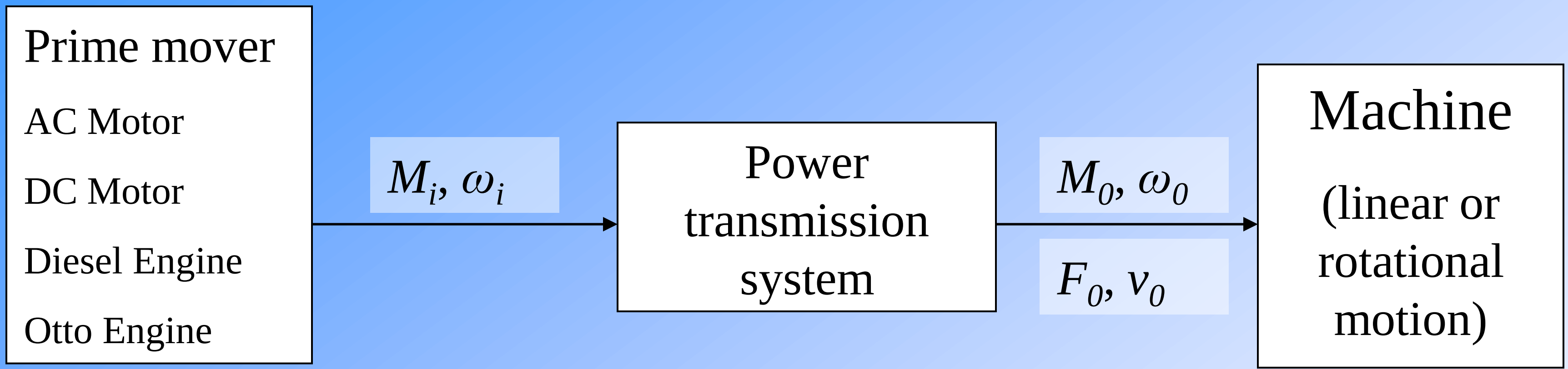
Hydraulic and Pneumatic Systems

Power train



- Mechanical power transmission:
  - Gears
  - Belt drive
  - Friction drive
  - Rigid couplings
  - Clutches

Properties:

- Continuously variable drive is difficult
- The relative spatial position of prime mover is fixed
- If the motor is electrical (DC motor or AC motor with variable frequency), then the rotational speed can be continuously changed but they are expensive

Hydraulic power transmission

- Hydraulic power transmission:

Hydro = water, aulos = pipe

The means of power transmission is a liquid (pneumatic → gas)

Hydrodynamic power transmission:

- Turbo pump and turbine
- Power transmission by kinetic energy of the fluid
- Still the relative spatial position is fixed
- Compact units

Hydrostatic power transmission:

- Positive displacement pump
- Creates high pressure and through a transmission line and control elements this pressure drives an actuator (linear or rotational)
- The relative spatial position is arbitrary but should not be very large because of losses (< 50 m)

✓ A continuously variable transmission is possible

Most of this lecture will be about hydrostatic systems (in common language it is also called simply hydraulics)

Hydrostatic vs hydrodynamic systems

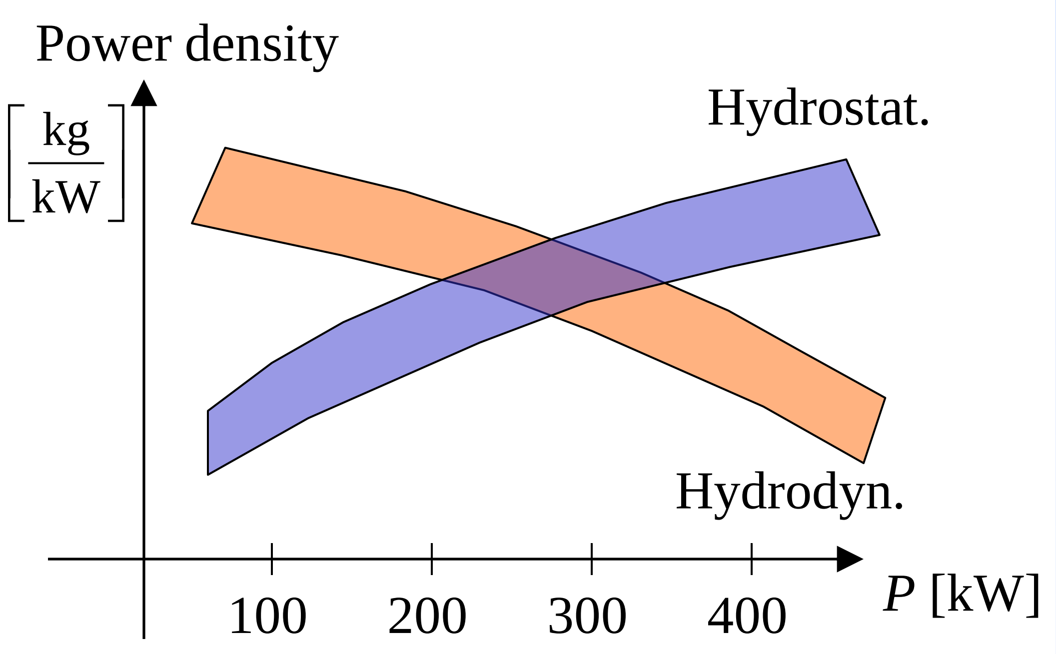
Roughly speaking:

$P = \Delta p \cdot Q$

Large Q, small Δp $\rightarrow$ **hydrodynamic** transmission

Large Δp, small Q $\rightarrow$ **hydrostatic** transmission.

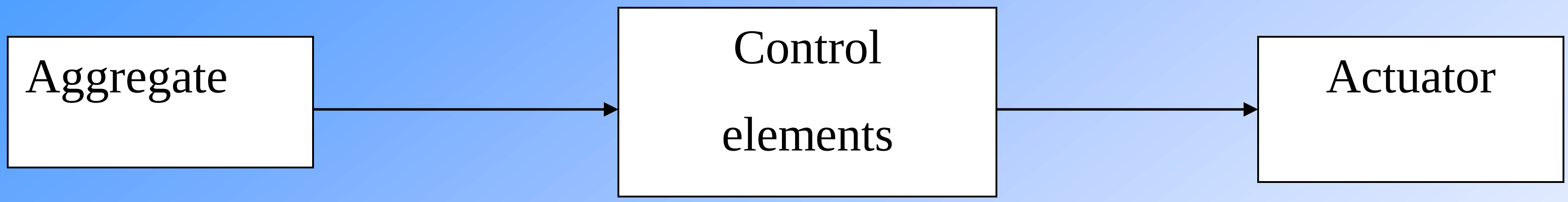
But there is no general rule, depends on the task.



- Generally larger than 300 kW power hydrodynamic is more favourable.
- But for soft operation (starting of large masses) hydrodynamic is used for smaller powers either.

- ❑ Linear movement against large forces: hydrostatic
- ❑ Linear movement and stopping in exact position: also hydrostatic

Structure of a hydrostatic drive



Pump, motor

Fluid reservoir

Pressure relief valve

Filter

Piping

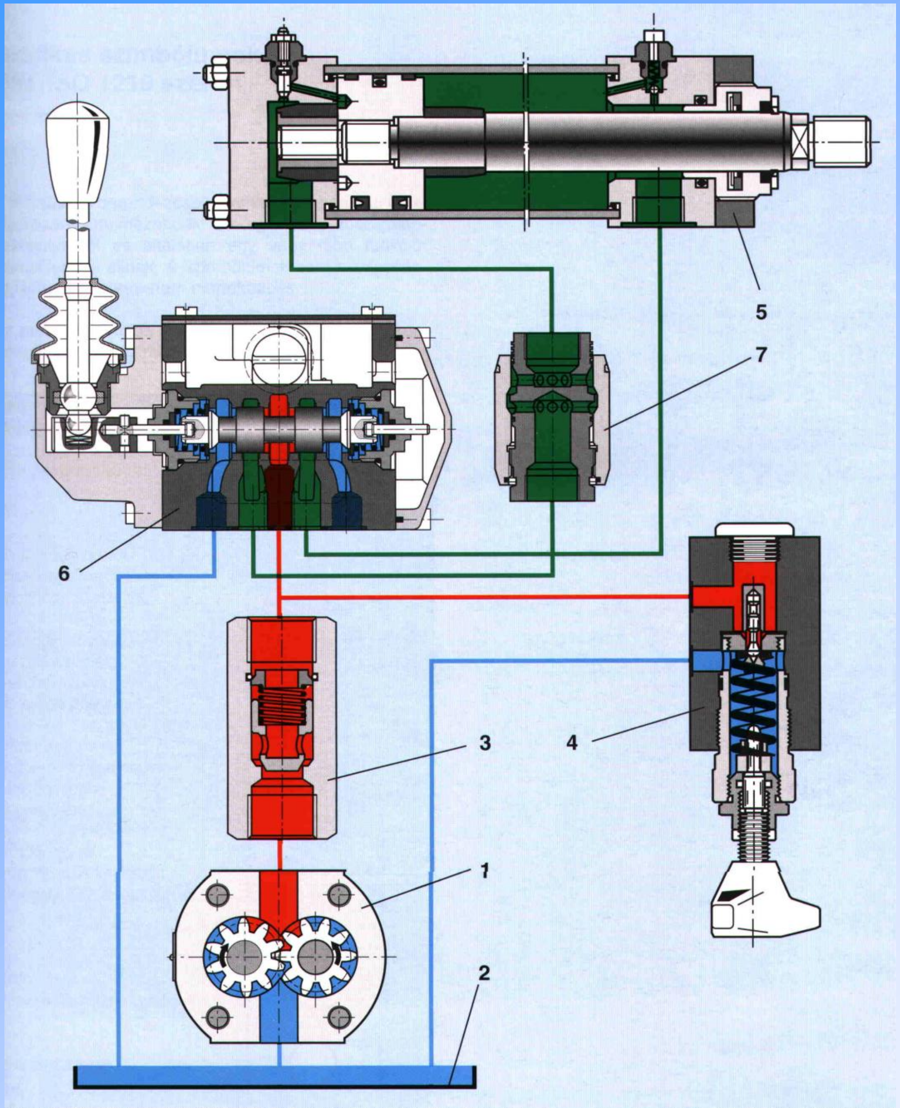
Valves, determining the path, pressure, flow rate of the working fluid

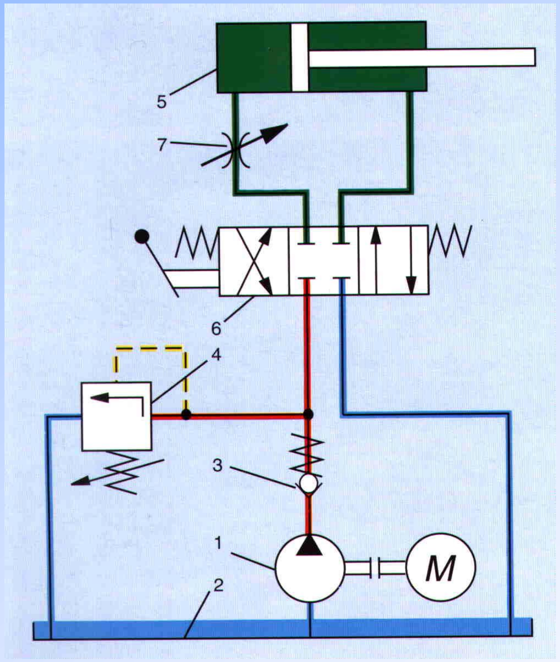
Elements doing work

- Linear
- Rotational
- Swinging

These components and their interaction is the subject of this semester

A typical hydraulic system





1 – pump
2 – oil tank
3 – flow control valve
4 – pressure relief valve
5 – hydraulic cylinder
6 – directional control valve
7 – throttle valve

Advantages of hydrostatic drives

- Simple method to create linear movements
- Creation of large forces and torques, high energy density
- Continuously variable movement of the actuator
- Simple turnaround of the direction of the movement, starting possible under full load from rest
- Low delay, small time constant because of low inertia
- Simple overload protection (no damage in case of overload)
- Simple monitoring of load by measuring pressure
- Arbitrary positioning of prime mover and actuator
- Large power density (relatively small mass for a given power compared to electrical and mechanical drives)
- Robust (insensitive against environmental influences)

Disadvantages of hydrostatic drives

- Working fluid is necessary (leakage problems, filtering, etc.)
- It is not economic for large distances

Hydraulic fluids - tasks

They have the following primary tasks:

- Power transmission (pressure and motion transmission)
- Signal transmission for control

Secondary tasks:

- Lubrication of rotating and translating components to avoid friction and wear
- Heat transport, away from the location of heat generation, usually into the reservoir
- Transport of particles to the filter
- Protection of surfaces from chemical attack, especially corrosion

Hydraulic fluids - requirements

- Functional
  - Good lubrication characteristics
  - Viscosity should not depend strongly on temperature and pressure
  - Good heat conductivity
  - Low heat expansion coefficient
  - Large elasticity modulus

- Economic
  - Low price
  - Slow aging and thermal and chemical stability $\Rightarrow$ long life cycle

Hydraulic fluids - requirements (contd.)

- Safety
  - High flash point or in certain cases not inflammable at all
  - Chemically neutral (not aggressive at all against all materials it touches)
  - Low air dissolving capability, not inclined to foam formation

- Environmental friendliness
  - No environmental harm
  - No toxic effect

Hydraulic fluid types

1. Water (3%) ↑
2. Mineral oils (75%) ↓
3. Not inflammable fluids (9%)
4. Biologically degradable fluids (13%) ↑
5. Electrorheological fluids (in development)

Hydraulic fluid types (contd.)

1. Water:

- Clear water
- Water with additives

- Oldest fluid but nowadays there is a renaissance
- Used where there is an explosion or fire danger or hygienic problem: Food and pharmaceutical industry, textile industry, mining

Advantages:

- No environmental pollution
- No disposal effort
- Cheap
- No fire or explosion danger
- Available everywhere
- 4 times larger heat conduction coefficient than mineral oils
- 2 times higher compression module than mineral oils
- Viscosity does not depend strongly on temperature

Hydraulic fluid types (contd.)

1. Water:

Disadvantages:

- Bad lubrication characteristics
- Low viscosity (problem of sealing, but has good sides: low energy losses)
- Corrosion danger
- Cavitation danger (relatively high vapour pressure)
- Limited temperature interval of applicability (freezing, evaporating)

Consequences: needs low tolerances and very good materials (plastics, ceramics, stainless steel) ⇒ components are expensive

Hydraulic fluid types (contd.)

2. Mineral oil:

- Without additives
- With additives

- o „Conventional" use, stationary hydraulics
- o Always mixtures of different oils, often with additives

  Additives:
  - decrease corrosion
  - increase life duration
  - improve temperature dependence of viscosity
  - improve particle transport

Advantages:

- Good lubrication
- High viscosity (good for sealing, bad for losses)
- Cheap

Disadvantages:

- Inflammable
- Environmental pollution

Hydraulic fluid types (contd.)

