Aalto University
School of Engineering

MEC-E5003

FLUID POWER BASICS

Study Year 2018 - 2019

Pumps
Actuators
Accumulators

Aalto University
School of Engineering
Mechanical Engineering / Engineering Design / Mechatronics / Fluid Power

Lecture themes

Flow to the system – How?

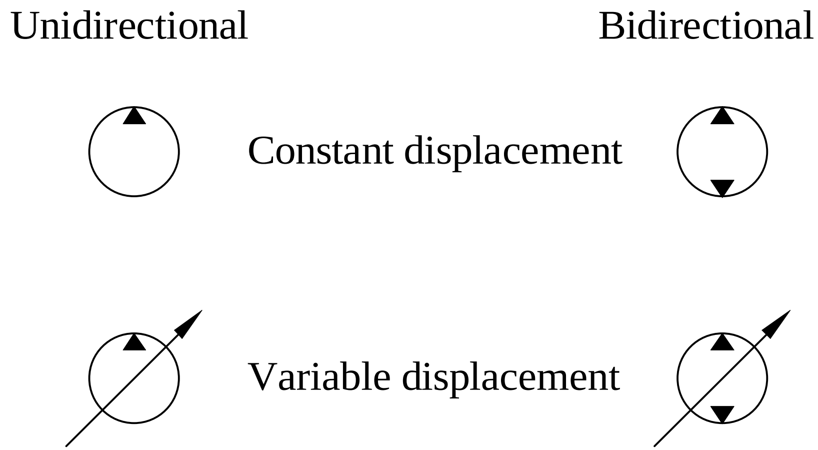
Making use of the hydraulic power – How?

Storing energy in hydraulic system – Why and is that even possible?

Hydrostatic pumps

Convert mechanical power into hydraulic power

Hydrostatic pumps produce <u>flow</u>, not pressure



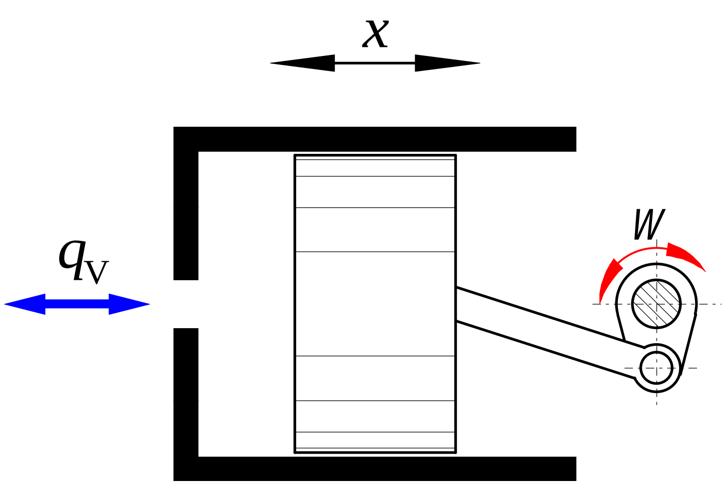
Construction

Most common construction types:

- gear
- vane
- screw
- piston

All operate on positive displacement principle

Positive displacement principle



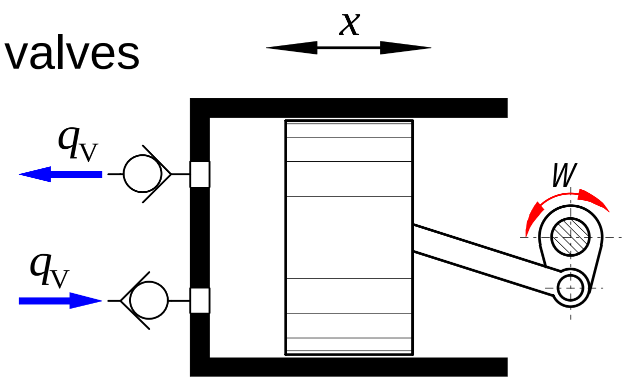
Operating phases:

Fluid flows into transfer volume – suction phase

Fluid flows out from volume – pressure phase

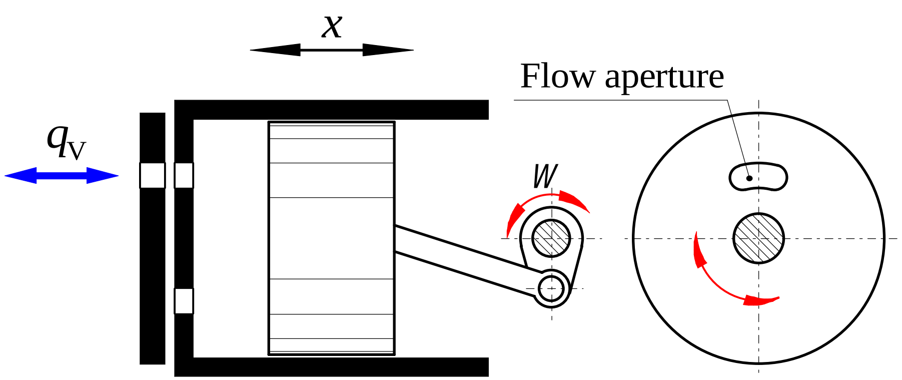
Control of flow direction

Check valves

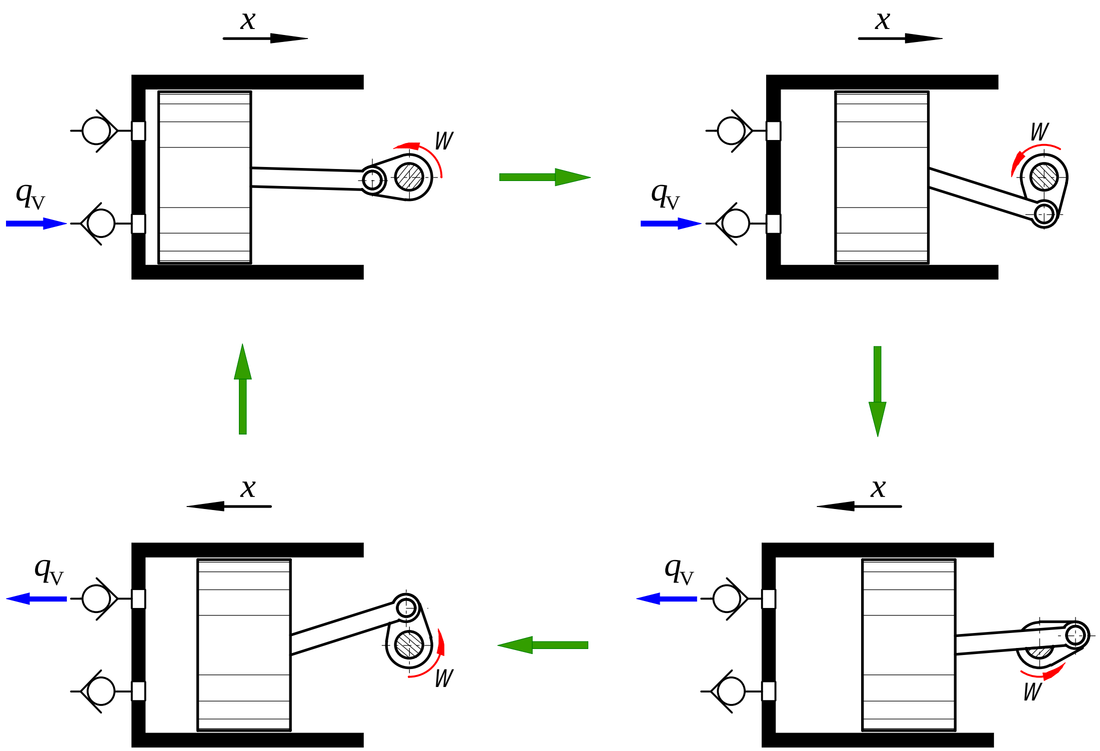


¬ Pressure control
aka valve control

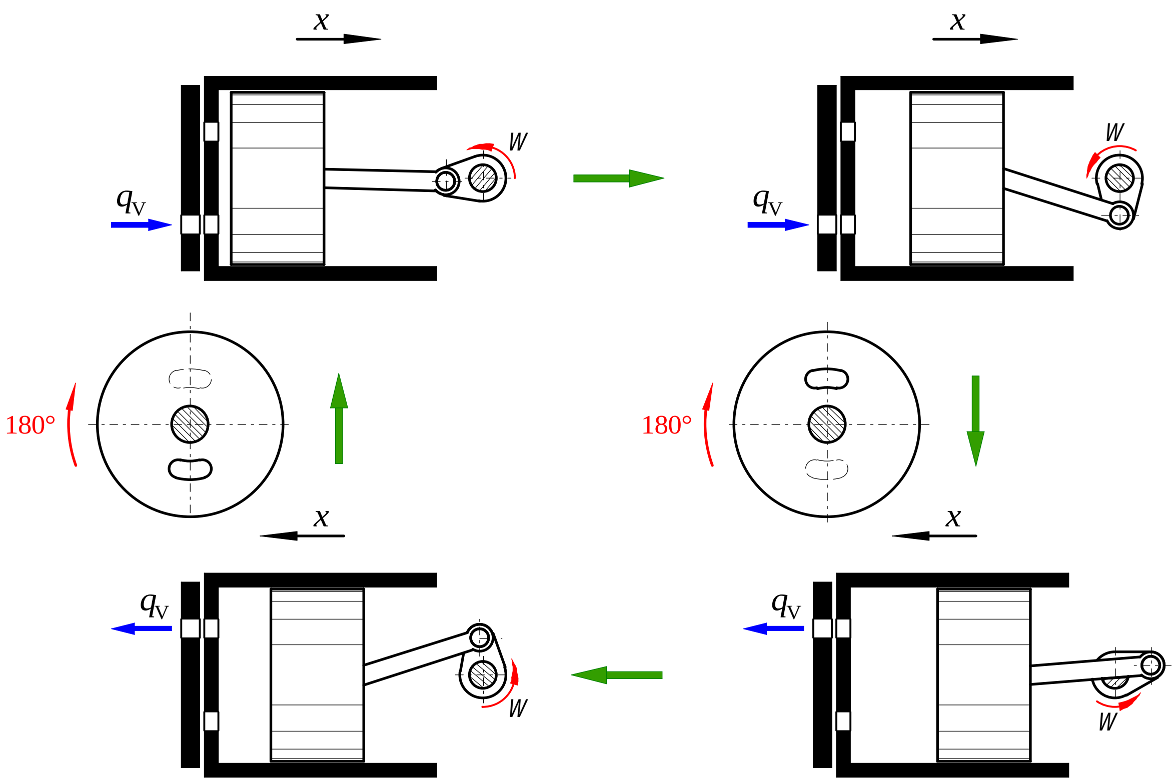
Forced control ®



Pressure control aka valve control

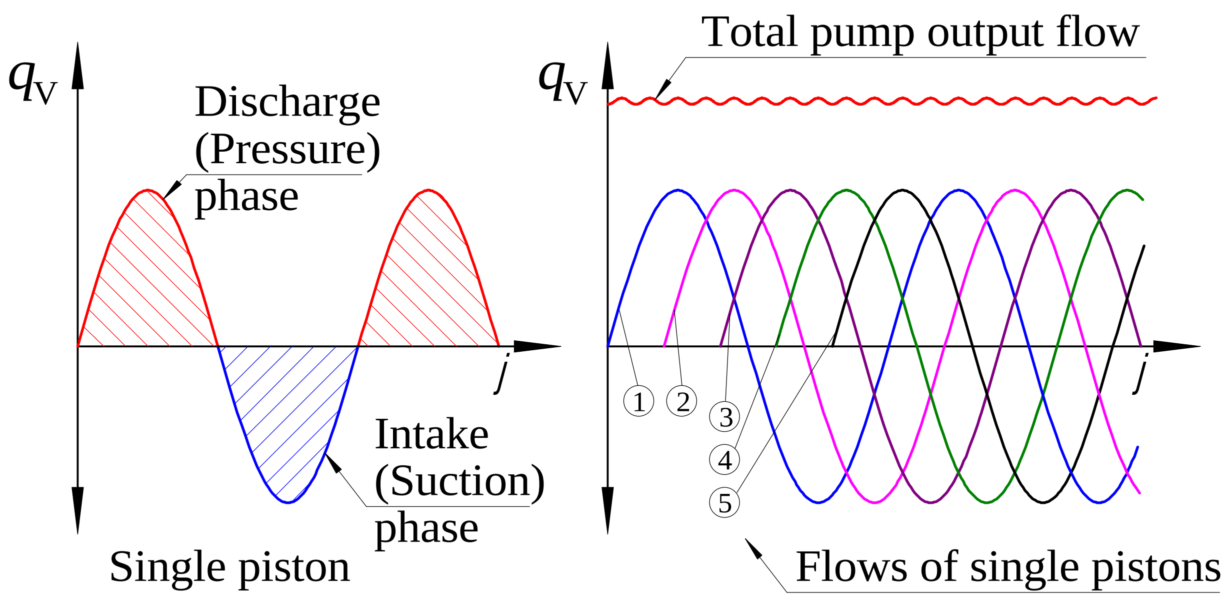


Forced control



Output flow variation ->
Internal pressure variation (depending on the system impedance) ->
External (air) pressure variation -> Noise

Flow pulsation



Flow pulsation is due to intermittent nature of positive displacement principle

Cavitation in pumps

Cause: Friction losses in inlet channel of pump

Pressure in fluid decreases to vapour pressure of the fluid

® fluid starts to vaporize (also size of air bubbles increases)

® vaporized fluid is pressurized in pump

® vapour bubbles collapse rapidly (”implosion”)

® pressure shocks

® material damages, noise, decreased output flow

Suction lines of pumps are
- short
- straight
- wide (large diameter) and the pump can be placed lower than the reservoir (tank) surface to avoid cavitation.

Pump characteristics

Theoretical output flow $$q_{V,\mathrm{theor}} = n \cdot V_\mathrm{g}$$

Swept volume V_g [m^3/r]   cm^3/r = 10^{-6} m^3/r

Rotation speed n [r/s]   r/min = 1/60 r/s

$$q_{V,\mathrm{theor}} = \omega \cdot V_\mathrm{rad}$$

$$\omega = 2\pi \cdot n$$ Angular velocity ω [rad/s]

$$V_\mathrm{rad} = \frac{V_\mathrm{g}}{2\pi}$$ Swept volume per radian V_rad [m^3/rad]

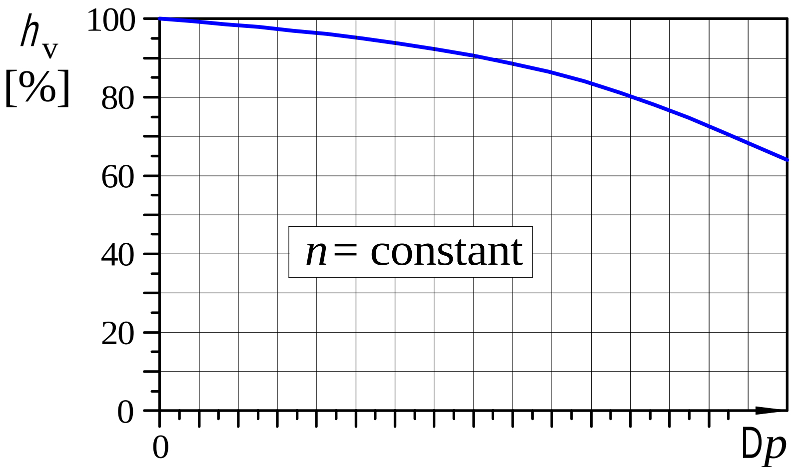
Effective output flow

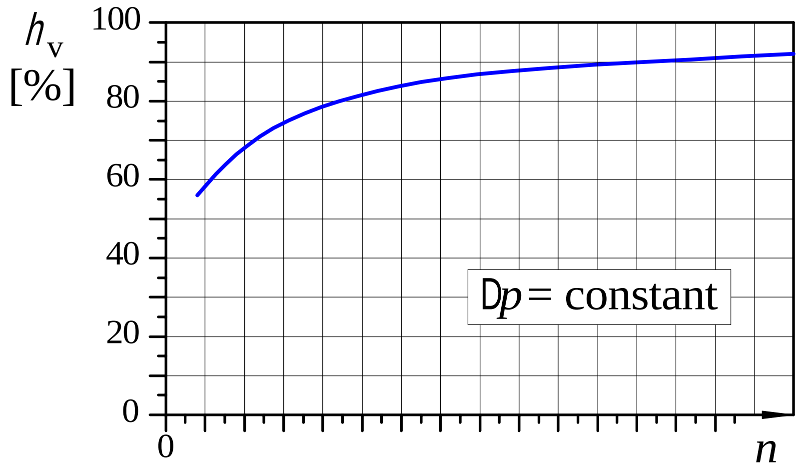
$$q_{V,real} = n \cdot V_g \cdot \eta_v$$

Leakage – volumetric efficiency η_v

Wilson's pump model

$$q_{V2} = \varepsilon V_i n - C_s \frac{V_i \Delta p}{2\pi \nu \rho}$$

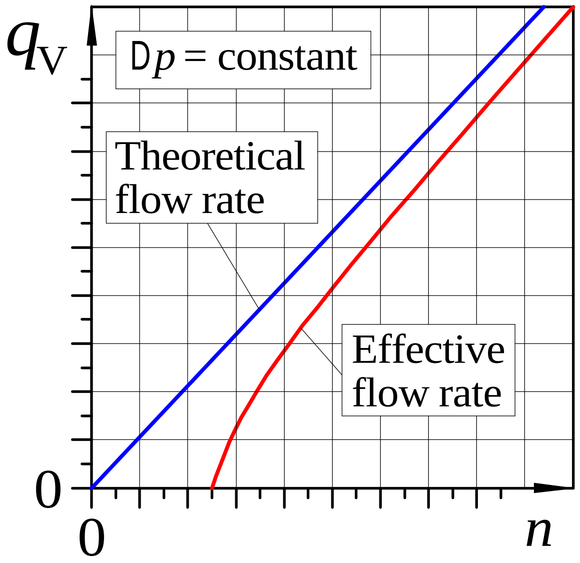


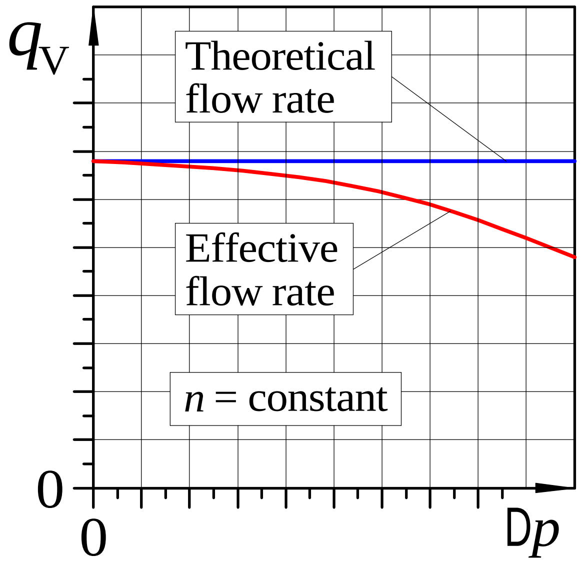


Wilson's pump model

$$q_{V2} = \varepsilon V_i n - C_s \frac{V_i \Delta p}{2\pi\nu\rho}$$

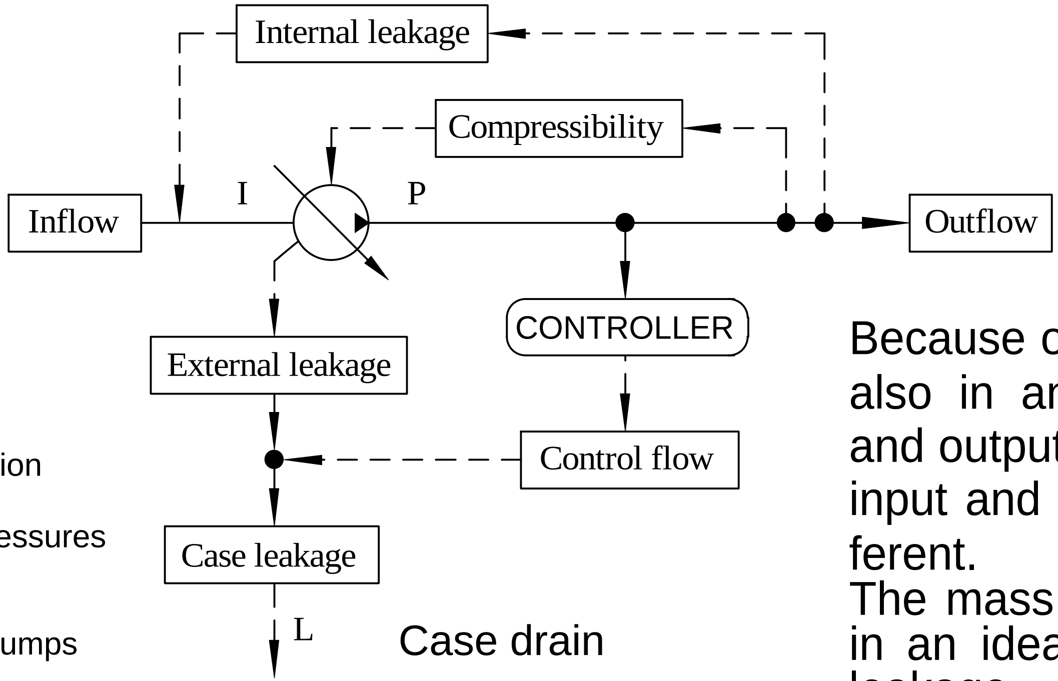
Theoretical output flow – Effective output flow





- ε pump angle set value (0 - 1)
- V_i max. displacement (per revolution)
- n rotational speed (1/s)
- C_s laminar flow loss coefficient
- Dp pressure difference over pump
- ν fluid kinematic viscosity
- ρ fluid density

Leakage flows in pumps



Internal leakage
- All pumps

External leakage
- With case drain connection
- To protect shaft seal
- To prevent high case pressures

Controller drain
- If pump has a controller
- Variable displacement pumps

Because of the fluid compressibility also in an **ideal pump** the input and output flow rates are different if input and output pressures are different.
The mass flow rates are the same in an ideal pump without external leakage.

