Design and Modeling of Fluid Power Systems

ME 597/ABE 591 - Lecture 2

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Fluid Properties

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Properties of Fluids

- Density
  - Change of density with pressure
  - Change of density with temperature
- Compressibility
- Viscosity
  - Viscosity- temperature behavior
  - Viscosity-pressure behavior

- Oxidative, hydrolytic and thermal stability
- Foaming (release air without forming emulsions)
- Lubricity (boundary lubricating property)
- Air/gas absorption
- Pour point
- Flash point/fire point

Fluid Properties

Compressibility of a real fluid

Density is defined: $\rho = \dfrac{m}{V}$ and $\rho = f\left(p,\theta\right)$

Change of fluid volume with pressure and temperature: $V = f\left(p,\theta\right)$

$$dV = \left(\frac{\partial V}{\partial p}\right)_{\theta} \cdot dp + \left(\frac{\partial V}{\partial \theta}\right)_{p} \cdot d\theta$$

$$\rho_{oil} \approx 870\,\mathrm{kg}\cdot\mathrm{m}^{3}$$

Isothermal coefficient of compressibility

$$\beta_p = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_{\theta} = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_{\theta} \quad \Rightarrow \quad dV = -V \cdot \beta_p \cdot dp$$

Bulk modulus is defined as reciprocal of compressibility coefficient $K = \dfrac{1}{\beta_p}$

Therefore we can write: $dV = -\dfrac{V}{K} \cdot dp$

Fluid can be compressed isothermally or isentropically (adiabatic process)

Isothermal bulk modulus K

Adiabatic bulk modulus K_A

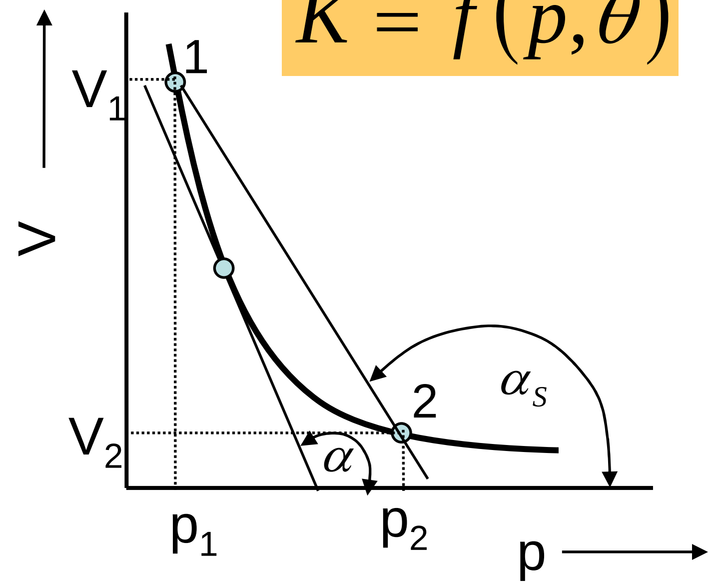
$$\tan\alpha = \frac{dV}{dp} = -\frac{V}{K} \Rightarrow \int_1^2 \frac{dV}{V} = -\int_1^2 \frac{1}{K}\cdot dp$$

$$K = f(p,\theta)$$

$$\ln V_2 - \ln V_1 = -\frac{1}{K}\cdot(p_2 - p_1)$$

$$V_2 = V_1 \cdot e^{-\frac{1}{K}(p_2-p_1)}$$

$$\Delta V = V_1 - V_2 = V_1 \cdot \left[1 - e^{-\frac{1}{K}(p_2-p_1)}\right]$$



In practice secant bulk modulus K_S is often used!

$$\tan\alpha_S = \frac{\Delta V}{\Delta p} = \frac{V_2 - V_1}{p_2 - p_1} = -\frac{V_1}{K_S}$$

$$K = 1.8\cdot 10^9 \div 2.1\cdot 10^9 \text{ Pa}$$

Influence of unsolved air

Due to unsolved air the compressibility of the fluid (fluid-air mixture) changes.

