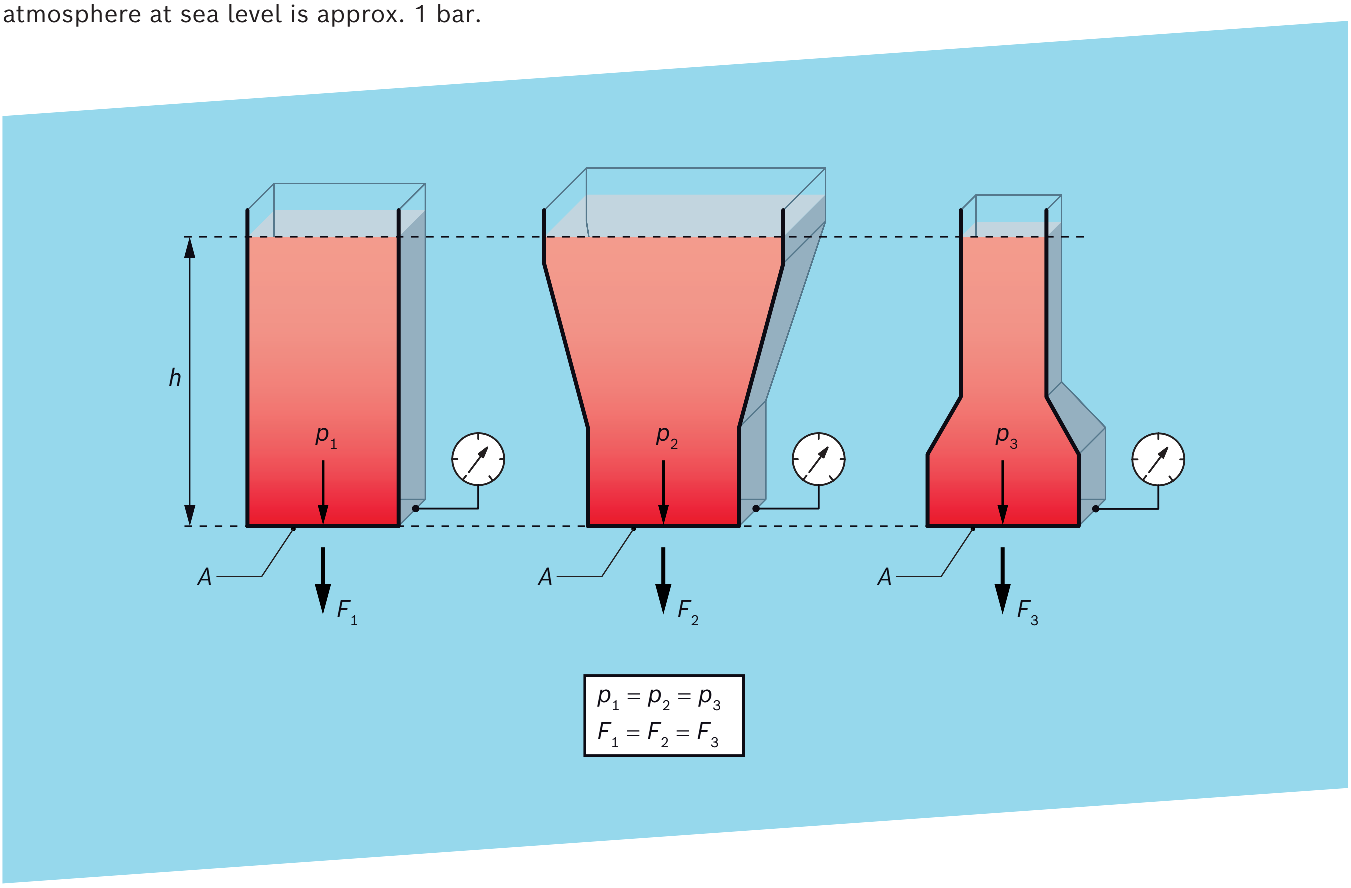
For practical reasons, the following conversion factors are applied:
- 1 bar = 14.49 psi
- 1 psi = 0.069 bar

## Hydrostatic pressure due to gravity

If it is only gravity which acts on a fluid, then the pressure in it will depend on the height of the fluid column and the density of the fluid. This pressure is referred to as gravitational pressure.

In water, the increase in the hydrostatic pressure with the height of the water column amounts to approx. 1 bar per 10 m. In air, the pressure of the earth's entire atmosphere at sea level is approx. 1 bar.

With a series of vessels of different shape, it can be observed that, provided the same fluid is used, the pressure at the bottom will only depend on the height of the fluid column and not on the shape of the vessel or the fluid quantity. This phenomenon is referred to as a **hydrostatic paradox**.




*Hydrostatic paradox (for the same area A)*

The following relationship is derived from this:

$$p = \rho \cdot g \cdot h$$

- $p$ Hydrostatic pressure
- $\rho$ Specific density of the fluid
- $g$ Acceleration due to gravity (9.81 m/s²)
- $h$ Height of the fluid column

The hydrostatic pressure due to gravity as described by **Pascal's Law**:

> The effect of a force on a resting fluid propagates in all directions within the fluid. Without external forces, the level of pressure in the fluid corresponds to the weight, referred to its effective area.
> The pressure always acts vertically on the tank boundary surfaces.