Theoretic drive torque $$T_{\text{theor}} = \frac{\Delta p \cdot V_g}{2 \cdot \pi}$$

Swept volume V_g [m^3/r]

Pressure difference Δp [N/m^2]

Performance of pumps and motors

PUMP

Wilson's model

Flow rate (output)

$$q_{V2} = \varepsilon V_i n - C_s \frac{V_i \Delta p}{2\pi \nu \rho}$$

Pump torque (input)

$$T = \varepsilon \frac{V_i \Delta p}{2\pi} + C_f \frac{V_i \Delta p}{2\pi} + C_v V_i n \nu \rho + T_c$$

Ideal pump and motor

ε	Pump angle set value (0 - 1)
V_i	displacement (per revolution)
n	rotational speed (1/s)
C_s	laminar flow loss coefficient
Δp	pressure difference over pump
ν	fluid kinematic viscosity
ρ	fluid density
C_f	Coulomb friction coefficient
C_v	viscous friction coefficient
T_c	constant torque loss

Wilson's model is very simplistic and it can't explain all the phenomena in pumps (and motors).

Reference:
Ellmann, A., Kauranne, H. Kajaste, J. & Pietola, M.
EFFECT OF PARAMETER UNCERTAINTY ON RELIABILITY OF HYDRAULIC TRANSMISSION SYSTEM SIMULATION
Proceedings of IMECE2005 2005 ASME International Mechanical Engineering Congress and Exposition November 5-11, 2005, Orlando, Florida USA

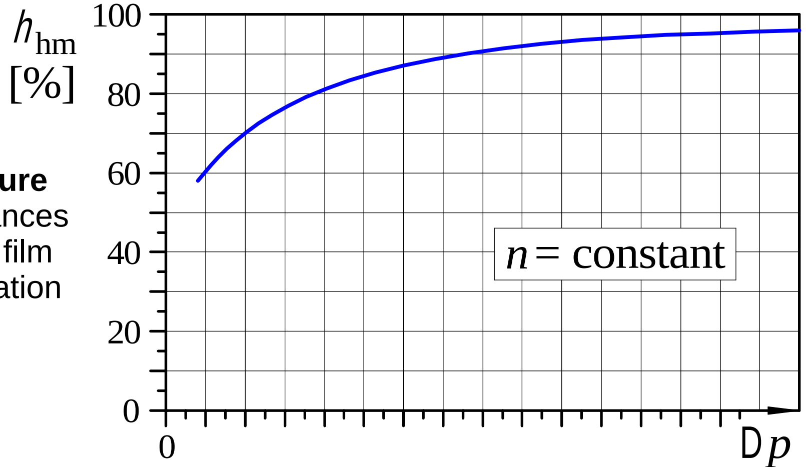
Effective drive torque $T_{real} = \dfrac{\Delta p \cdot V_g}{2 \cdot \pi \cdot \eta_{hm}}$

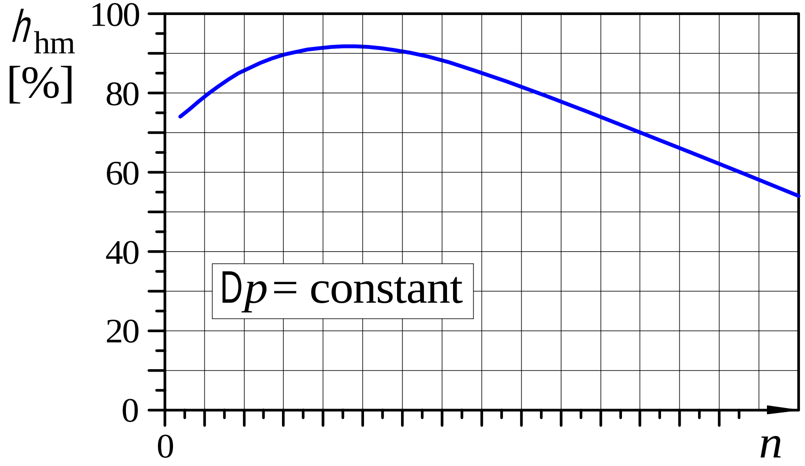
Wilson's pump model does not explain the phenomena seen in the figures below well

Friction – hydromechanical efficiency η_{hm}

$$T = \varepsilon \frac{V_i \Delta p}{2\pi} + C_f \frac{V_i \Delta p}{2\pi} + C_v V_i n \nu \rho + T_c$$

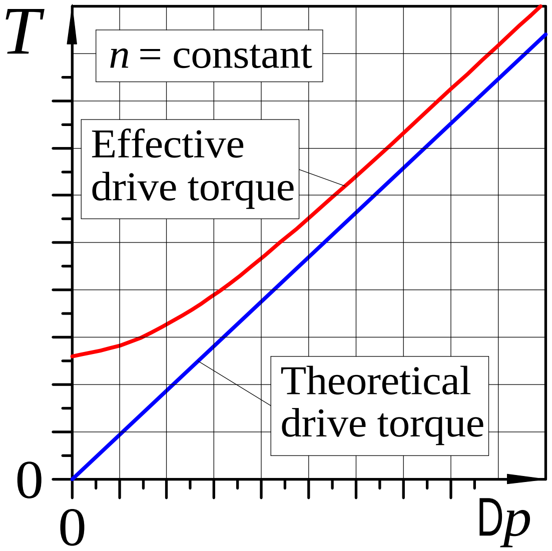
Higher pressure
- Wider clearances
- Thicker fluid film
- Better lubrication

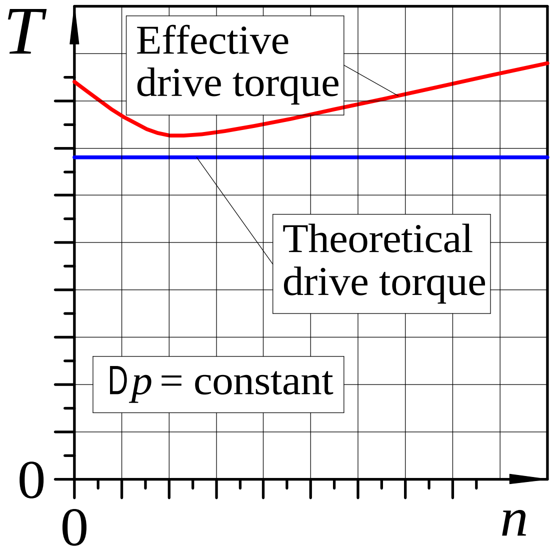




Effect of *n*
- At first Coulomb friction dominates
- Then better lubrication
- Finally hydraulic losses increase

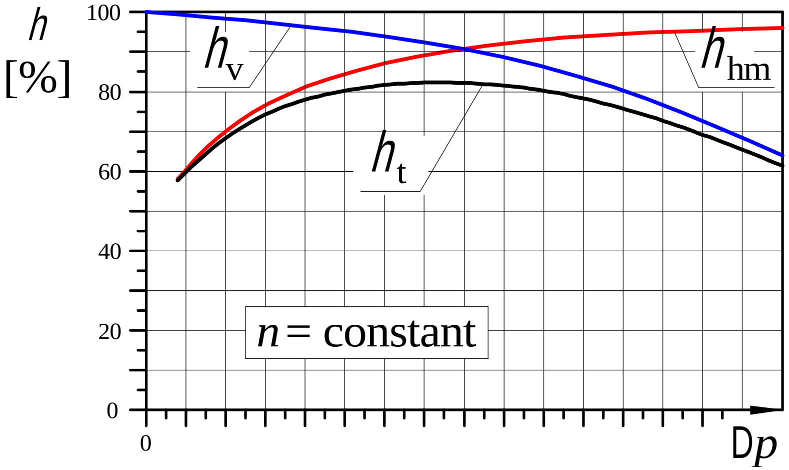
Theoretical drive torque – Effective drive torque

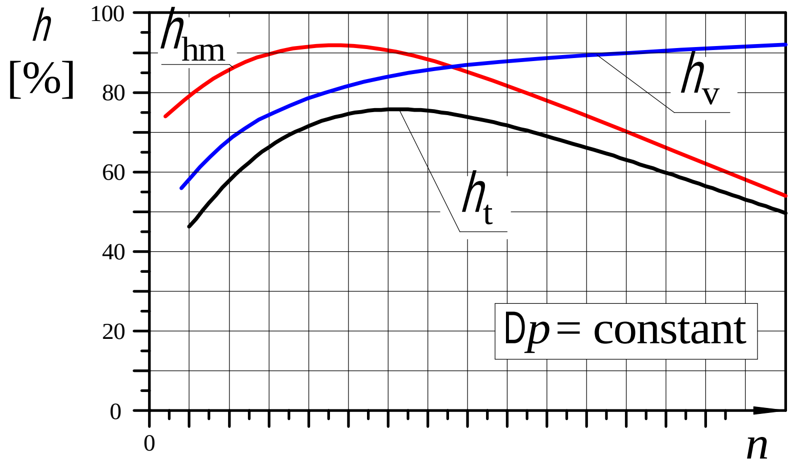




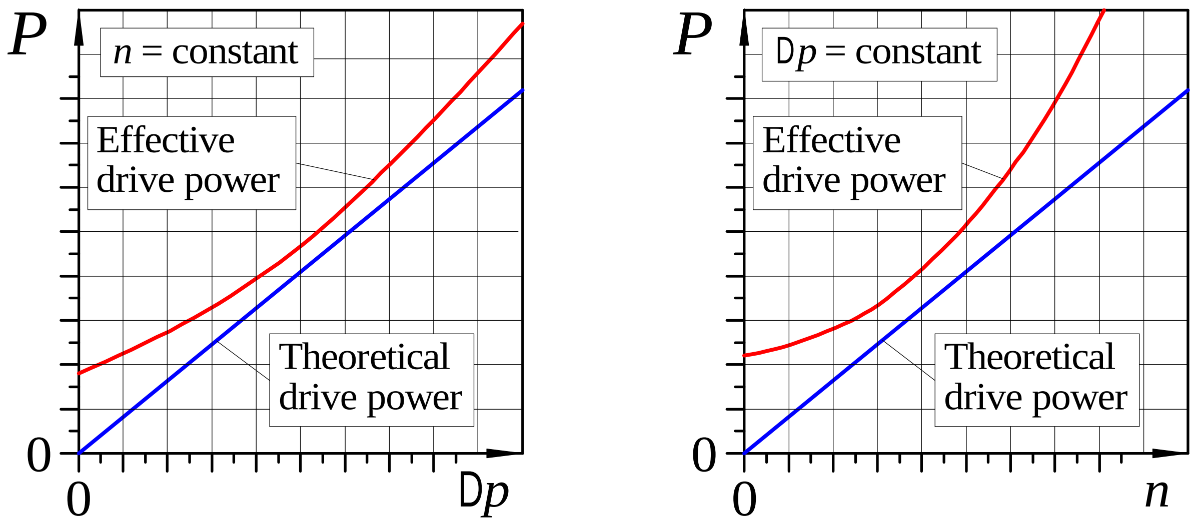
Theoretic drive power $P_{\mathrm{theor}} = q_{\mathrm{V}} \cdot \Delta p$

Effective drive power $P_{\mathrm{real}} = \dfrac{q_{\mathrm{V}} \cdot \Delta p}{\eta_{\mathrm{t}}}$ $\eta_{\mathrm{t}} = \eta_{\mathrm{v}} \cdot \eta_{\mathrm{hm}}$

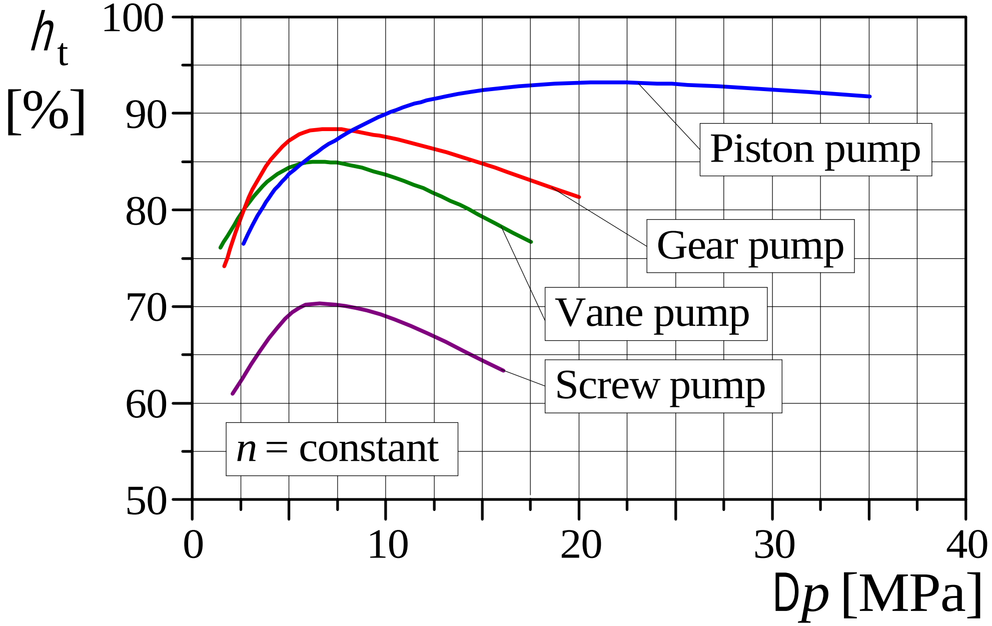




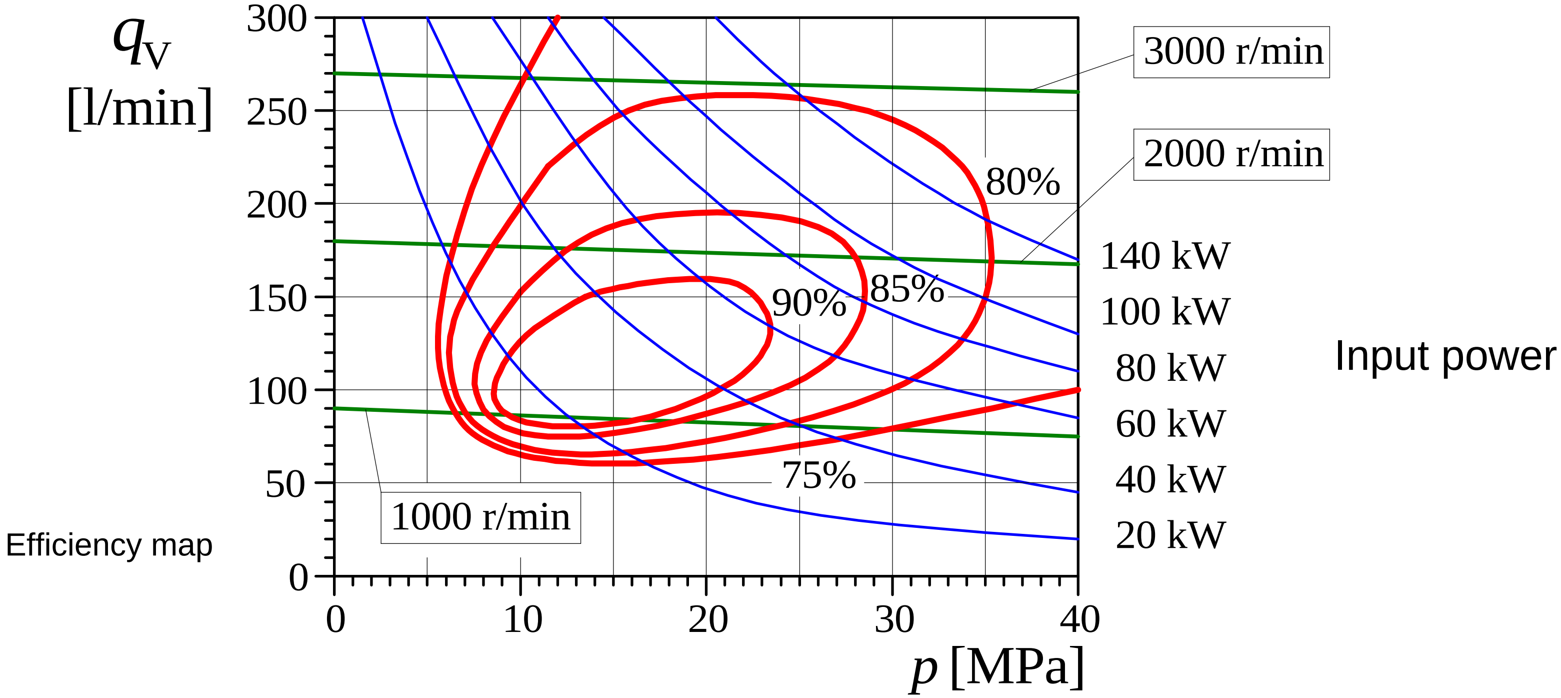
Theoretical drive power – Effective drive power



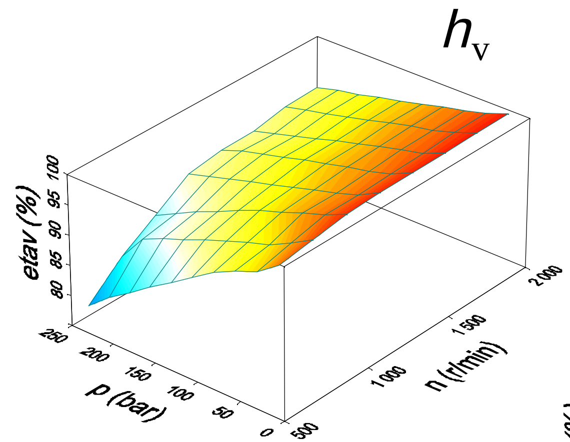
Comparison of structure types

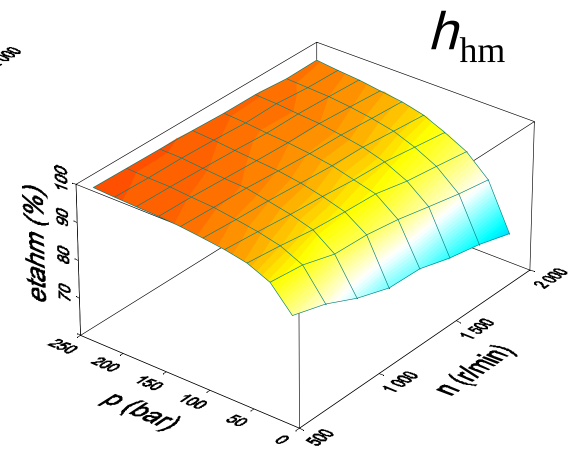


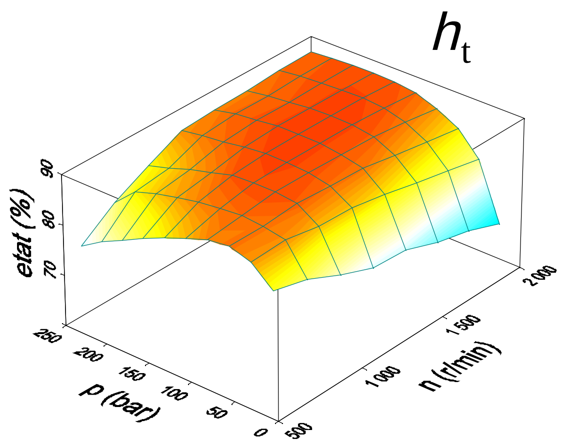
Characteristic curves of pump



Example:
Pressure-rotational speed-dependency of axial piston pump







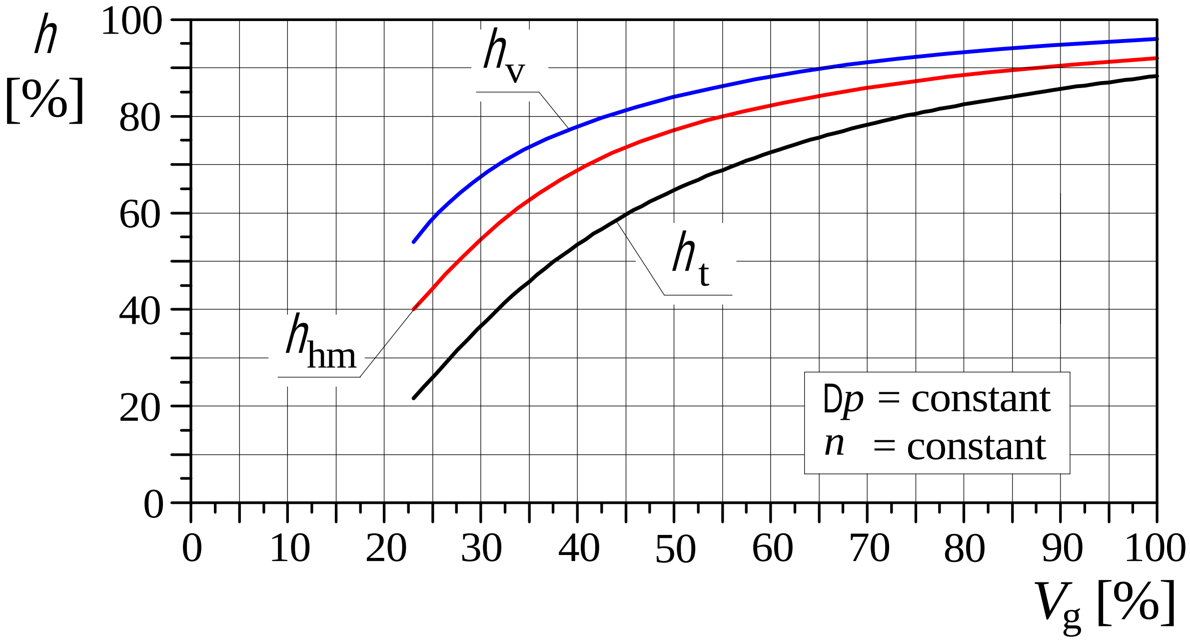
$$T = \varepsilon \frac{V_i \Delta p}{2\pi} + C_f \frac{V_i \Delta p}{2\pi} + C_v V_i n \nu \rho + T_c$$