3. Not inflammable fluids:

- Contains water
- Does not contain water

- o mines, airplane production, casting, rolling, where there is explosion and fire danger
- o Water-oil emulsions (oil synthetic) or water-free synthetic liquids

Disadvantages:

- Higher density, higher losses, more inclination to cavitation
- Limited operational temperature < 55 °C
- Worse lubrication characteristics, reduction of maximum load
- Worse de-aeration characteristics
- Sometimes chemically aggressive against sealing materials

Hydraulic fluid types (contd.)

4. Biologically degradable fluids:

- Natural
- Synthetic

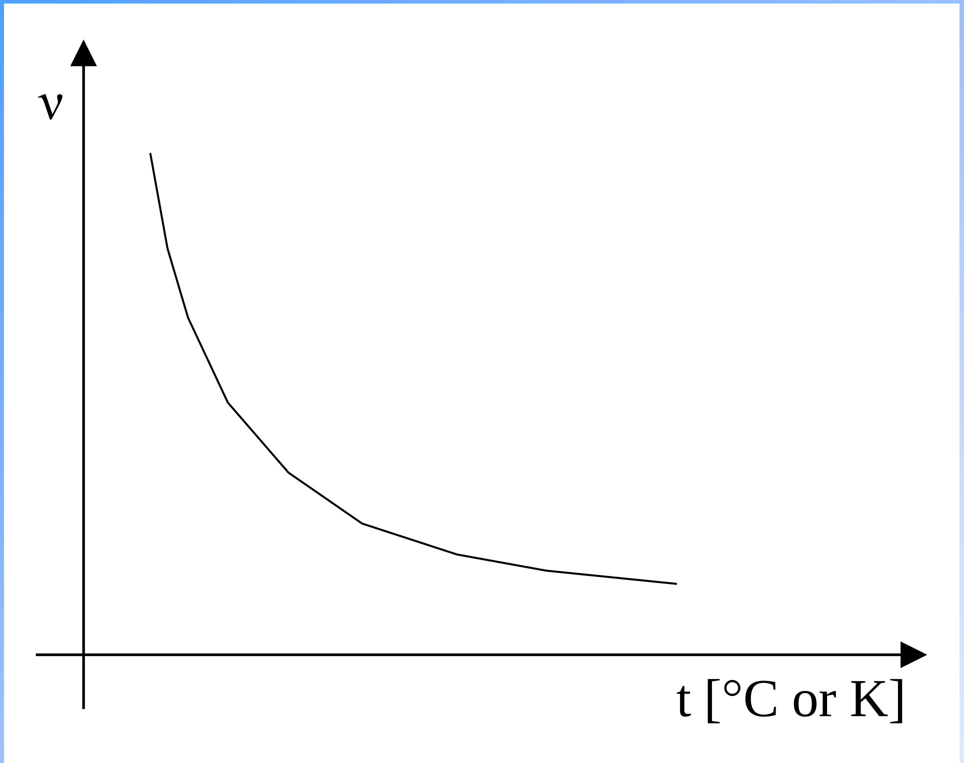
- o Environmental protection, water protection
- o Agricultural machines
- o Mobile hydraulics

Characteristics similar to mineral oils but much more expensive.

If the trend continues its usage expands, price will drop.

Properties of hydraulic fluids

Viscosity: well-known



Temperature dependence

⇒ log-log scale

Ubbelohde-Walther:

$$\lg(\lg(\nu + c)) = K_\nu - m \cdot \lg T$$

c, m, K_ν are constants,

T is in K

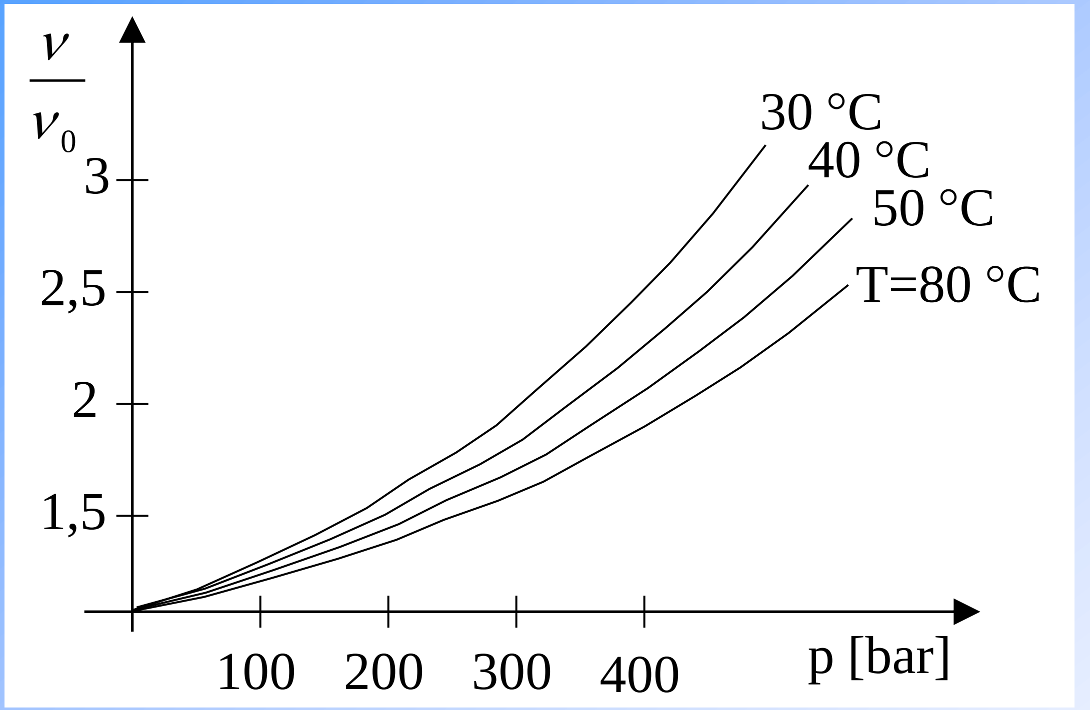
Vogel-Cameron:

$$\mu_t = A \cdot e^{\frac{B}{t+c}}$$

A, B, C are constants,

t is in °C

Properties of hydraulic fluids (contd.)



Pressure dependence of viscosity

$$\mu_p = \mu_0 \cdot e^{\alpha p}$$

μ_0, ν_0 viscosity at atmospheric pressure

Properties of hydraulic fluids (contd.)

Temperature dependence of density is small

Density dependence on pressure:

$$\frac{\Delta V}{V} = -\frac{\Delta p}{K}$$ like Hooke's law, *K* is the compressibility

K is not a constant but depends on pressure itself

effective *K* is also influenced by:

- ☞ Air content
- ☞ Flexibility of the pipe

Hydraulic Fluids

Air content in oil is harmful.

Sucking air with the pump happens but is by proper installation avoidable.

The oil is quickly into solution during the increasing pressure.

Air bubbles come to oil mostly so that with decreasing pressure the air „goes out of solution”.

$$V_a = V_f \cdot \alpha \cdot \frac{p_2}{p_1}$$

α - dissolving coefficient at normal pressure

At normal pressure $V_a = V_f$.

At high pressure, the volume of the dissolved air is much more than the volume of the liquid.

When the pressure drops the air leaves the solution suddenly but the dissolution happens gradually.

Hydraulic Fluids

Problems with air content:

- Sudden, jerky movements, oscillation, noise
- Late switching
- Reduced heat conduction
- Accelerated aging of the liquid, disintegration of oil molecules
- Cavitation erosion

$$K_{mixture} = K_l \frac{\frac{V_f}{V_{a0}} + 1}{\frac{V_f}{V_{a0}} + K_l \frac{p_0}{p^2}}$$

K_l : liquid compressibility

V_f : volume of liquid

V_{a0} : volume of gas in normal state

p_0 : normal pressure

p : p under investigation

Hydraulic Fluids

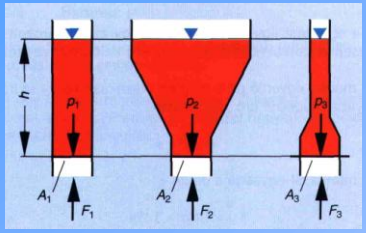
The manufacturer specifies the characteristics of the required liquid and the duration of usage.

Before filling in the new oil, the rig has to be washed with oil.

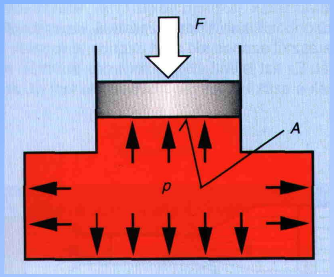
Never mix old and new oil!

Calculation basics

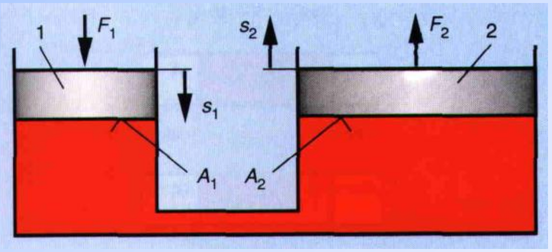
a) Hydrostatic pressure



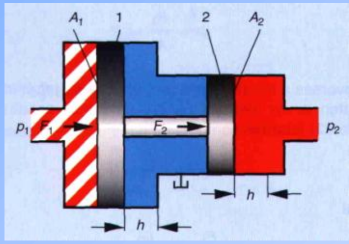
b) Pascals's law



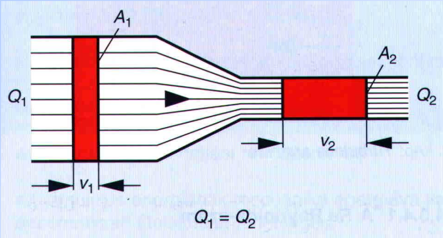
c) Transmission of power



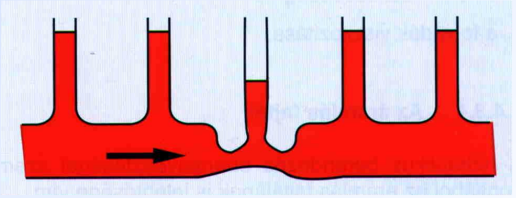
d) Transmission of pressure



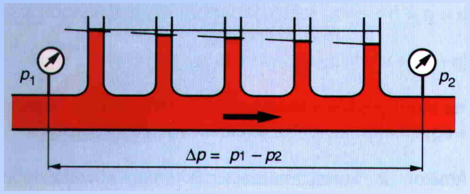
e) Continuity



g) Bernoulli equation



f) Flow resistance

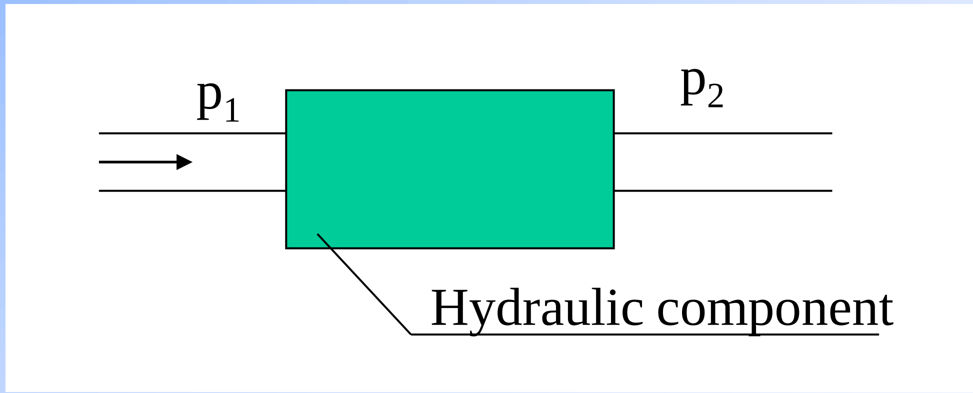


Calculation basics

Flow resistance:

$$p_1 - p_2 = \Delta p_{loss} = f(Q)$$

$$\Delta p_{loss} = \zeta \frac{\rho}{2} \bar{v}^2 \text{ or } \Delta p_{loss} = \zeta \frac{\rho}{2} \frac{Q^2}{A^2}$$



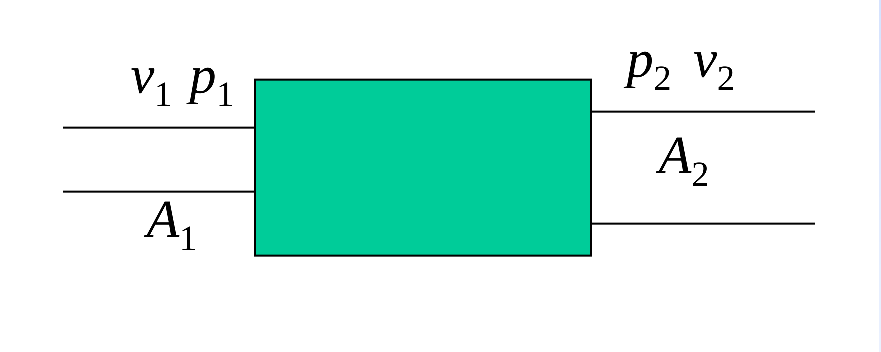
Calculation basics

Calculation basics:

If the two cross sections are not the same then:

$$p_1 - p_2 = \frac{\rho}{2}\left(\bar{v}_2^2 - \bar{v}_1^2\right) + \Delta p_{loss}$$

$$\Delta p_{loss} = \zeta_{1,2}\frac{\rho}{2}\bar{v}_{1,2}^2 \text{ or } \Delta p_{loss} = \zeta_{1,2}\frac{\rho}{2}\frac{Q^2}{A_{1,2}^2}$$



$$\frac{\zeta_1}{\zeta_2} = \frac{A_1^2}{A_2^2}$$

$$\zeta = \zeta(\mathrm{Re}) \qquad \mathrm{Re} = \frac{d_h \cdot \bar{v}}{\nu} \qquad d_h = \frac{4A}{U}$$

For a straight, stiff pipe:

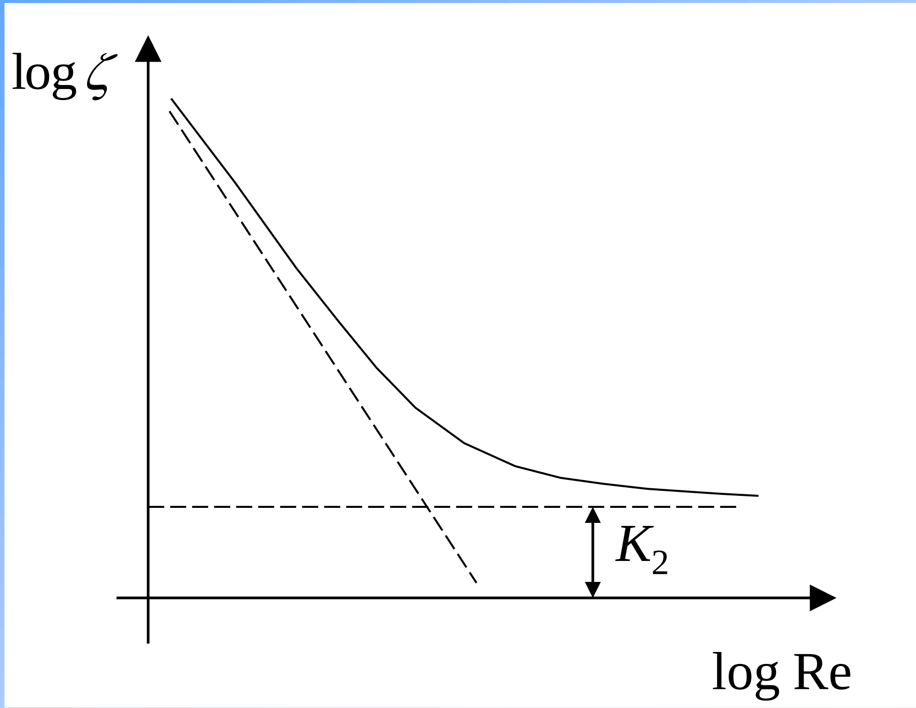
$$\zeta = \lambda \cdot \frac{l}{d_h}, \lambda = \begin{cases} \dfrac{64}{\mathrm{Re}} & \text{laminar} \\ \dfrac{0{,}3164}{\sqrt[4]{\mathrm{Re}}} & \text{turbulent} \end{cases}$$

Calculation basics

<u>Calculation basics:</u>

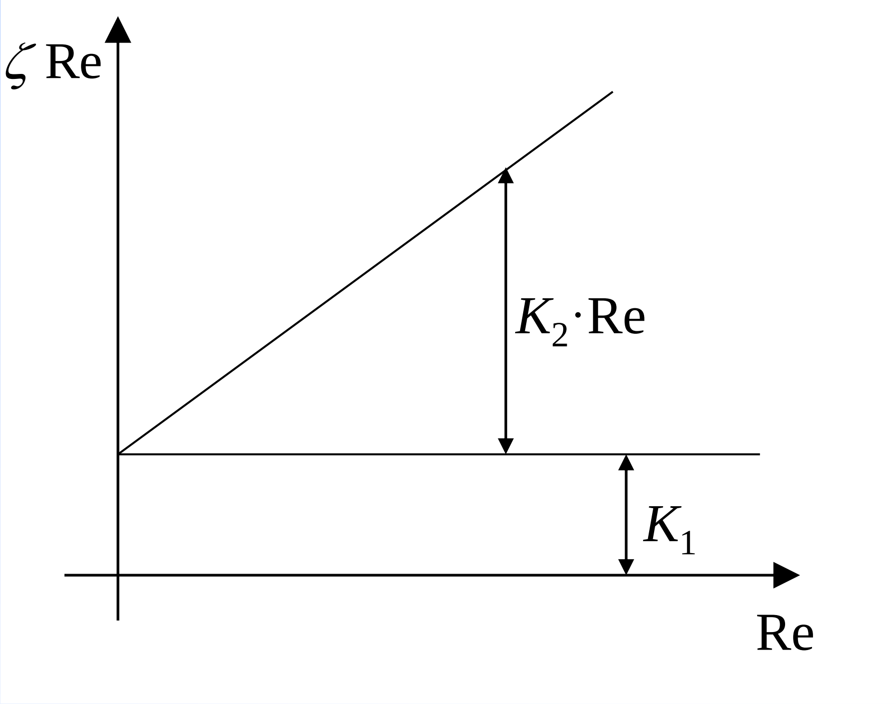
Usually the function $\zeta = \zeta(\mathrm{Re})$ looks like the following:

$$\zeta = \frac{K_1}{\mathrm{Re}} + K_2$$



Practically:

$$\zeta\,\mathrm{Re} = K_1 + K_2 \cdot \mathrm{Re}$$



Calculation basics

<u>Calculation basics:</u>

On this basis we can define two hydraulic resistances:

$$\Delta p_{l1} = R_h \cdot Q$$

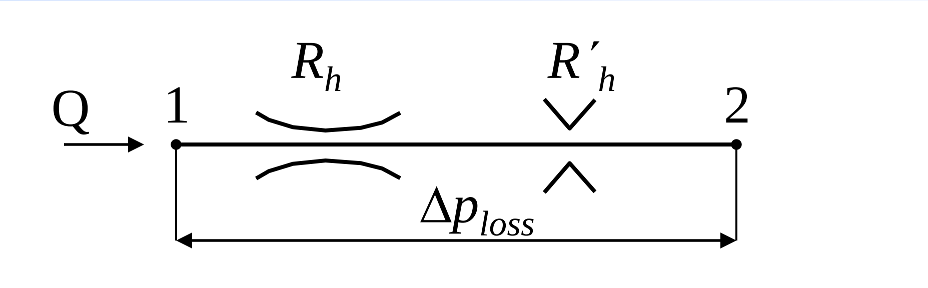
$$R_h = \frac{\rho \cdot \nu \cdot K_1}{2 d_h \cdot A}$$

Depends on viscosity

$$\Delta p_{l2} = R_h' Q^2$$

$$R_h' = \frac{\rho \cdot K_2}{2 A^2}$$

Does not depend on viscosity



Calculation basics

Three different coefficients are used to express pressure loss:

$$Q = A \cdot \alpha \cdot \sqrt{\frac{2}{\rho}\Delta p} \qquad Q = G_h \cdot \Delta p_1 \qquad Q = G_h' \cdot \sqrt{\Delta p_2}$$

$$\alpha = \sqrt{\frac{1}{\zeta}} \qquad G_h = \frac{2d_h \cdot A}{\rho \cdot \nu \cdot K_1} \qquad G_h' = \sqrt{\frac{2}{\rho \cdot K_2}} \cdot A$$

G_h: Hydraulic admittance

For elbows, sudden expansions, T-pieces, etc. values are given as a function of Re, roughness and geometric parameters

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For a series circuit:

$$\Delta p_{total} = \sum_{i=1}^{n} \Delta p_i \text{ and } Q = Q_i$$

For a parallel circuit:

$$Q_{total} = \sum_{i=1}^{n} Q_i \text{ and } \Delta p = \Delta p_i$$

Leakage losses

Leakage losses:

- External losses
- Internal losses

Occur always when components move relative to each other

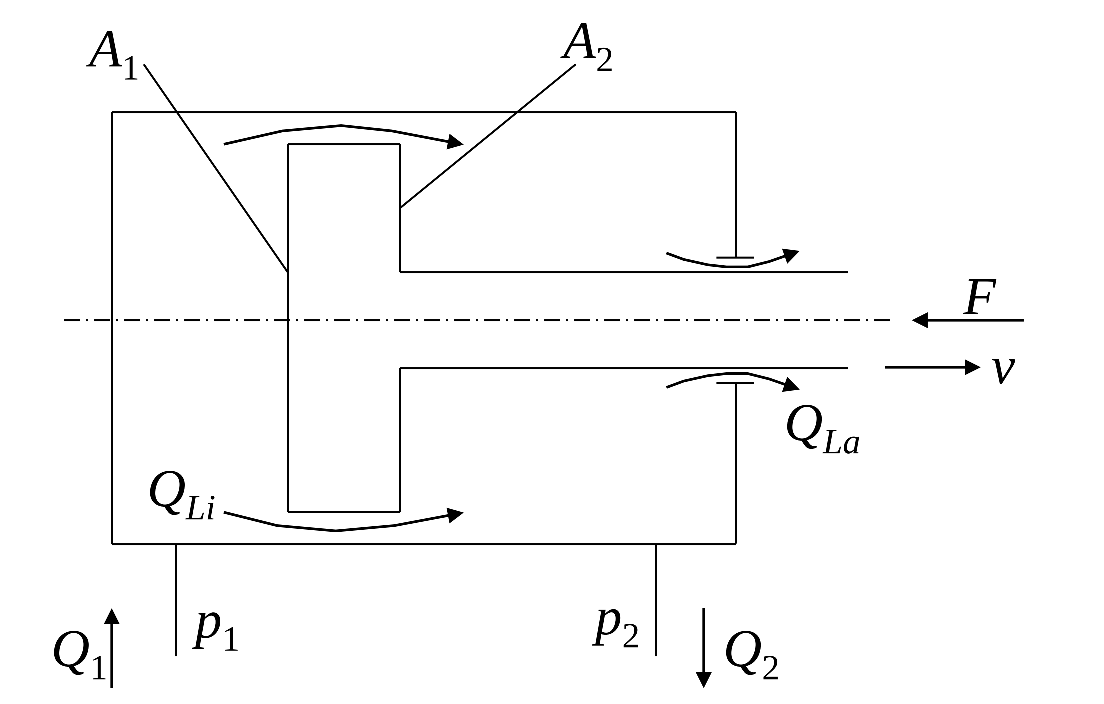
They reduce efficiency

In case of external leakages there is environmental damage and the lost fluid has to be refilled. External losses can be avoided by careful design and maintenance.

Internal losses cannot be avoided.

Leakage losses

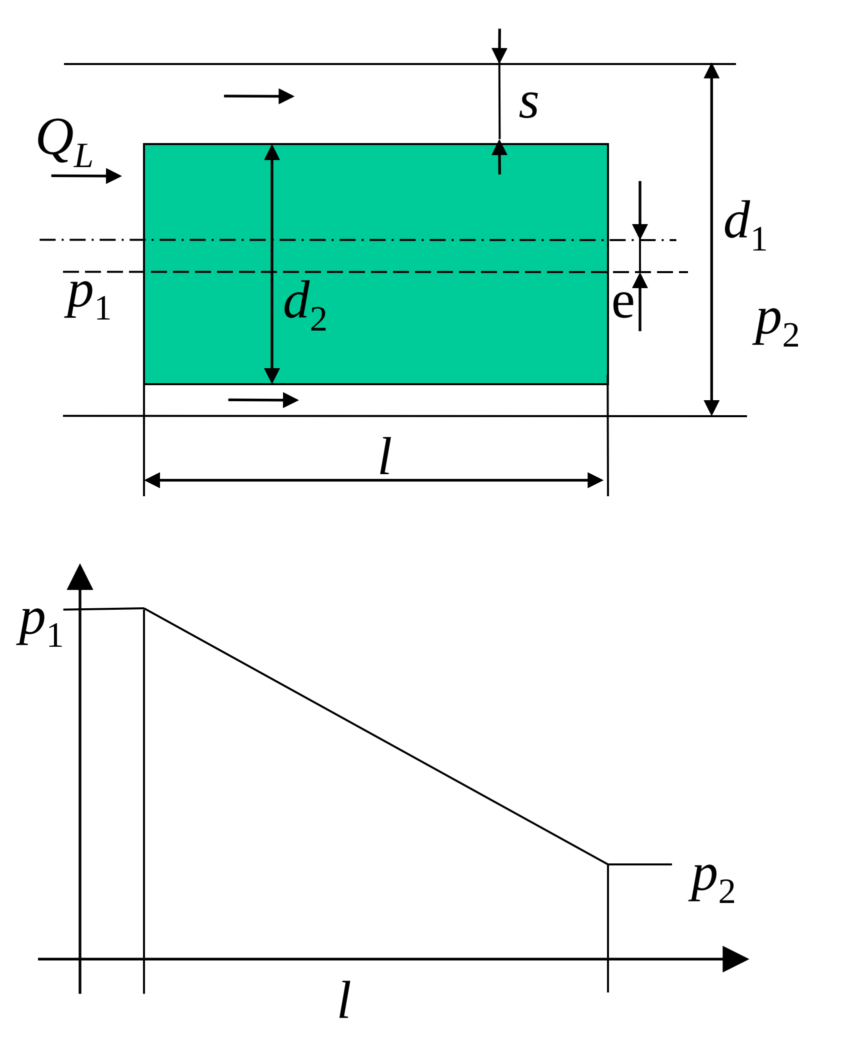
$$p_1 = \frac{F}{A_1} + p_2 \frac{A_2}{A_1}$$



$$v = \frac{Q_1}{A_1} - \frac{G_{Li}}{A_1}\left[\frac{F}{A_1} - p_2\left(1 - \frac{A_2}{A_1}\right)\right]$$

$$Q_2 = Q_1 \frac{A_2}{A_1} + G_{Li}\left(1 - \frac{A_2}{A_1}\right)\left[\frac{F}{A_1} - p_2\left(1 - \frac{A_2}{A_1}\right)\right] - p_2 G_{La}$$

Leakage losses



$$s << d_1$$

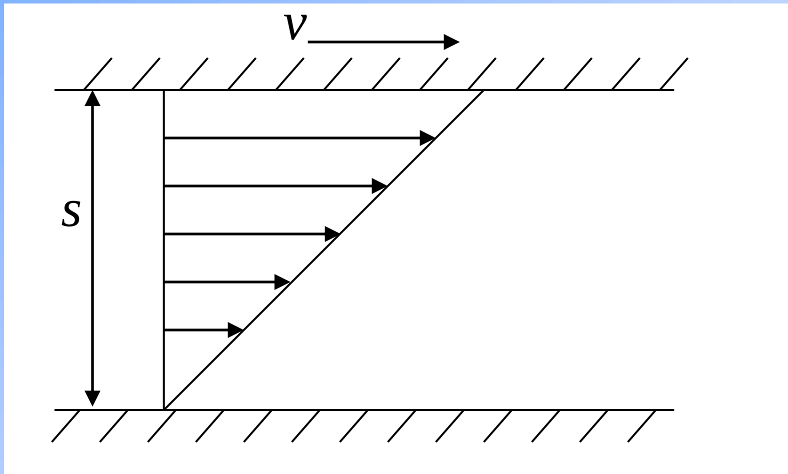
$$Q_L \approx \frac{d_m \cdot \pi \cdot s_m^3}{12 \cdot \nu \cdot l \cdot \rho} \Delta p \left(1 + \frac{3}{2} \frac{e^2}{s_m^2}\right)$$

$$G_L \approx \frac{d_m \cdot \pi \cdot s_m^3}{12 \cdot \nu \cdot l \cdot \rho} \left(1 + \frac{3}{2} \frac{e^2}{s_m^2}\right)$$

$$d_m = \frac{d_1 + d_2}{2} \qquad s_m = \frac{d_1 - d_2}{2}$$

Leakage losses

- the eccentricity increases the leakage flow by a factor of 2,5 if *e* increases to the limit
- $Q_L \sim s^3_m$!
- Because of the large Δp, there are large temperature differences along *l*. Medium viscosity has to be substituted.
- In addition there is a Couette flow – dragged flow, which increases or decreases the leakage



$$Q_d = \frac{v \cdot s \cdot b}{2}$$

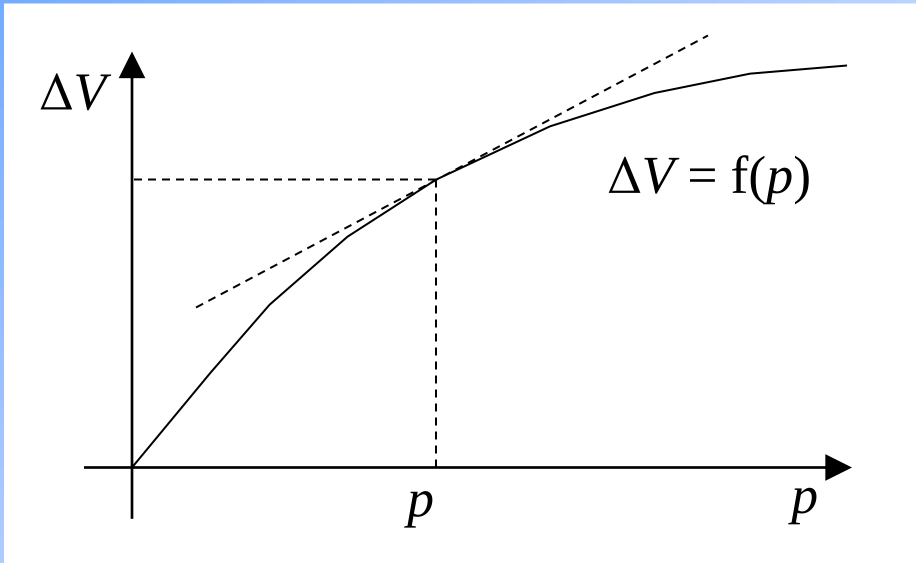
$$Q_L = G_L \cdot \Delta p \pm \frac{v \cdot s_m \cdot d_m \cdot \pi}{2}$$

Hydraulic capacity and inductivity

Hydraulic capacity:

All the things discussed so far referred to steady processes. In practice, however, very often unsteady processes are encountered: starting, stopping, change of load, change of direction of motion, etc.