## Path transmission (hydraulic lever rule)

For incompressible fluids, the following applies:
*In a closed system, the total volume of the fluid does not change.*

As shown in the graph "Force and path transmission" (on page 27), the volume of hydraulic fluid displaced by one piston must push against and move the other piston (displacement principle).
The change in partial volumes is the same in both cylinder spaces within the system and is determined by the following formula:

$$\Delta V = A_1 \cdot s_1 = A_2 \cdot s_2$$

The paths are inversely proportional, as with the associated piston areas.

$$\frac{s_1}{s_2} = \frac{A_2}{A_1}$$

Therefore, the piston with the smaller piston area performs a larger stroke than the piston with the larger piston area:

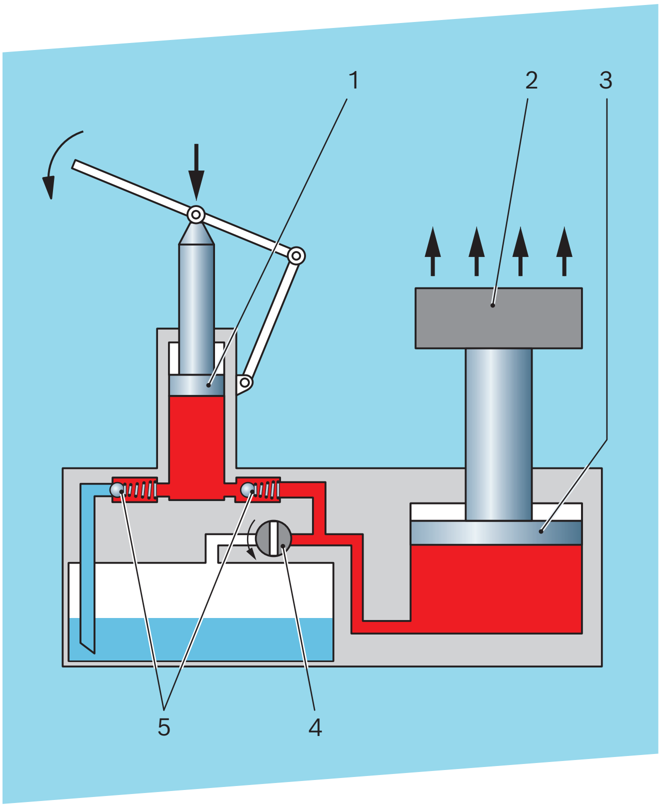
$$s_1 = s_2 \cdot \frac{A_2}{A_1}$$

As with mechanics, this correlation applies as the hydraulic lever rule. "Path transmission" is derived from this correlation.

## Application of force and path transmission

Force and path transmission are used, for example, in hydraulic lifting platforms for lifting heavy loads. The cylinder of the hand pump is characterized by a large stroke with a small piston area. This means that only a low force is required to deliver the necessary volume of hydraulic fluid to the working cylinder with many strokes.
At the working piston with a larger area, there is transmission into a large force at the lifting platform with a shorter path.

The following figure is intended to illustrate the application of force and path transmission to a hydraulic lift. Non-return valves prevent the hydraulic fluid from flowing back into the hand pump and thus prevent the working piston from lowering.
To lower the load on the lifting platform, a blocking element is provided (here a rotary spool), which controls the discharge of the hydraulic fluid into the tank.



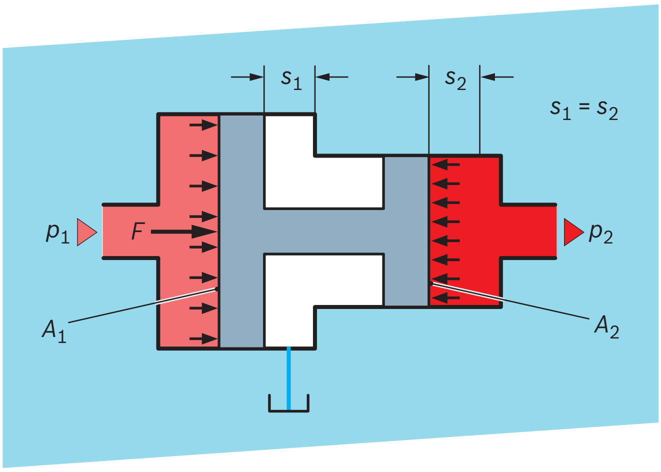

1 Cylinder piston of hand pump
2 Lifting platform
3 Cylinder piston of lifting platform
4 Rotary spool
5 Non-return valves

*Principle of a hydraulic lifting platform (application of force and path transmission)*

*Hydraulic jack*
*(practical example of application of force and path transmission)*

## Pressure intensification

The principle of pressure intensification is the conversion of an input or primary pressure to a generally higher outlet pressure or secondary pressure.
At mechanical coupling of pressurized areas, the pressure is intensified proportionally to these areas.
The prerequisite is two firmly connected piston areas of different sizes in a closed hydraulic system.




*Principle of pressure intensification (intensifier)*

Pressure $p_1$ acts on the large piston and generates force $F$ that generates pressure $p_2$ by means of the small piston.

$$p_1 \cdot A_1 = F = p_2 \cdot A_2$$

Therefore, the pressure is inversely proportional to the associated piston areas.

$$\frac{p_1}{p_2} = \frac{A_2}{A_1}$$

"Pressure intensification" is derived from this correlation.

### Application of pressure intensification

A typical application example of pressure intensification uses a component known as a pressure intensifier (see figure above "Principle of pressure intensifiers" and section "Pressure intensifiers"on page 342).
The pressure intensifier increases an existing pressure.
The primary pressure at the input side is intensified to a higher secondary pressure at the output side at an inverse ratio of the effective piston area.

The flows at the primary and secondary sides behave as the piston areas do.