For the bulk modulus of fluid – air mixture K* can be derived:

p_0 … atmospheric pressure

$$\frac{K^*}{K} = \frac{1 + \frac{V_{air}}{V_F}}{1 + \frac{p_0 \cdot V_{air}}{p \cdot V_F} \cdot \frac{K}{p}}$$

In a simplified way for the change of volume of the fluid – air mixture dV_M we can derive:

$$dV_M = dV_F + dV_{Air}$$

For isothermal process follows:

$$p \cdot V_{Air} = (p + dp) \cdot (V_{Air} - dV_{Air})$$

simplified:

$$dp \cdot V_{Air} = dV_{Air} \cdot p$$

Change of air volume with pressure:

$$dV_{Air} = \frac{V_{Air}}{p} dp$$

and for the change of fluid volume:

$$dV_F = \frac{V_F}{K} dp$$

$$dV_M = dV_F + dV_{Air} = \frac{V_F}{K} \cdot dp + \frac{V_{Air}}{p} \cdot dp$$

Influence of unsolved air

$$dV_M = dV_F + dV_{Air} = \frac{V_F}{K}\cdot dp + \frac{V_{Air}}{p}\cdot dp \quad (1) \quad \text{and} \quad dV_M = \frac{V}{K^*}dp \quad (2)$$

Due to $V_{Air} << V_F$ we can make the following simplification: $V_F = V$

then

$$dV_F = \frac{V}{K}dp \qquad (3)$$

Substituting Eq. (3) in Eq. (1) and (2) follows:

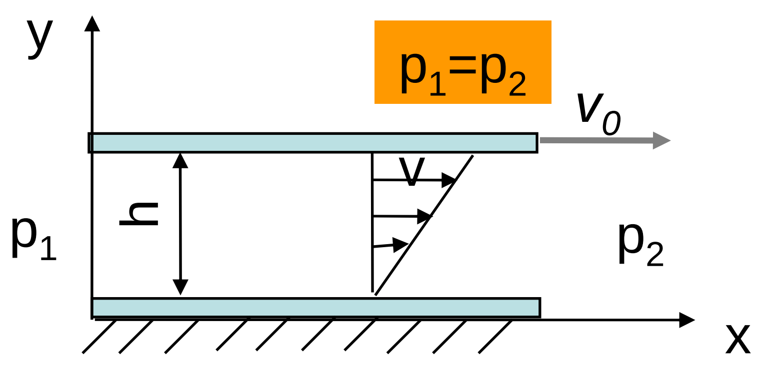
$$\frac{V}{K^*}\cdot dp = \frac{V}{K}\left(1+\frac{V_{Air}}{V}\cdot\frac{K}{p}\right)\cdot dp \quad \Rightarrow \quad \frac{K^*}{K} = \frac{1}{1+\frac{V_{Air}}{V}\cdot\frac{K}{p}}$$

Example: Calculate how the bulk modulus of the fluid – air mixture with 0.5% unsolved air at p = 100 bar=10^7 Pa is changed. The bulk modulus of the fluid is K=$2\cdot10^9$Pa.

$$K^* = \frac{K}{1+\frac{V_{Air}}{V}\cdot\frac{K}{p}} = \frac{2\cdot10^9\ \text{Pa}}{1+0.005\cdot\frac{2\cdot10^9\ \text{Pa}}{10^7\ \text{Pa}}} = 1\cdot10^9\,\text{Pa} = 0.5\,\text{K}$$

Viscosity of a real fluid

The viscosity of a fluid is the measure of its resistance to flow or of its internal friction. According to Newton's law the shearing stress between adjacent layers of a viscous fluid is proportional to the rate of shear in the direction perpendicular to the fluid motion (flow direction).



$$\tau = \mu \cdot \frac{\partial v}{\partial y}$$ μ … dynamic viscosity [Pa·s=N·s/m²]

$$\mu = f\left(p,\theta\right) = \mu_0 \cdot e^{\alpha_p \cdot p - k_\theta \cdot \left(\theta - \theta_0\right)}$$