⇐ Wilson's model (check the effect of decreasing ε)

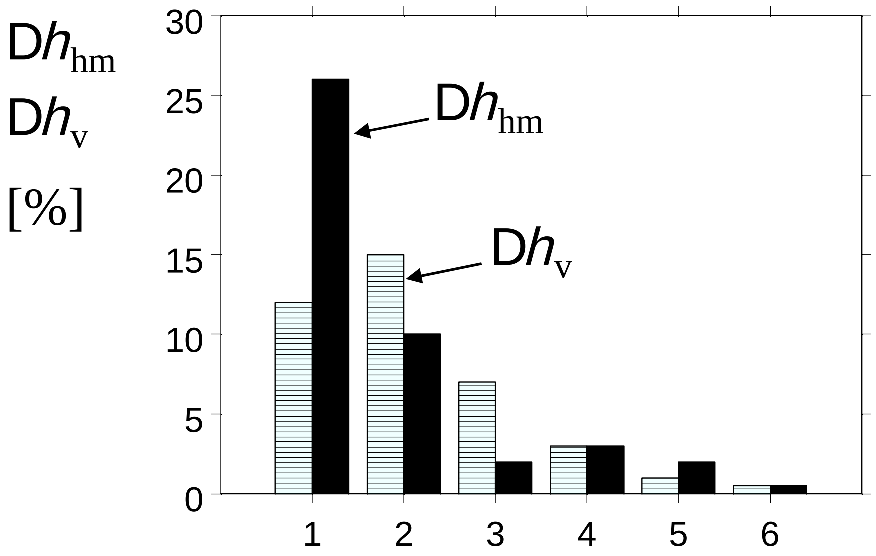
ε Pump angle set value (0 - 1) (axial piston pumps)

$$q_{V2} = \varepsilon V_i n - C_s \frac{V_i \Delta p}{2\pi \nu \rho}$$

Effect of displacement setting value to the efficiencies in variable displacement pumps



Factors affecting efficiency



1: pressure
2: swept volume
3: rotational speed
4: temperature
5: pump specimen
6: fluid

Pump types

Gear pumps
- external gear
- internal gear

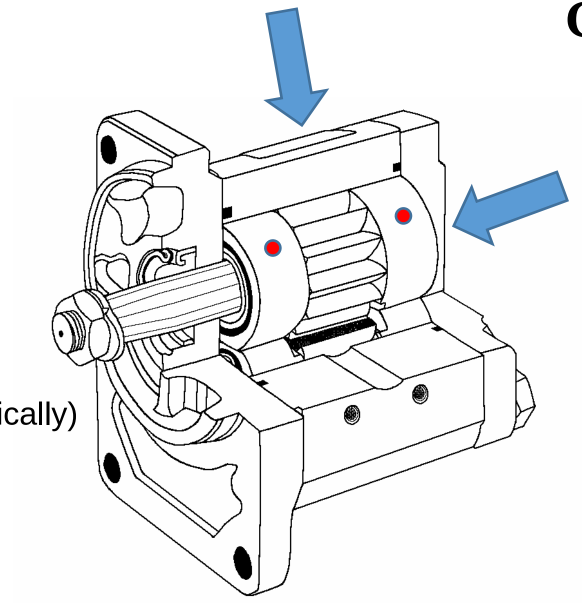
Screw pumps

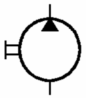
Vane pumps
- vanes in rotor
- vanes in stator

Piston pumps
- line piston pumps
- radial piston pumps
- axial piston pumps

Gear pumps

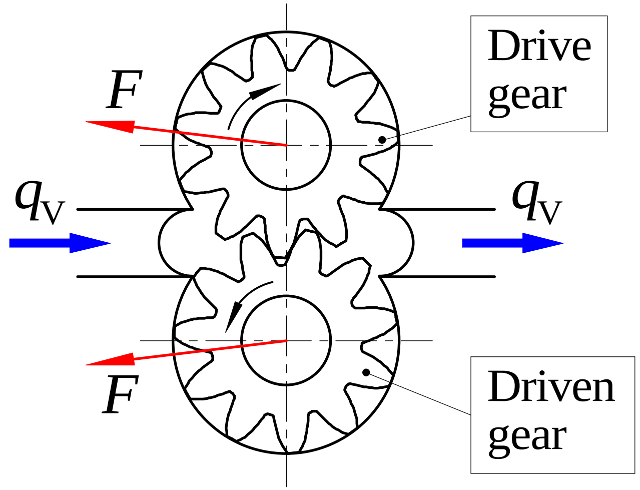
Reduction of leakage by
- axial gap compensation
- radial gap compensation
in some models





- Hydrodynamic bearings (typically)
- Roller bearings

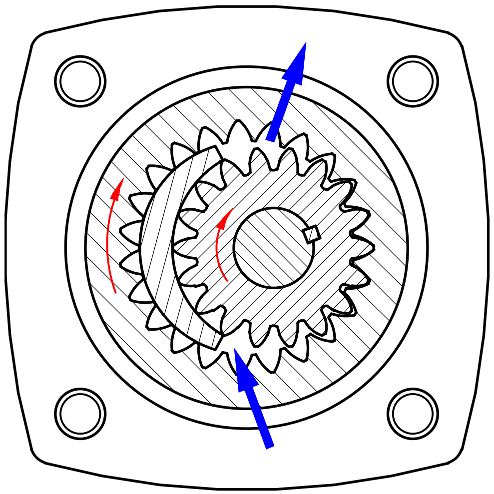
External gear
- two gear
- multi gear



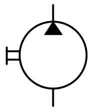
Internal rotor
External rotor

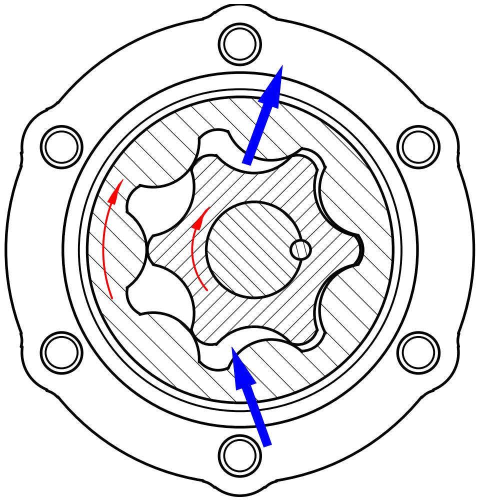
Axial compensation
Radial compensation
possible

- Low noise
- Even flow



q_V





q_V

Internal rotor
External rotor

Also "roller rotor" design

Internal gear

- crescent (segment pump)
- gerotor (ring pump)

Performance characteristics of gear pumps

Total efficiency max. h_t » 0.8 – 0.93

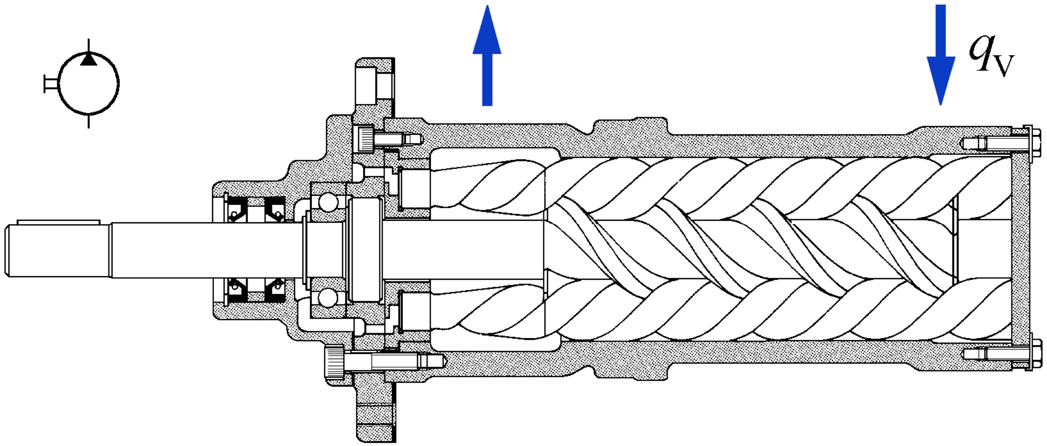
Rotational speed range n » 500 – 5000 r/min

Operating pressure max. p » 14 – 21 (– 32) MPa

- depends on compensation of leakage
  and radial forces

Screw crests roll against screw roots and seal fluid chambers

Screw pumps



Fluid volumes do not change during movement
- Even flow
- Low noise
- High rotational speeds possible

Number of screws
- one
- two
- three

Total efficiency max. h_t » 0.7 – 0.8

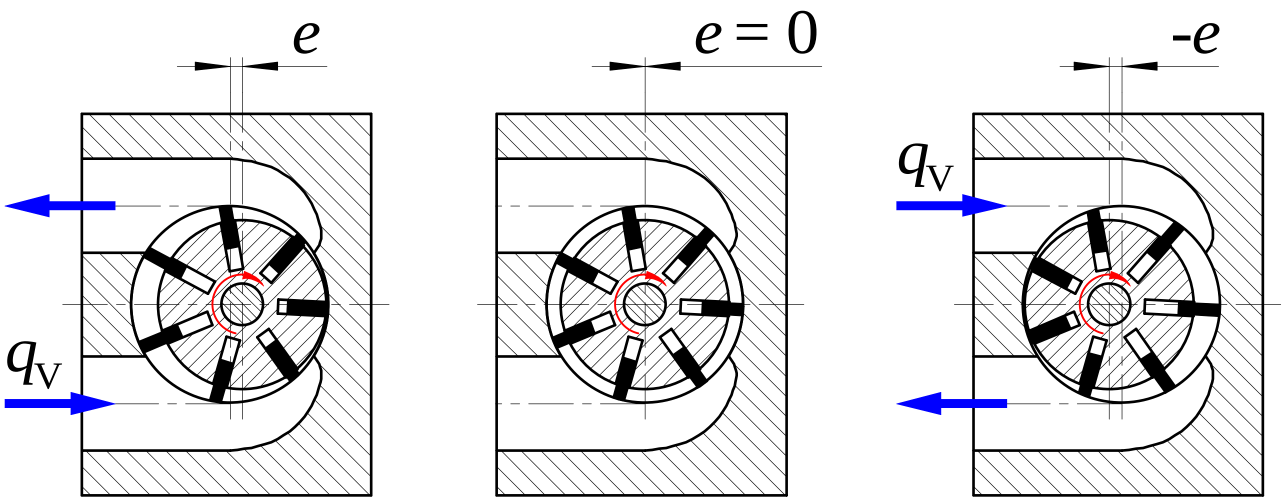
Rotational speed max. n » 30000 r/min

Operating pressure max. p » 14 – 20 MPa

By altering eccentricity of rotor the displacement and even the flow direction can be changed.

Vane pumps

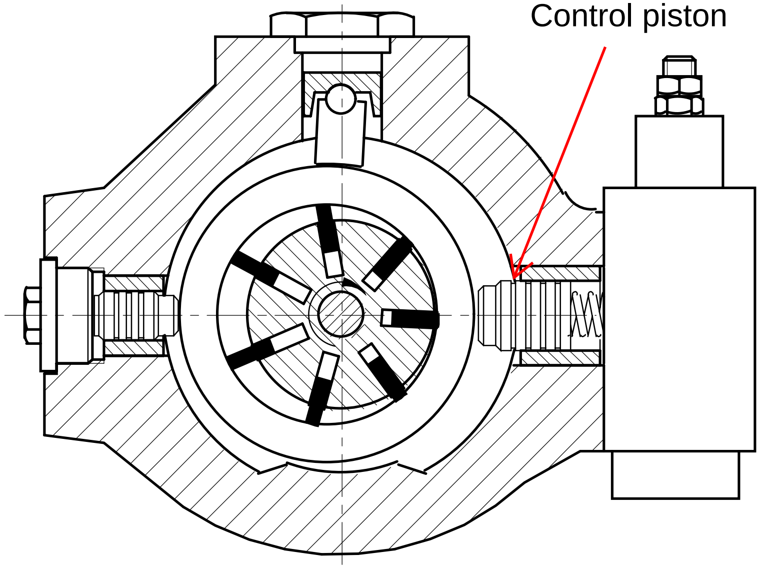
Eccentricity

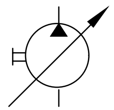


Radially moving (OUT - IN) vanes taking care of sealing

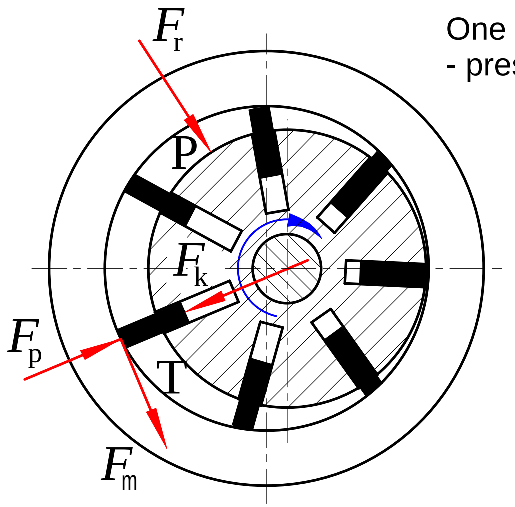
Vanes are pushed outwards to make a contact with the pump body
- with extra force behind vane (spring or pressure)
- "centrifugal force" (not a real force)

Variable displacement operation





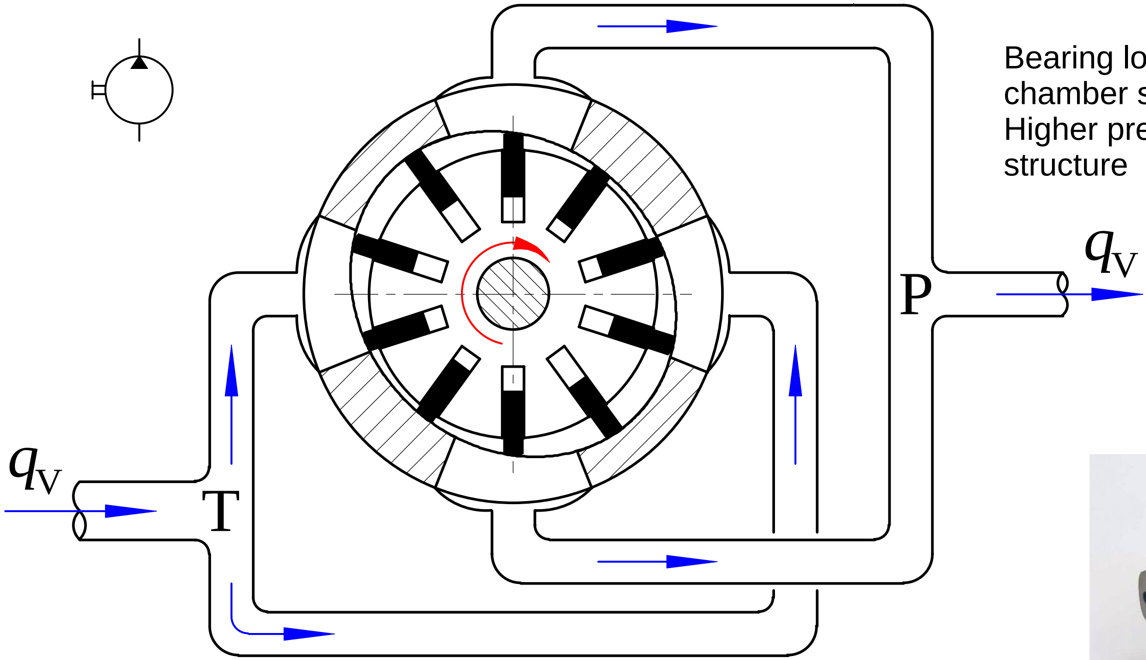
Vanes in rotor
- one chamber



One chamber structure
- pressure forces acting on the shaft

Even flow
- low noise

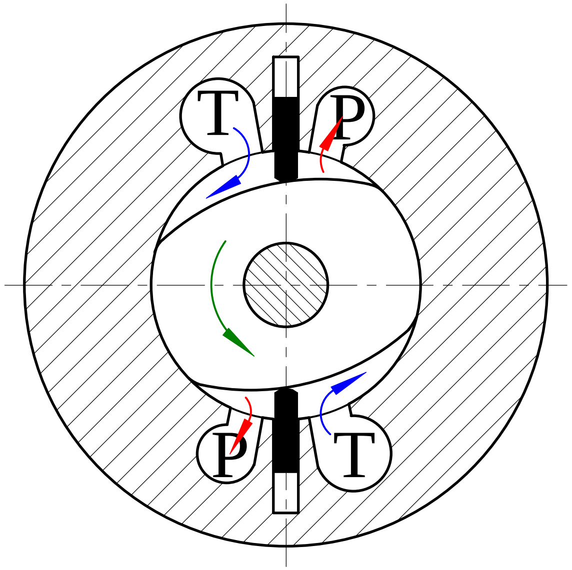
Two chamber structure doubles the flow rate
(compared with one chamber models)

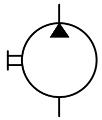


Bearing load forces are smaller than in one chamber structure
Higher pressures possible than in one chamber structure

Variable displacement operation possible with two pump rings in series

Vanes in rotor
- two chamber





Flow rate varies slightly more than in other structures

Vanes in stator

Performance characteristics of vane pumps

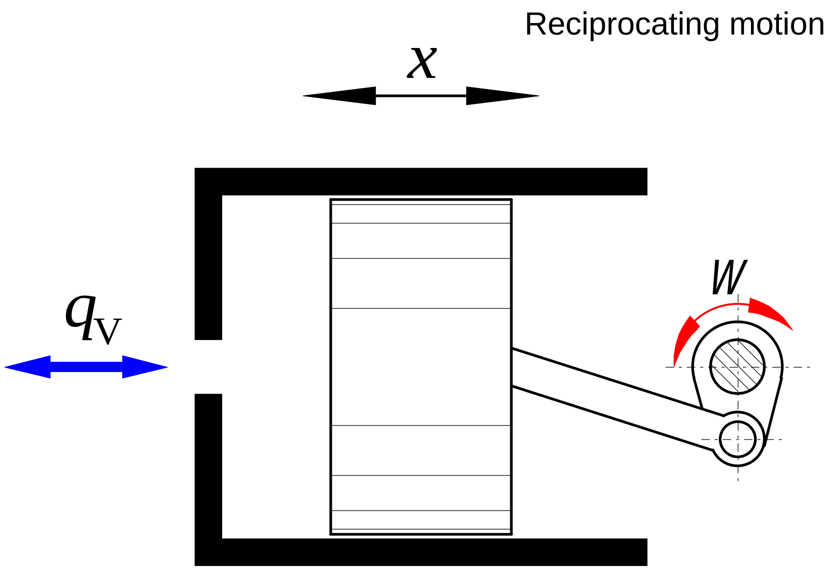
Total efficiency max. h_t » 0.8 – 0.92

Rotational speed range *n* » 600 – 2500 r/min

Operating pressure max. *p* » 7 – 14 (– 18) (– 21– 28) MPa

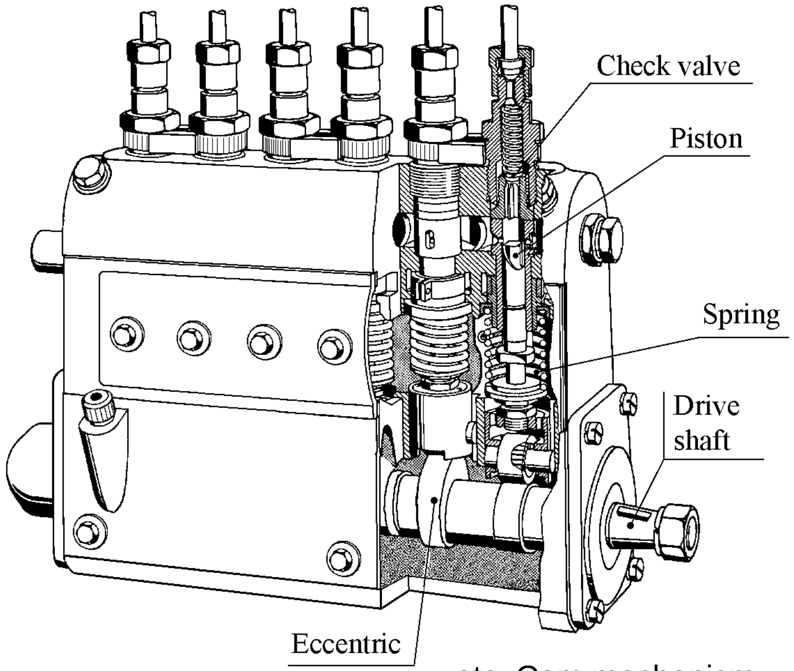
- depends on compensation of leakage,
  radial forces and number of chambers