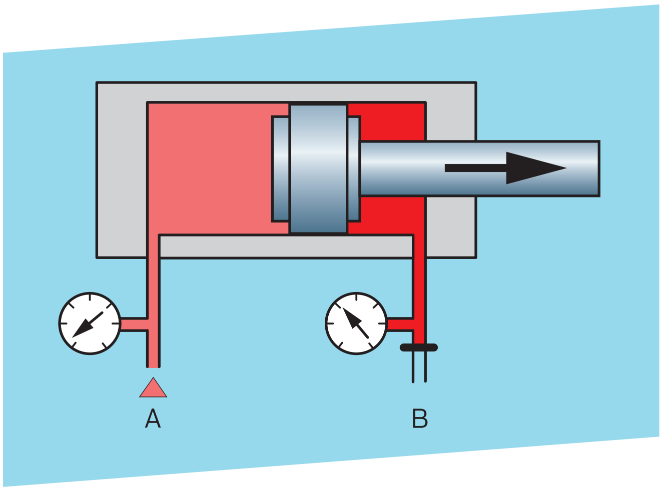
$$\frac{q_{v1}}{q_{v2}} = \frac{A_1}{A_2}$$

The flow is calculated according to the following formula.

$$q_V = \frac{A \cdot s}{t}$$

Due to the mechanical separation of the two areas of the pressure intensifier, different pressure media (e.g. hydraulic oil) can be used for the primary area and for the secondary area (e.g. water).

### Hazard due to pressure intensification




*Pressure intensification in double-acting hydraulic cylinder*

If the hydraulic cylinder is to be extended by pressurizing port A, but port B is closed, this would cause a pressure intensification between the cylinder chambers (corresponding to the ratio of the areas of the piston base side and the piston rod side).
In extreme cases, this pressure increase can cause the cylinder pipe and associated components to burst.

***Notice:***
*With regard to planning and dimensioning of hydraulic systems, it is important to consider the possible pressure intensification and pressure increase by hydraulic cylinders.*

# 3.2 Hydraulic pumps

## 3.2.1 External gear pumps

### Short description

External gear pumps are displacement machines in which the displacement chambers are made up gears with external gearing.
In the housing bores of external gear pumps, two gears engage, one of which is driven (e.g. by means of an electric motor). This driven gear drives the second gear in the opposite direction. The hydraulic fluid is delivered in the tooth clearances.

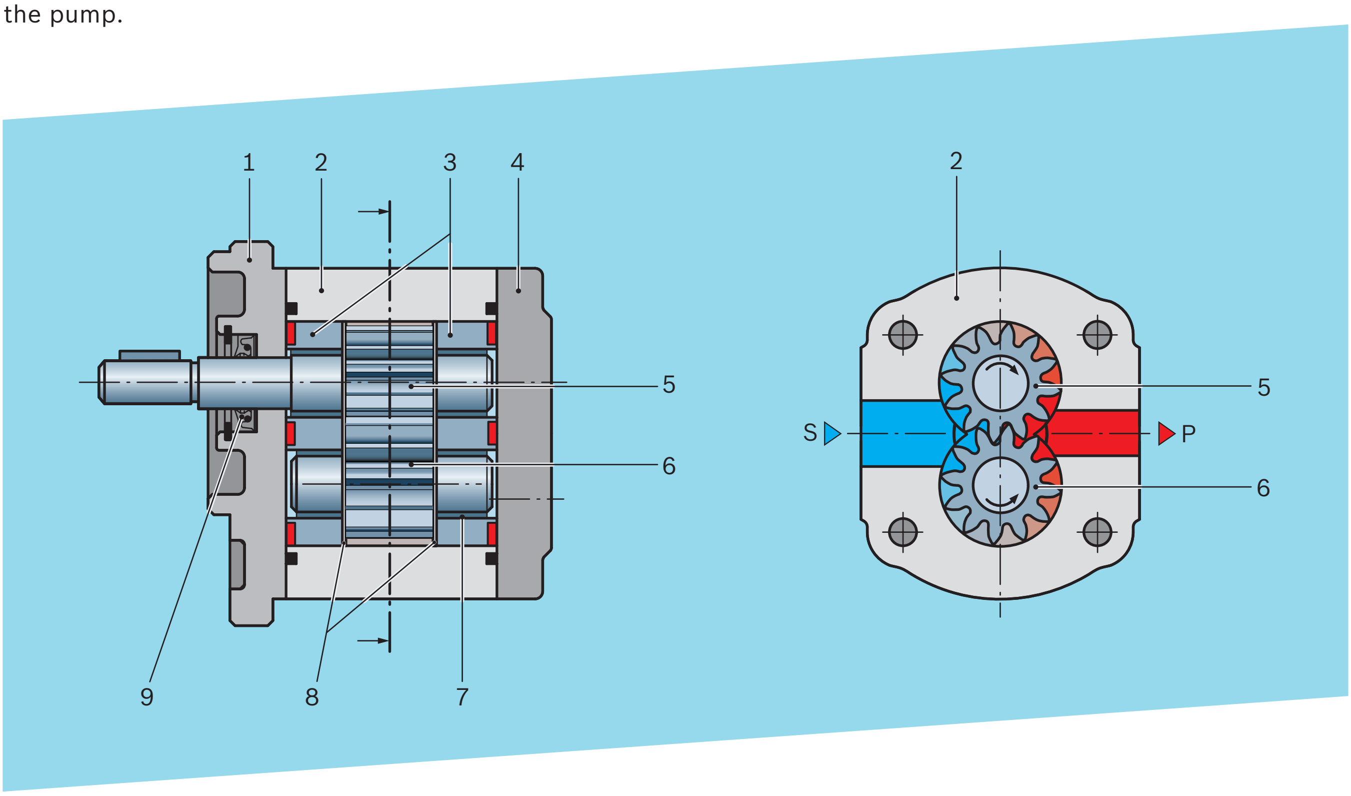
### Characteristics

External gear pumps are fixed displacement pumps. They are characterized by a compact design and high power density. They have good emergency running properties, so that momentarily insufficient lubrication, e.g. during start-up, does not cause damage to the pump.

Disadvantages are leakage and frictional losses as well as considerable noise development, which occur to varying degrees depending on the design and use of the pump.
External gear pumps consist of only a few components. The pump housing can be manufactured from an extruded aluminum profile with low manufacturing costs. External gear pumps can be used in a wide speed range and have only low requirements on the viscosity of the hydraulic fluid used. This results in numerous possible applications, particularly in mobile hydraulics (tractors and forklifts) and industrial applications.