α_p and k_θ are empirical constants for a given fluid, whereas $\alpha_p = f\left(\theta\right)$

Typical values for mineral oil:

$$\alpha_p = 2.1 \cdot 10^{-8}\ \text{Pa}^{-1}$$

$$k_\theta = 0.036\ \text{K}^{-1} \div 0.057\ \text{K}^{-1}$$

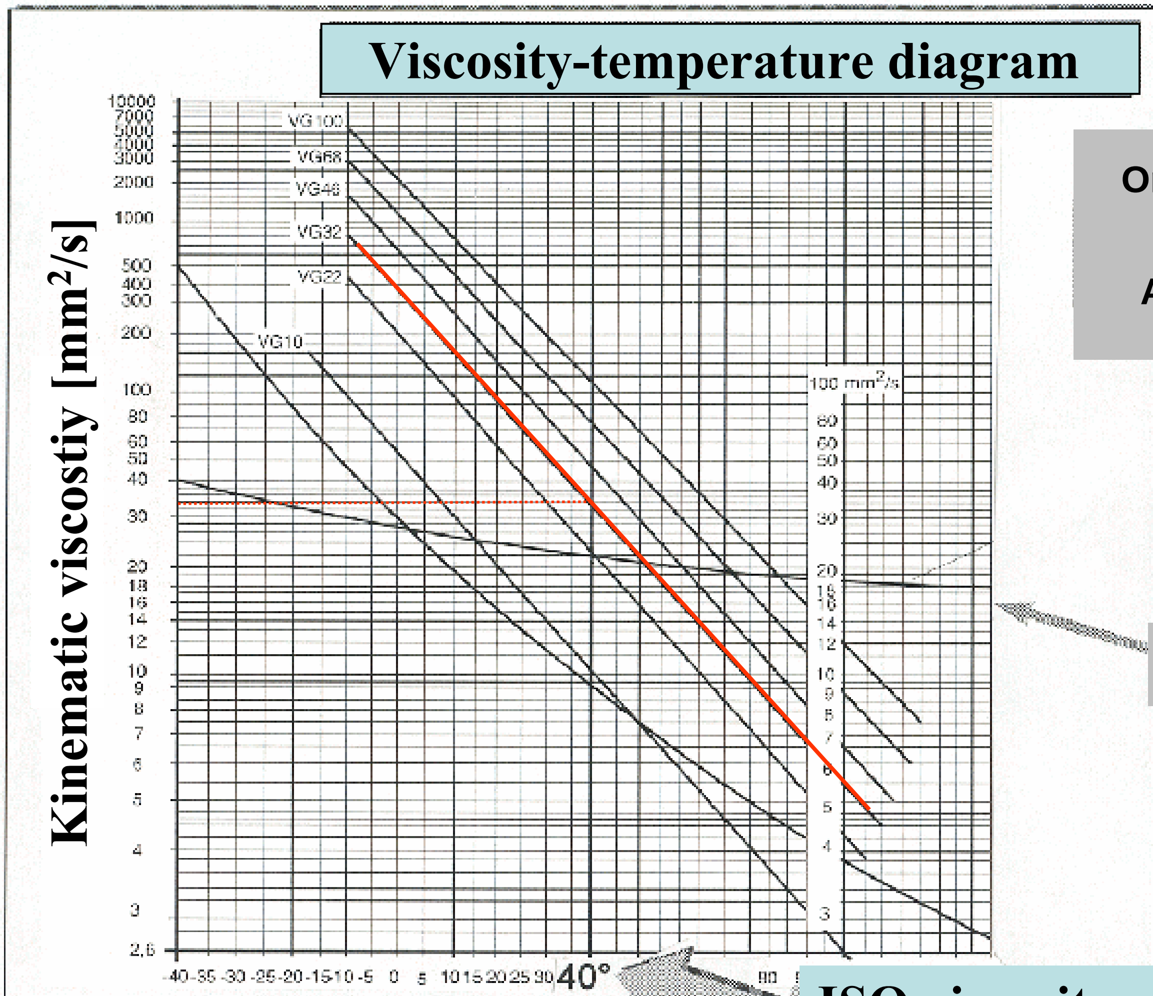
Viscosity of a real fluid

Kinematic viscosity

Kinematic viscosity: $\nu = \frac{\text{dynamic viscosity}}{\text{density}} = \frac{\mu}{\rho}$ $[m^2 \cdot s^{-1}]$ or [cSt]