Piston pumps

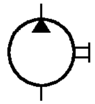


Piston pumps
- line piston pumps
- radial piston pumps
- axial piston pumps

Small clearances ⟹ Small leakages ⟹ Good volumetric efficiency

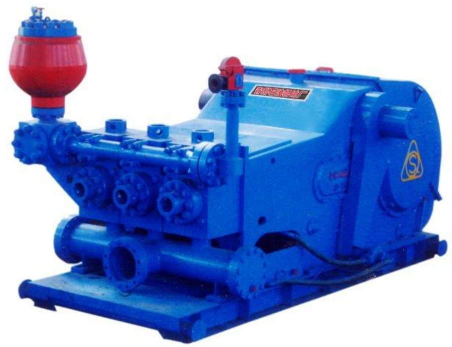


etc. Cam mechanism



Mainly for high very pressures

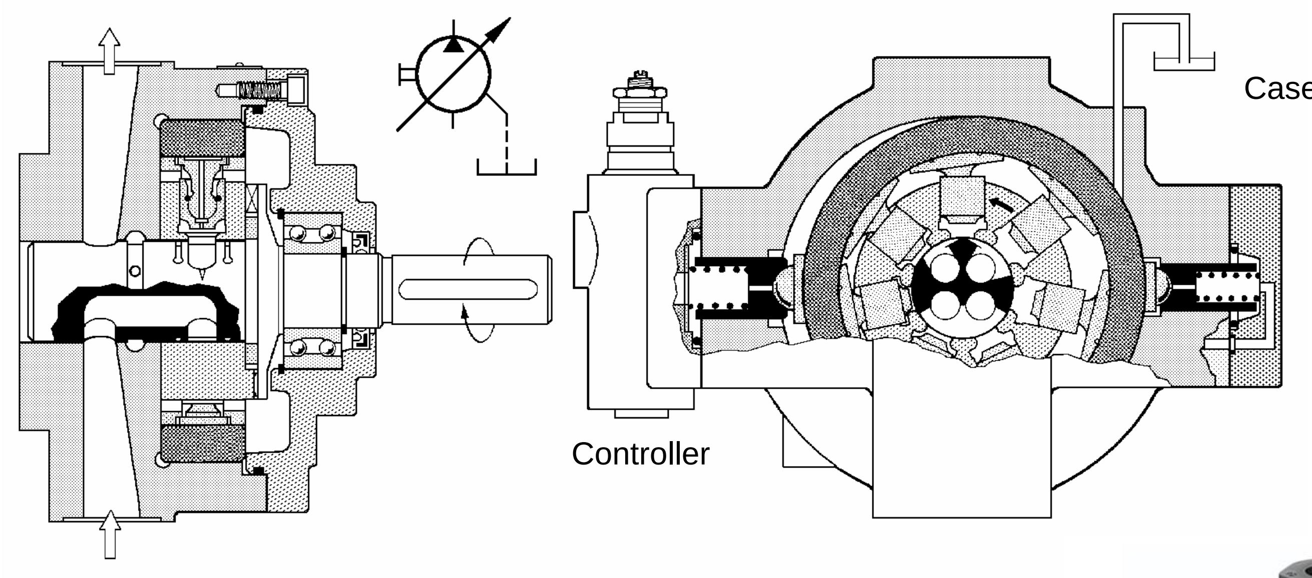
⇒ 1200 bar ⇒2500 bar



Line piston pumps

Hydrostatic bearings between pistons and pump ring

Cylinder flows through hollow shaft



Case drain

Variable displacement design
Movable pump ring

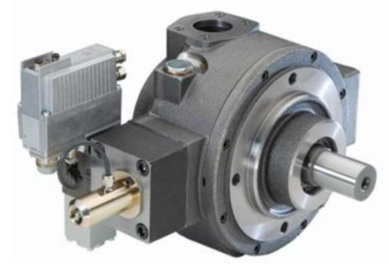
Eccentricity ⟹ stroke

Controller

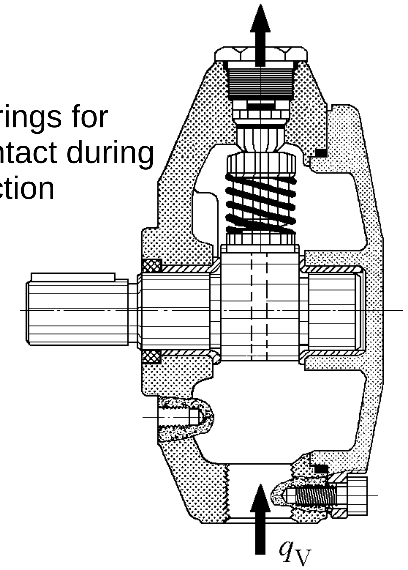
Radial piston pumps

- internal flow channels
- external flow channels

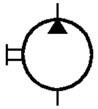
High pressures possible up to 450 bar

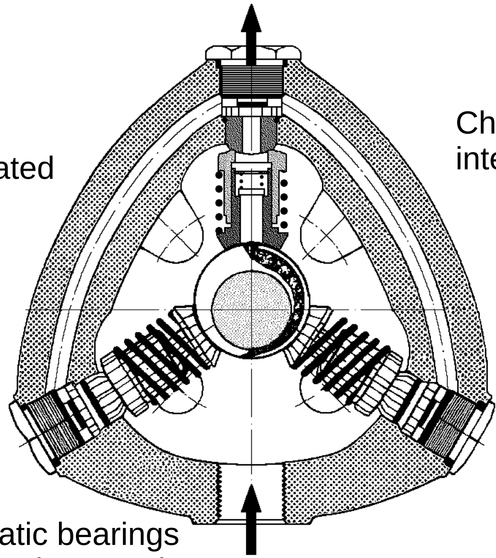


Springs for contact during suction



Cam operated





Check valves integrated in pistons

Pistons do not rotate in this model

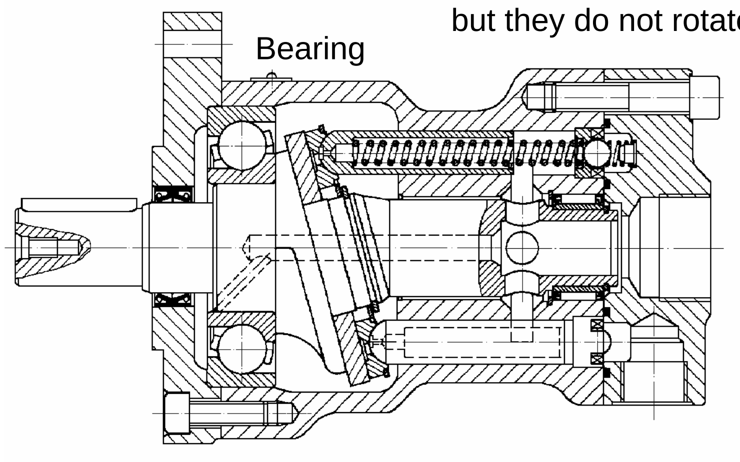
Hydrostatic bearings between piston and cam

Radial piston pumps

- internal flow channels
- external flow channels

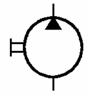
High pressures up to 600 - 700 bar possible

Pistons in contact with the plate, but they do not rotate



Pistons in parallel with the shaft

Wobble plate rotates with shaft



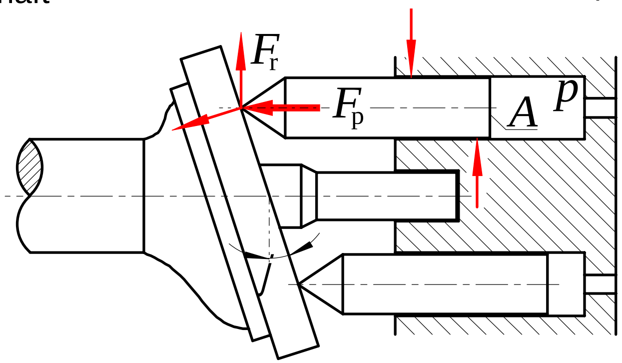
Possibility to transform this type to "digital" by disconnecting some of the pistons

The rotating masses are not in balance which limits the rotational speed

Without special arrangements the contact forces between piston and wobble plate cause radial forces to piston

Axial piston pumps

- wobble plate pumps
- swash plate pumps
- bent axis pumps



The direction of flow can be changed in some models

(-18° ®) 0° ® +18°

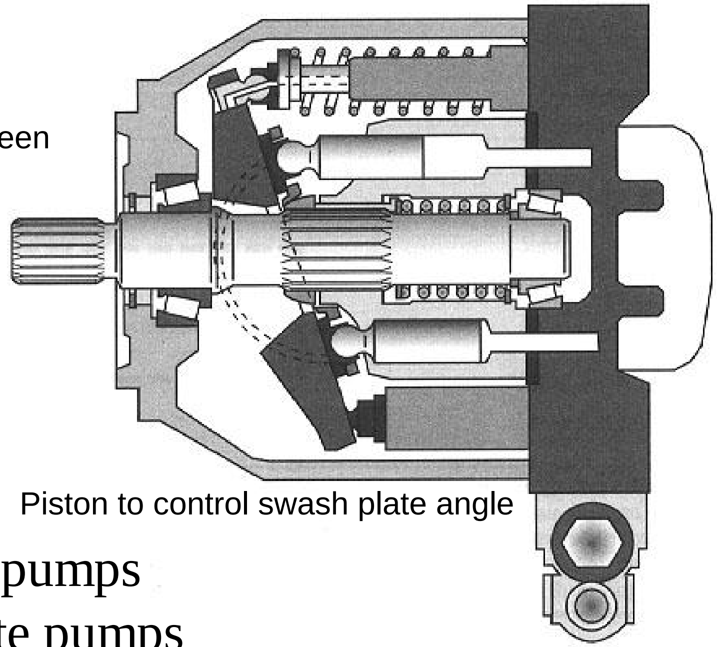
Contact forces between pistons and swash plate limit the control angle

Rotational speeds can be 1500 - 3000 rpm

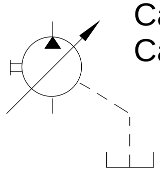
Cylinder block rotates with the shaft
Swash plate does not rotate, it can turn to control the piston stroke and pump displacement

Counter piston for swash plate control

Hydrostatic bearing between pistons and swash plate



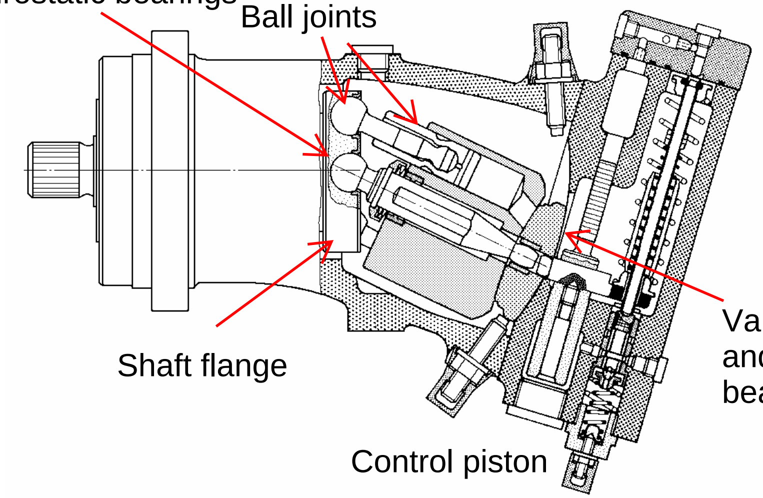
Piston to control swash plate angle

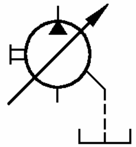


Case drain because of hydrostatic bearings
Case pressure must be kept small!

Axial piston pumps
- wobble plate pumps
- swash plate pumps
- bent axis pumps

swashplate pump - inline piston pump

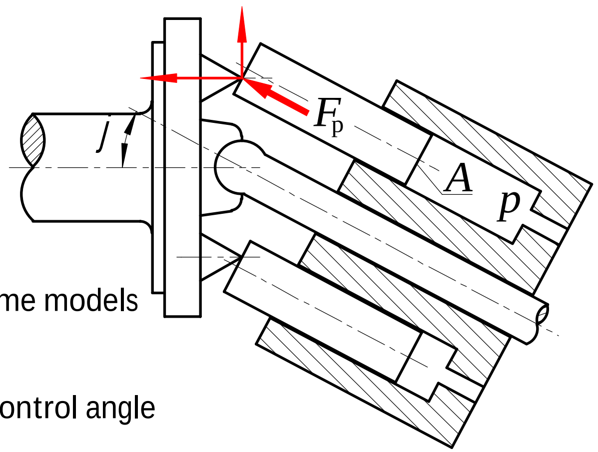




Size is typically large especially with controllers

Rotation transmitted with
- Cardan shaft
- Bevel gear
- Pistons

Radial forces on piston are small



Axial piston pumps

- wobble plate pumps
- swash plate pumps
- bent axis pumps

The direction of flow can be changed in some models

(-25° ®) 0° ® +25°

Contact forces of pistons do not limit the control angle as much in this model

Rotational speeds can be 800 - 8000 rpm

Performance characteristics of piston pumps

Total efficiency max. h_t » 0.8 – 0.9 even higher

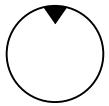
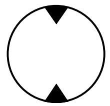
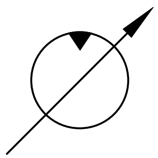
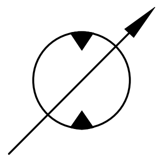
Rotational speed range *n* » 300 – 8000 r/min

Operating pressure max. *p* » 20 – 35 (– 45) (– 70) (– 250) MPa

- depends on structure type

Hydraulic motors

Convert hydraulic power into mechanical power

Unidirectional		Bidirectional
	Constant displacement	
	Variable displacement	

Speed ranges and structures

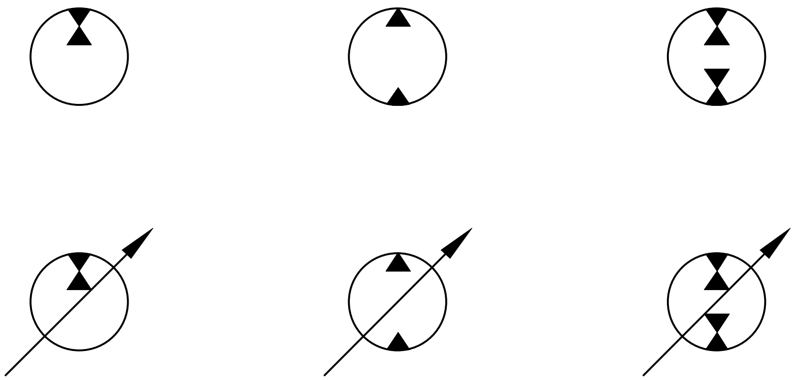
Speed range	r/min
Slow	1- 150
Middle	10- 750
High	300- 5000

Most common construction types:

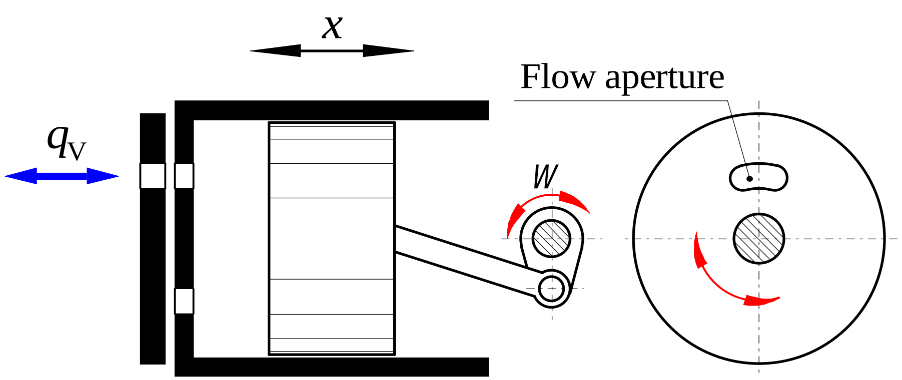
- gear
- vane
- piston

All operate on positive displacement principle

Pump-motors



Control of flow direction



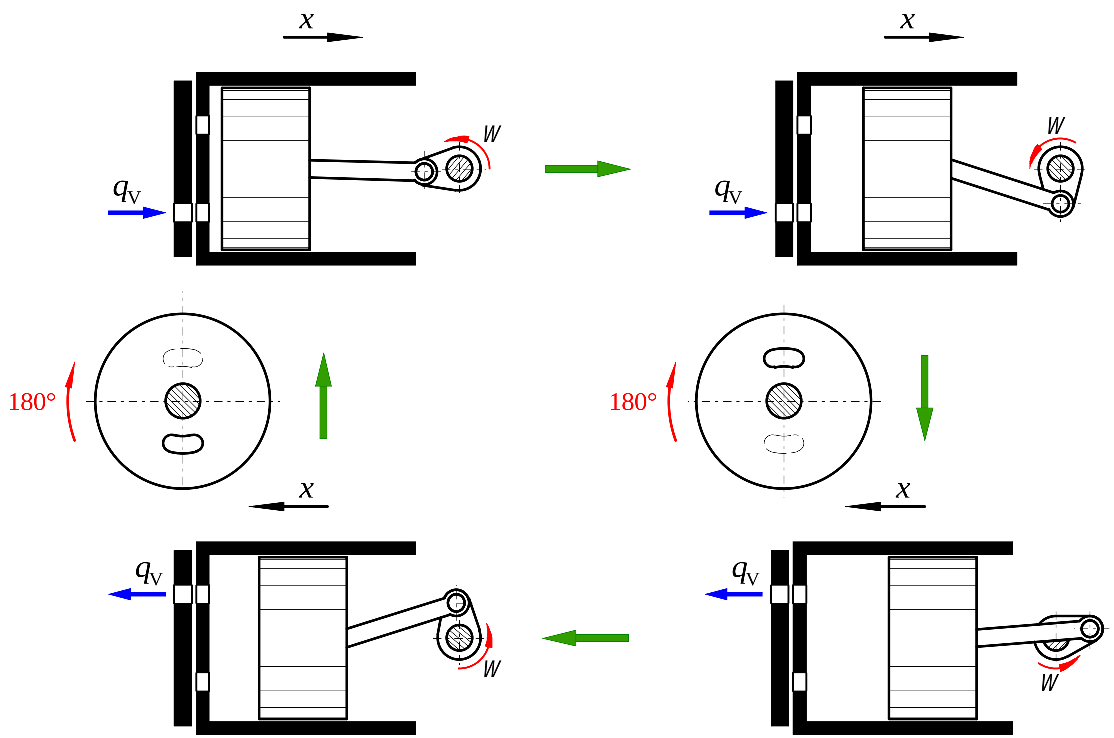
Only forced control is applicable

Operating phases:

Fluid flows into transfer volume – work phase

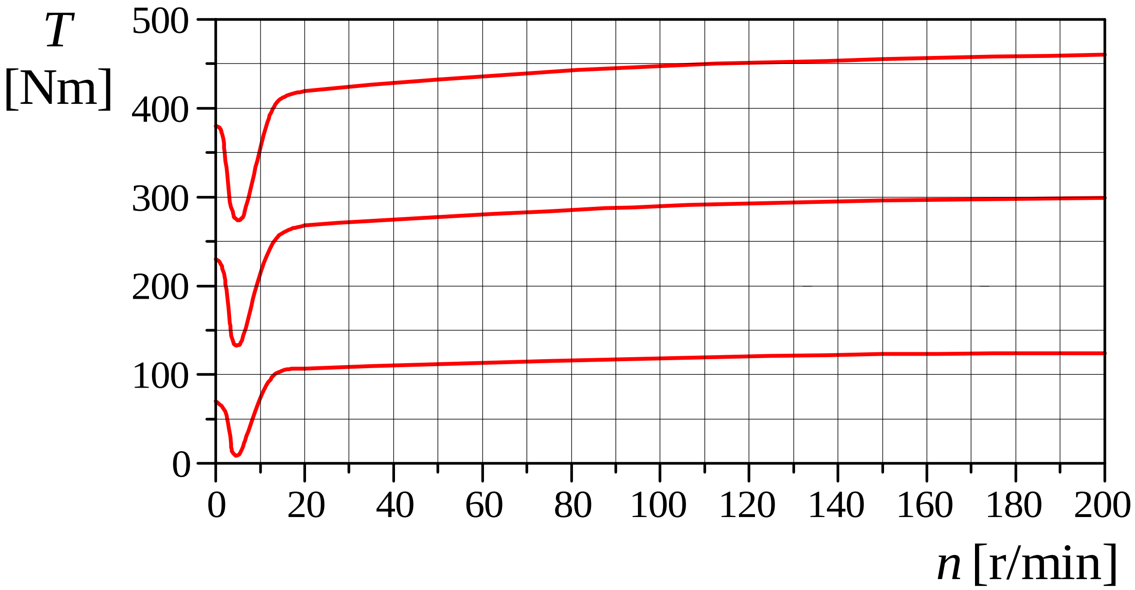
Fluid flows out from volume – free phase