### Design

The figure illustrates the general design of an external gear pump in longitudinal and cross-section.




1 Flange (front cover)
2 Housing
3 Bearing blocks
4 Housing cover (end cover)
5 Drive shaft with driving gear
6 Driven gear
7 Bearing
8 Sealing surface between bearing blocks and gears
9 Shaft seal ring
P Pressure port
S Suction port

*Longitudinal and cross-section of an external gear pump*

# 3.3 Hydraulic valves

## 3.3.1 Overview of hydraulic valves

### Short description

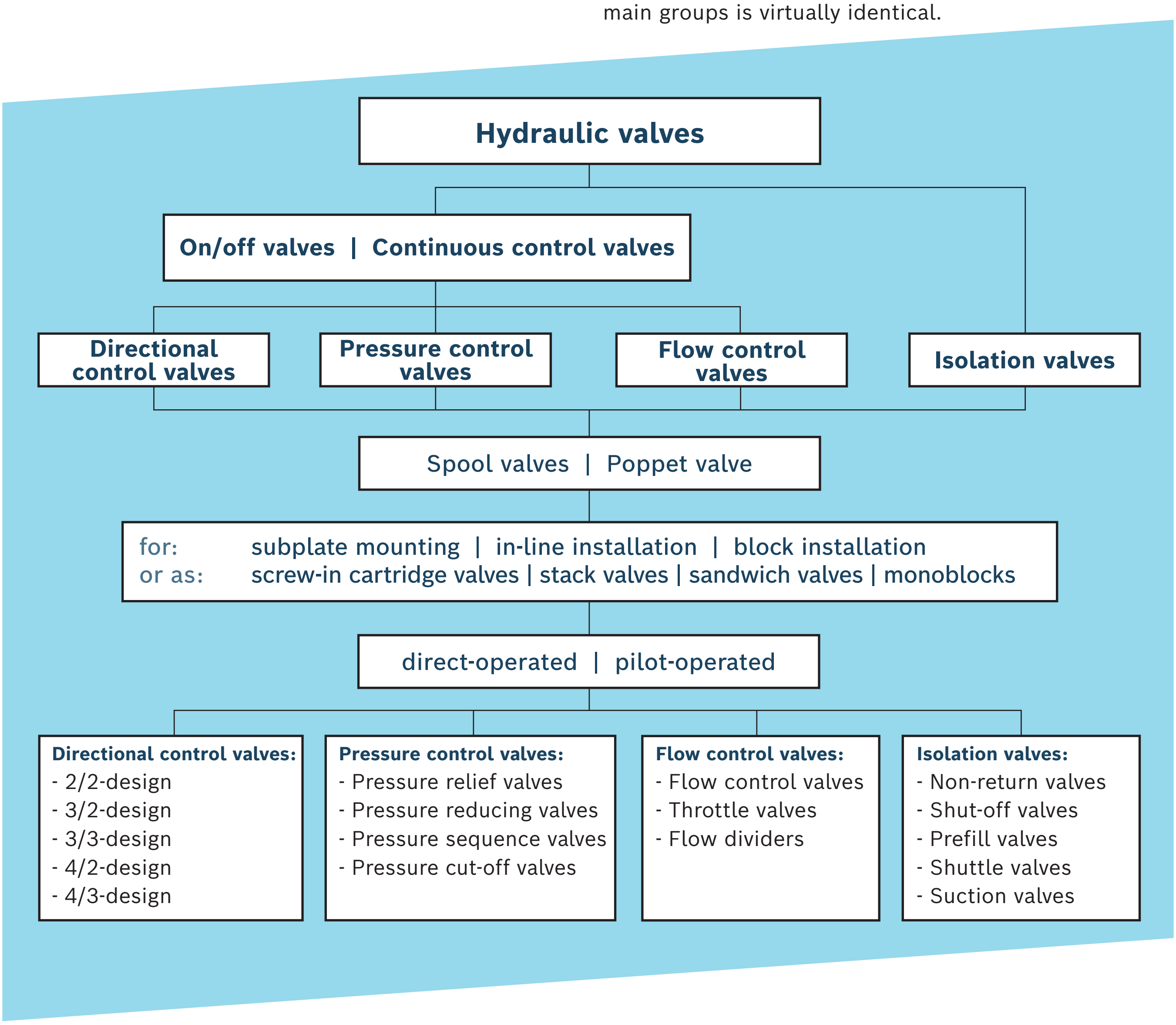
Hydraulic valves are components for open and closed-loop control of the energy flow in hydraulic systems. Depending on their design, they influence start, stop and volume of the flow, and thus also the direction of motion, the velocity of hydraulic actuators and the pressure level in hydraulic systems.

### Classification of hydraulic valves

The main distinction with this line of components is made between the signal behavior and mode of operation of the valve:

- **On/off valves**
  A change in the input signal results directly in an abrupt change of the hydraulic output signal (binary behavior; also referred to as "black and white valves"), without assuming an intermediate position.
- **Continuous control valves**
  A variable input signal is converted into a continuous and proportionally adjustable hydraulic output signal. With continuous control valves, a basic distinction is made between proportional control and servo valves.

Further subdivision of hydraulic valves within these two main groups is virtually identical.




*General criteria for classification of hydraulic valves*

# 3.4 Hydraulic cylinders

## 3.4.1 Basic principles of hydraulic cylinders

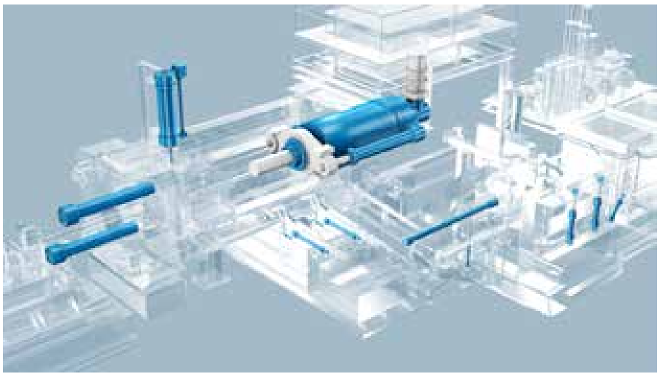
### Short description

Hydraulic cylinders are components for energy conversion that work according to the displacement principle. They convert the flow directed into the cylinder chamber into translational, i.e. linear motion.