ISO Viscosity Grades for mineral oils (ISO 3448)

ISO VG 10	**mean value at 40°C**	**10 $mm^2 \cdot s^{-1}$, (cSt)**
ISO VG 22		**22 $mm^2 \cdot s^{-1}$**
ISO VG 32		**32 $mm^2 \cdot s^{-1}$**
ISO VG 46		**46 $mm^2 \cdot s^{-1}$**
ISO VG 100		**100 $mm^2 \cdot s^{-1}$**



Viscosity-temperature diagram
Kinematic viscostiy [mm²/s]
VG 100
VG68
VG46
VG32
VG22
VG10
100 mm²/s
40°
Temperature [°C]
Ordinate: lg lg (*v+0.8)*
Abszissa: lg *T*
Skydrol (Phosphate ester)
ISO viscosity grade reference temperature

Types of Hydraulic Fluids

- **Petroleum based fluids (mineral oils) usually with additives to**
  -prevent oxidation and corrosion
  -reduce foaming
  -improve lubricity
  -increase viscosity index

Water

- **Fire resistant fluids**
  - oil – water emulsions (20% H_2O)
  - water in oil emulsion (about 40% H_2O)
  - water free synthetic fluids (Phosphate ester)

- **Biodegradable fluids**
  -Vegetable oil base
  -Polyglycol base
  -Synthetic ester