Forced control

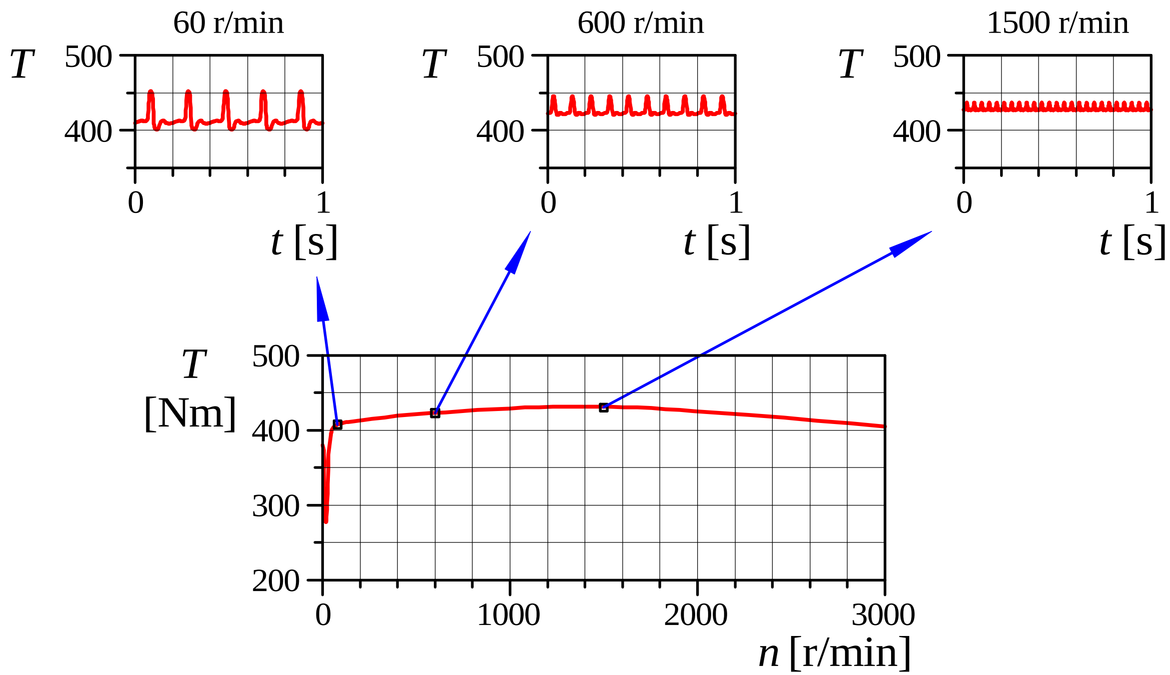


Motor characteristics

Starting characteristics



Running characteristics



Theoretical flow demand $$q_{V,\mathrm{theor}} = n \cdot V_g$$

Swept volume V_g [m^3/r] cm^3/r = 10^{-6} m^3/r

Rotation speed n [r/s] r/min = 1/60 r/s

$$q_{V,\mathrm{theor}} = \omega \cdot V_{\mathrm{rad}}$$

$$\omega = 2\pi \cdot n$$

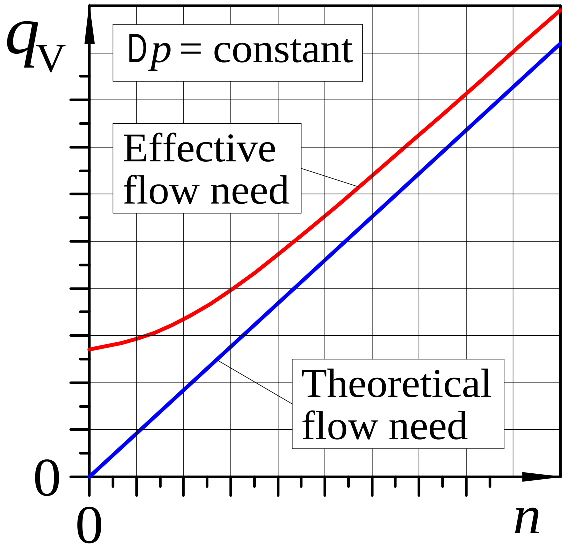
Angular velocity ω [rad/s]

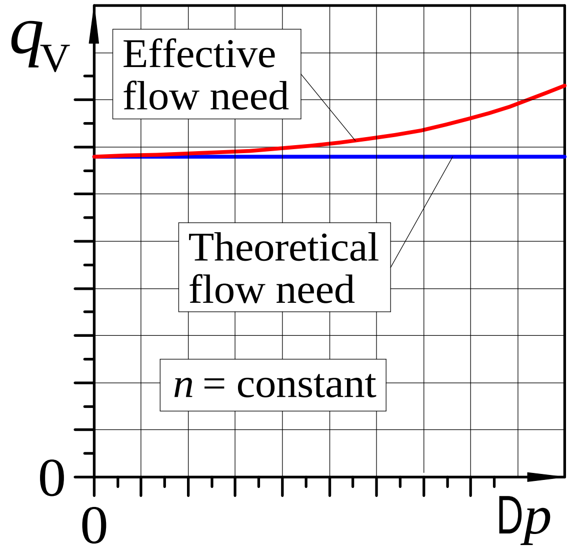
$$V_{\mathrm{rad}} = \frac{V_g}{2\pi}$$

Swept volume per radian V_{rad} [m^3/rad]

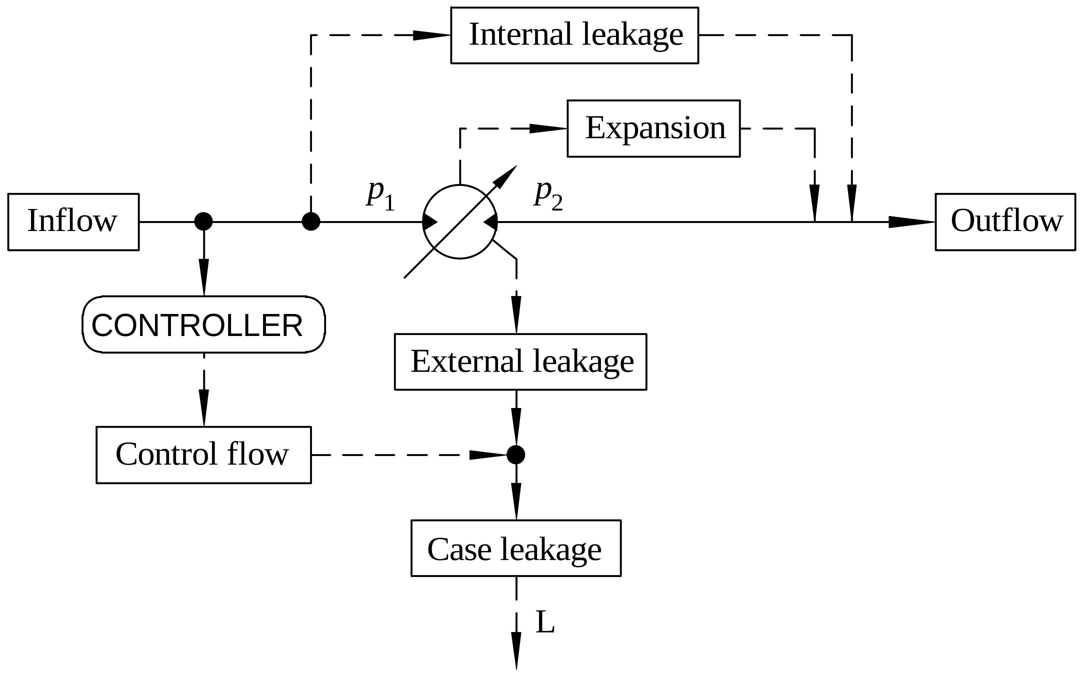
Effective flow demand $$q_{V,\text{real}} = \frac{n \cdot V_g}{\eta_v}$$

Leakage – volumetric efficiency η_v





Leakage flows in motors



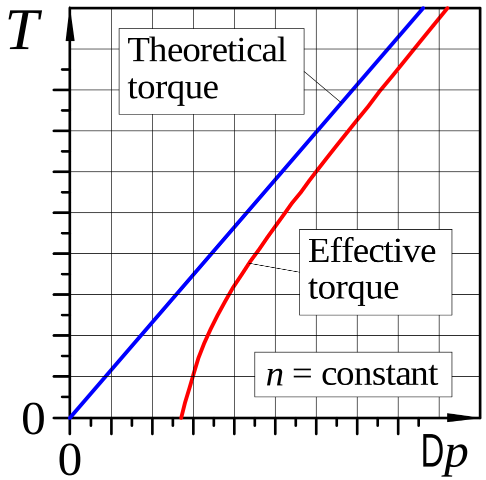
Theoretic pressure demand

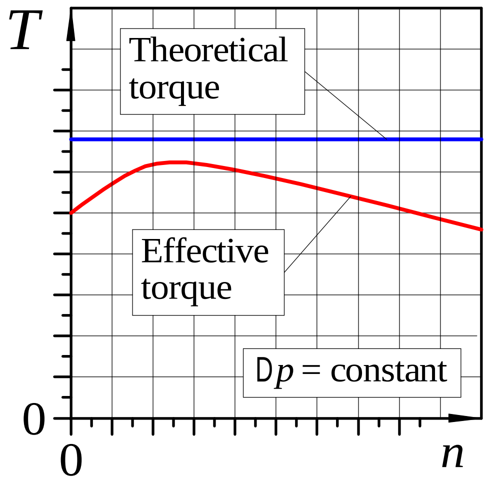
$$\Delta p_{\mathrm{theor}} = \frac{2 \cdot \pi \cdot T}{V_{\mathrm{g}}}$$

Effective pressure demand

$$\Delta p_{\mathrm{real}} = \frac{2 \cdot \pi \cdot T}{V_{\mathrm{g}} \cdot \eta_{\mathrm{hm}}}$$

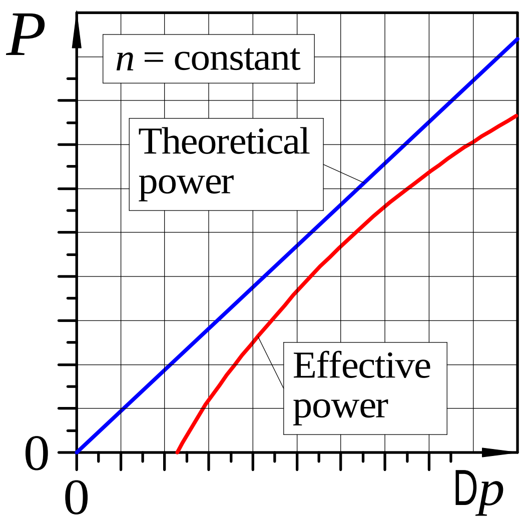
Friction – hydro-mechanical efficiency η_{hm}

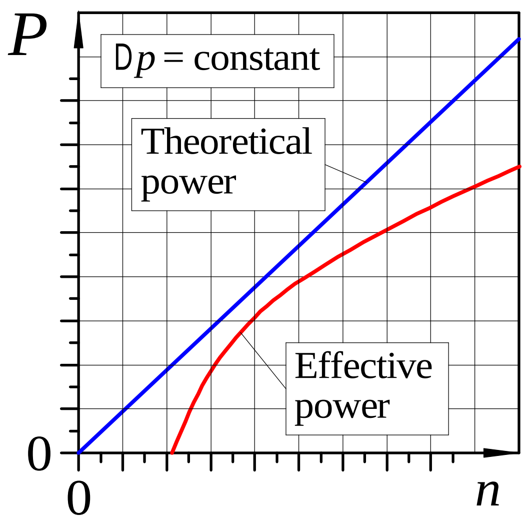




Theoretic power demand $P_{\text{theor}} = q_V \cdot \Delta p = T \cdot \omega$

Effective power demand $P_{\text{real}} = q_V \cdot \Delta p = \dfrac{T \cdot \omega}{\eta_t}$ $\quad \eta_t = \eta_v \cdot \eta_{hm}$

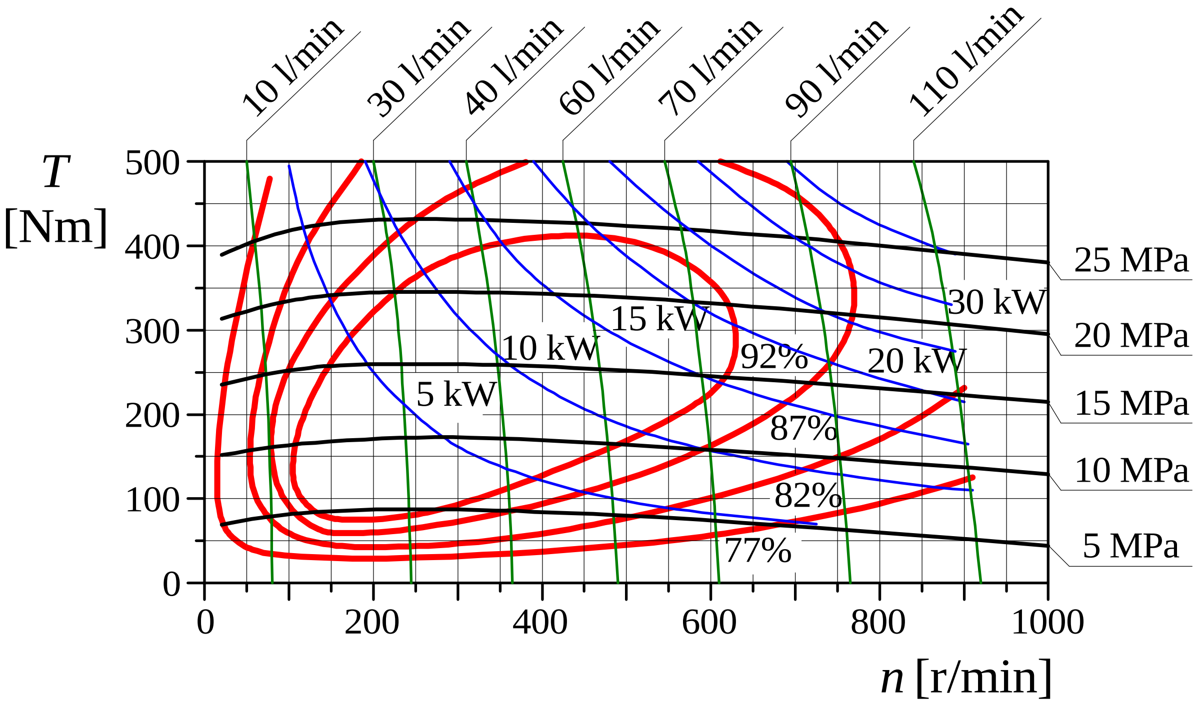




Power demand of load

$$P_{\text{mech}} = T \cdot \omega = 2 \cdot \pi \cdot n \cdot T$$

Characteristic curves of motor



Low speed high torque motors (LSHT)

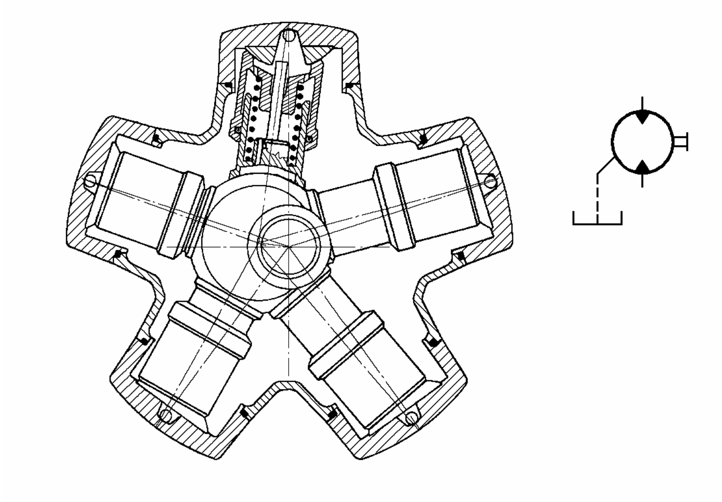
Large swept volume
- large displacement area of working elements
- several work stages per one rotation of the axle

Radial piston motors
Vane motors with several chambers
Orbital motors

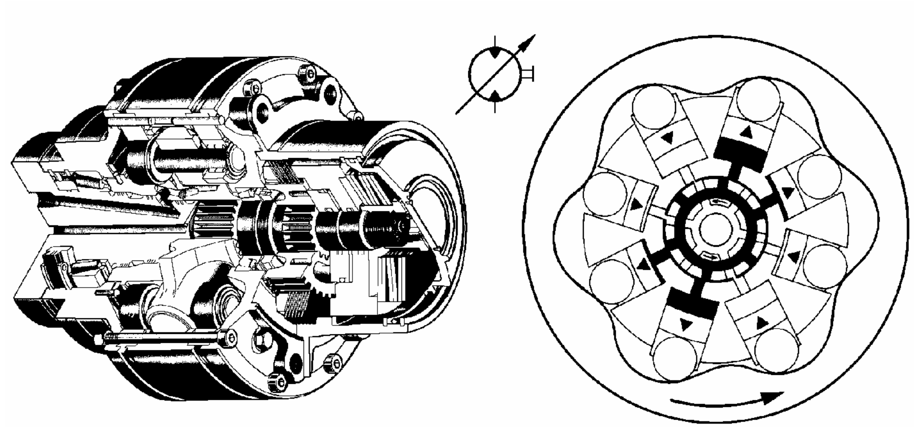
Total efficiency max. h_t » 0.8 – 0.92

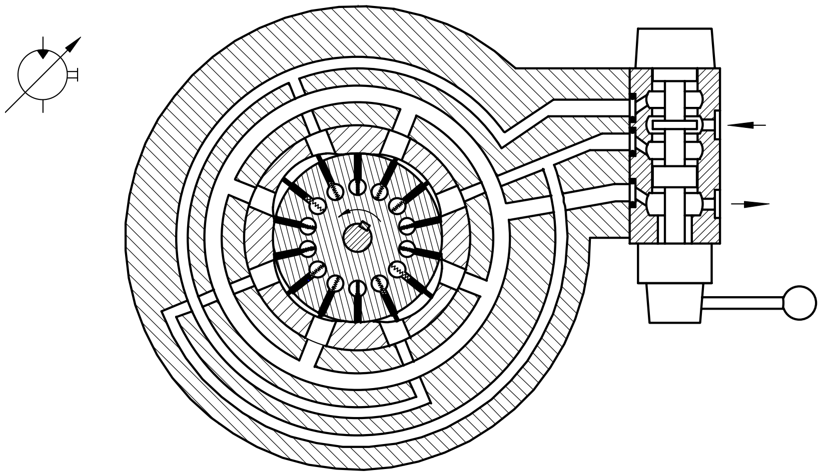
Rotational speed range n » 1 – 500 (– 2400) r/min

Torque max. T » 1000 – 20000 (– 125000) Nm



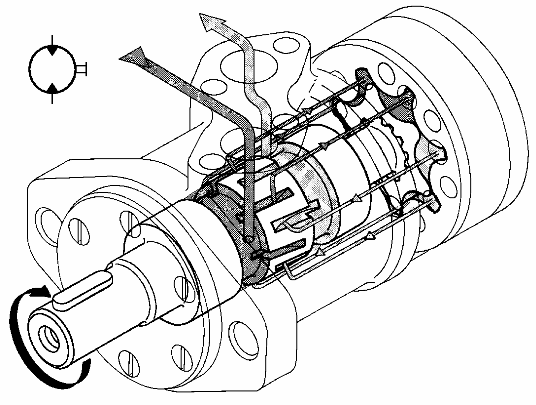
Radial piston motors
- external flow channels
- internal flow channels

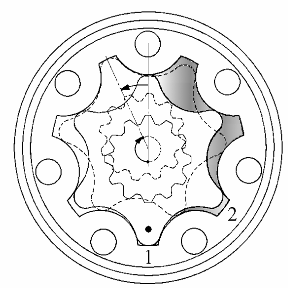




¬ Multi chamber vane motor

Orbital motor ®





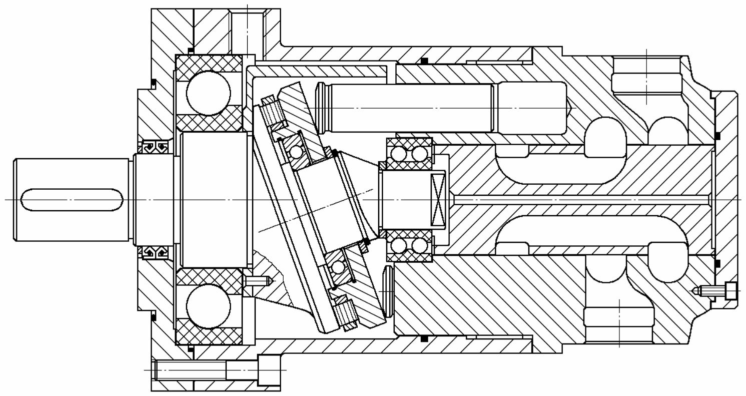
Middle speed range motors

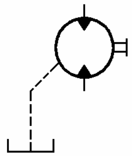
Gerotor motors (ring motors)
Wobble plate motors

Total efficiency max. h_t » 0.8 – 0.88

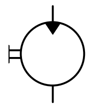
Rotational speed range n » 200 – 1000 (– 1500) r/min

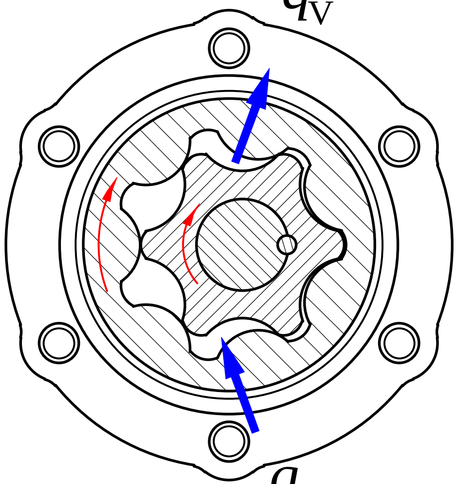
Torque max. T » 20 – 200 (– 1200) Nm





¬ Wobble plate motors





Gerotor motor (ring motor) ®

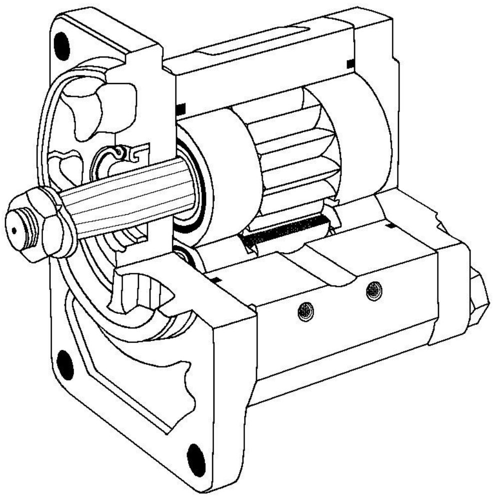
High speed range motors

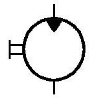
External gear motors
Vane motors
Axial piston motors