### Characteristics

Hydraulic cylinders are able to transmit large forces along a route limited by their effective length. Depending on their construction type, hydraulic cylinders are able to transmit forces either in one or two directions.
In relation to their frame size, hydraulic cylinders are very powerful and are therefore used in all fields of industrial and mobile hydraulics.

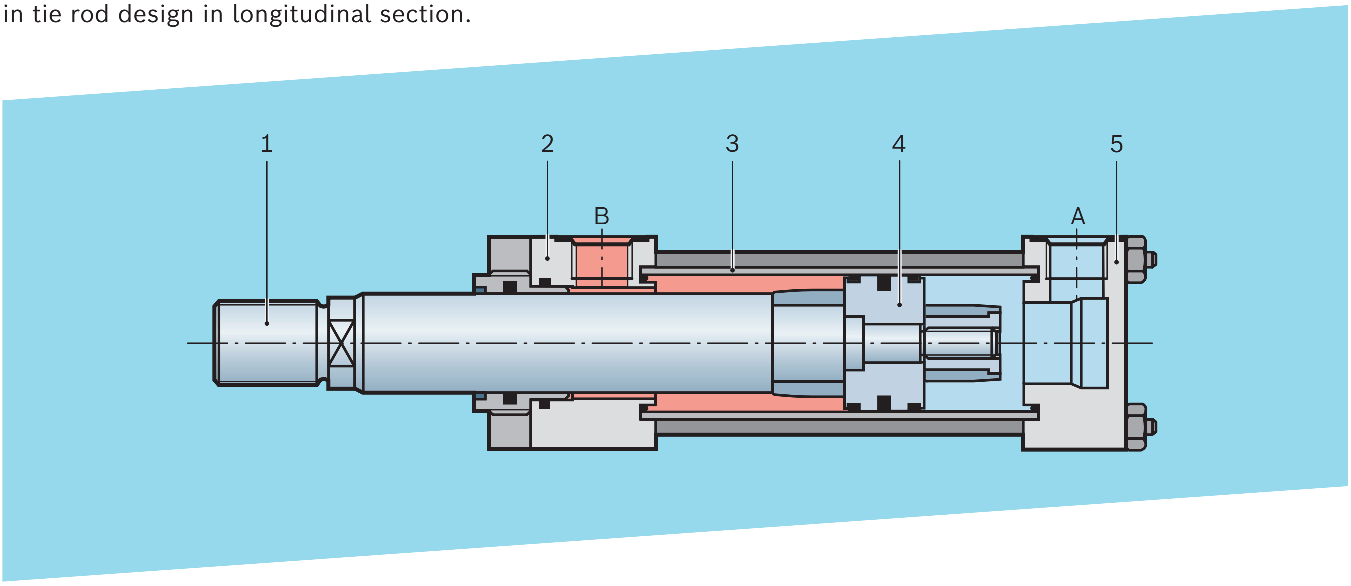
*Use of hydraulic cylinders in a wheel loader*



*Use of hydraulic cylinders in an extrusion press*

### Design

The figure illustrates a double-acting hydraulic cylinder in tie rod design in longitudinal section.




1 Piston rod
2 Cylinder head
3 Cylinder pipe
4 Piston
5 Cylinder base

A Piston base side port
B Piston rod side port

*Longitudinal section of a double-acting hydraulic cylinder in tie rod design*

# 3.5 Hydraulic motors

## 3.5.1 External gear motors

### Short description

External gear motors are displacement machines in which the displacement chambers are made up of gears with external gearing. High and low-pressure range are separated by the contact of the meshing gears.