Water versus Mineral Oil

Viscosity 30 lower

50% reduction of pressure loss

Viscosity-temperature dependency 14 lower

Specific heat 2.3 higher

5 times higher thermal conductivity

Better cooling-ability

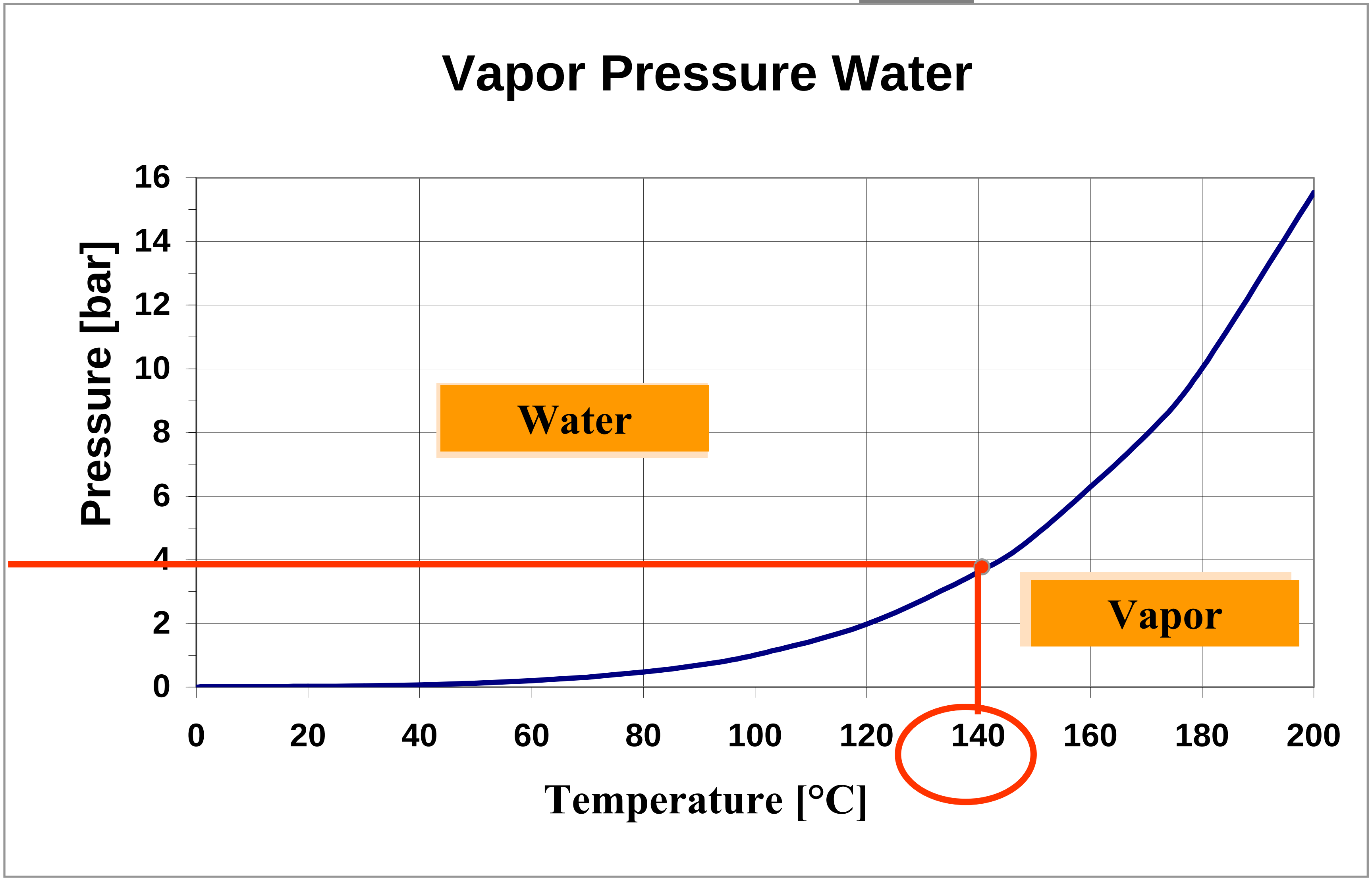
50 % higher bulk modulus

Higher stiffness

Air –release ability 30times better

→ **but** **Higher vapor pressure**

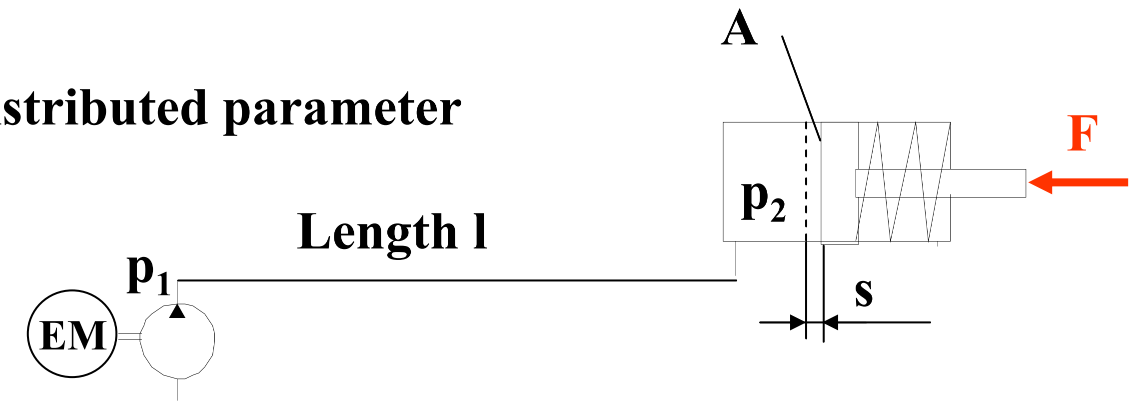
Vapor Pressure of Water



Modeling of transmission lines

Purpose of the model

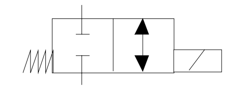
Lumped parameter versus distributed parameter



Pressure loss (type of flow)

$$\Delta V = s \cdot A$$

Transient pressure, p=f (time)