In these cases the compressibility of the fluid and the pipes, and the inertia of the fluid have to be taken into consideration.



Nonlinear function.

It can be locally linearized and:

$$\frac{d\Delta V}{dp} = C_h, \text{ hydraulic capacity.}$$

Hydraulic capacity and inductivity

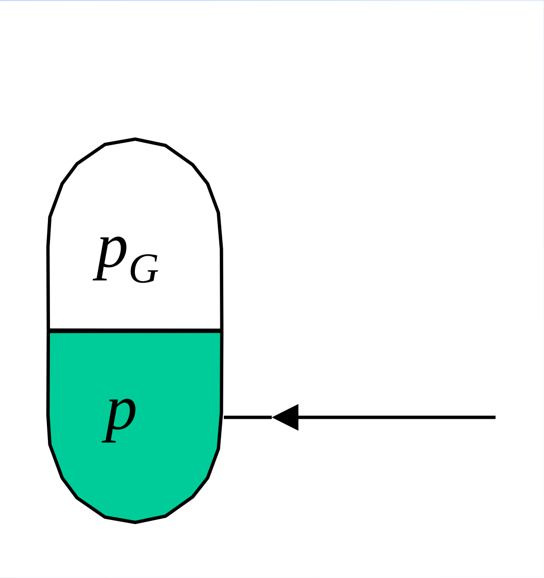
Hydraulic capacity:

The capacity has three parts:

$$C_h = C_{fl} + C_{pipe} + C_{accumulator}$$

The capacitive flow rate:

$$Q_c = \Delta \dot{V}_c = C_h \cdot \dot{p} \Longrightarrow p = \frac{1}{C_h} \cdot \int Q_c \,\mathrm{d}t$$



$$C_{fl} = \frac{V_0}{K}$$ K compression module

C_{pipe} is negligible if the pipe is made of metal

C_{pipe} is not negligible if the pipe is flexible.

$$C_{accumulator} = \frac{V_1}{n \cdot p} \cdot \left(\frac{p_G}{p} \right)^{\frac{1}{n}},$$ n is the polytropic exponent.

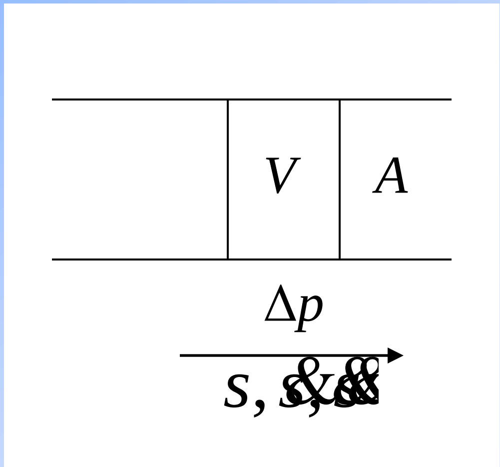
Hydraulic capacity and inductivity

Hydraulic inductivity:

$$\Delta p \cdot A = \rho \cdot V \cdot \ddot{s}, \quad \ddot{s} = \frac{\dot{Q}}{A}$$

$$\Delta p = \frac{V \cdot \rho}{A^2} \dot{Q}$$

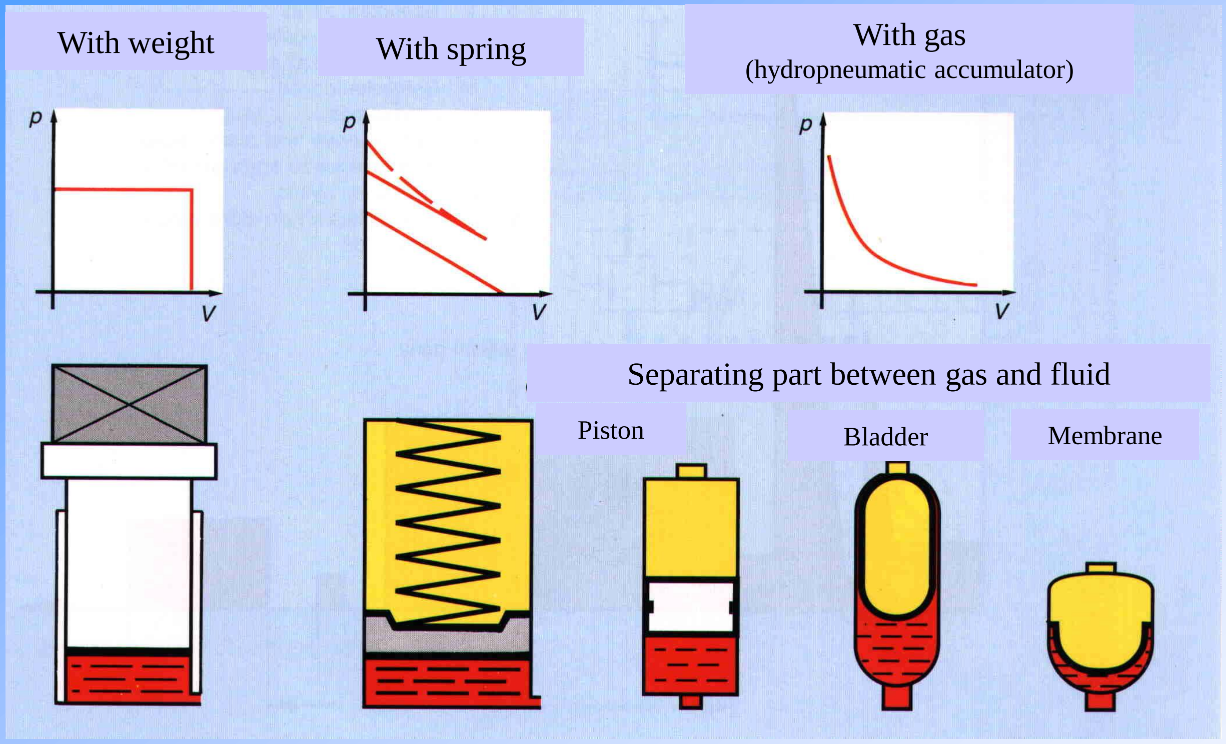
$$\Delta p = L_h \cdot \dot{Q}_{in} \quad \Rightarrow \quad Q_{in} = \frac{1}{L_h} \int \Delta p \, \mathrm{d}t$$



$L_{total} = L_h + L_{sol}$, where L_{sol} is the inertia of solid parts.

Hydraulic Accumulators

Constructions and tasks in the hydraulic system



Constructions

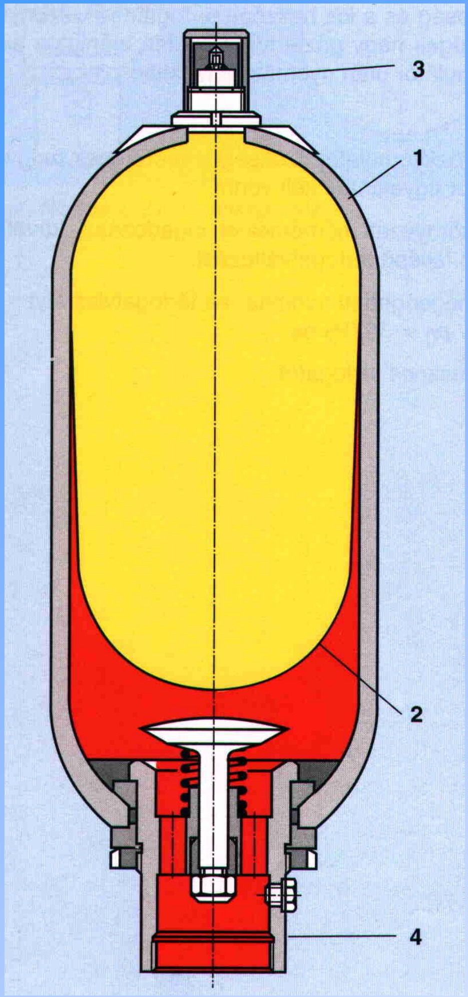
Tasks:

The hydropneumatic accumulators perform different tasks in the hydraulic systems, e.g.:

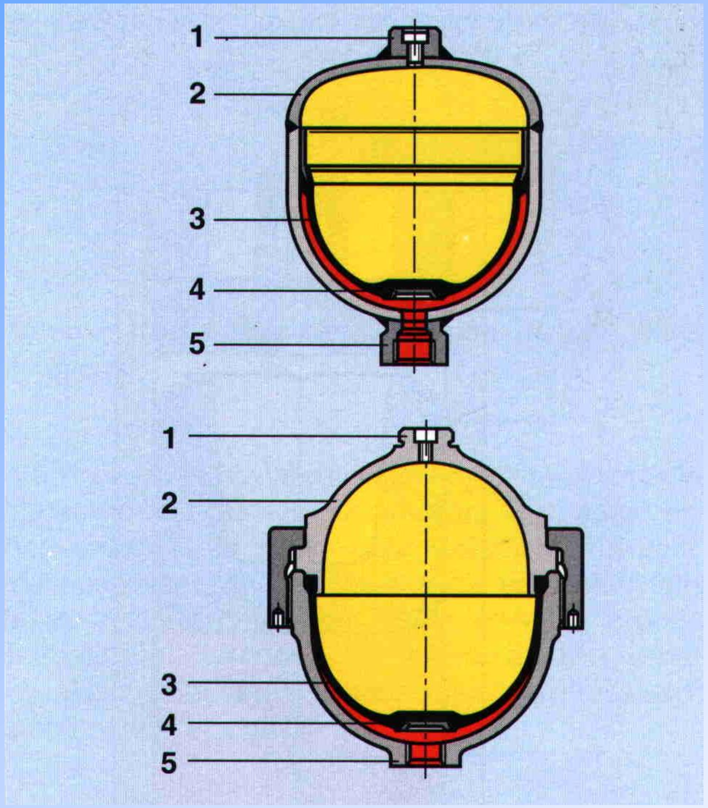
- reserve energy
- store fluid
- emergency operate
- force compensating
- damp mechanical shocks
- absorb pressure oscillations
- compensate leakage losses
- springs in vehicles
- recover of braking energy
- stabilize pressure
- compensate volumetric flow rate (expansion reservoir)

Hydraulic Accumulators

Constructions



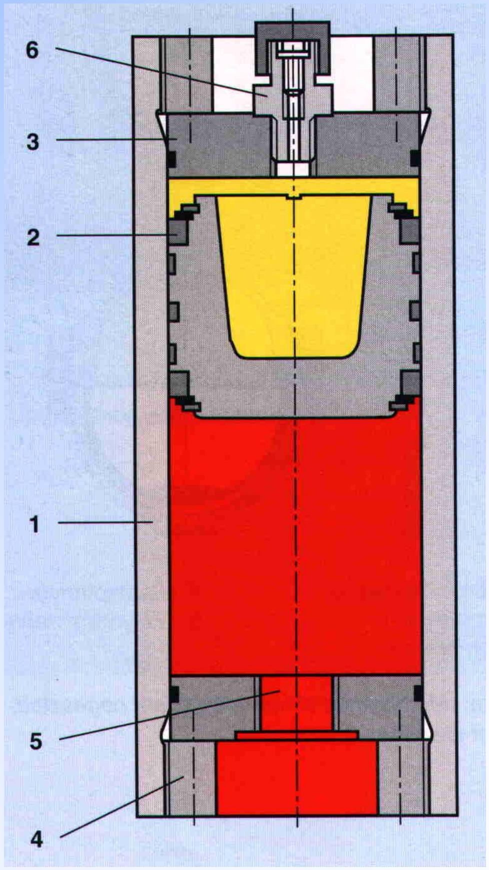
With bladder



With membrane

above welded

below screwed



With piston

Hydraulic Accumulators

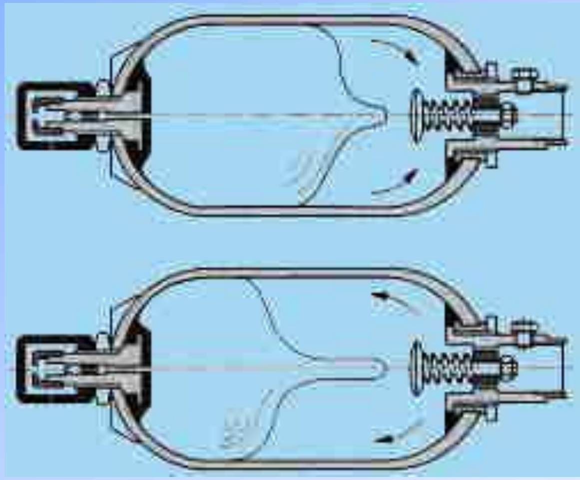
<u>Working states of hydroaccumulators with bladder:</u>

This installation is practically a bladder filled with gas and placed in a tank made out of steal. The bladder is filled with carbon dioxide (gas pressure). At the starting of the pump the fluid flows in the tank and compresses the gas. When required (if there is a high enough pressure difference) the fluid flows very quickly back in the system.