Total efficiency max. h_t » 0.82 – 0.9

Rotational speed range n » 100 – 3000 (– 6000) r/min

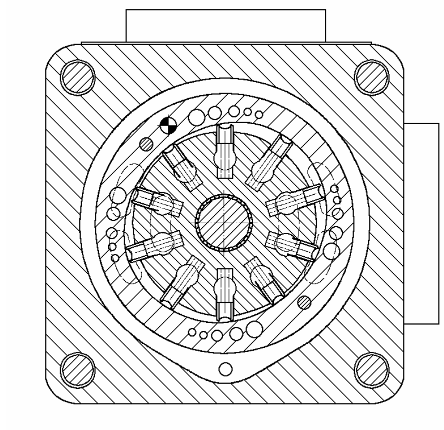
Torque max. T » 10 – 700 (– 3000) Nm

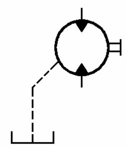


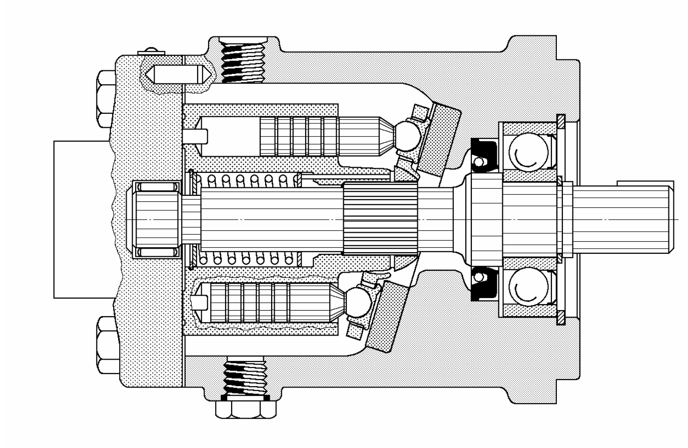


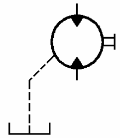
¬ External gear motor

Vane motor ®



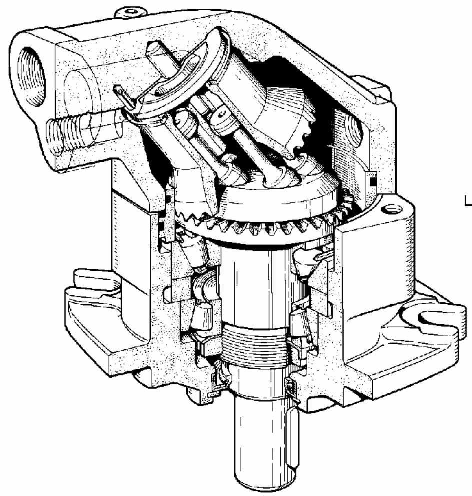


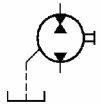




¬ Swash plate
piston motor

Bent axis ®
piston motor





Hydraulic cylinders

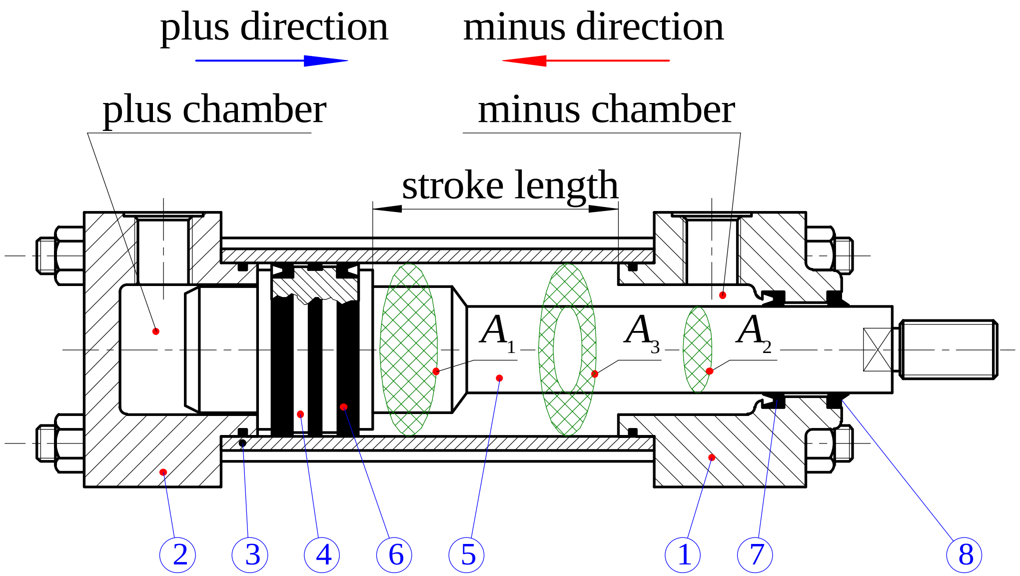
Convert hydraulic power into mechanical power

Construction types:

- single acting
- double acting

Both operate on positive displacement principle

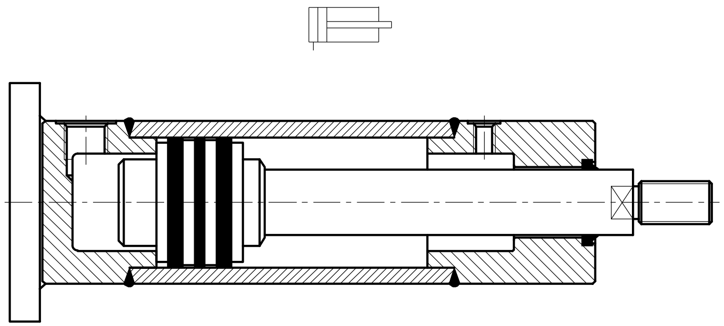
Terminology



1. Head with inlet
2. Cap with inlet
3. Cylinder tube
4. Piston
5. Piston rod
6. Piston seals
7. Piston rod seal
8. Piston rod wiper seal

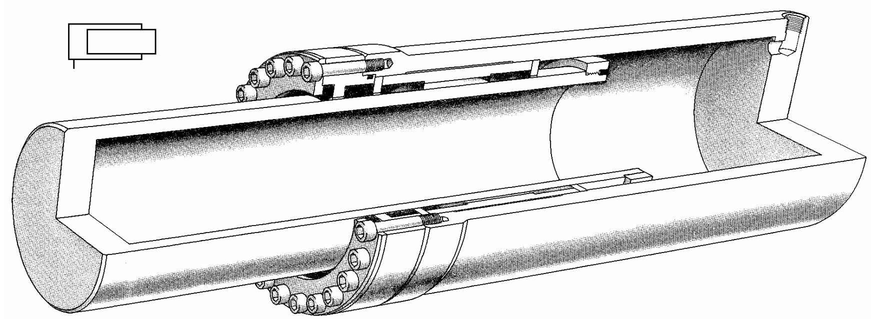
Single acting cylinders

Operate hydraulically to only one direction



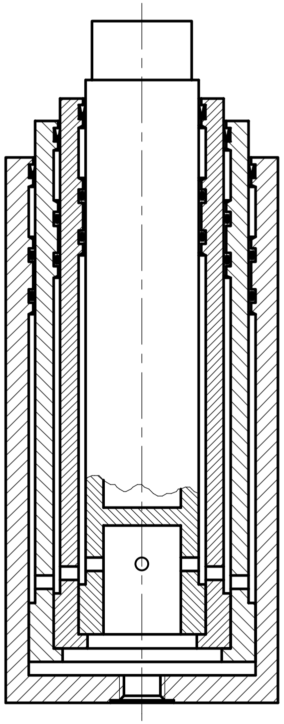
¬ Piston type cylinder

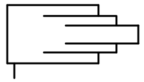
Plunger
cylinder ®



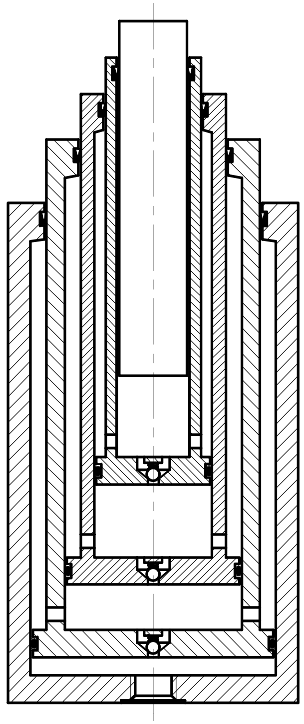
Telescopic cylinder

a





b



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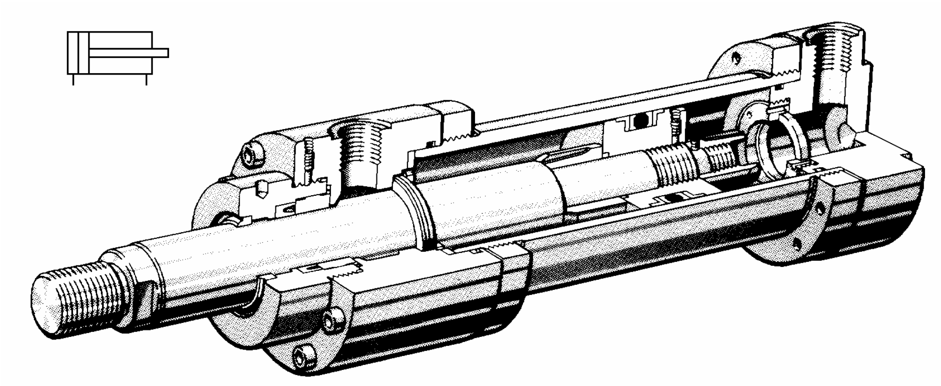
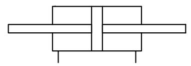
Double acting cylinders



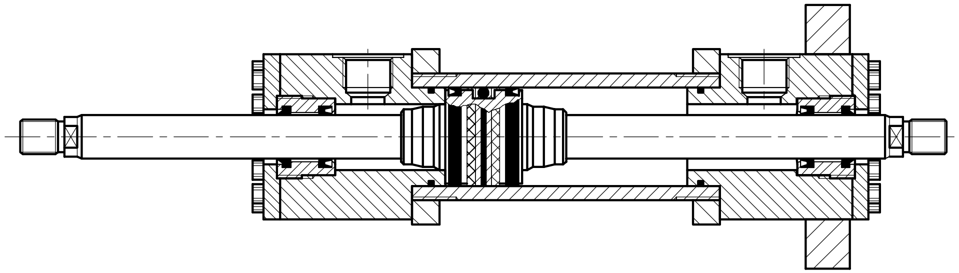
¬ Single piston rod



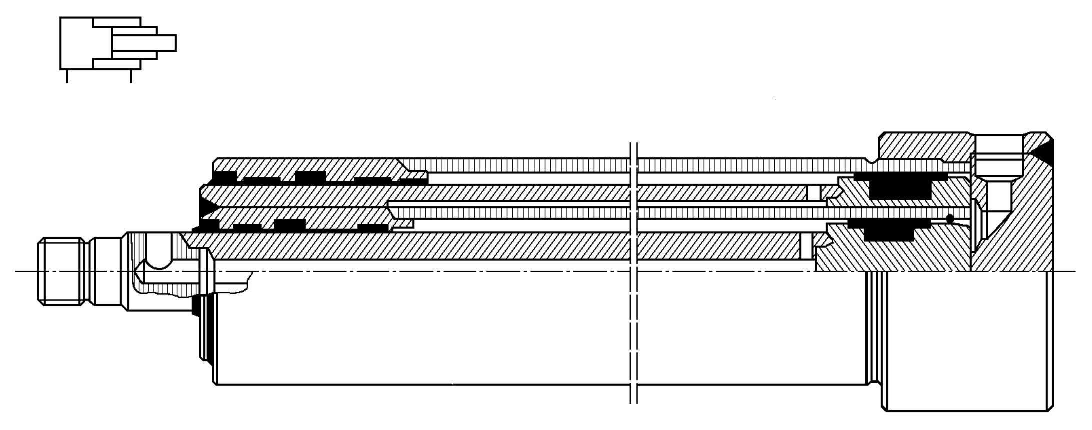
Double piston rod

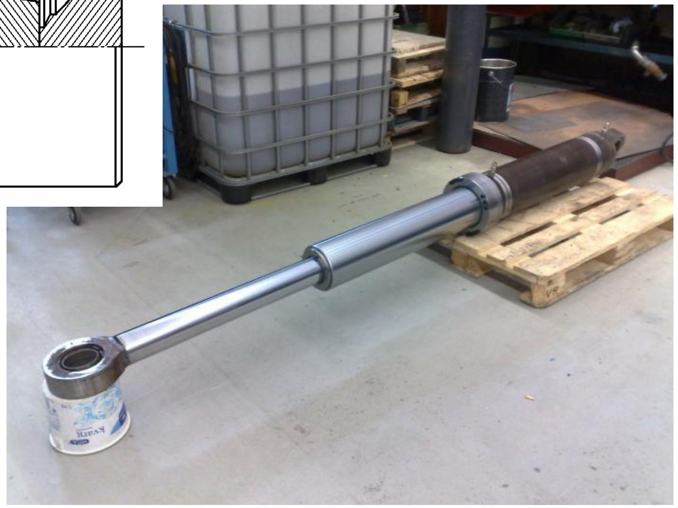
®

Symmetric cylinder



Telescopic cylinder





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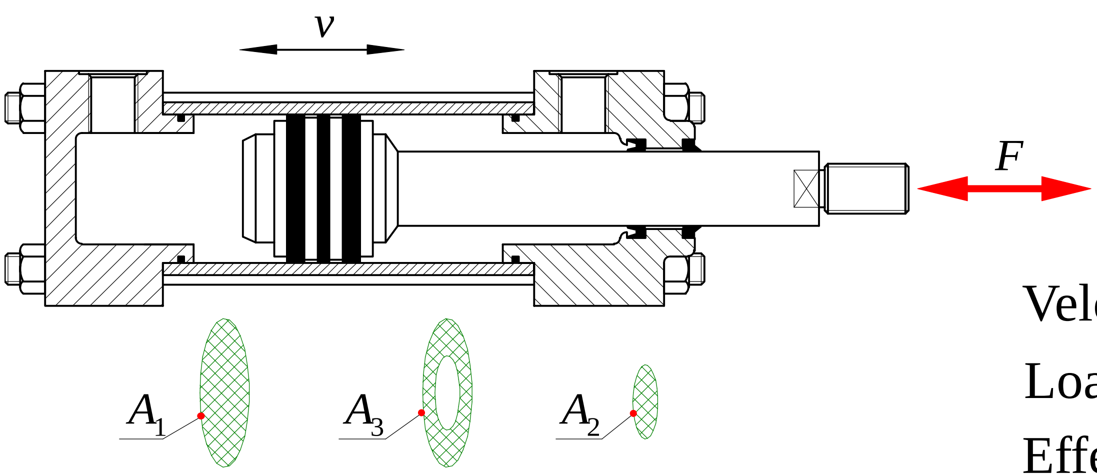
Characteristics of cylinders

Theoretic pressure demand $p_{\text{theor, in}} \times A_{\text{in}} = F + p_{\text{out}} \times A_{\text{out}}$

Theoretic flow demand $q_{\text{V,in,theor}} = A_{\text{in}} \times v$

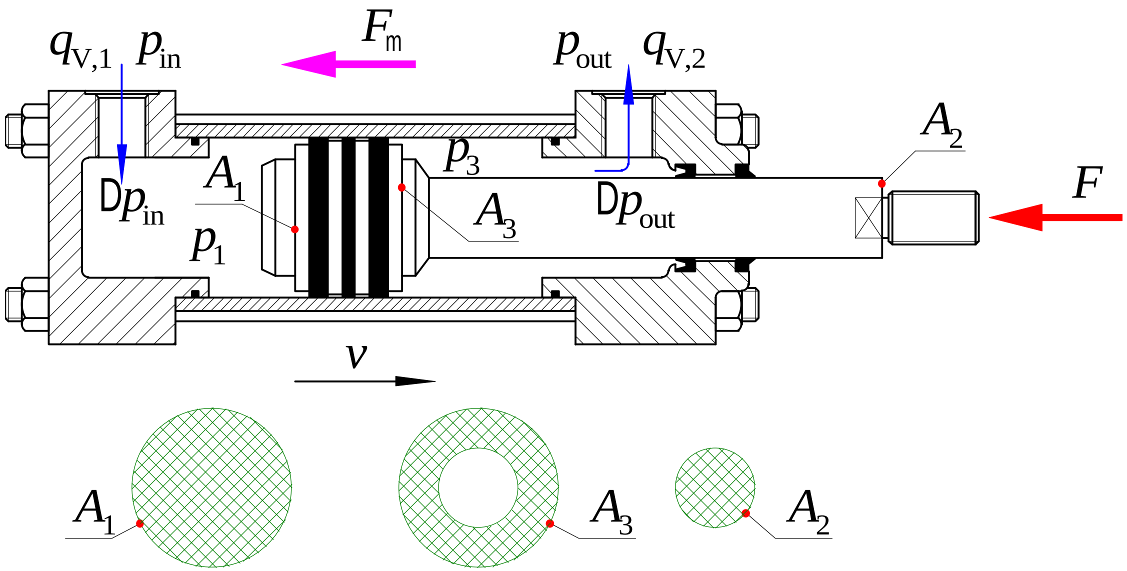


Velocity v [m/s]

Load force F [N]

Effective piston area A [m^2]

Reality



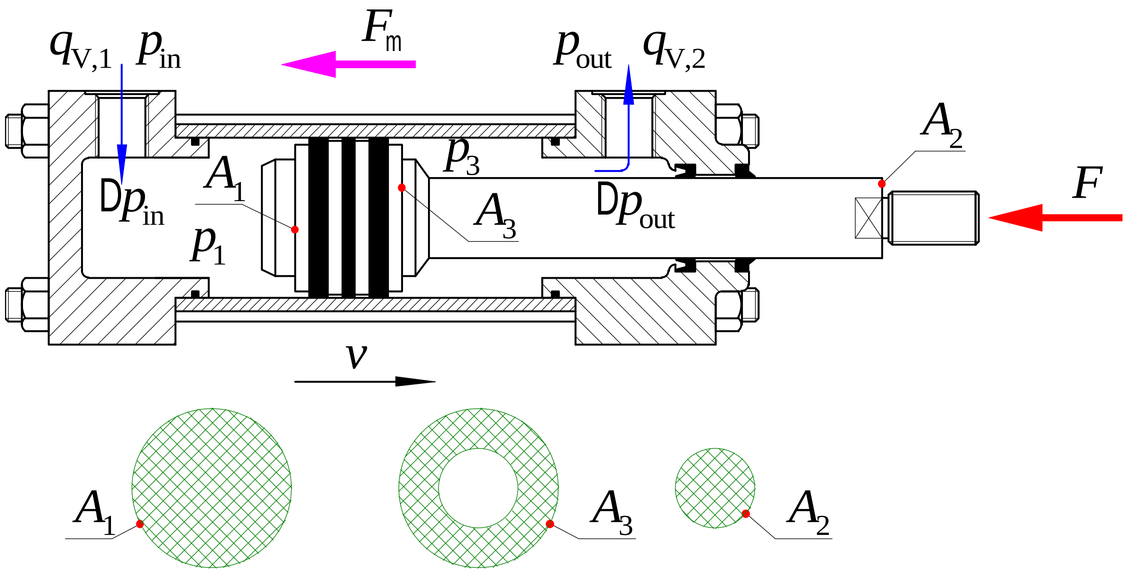
Example case:
plus-direction movement,
opposing force

Friction – hydromechanical efficiency η_{hm}

Leakage – volumetric efficiency η_{v}

Pressure

Example case:
plus-direction movement,
opposing force



Force equation $p_{in} \cdot A_1 - \Delta p_{in} \cdot A_1 = p_{out} \cdot A_3 + \Delta p_{out} \cdot A_3 + F + F_{\mu}$

Force equation in general form

$$p_{\text{real,in}} \cdot A_{\text{in}} - \Delta p_{\text{in}} \cdot A_{\text{in}} = F + F_{\mu} + p_{\text{out}} \cdot A_{\text{out}} + \Delta p_{\text{out}} \cdot A_{\text{out}}$$

Actual pressure demand

$$p_{\text{real,in}} = \frac{F + F_{\mu} + p_{\text{out}} \cdot A_{\text{out}} + \Delta p_{\text{out}} \cdot A_{\text{out}} + \Delta p_{\text{in}} \cdot A_{\text{in}}}{A_{\text{in}}}$$

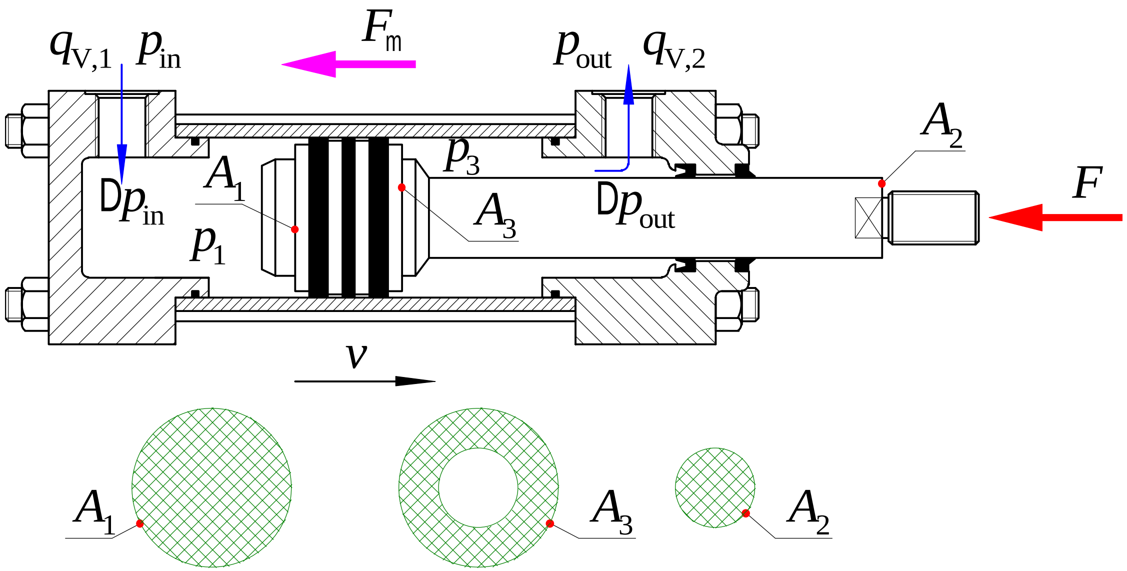
In efficiency form

$$p_{\text{real,in}} = \frac{F}{A_{\text{in}} \cdot \eta_{\text{hm}}} + p_{\text{out}} \cdot \frac{A_{\text{out}}}{A_{\text{in}}}$$

Correct or not?
Hydromechanical efficiency depends on what?