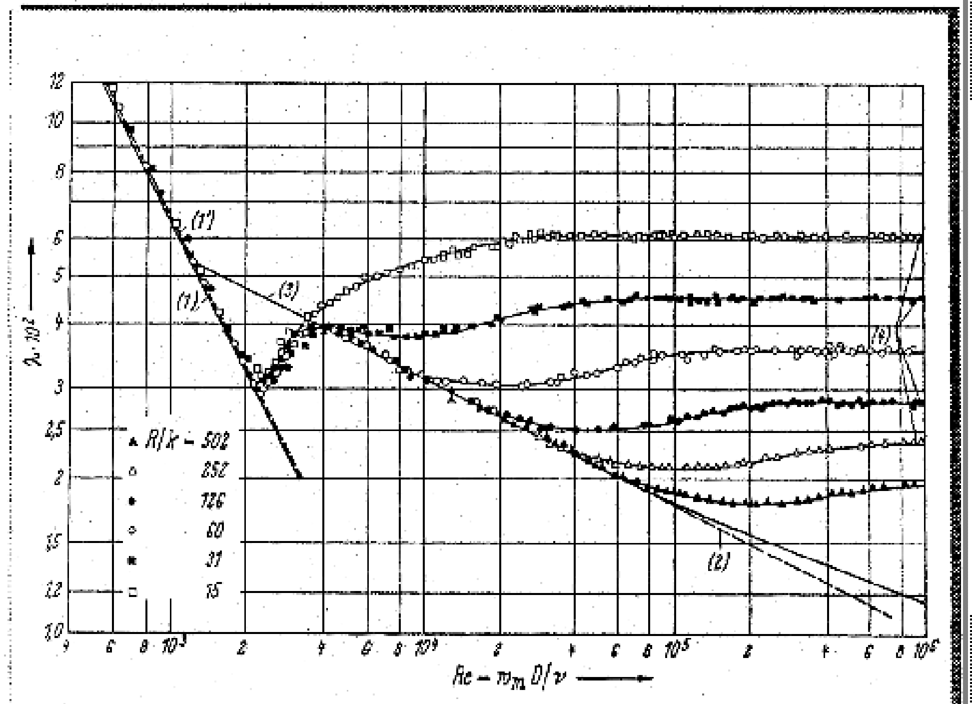
Fluid inertia

Pressure loss

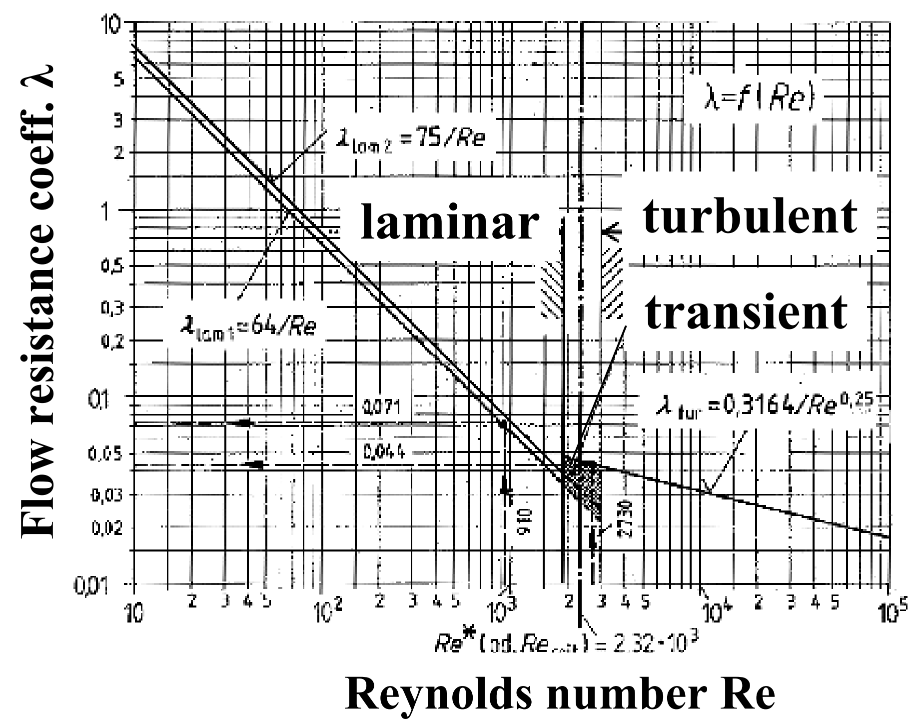
Flow resistance coefficient (friction factor) **8** = f(Re)