Requirements on the system side:

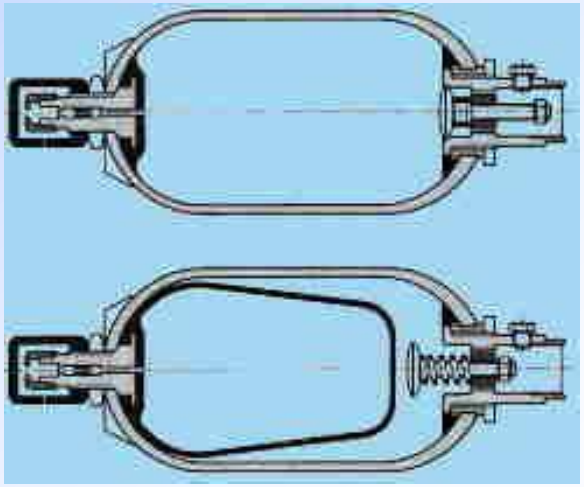
- locks both in the T and P lines,
- controlled release valves,
- juncture for pressure manometer (mostly built with the hydroaccumulator together),
- throw back valve in the P line.

Fluid flows out



Fluid flows in

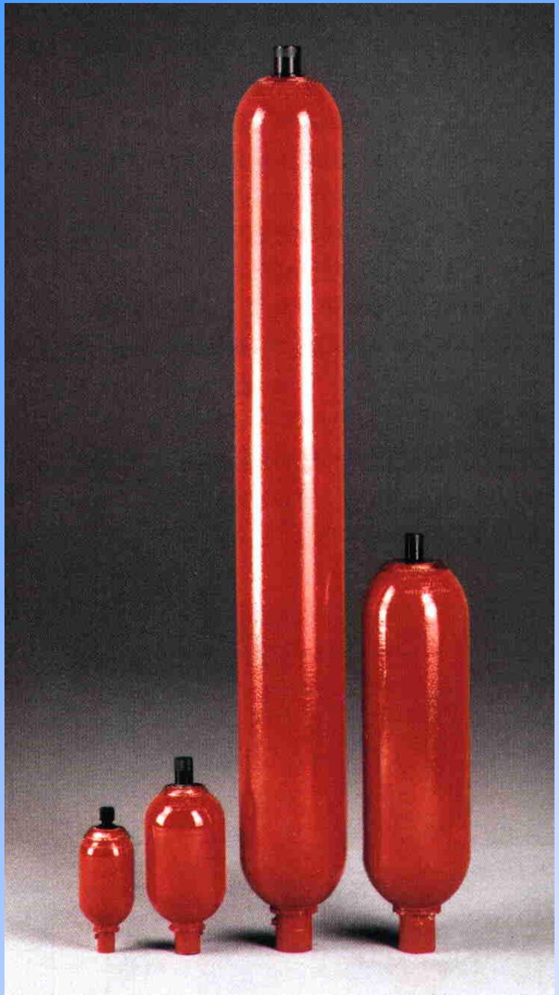
Hydroaccumulator with pre-stressed bladder