### Characteristics

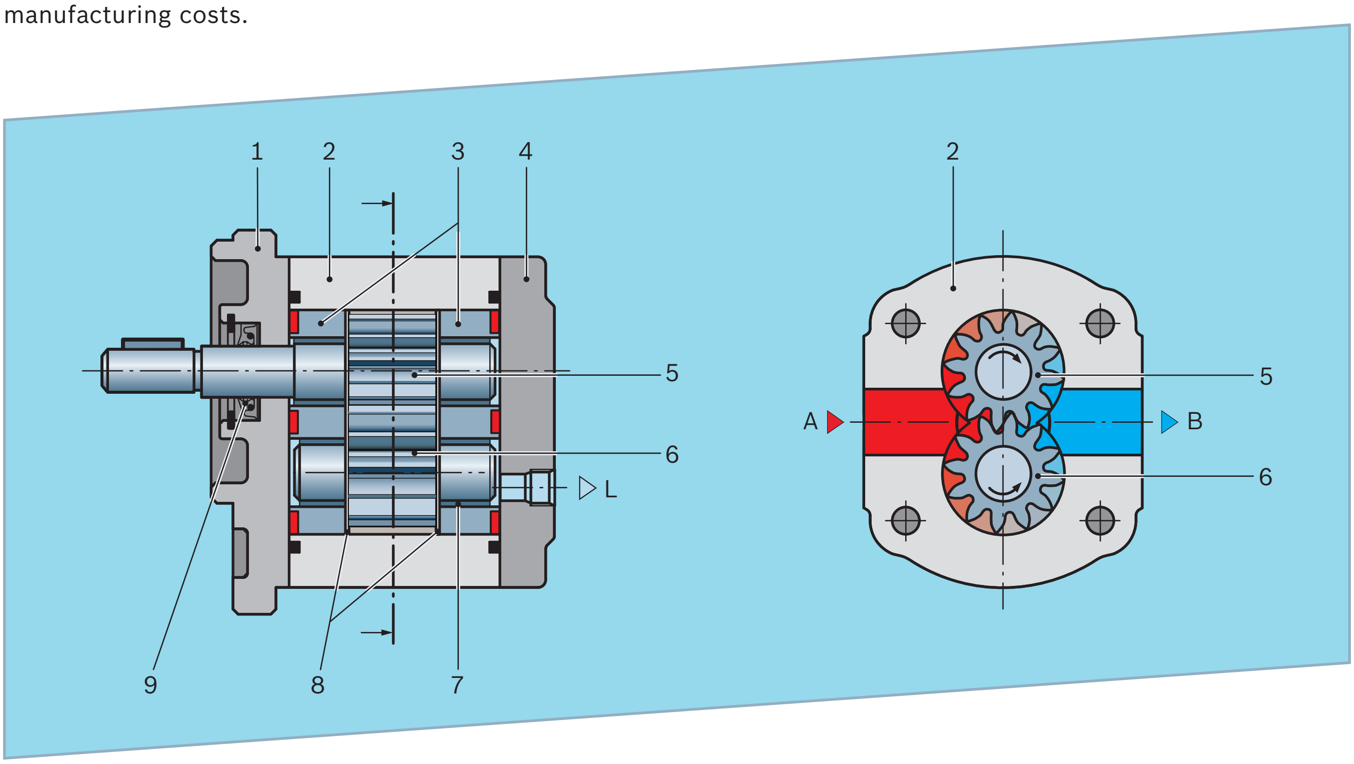
External gear motors are fast-running fixed displacement motors. They are characterized by a compact design and high power density.
These motors consist of few components and are compact in design. The housing can be manufactured from an extruded aluminum profile with low manufacturing costs.

External gear motors can be used across a wide speed range and operated with hydraulic fluids within a large viscosity range. This results in numerous possible applications, particularly in mobile hydraulics and industrial applications.
Application examples of external gear motors are as follows:

- Construction machines (road rollers and paving machinery)
- Road vehicles (buses and trucks)
- Agriculture and forestry (combined harvesters and forestry machinery)
- Plant construction (fan drives)

### Design

The figure illustrates the general design of an external gear motor in longitudinal and cross-section.




1 Flange (front cover)
2 Housing
3 Bearing blocks
4 Housing cover (end cover)
5 Output shaft with gear
6 Gear
7 Bearing
8 Sealing surface between bearing blocks and gears
9 Shaft seal ring
A High-pressure port
B Low-pressure port
L Drain port

*Longitudinal and cross-section of an external gear motor*

# 4 Basic circuits of hydraulics

## 4.1 Circuit diagrams in hydraulics

### 4.1.1 Graphical illustration of hydraulic circuits

#### Hydraulic circuit diagrams

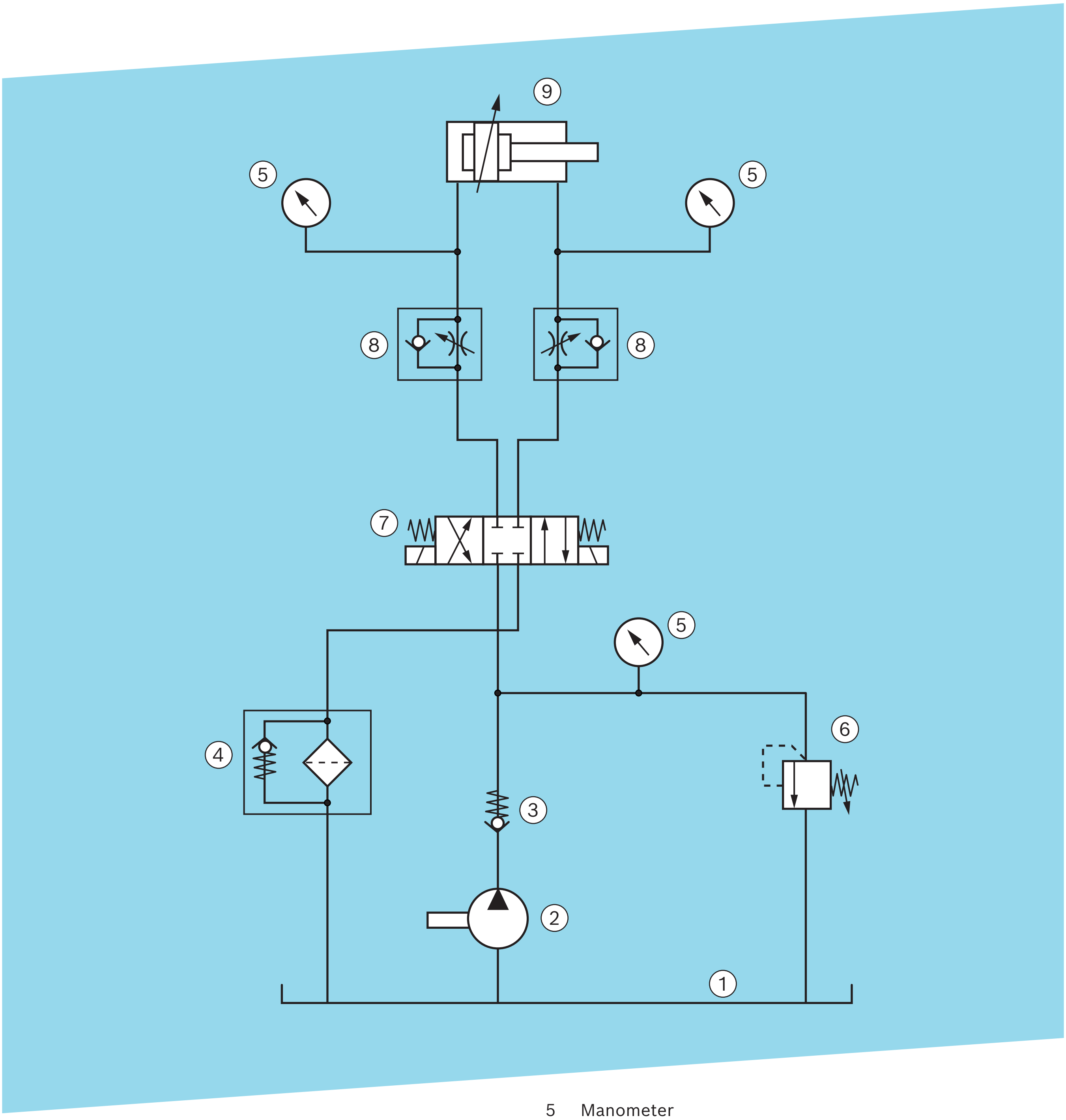
Circuit diagrams are created to graphically illustrate the components and their functions, their connections in the hydraulic system, and their interaction in the hydraulic system.
Circuit diagrams are aids to support understanding of the design and the description of hydraulic systems. They are also a suitable means of avoiding ambiguities and errors during the planning phase, production, assembly and maintenance of the hydraulic system by means of a standardized illustration of the hydraulic conditions.