Flow

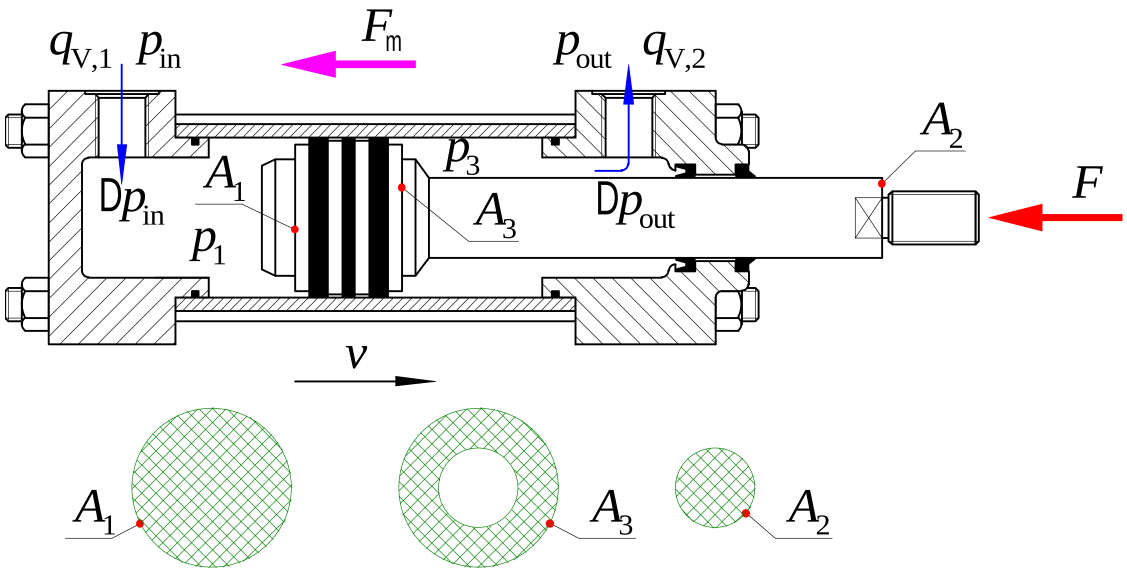
Example case:
plus-direction movement,
opposing force



Actual flow demand $q_{V,in,real} = \frac{A_{in} \cdot v}{\eta_v}$

Power

Example case:
plus-direction movement,
opposing force



Power demand of external force $P_{mech} = F \cdot v$

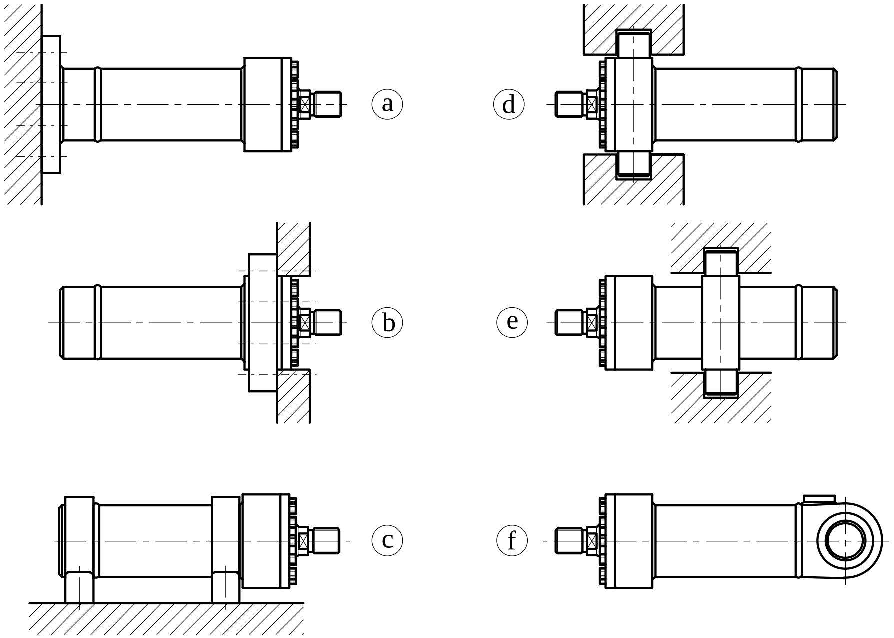
Theoretic power demand

$$P_{\text{theor}} = q_{\text{V,in}} \cdot \left(p_{\text{in}} - \frac{A_{\text{out}}}{A_{\text{in}}} \cdot p_{\text{out}} \right) = F \cdot v$$

Actual power demand

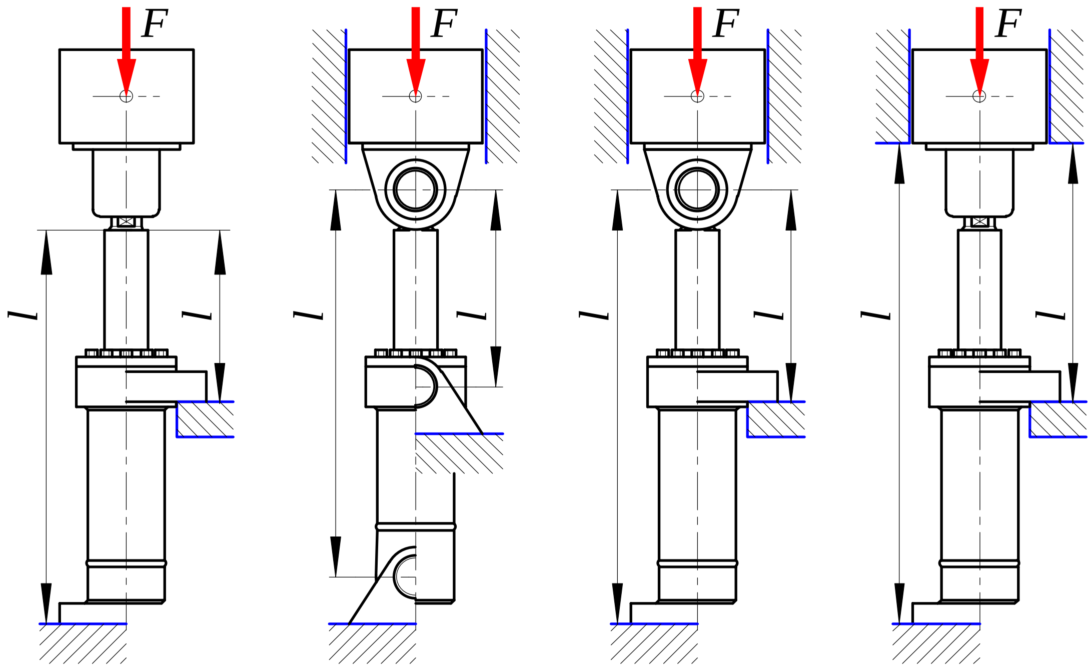
$$P_{\text{real}} = q_{\text{V,in}} \cdot \left(p_{\text{in}} - \frac{A_{\text{out}}}{A_{\text{in}}} \cdot p_{\text{out}} \right) = \frac{F \cdot v}{\eta_{\text{t}}}$$

Loading and buckling of cylinders



Loading only in parallel to the piston rod!

Mounting and buckling length



$l_R = 2l$ $l_R = l$ $l_R = \sqrt{\frac{1}{2}}\, l$ $l_R = \frac{1}{2}\, l$

Buckling diagram

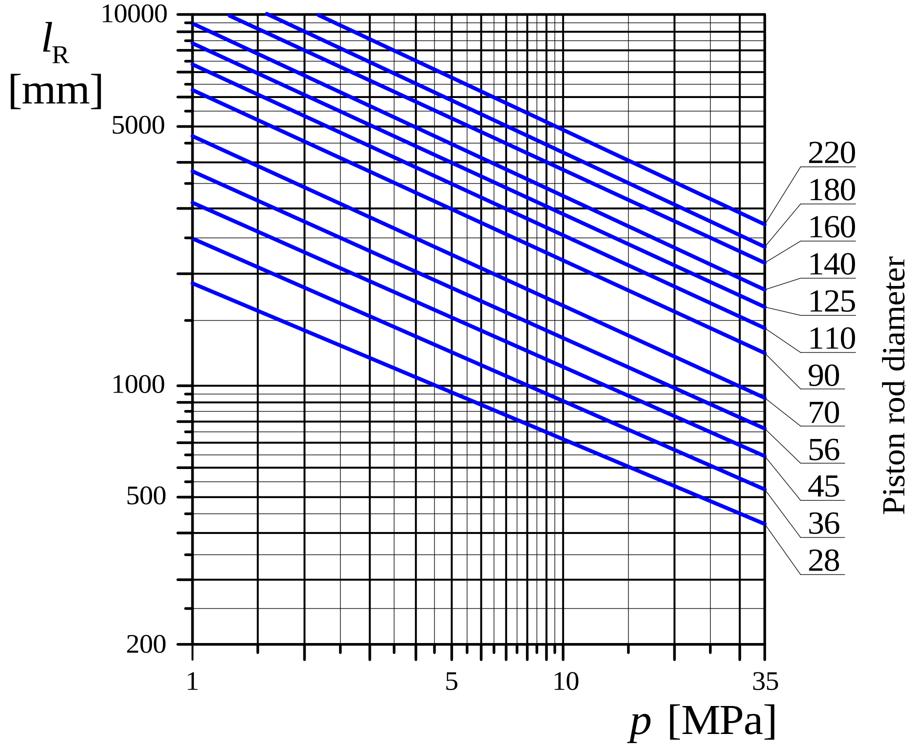
$$F = \frac{\pi^2 \times E_m \times I}{C_n \times l_R^2}$$

E_m modulus of elasticity

I area moment of inertia

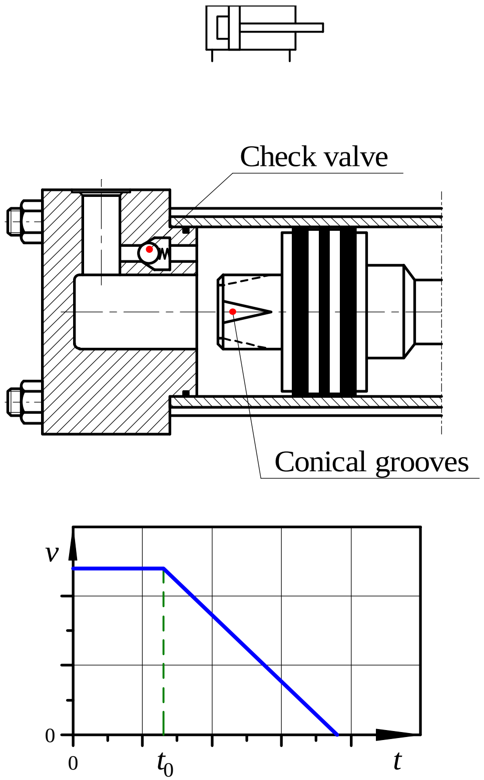
C_n safety factor

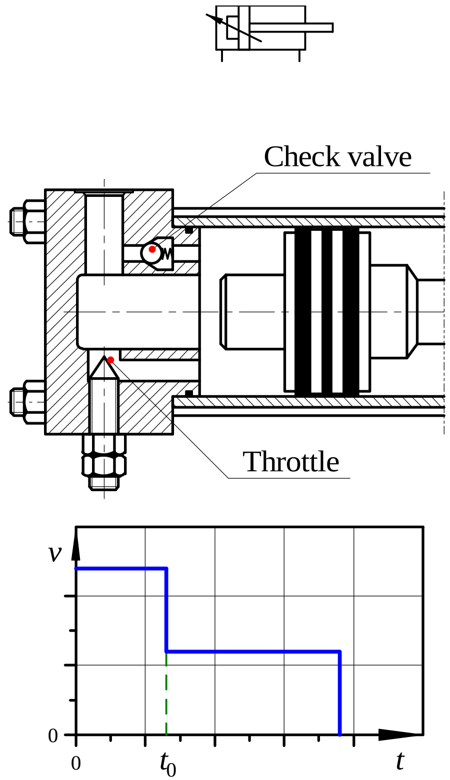
l_R effective length



End cushioning of cylinders

At velocities
> 0.1 m/s





Torque motors

Convert hydraulic power into mechanical power

Rotation angle restricted, generally < 360°

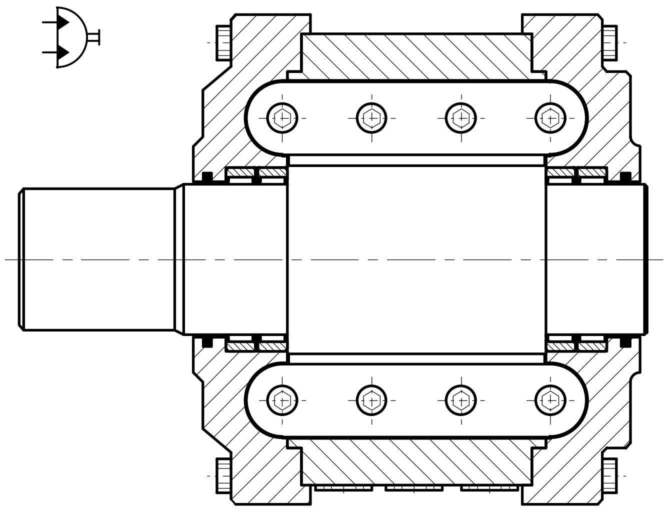
Construction types:
- vane
- piston

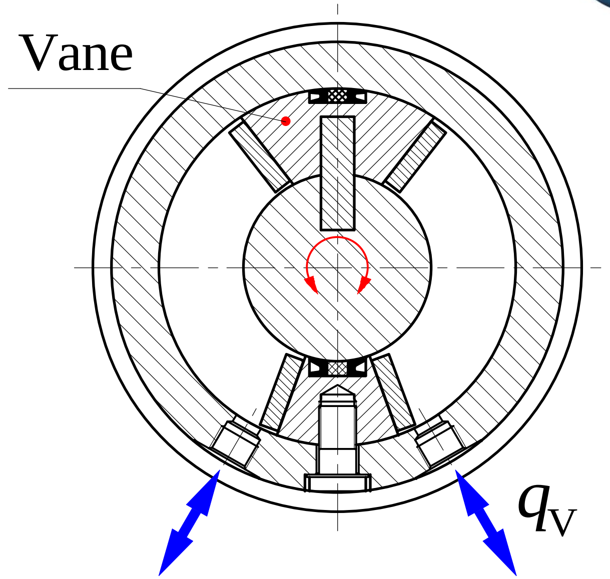
Both operate on positive displacement principle

Total efficiency max. h_t » 0.6 – 0.86

Torque max. T » 10000 – 20000 (– 300000) Nm

Vane type

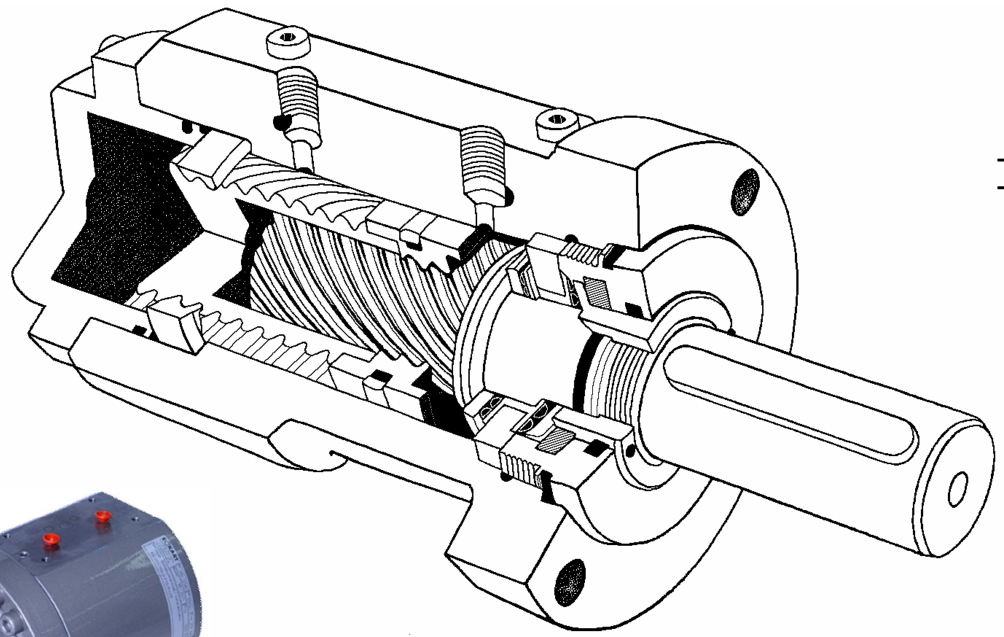


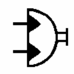


Piston type

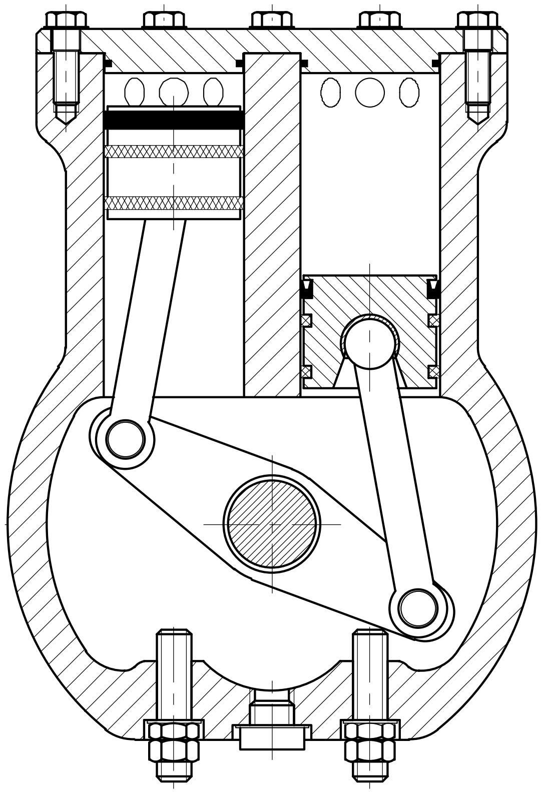
Gear type:

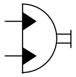
Screw gear
Crank mechanism
Cogwheel gear