pressureless, without pre-stress

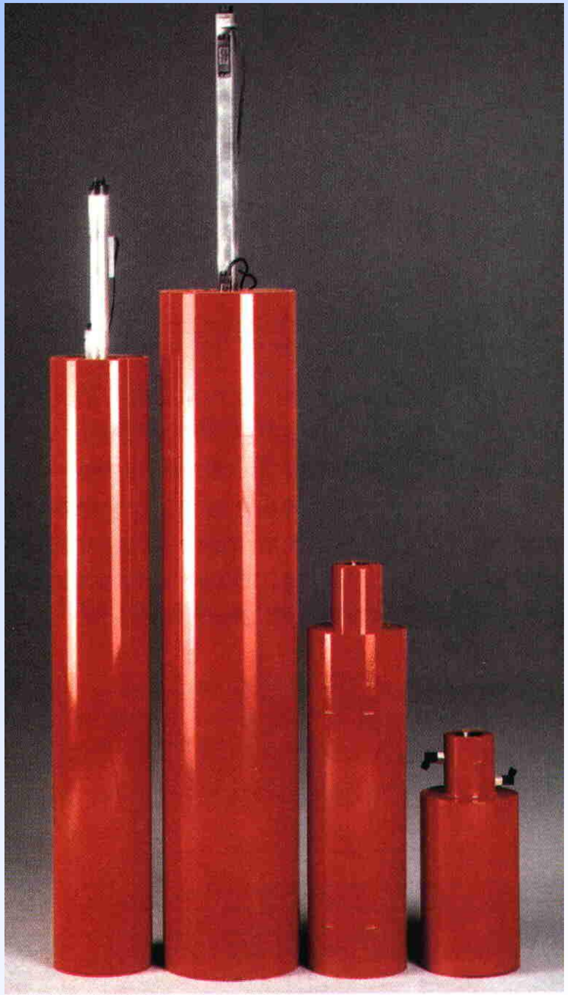
Hydraulic Accumulators

Construction



Bladder

Membrane



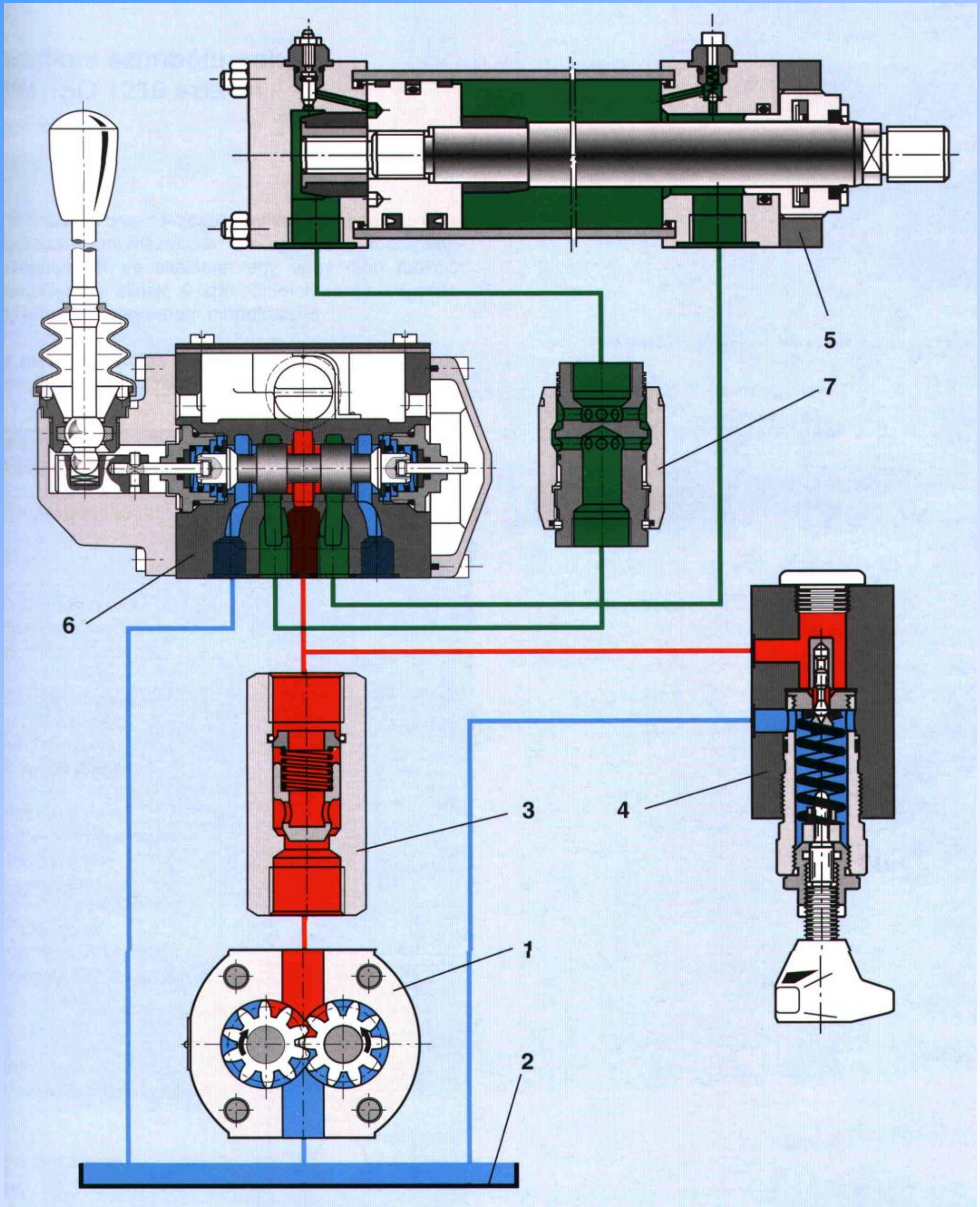
Piston

Big pictures

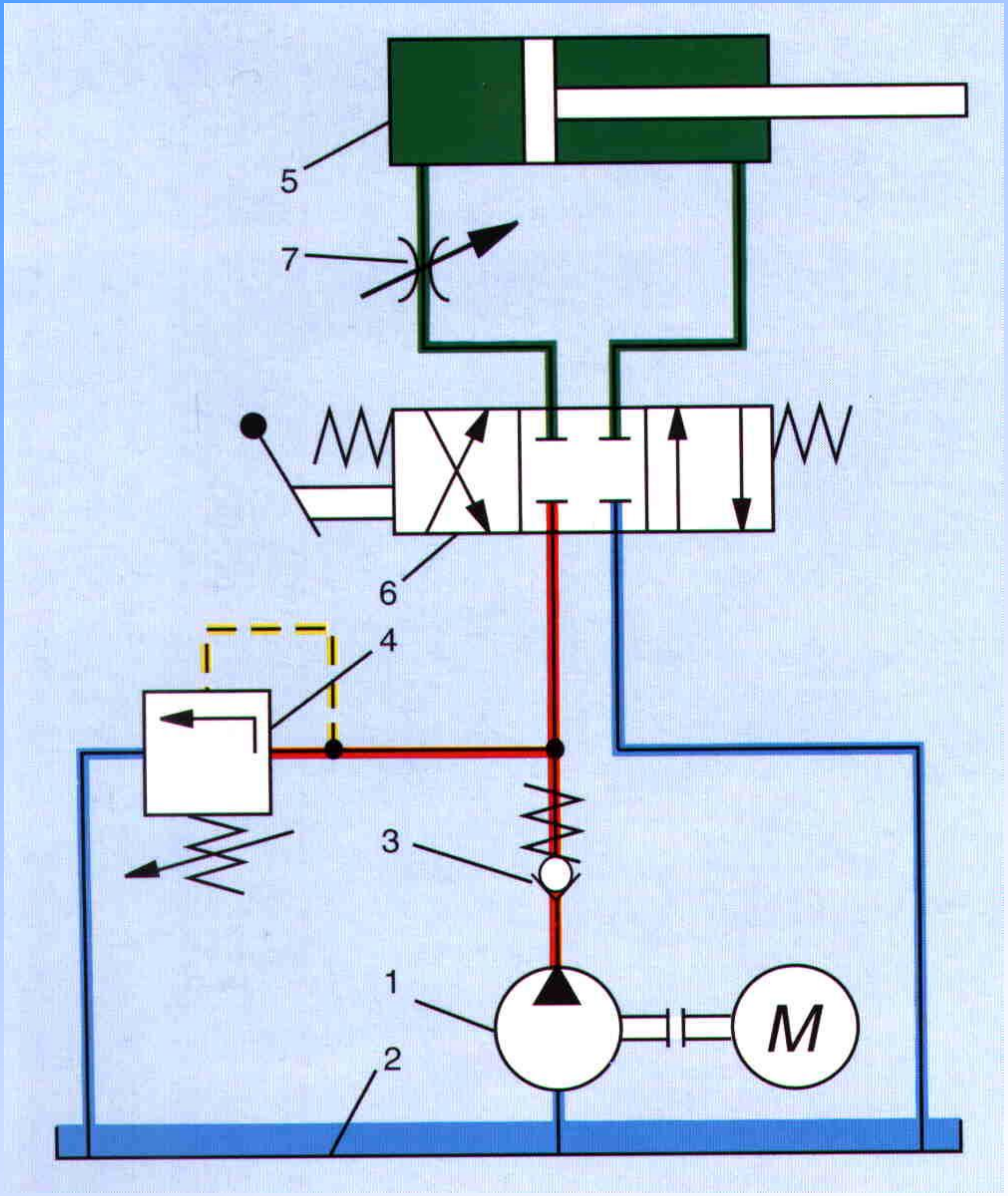
End of normal presentation

Beginning of big pictures

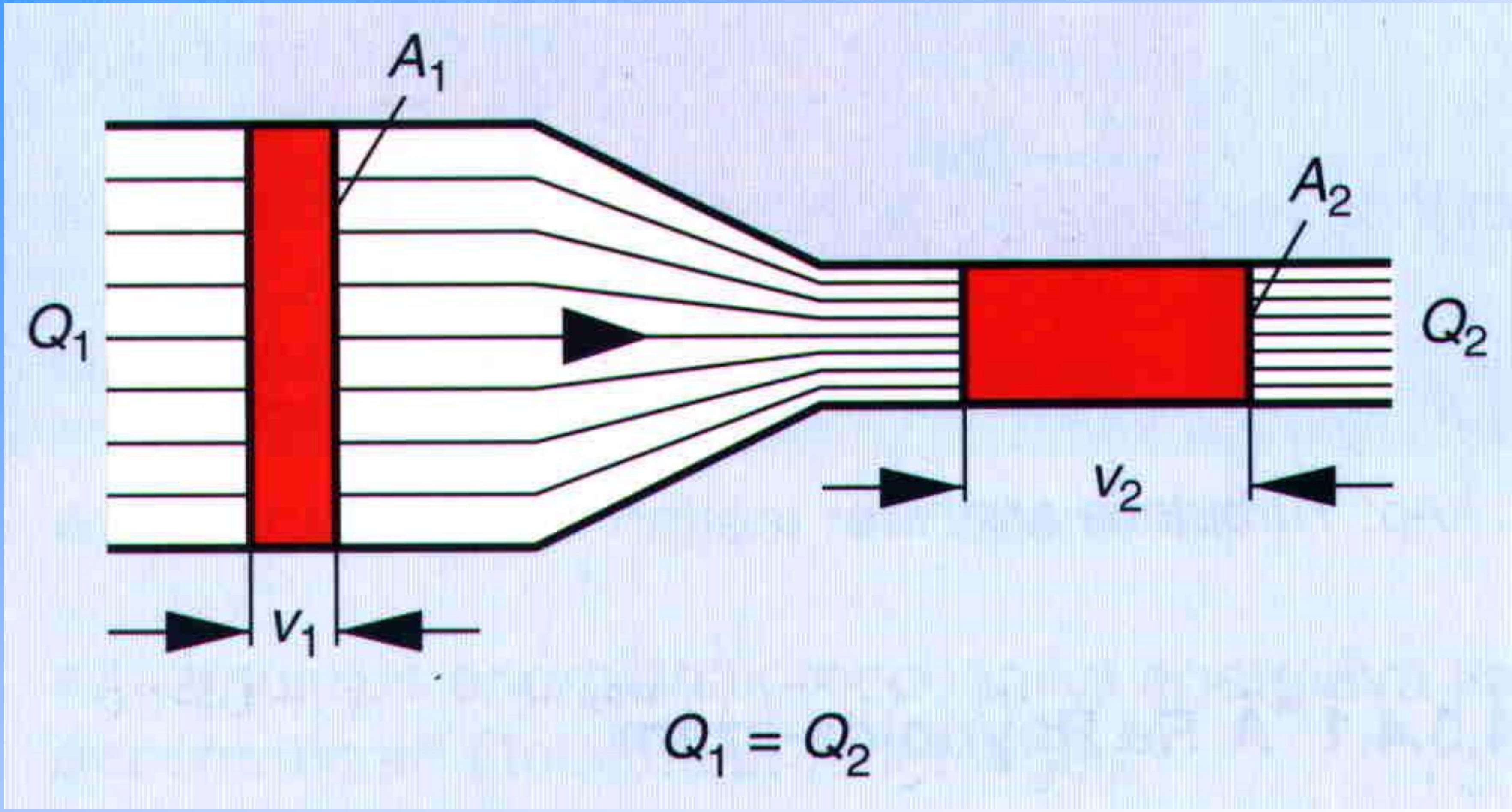
Hydraulic Systems



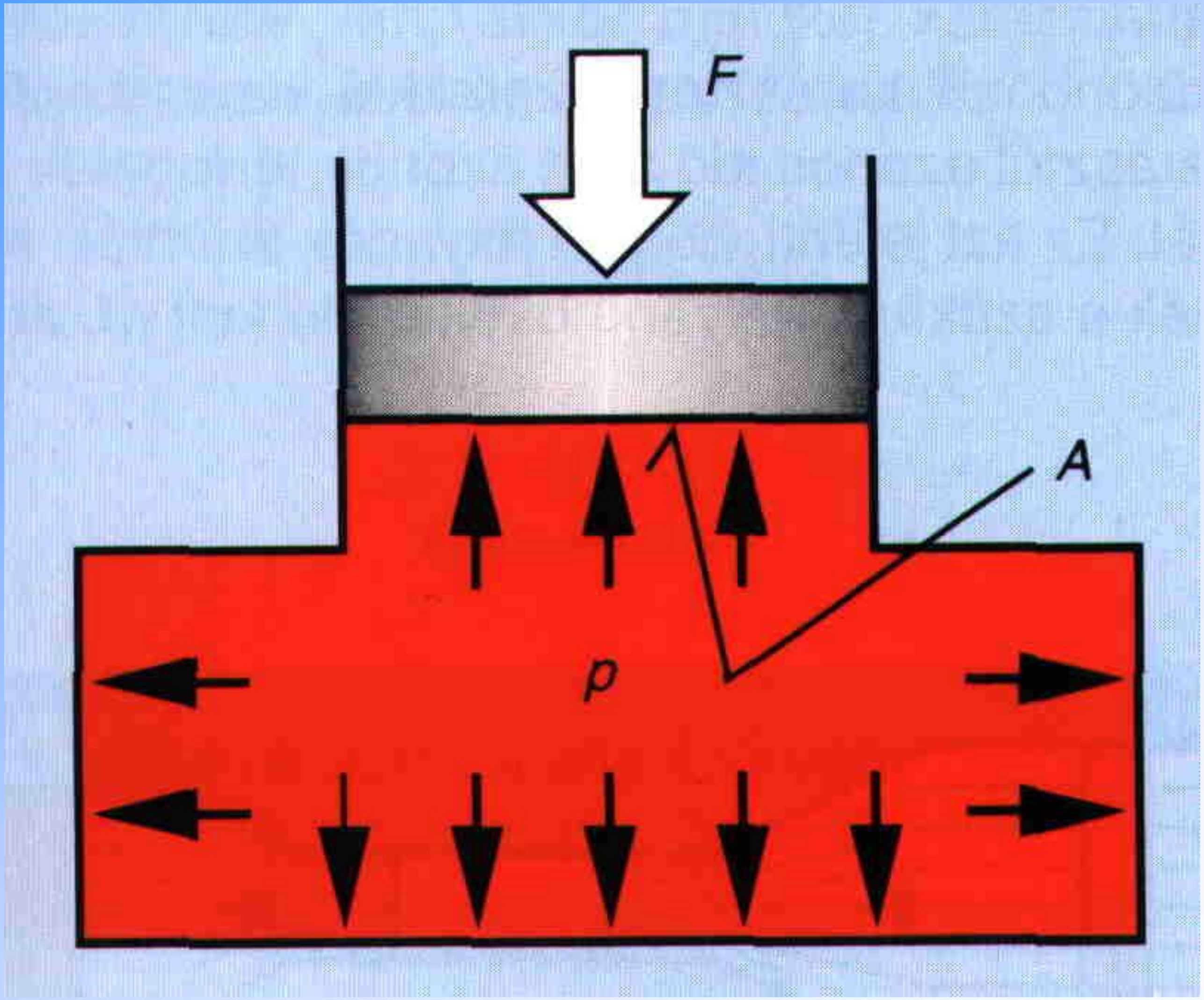
Hydraulic Systems



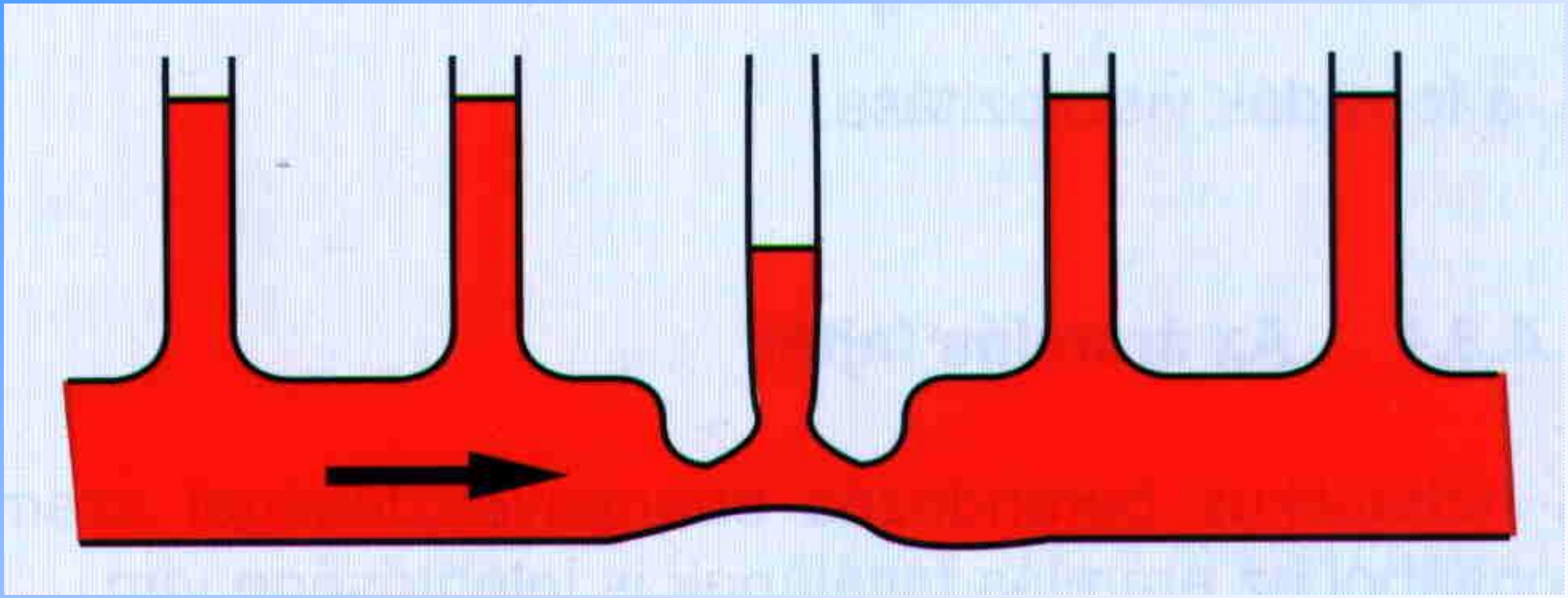
Continuity



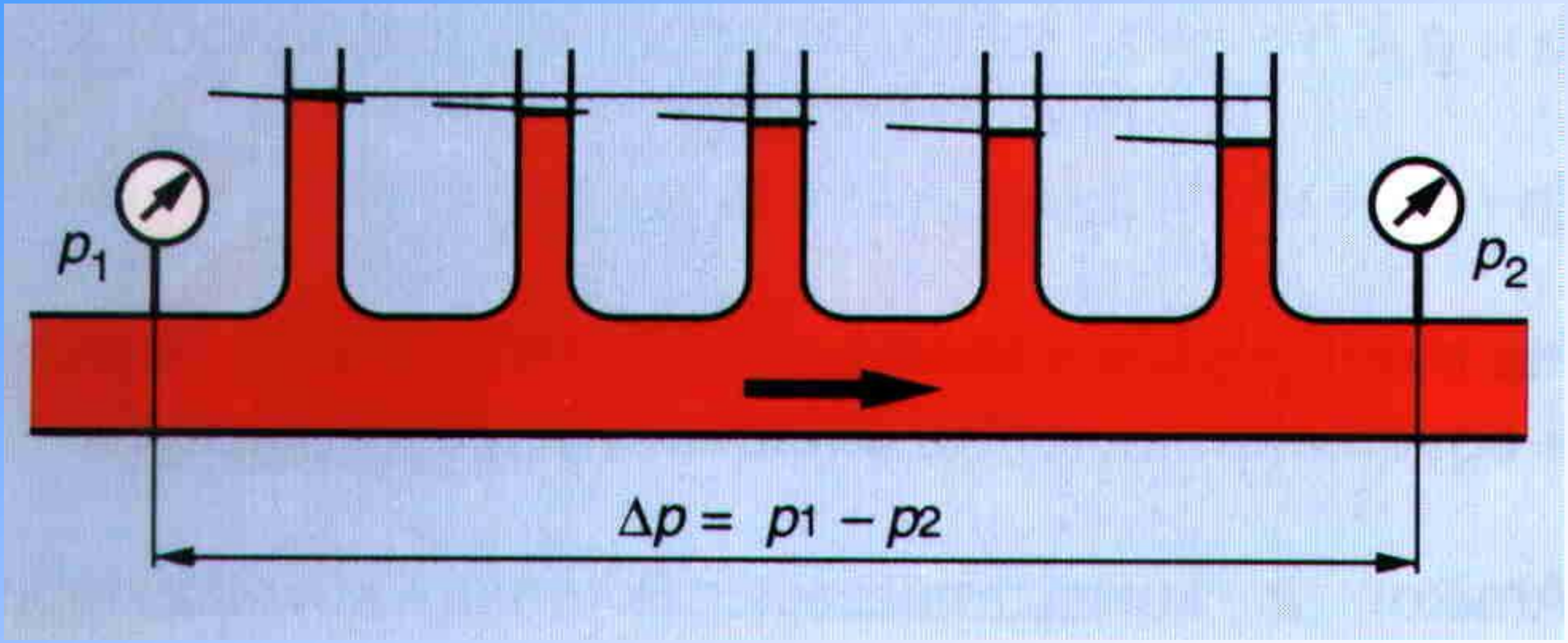
Pascal's law



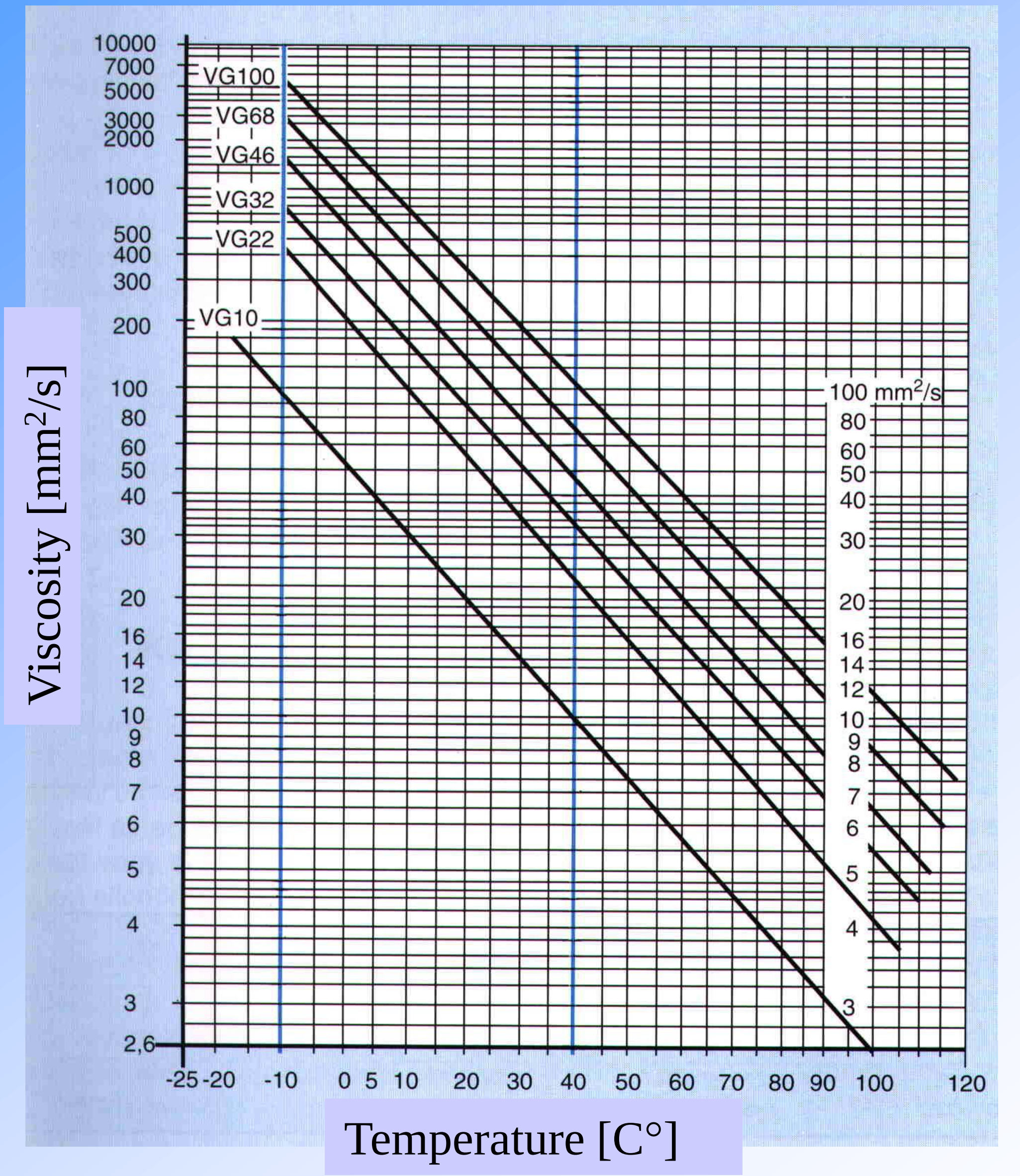
Bernoulli equation



Flow resistance



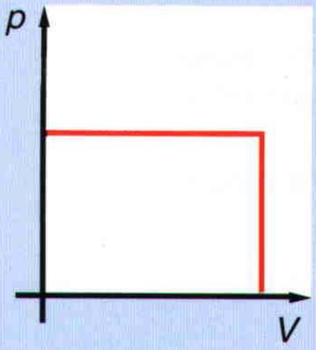
Viscosity over temperature



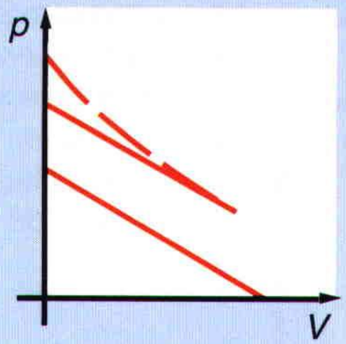
Hydraulic Systems

Accumulators:

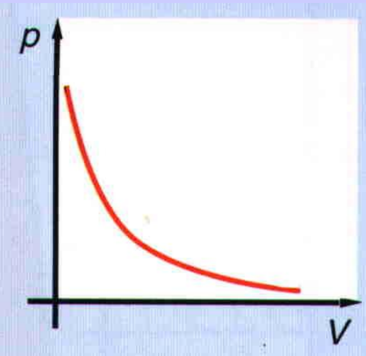
With weight

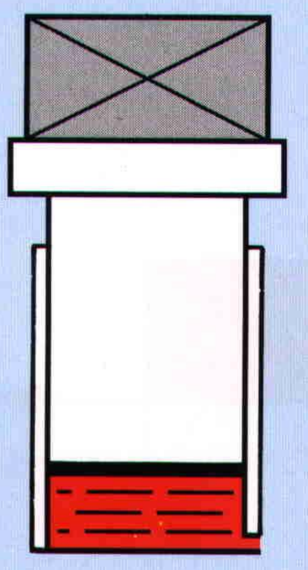


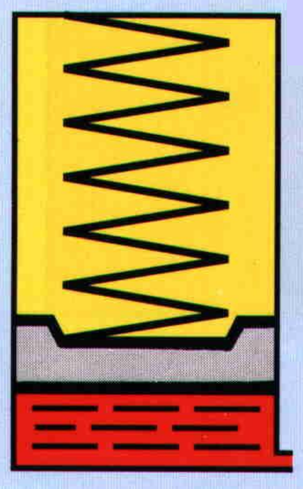
With spring



With gas
(hydropneumatic accumulator)

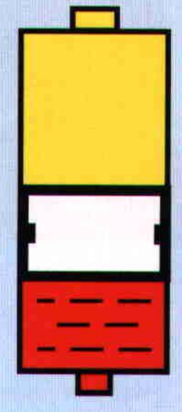




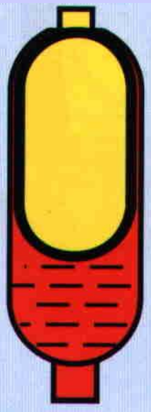


Separating part between gas and fluid

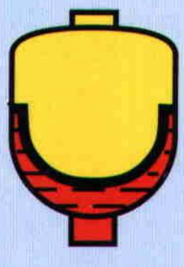
Piston



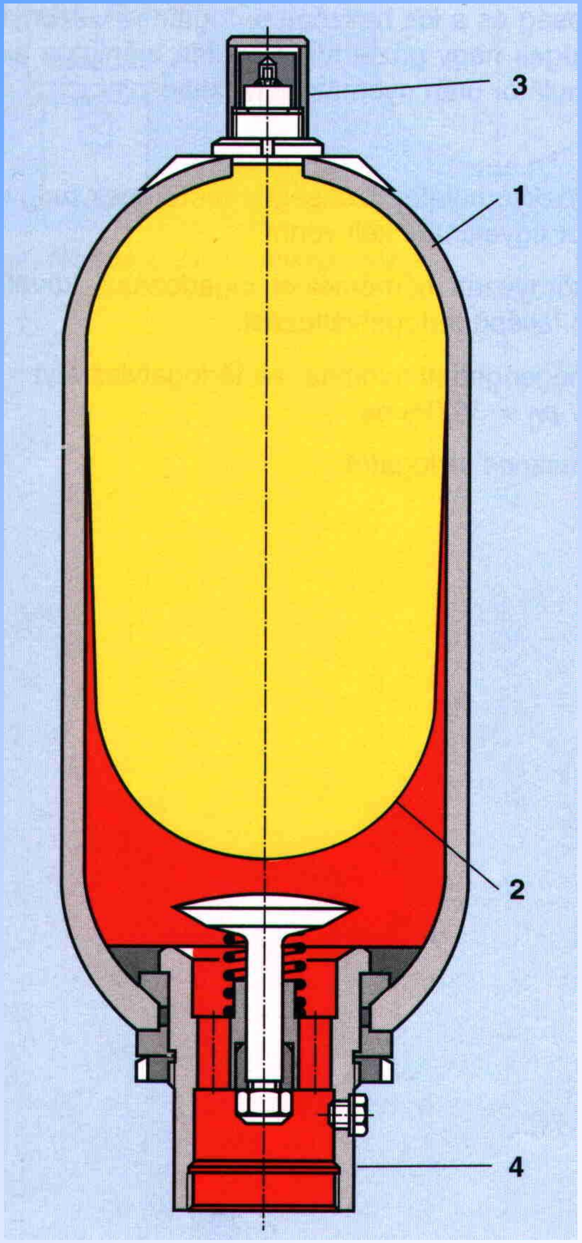
Bladder



Membrane

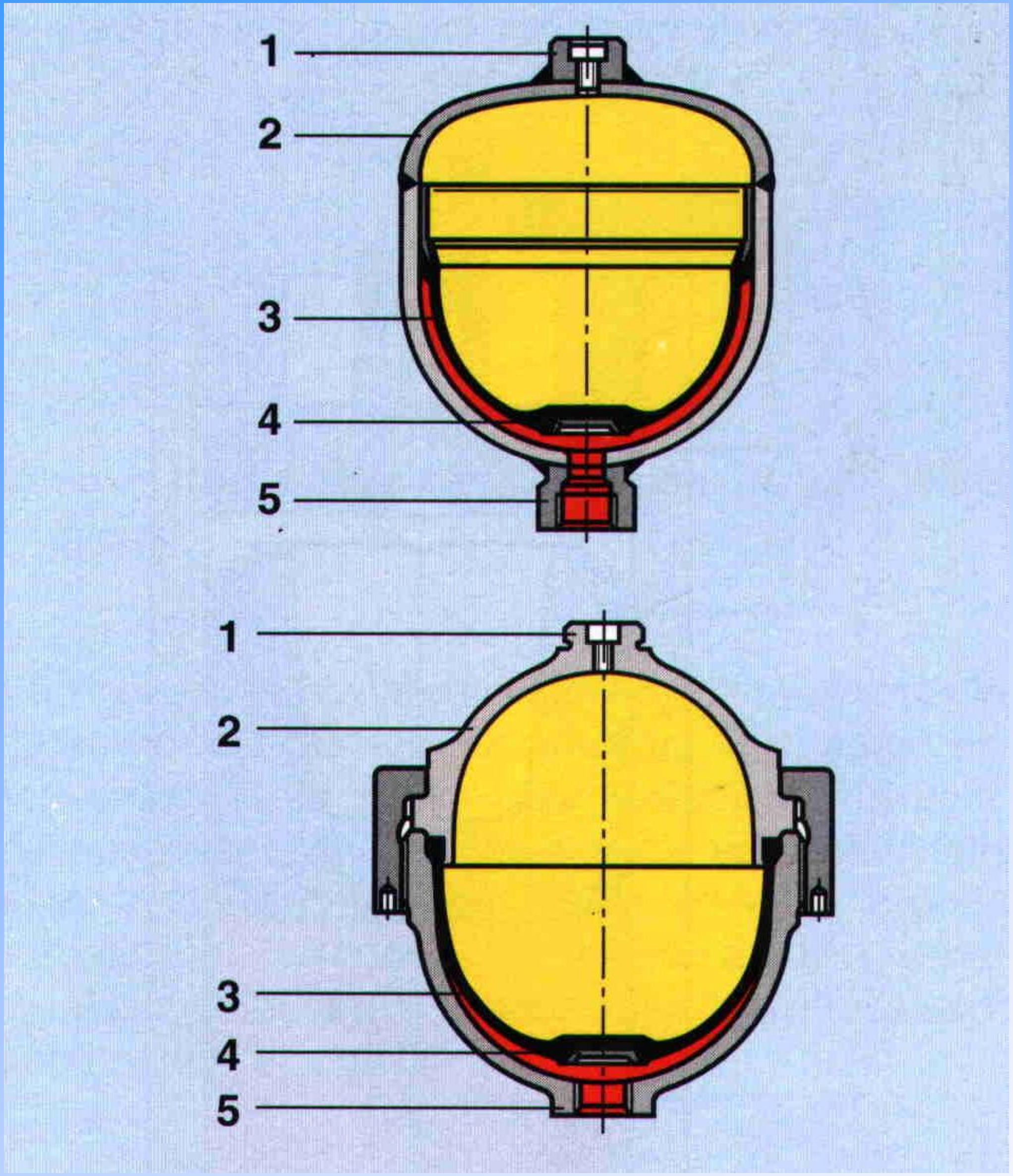


Accumulators:



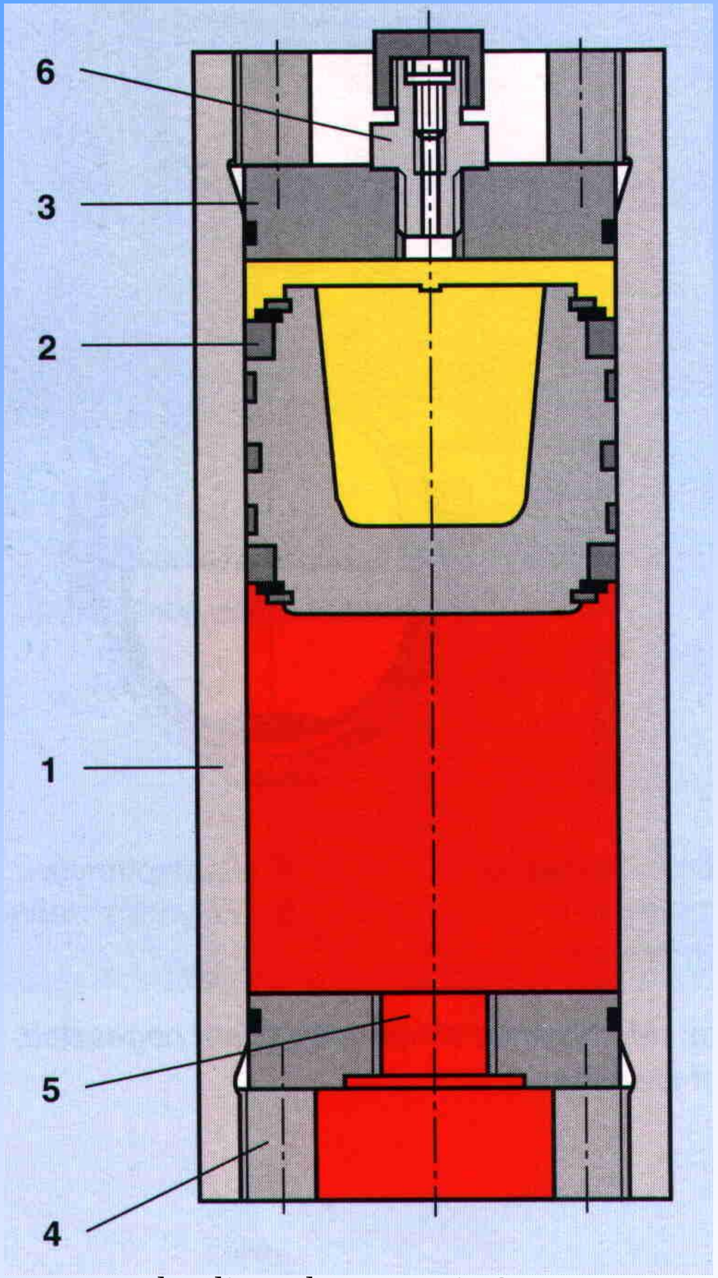
Hydraulic Systems

Accumulators:

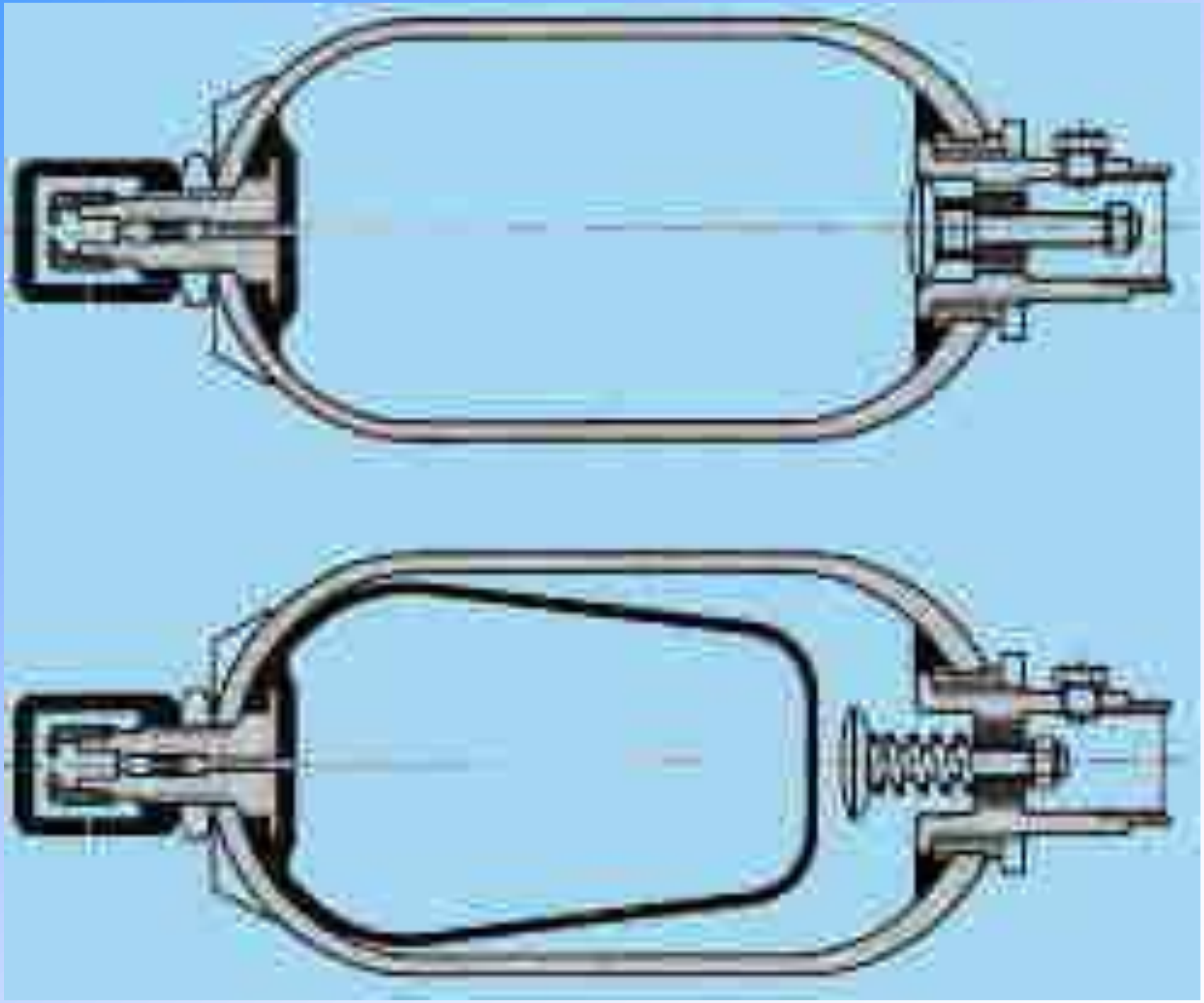


1. Gas filling screw
2. Tank
3. Membrane
4. Valve-disc
5. Juncture for hydraulic system

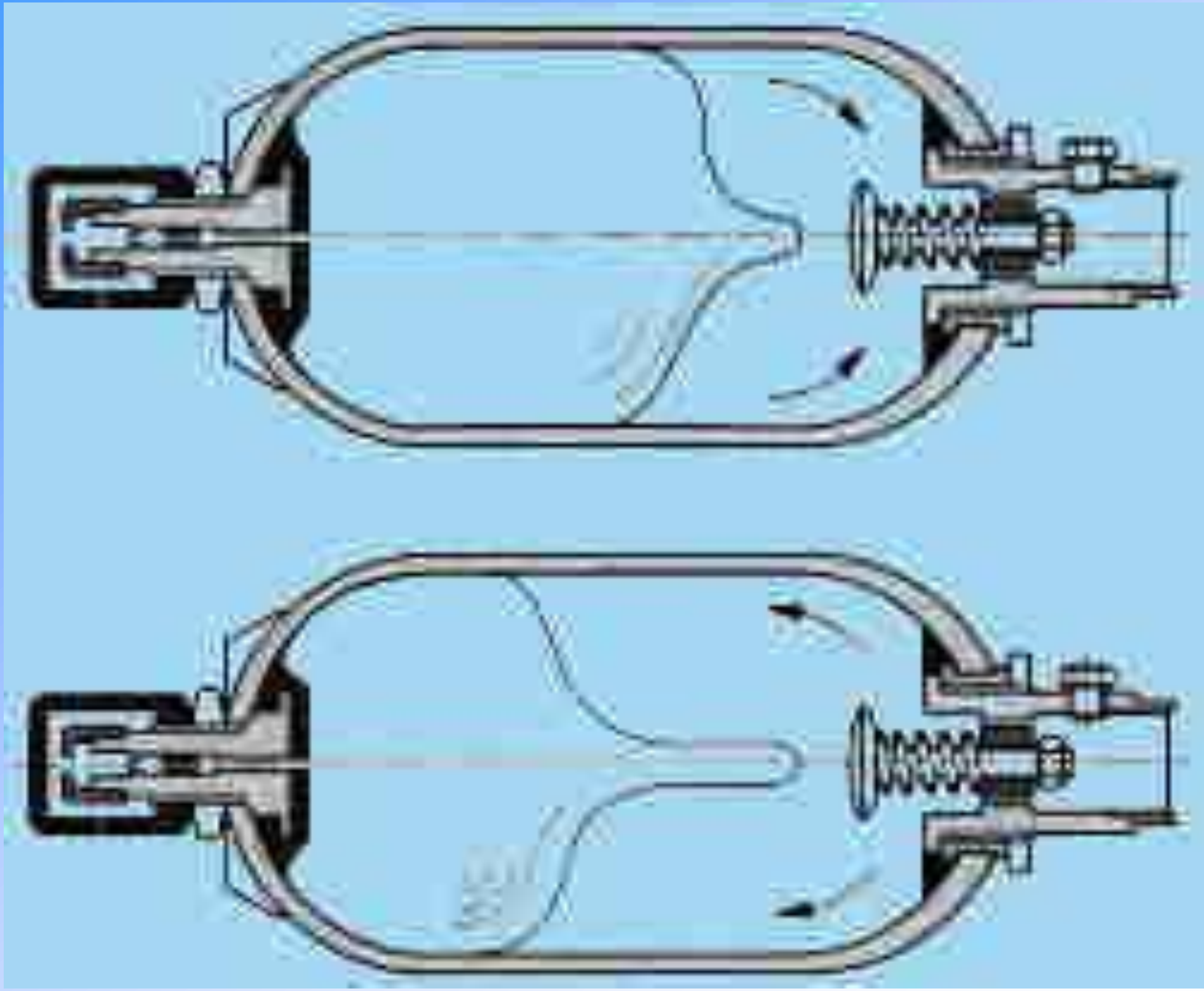
Accumulators:



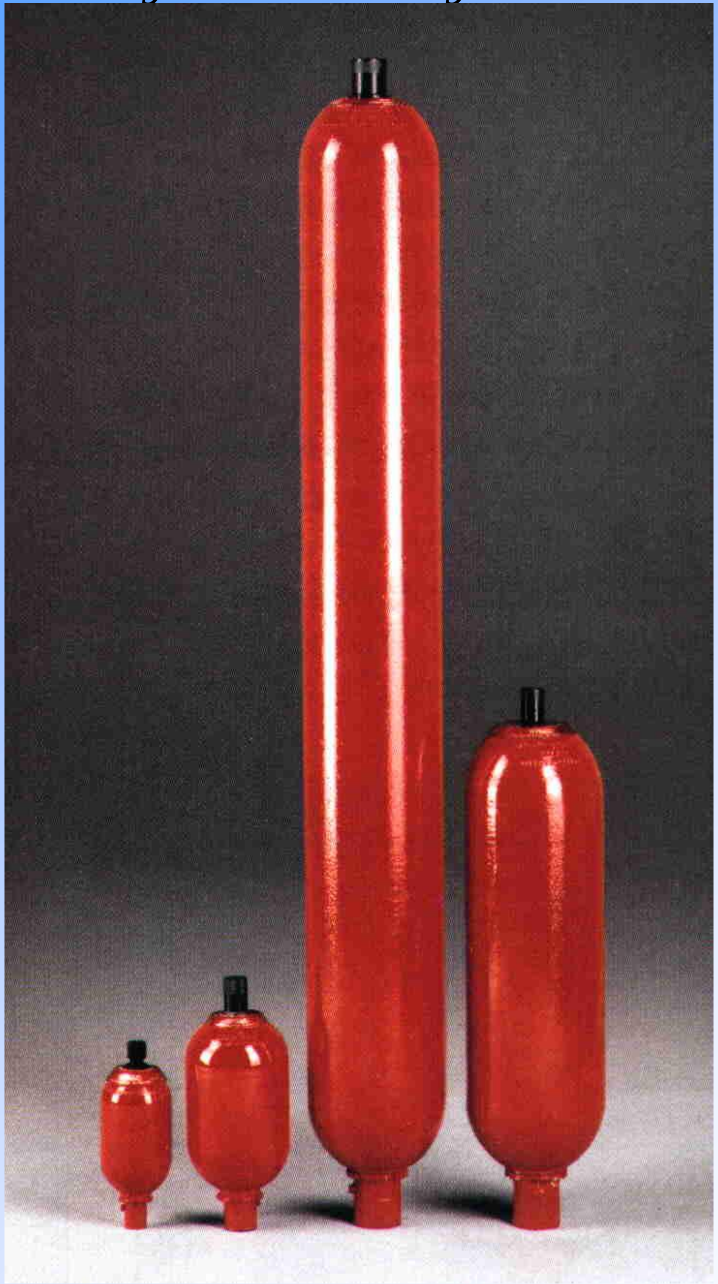
Accumulators:



Accumulators:

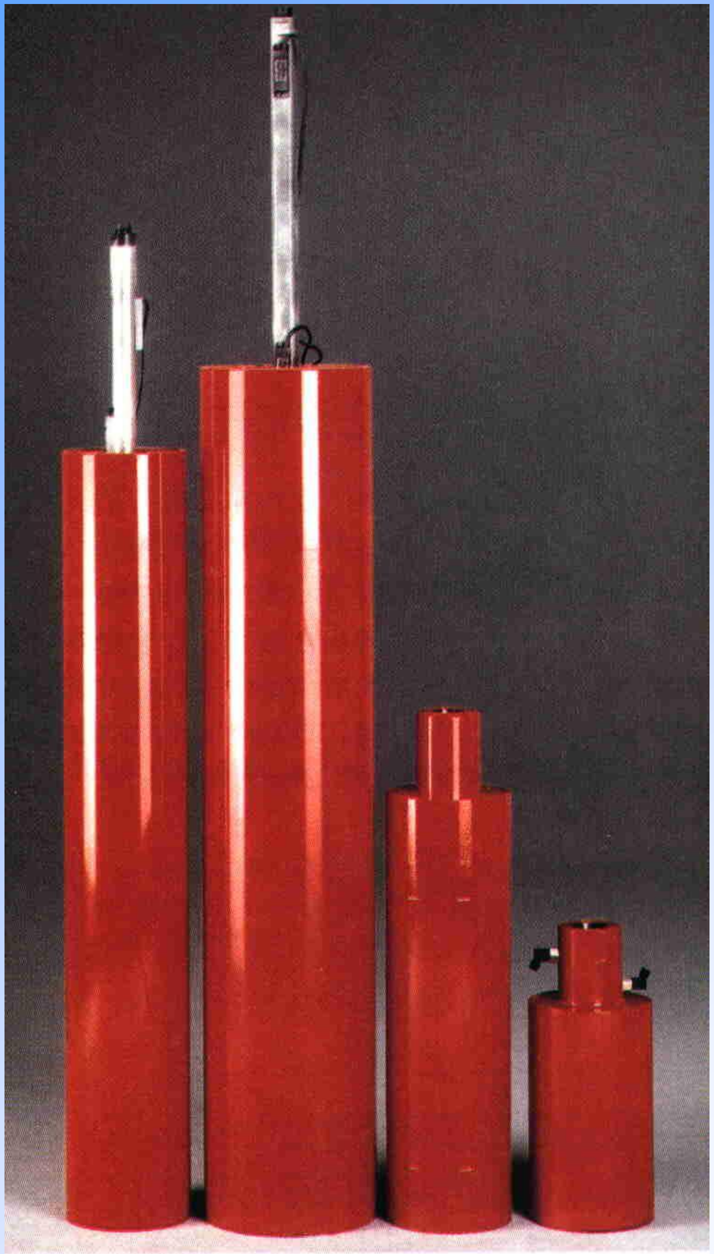


Accumulators with bladder:



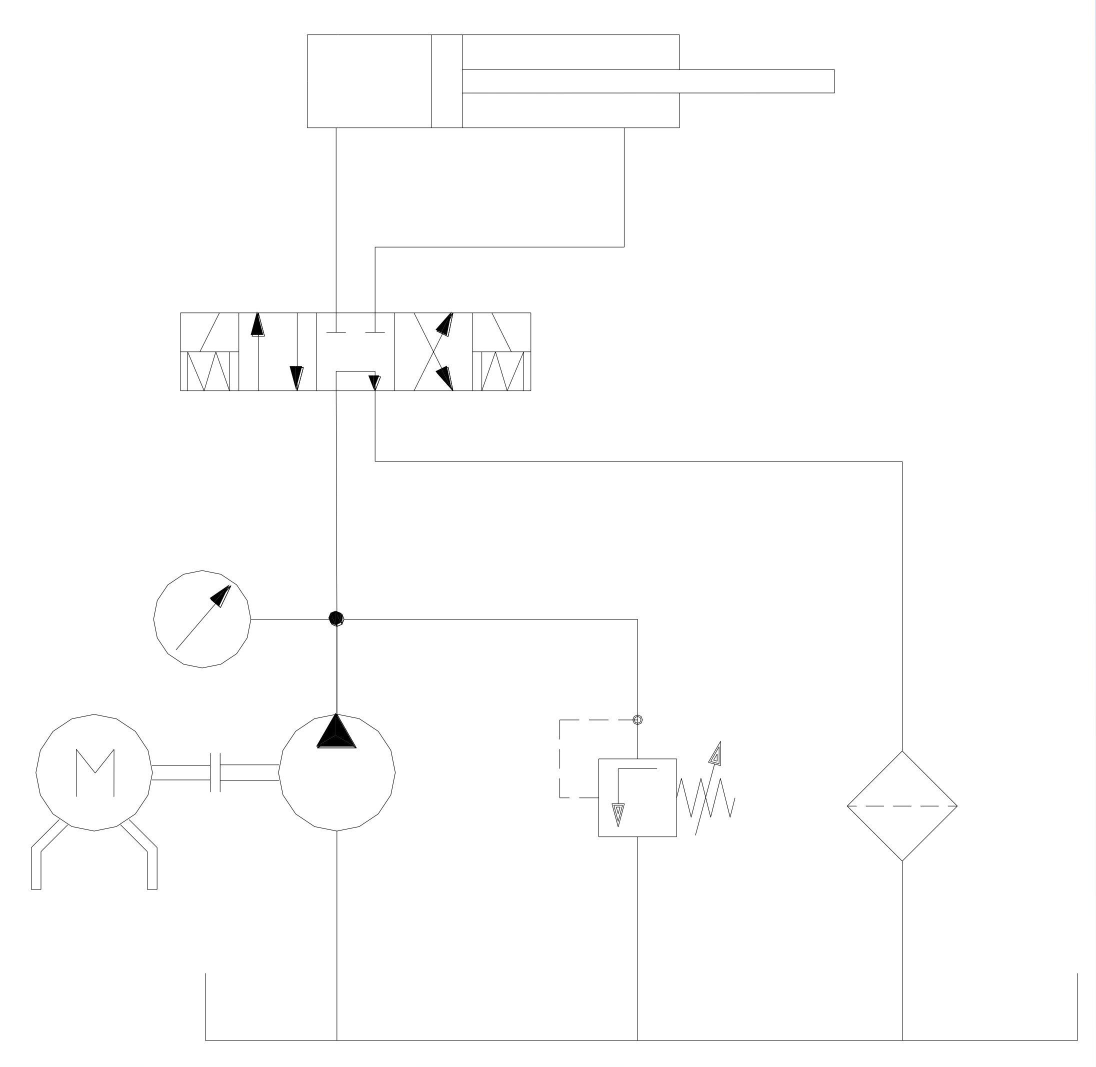
Accumulators with membrane:

Accumulators with piston:



Hydraulic Systems

Typical hydraulic system:



Pressure reservoirs = Accumulators

Serve three purposes:

- damping of pressure and volumetric flow rate oscillations,
- supplying the flow rate at variable demand,
- hydropneumatic spring.

They use the compressibility of a gas but the gas and liquid surface may not touch because then the gas will be dissolved in the liquid.

Three constructions:

a. Piston
b. Bladder (bag)
c. Membrane