Basic elements of hydraulic circuit diagrams are standardized graphic symbols of hydraulics according to ISO 1219 (see chapter "Graphic symbols" from page 18).
Graphic symbols of hydraulics do not provide information about the design structure of the components. They include abstractly represented functional units such as drive motors, hydraulic pumps, hydraulic valves, hydraulic cylinders or hydraulic motors, as well as accessory components or assemblies.
The illustration of the line links shows the connections between the individual components and assemblies.
Marking of components, compact assemblies and connection designations facilitates the assignment of the elements of the circuit diagram to the parts lists and conditions of the real hydraulic assembly. Furthermore, it is possible to enter required physical characteristic values at relevant positions of the circuit diagram.


*Reading and understanding a circuit diagram as a basis for working on hydraulic systems*

## Circuit diagram/circuit schematics

The following figure illustrates the **circuit diagram** of a hydraulic system with supply (hydraulic pump), components for control, safety and display as well as the hydraulic actuator (hydraulic cylinder).

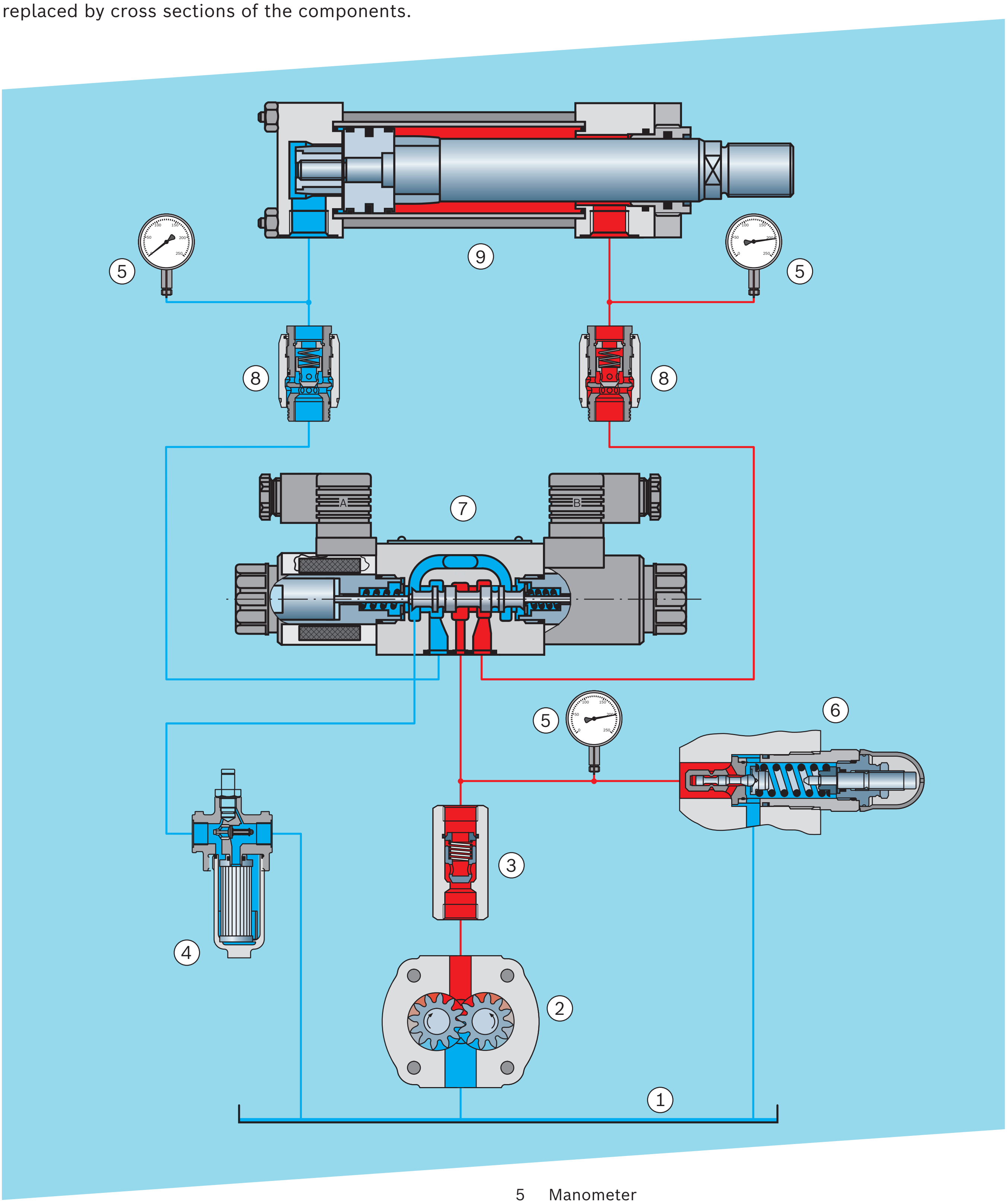



1 Tank
2 Hydraulic pump (here fixed displacement pump)
3 Non-return valve
4 Return filter
5 Manometer
6 Pressure relief valve
7 Directional control valve
8 Throttle/non-return valve
9 Hydraulic cylinder

*Circuit diagram of a hydraulic circuit with graphical symbols according to DIN ISO 1219*

The following figure illustrates the components of a hydraulic system in **circuit schematics**. These circuit schematics were derived from the illustrated circuit diagram. The abstract graphic symbols have been replaced by cross sections of the components.