Screw gear
Crank mechanism
Cogwheel gear

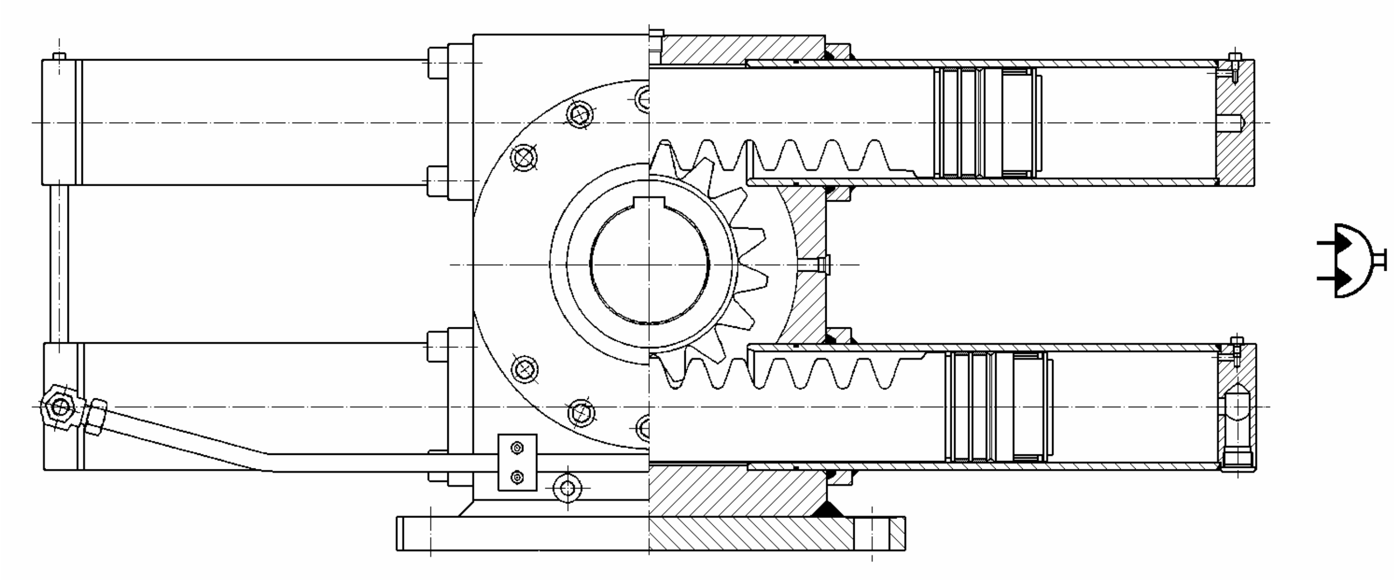




Screw gear

Crank mechanism

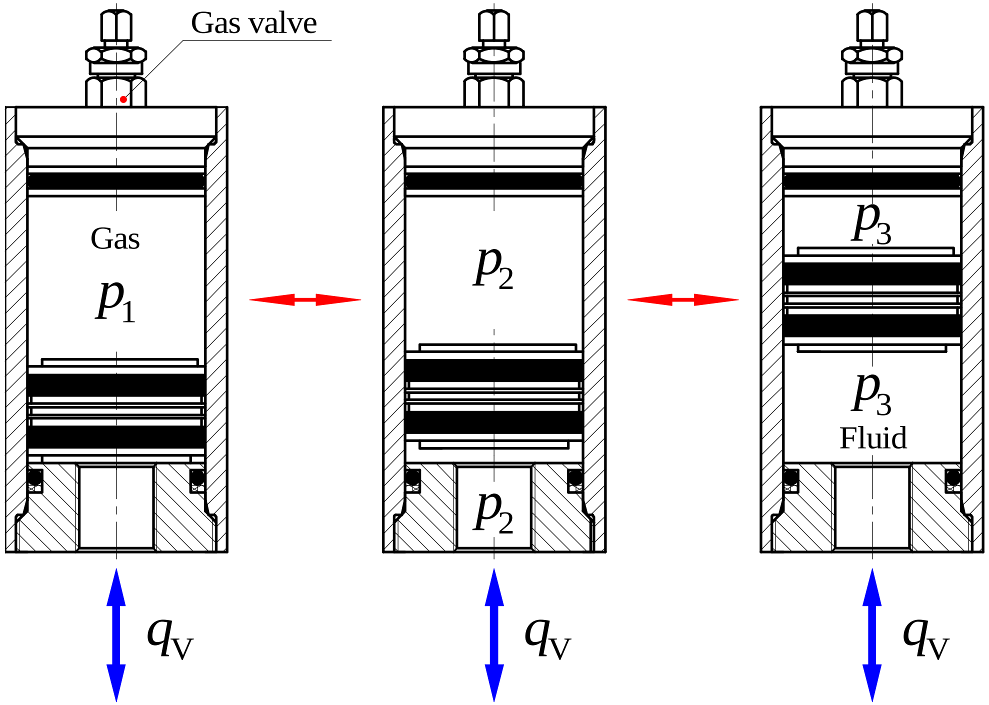
Cogwheel gear



Screw gear
Crank mechanism
Cogwheel gear

Pressure accumulators

Store hydraulic energy



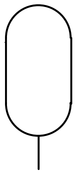
Construction and characteristics

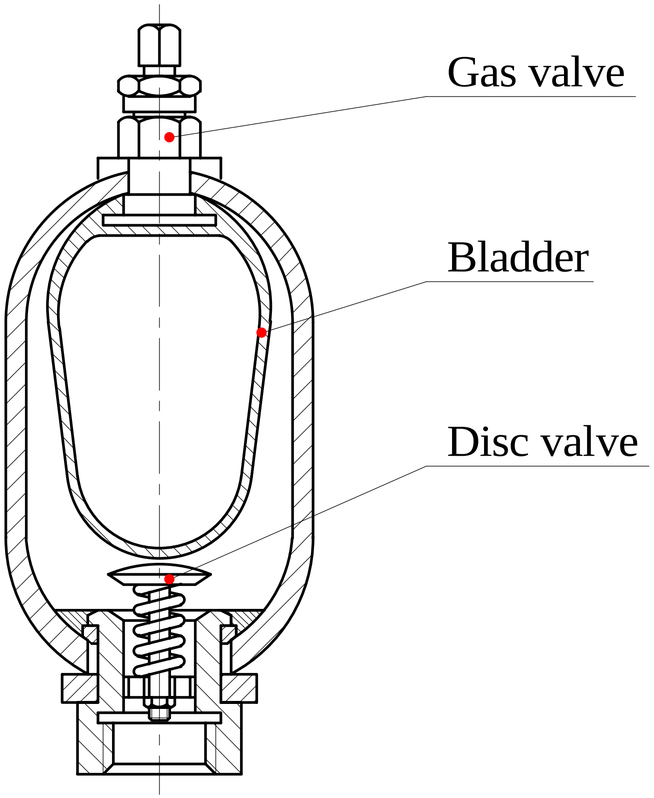
Construction types:

- bladder
- diagphram
- piston

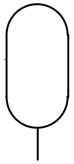
Nominal volumes V » 0.1 – 600 $\times 10^{-3}$ m^3

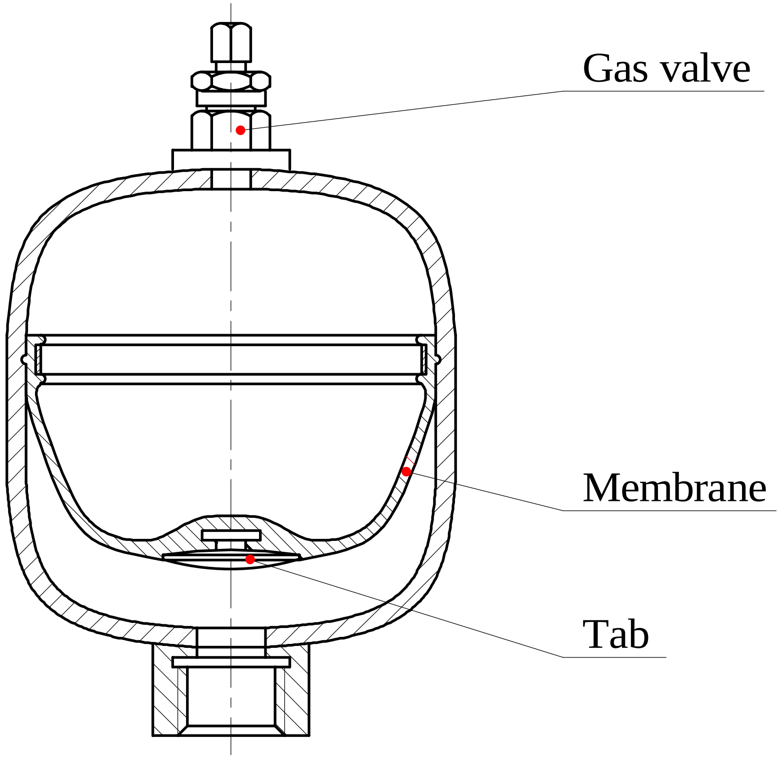
Charging and de-charging flows max. q_V » 120 – 140 $\times 10^{-3}$ m^3/s



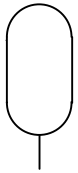


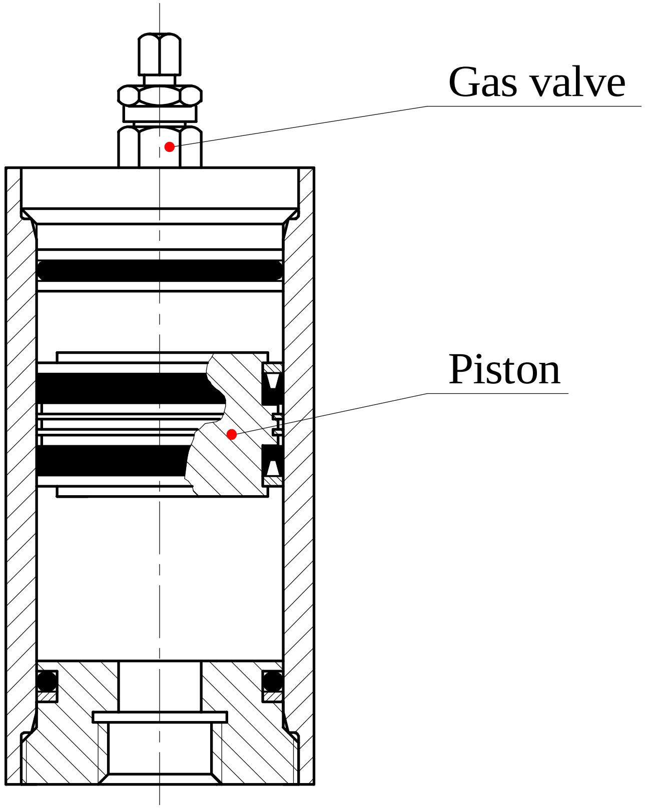
Bladder
Diagphram
Piston





Bladder
Diagphram (aka Membrane)
Piston



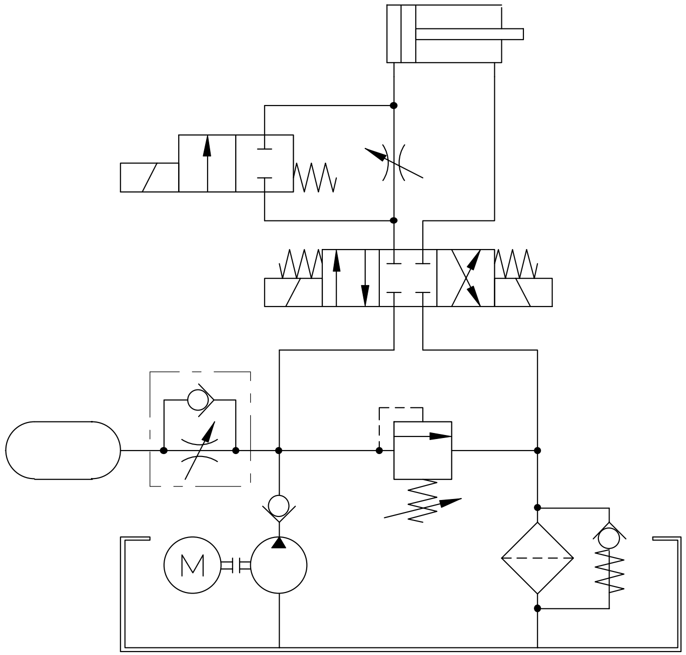


Bladder
Diagphram
Piston

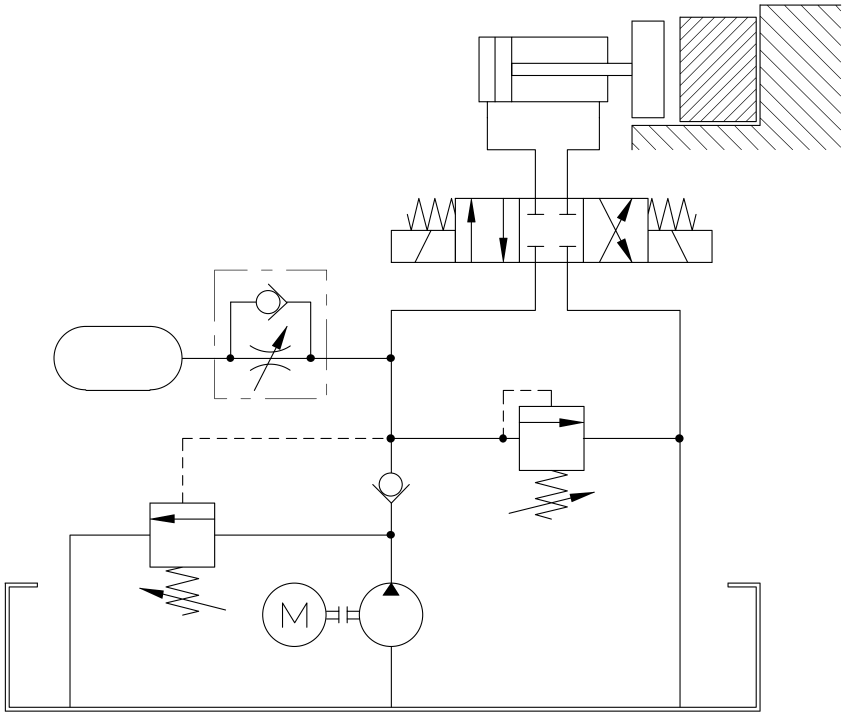
Application examples

Flow source
Upkeep of pressure
Levelling of flow fluctuation
Suppression of pressure shocks
Energy storage for exceptional situations
Storing of external energy
Levelling of volume changes
Levelling of shock-like loadings of actuators

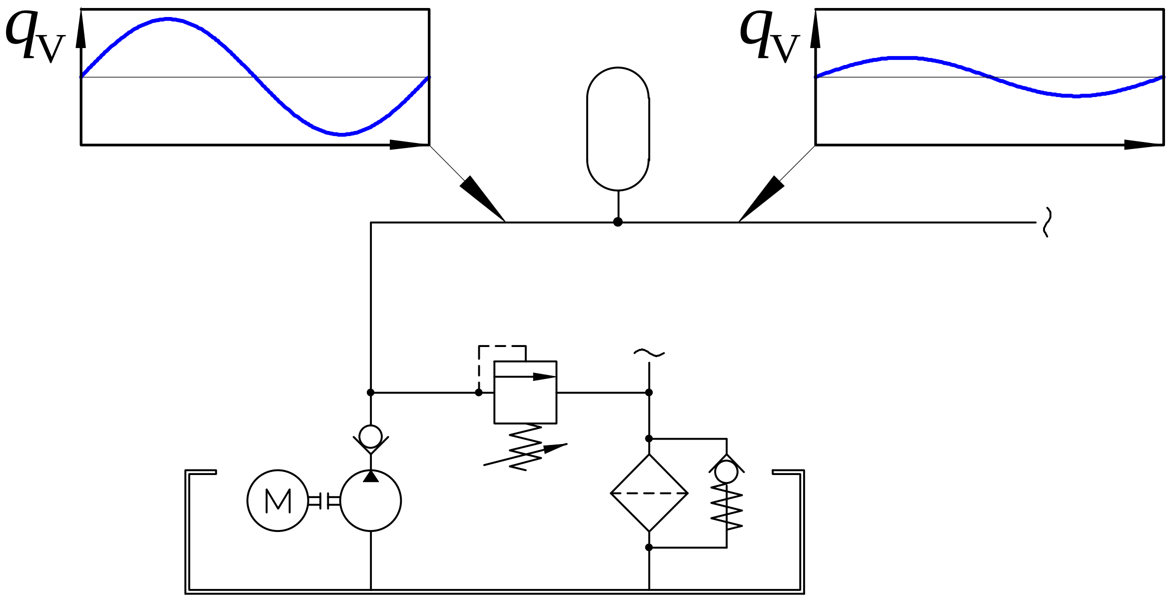
Flow source

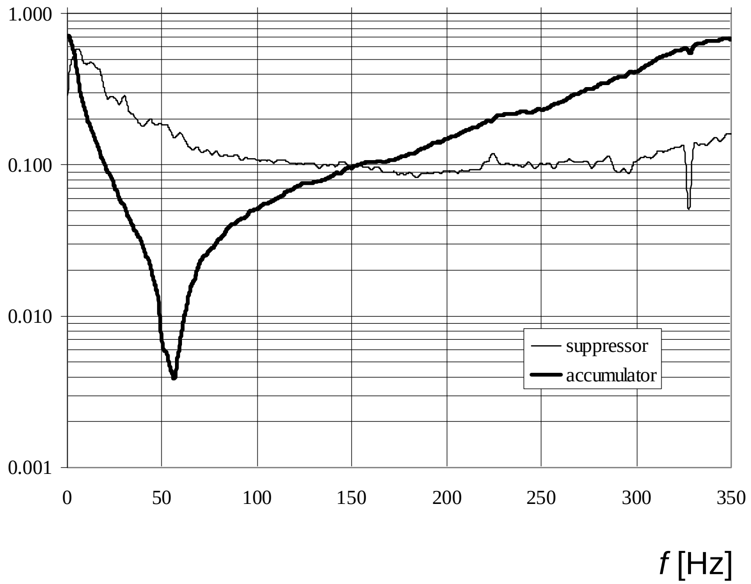


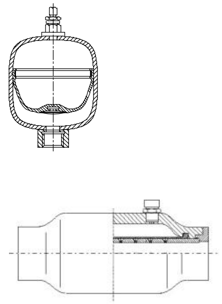
Upkeep of pressure



Levelling of flow fluctuation



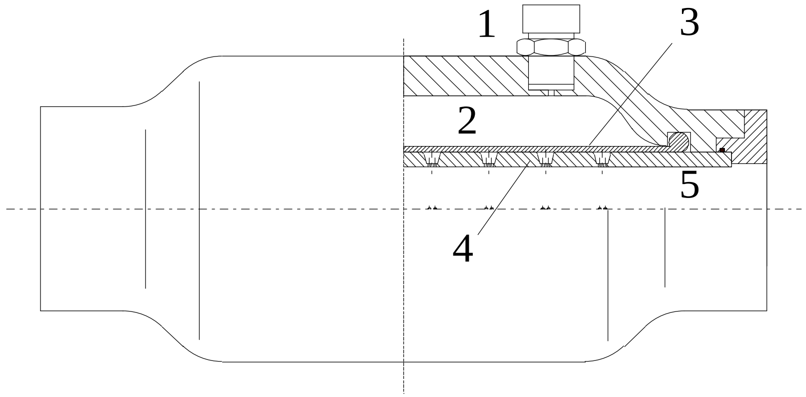




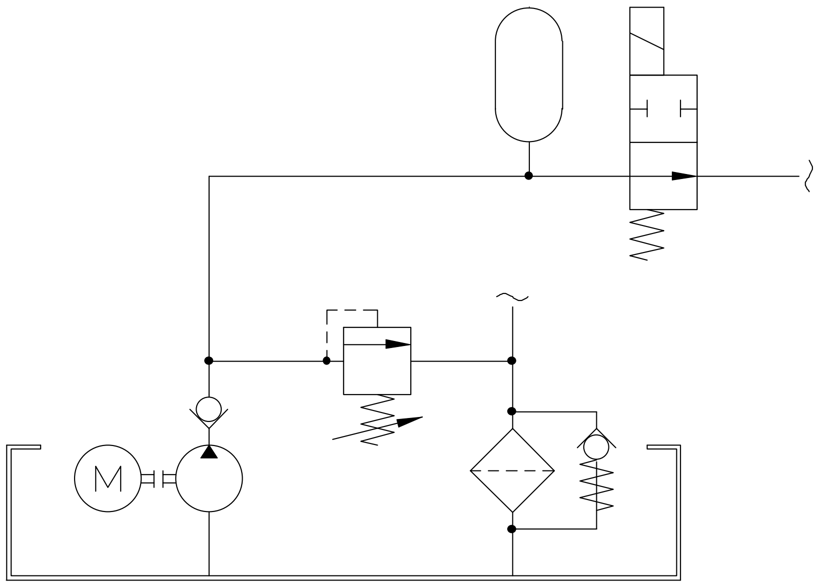
Example:

Levelling of flow fluctuation

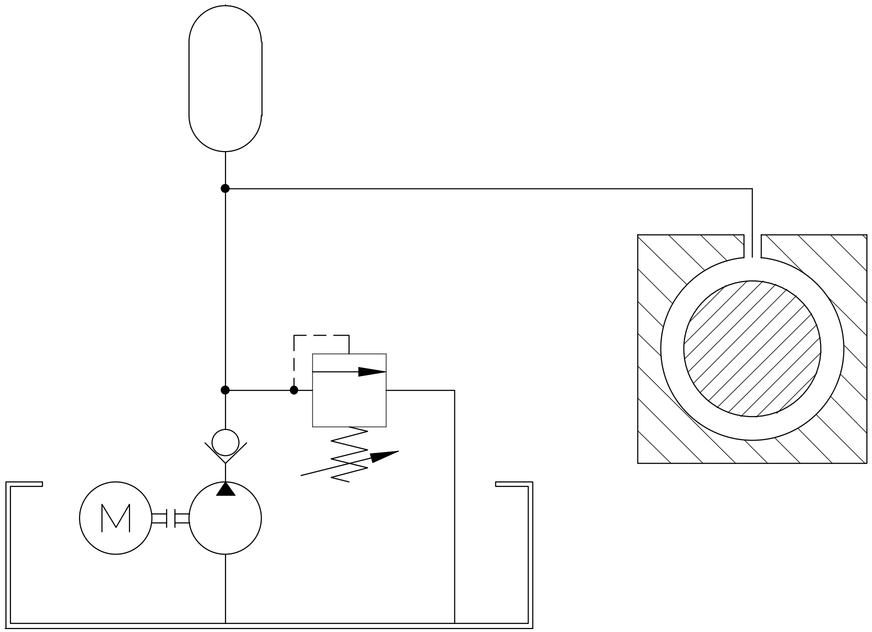
Inline suppressor ®



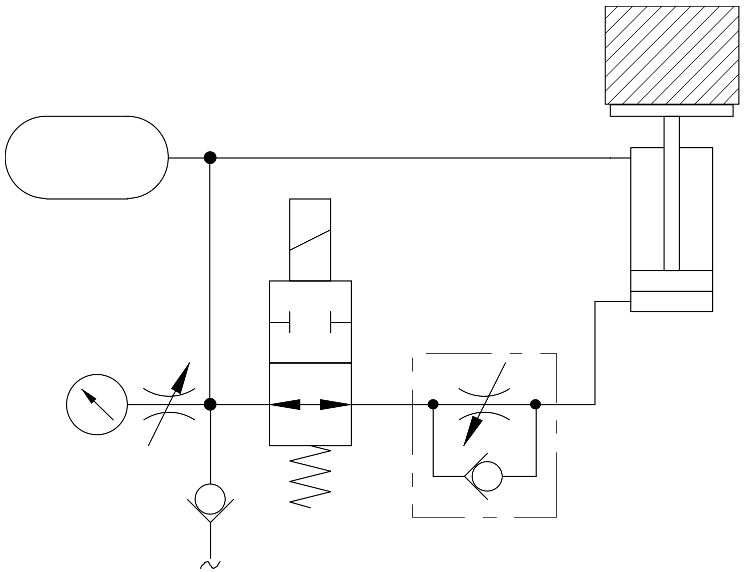
Suppression of pressure shocks



Enery storage for exceptional situations



Storing of external energy



Lecture themes - Recap

Pump's task in hydraulic system?

Converting hydraulic power into
- rotational movement?
- linear movement?

Operation principle of hydrostatic power converters?

Utilization possibilities of pressure accumulators?