This form of illustration of a hydraulic circuit, which is mainly used in basic and advanced training, clearly shows the design and interaction of individual assemblies, components and parts.




1 Tank
2 Hydraulic pump (here external gear pump)
3 Non-return valve
4 Return filter
5 Manometer
6 Pressure relief valve
7 Directional control valve
8 Throttle/non-return valve
9 Hydraulic cylinder

*Associated circuit schematics (with cross sections) of the hydraulic circuit*

# 4.2 Open and closed-loop control with valves

## 4.2.1 Open-loop control with directional control valves

### Short description

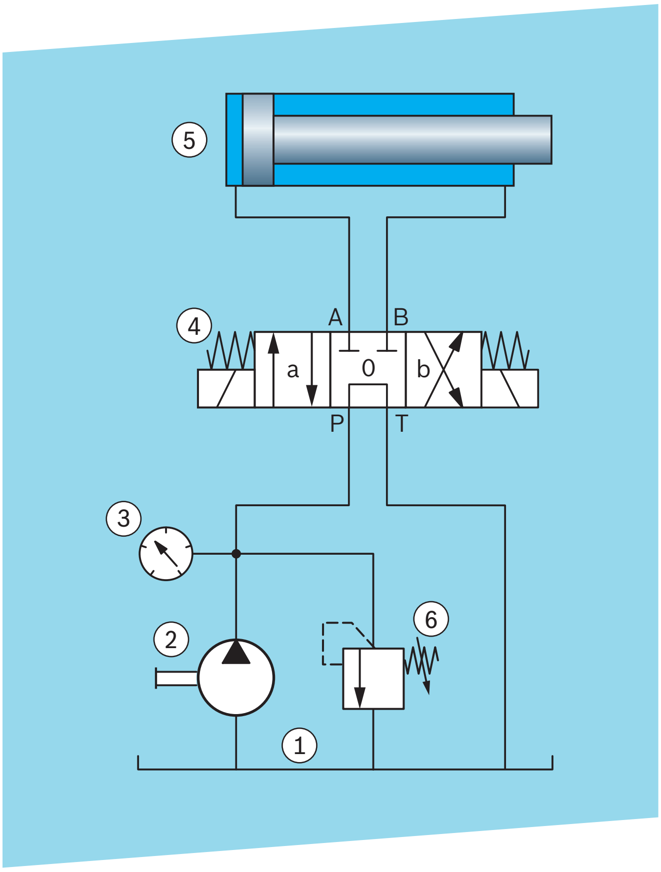
Hydraulic directional control valves are components manipulating start, stop, and flow direction of a hydraulic fluid. They establish line connections by opening, blocking or changing one or more flow paths. Depending on the application and task, different variants of control systems with directional control valves are realized, which differ in terms of design and function.

### Design

A control system with directional control valves essentially consists of the following main components:
- A hydraulic pump delivers the flow.
- A directional control valve controlling start, stop and the direction of flow.
- An actuator, here a hydraulic cylinder, performs work with the aid of the flow.
- A pressure relief valve limits the working pressure of the system.

*Continuous directional control valves with integrated electronics for use in industrial hydraulics*

The figure illustrates the circuit diagram for a cylinder control with an electrically operated 4/3 directional control valve in the center position.




1 Tank
2 Hydraulic pump
3 Manometer
4 4/3 directional control valve
5 Hydraulic cylinder
6 Pressure relief valve

*Cylinder control with electrically operated 4/3 directional control valve*

In the symbol of a directional control valve shown in the circuit diagram, ports P and T are connected to each other in center position (zero position). This is also called neutral circulation, and such a directional control valve is called an unloading valve. The advantage is that the hydraulic pump in this switching position of the directional control valve saves energy, since it only has to build up the low pressure to overcome the valve and line resistances.

# 5 Hydraulic power units and systems

## 5.1 Hydraulic drive units

### 5.1.1 Drive units in hydraulics

#### Short description

Hydraulic power units are independent assemblies of components for controlled provision of hydraulic energy. The system is driven either by an electric motor or a combustion engine.

#### Requirements

Hydraulic power units must be adjusted to the requirements and specifications of different hydraulic systems. For example, different specification profiles result from flow requirements, working pressure, environmental conditions or transport and installation options. Constant focus is placed on low noise level and optimum energy efficiency.

Use of standard components and modular assemblies in hydraulic power units ensures better handling of the diversity of variants resulting from the various requirements. Thanks to a modular design, it is possible to realize optimum structural solutions while taking into account economic aspects and ensuring a high degree of operational reliability, low noise emissions and energy consumption as well as ease of maintenance and high durability.

#### Fields of application

Typical application cases for hydraulic power units are stationary applications in general mechanical engineering (structural and hydraulic engineering, metallurgy), in the plastic-processing industry, in lifting and elevation units and in presses. Small power units with electric motors are used in mobile hydraulics, for example, for operation of tailgates of trucks or hydrostatic fan drives.

*Large hydraulic power unit (with oil-air heat exchanger)*

# Index

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