@ high Re dependent on surface roughness

for hydraulically smooth pipes

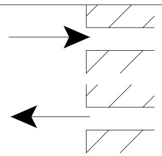
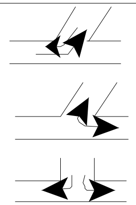
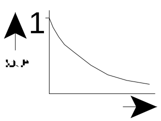
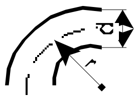
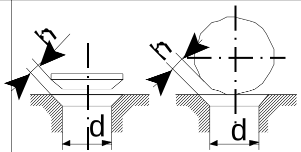
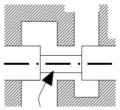
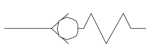
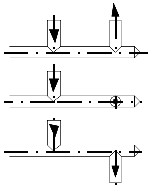


J.Nikuradse (Moody diagram)



Pressure loss

Drag coefficient > - experimentally determined

Type	>	
Inlet Outlet	0,5 1	
Tee	0,5 3 1,3	
Bend		
Seat valve	2.5	
Spool Valve	8 - 16	
Check valve	3 - 10	
Double change of flow direction	1,5 1,8 2,3	

$$\Delta p_F = \sum_{i=1}^{k} \xi_i \cdot \rho \cdot \frac{v_i^2}{2}$$

Due to change of flow path in fittings, bends, valves

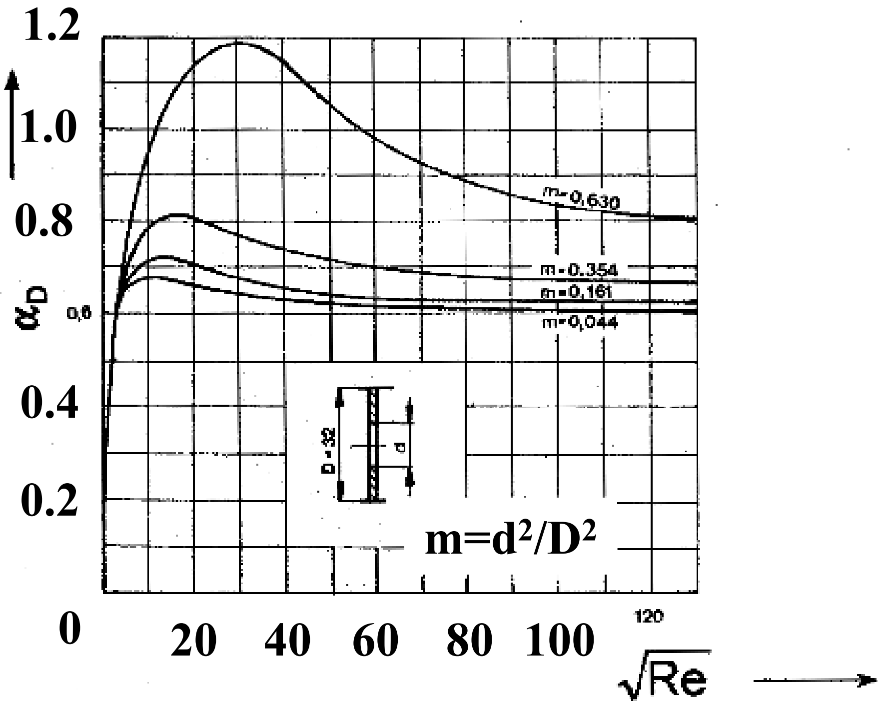
$$\Delta p_S = \Delta p_F + \Delta p_L$$

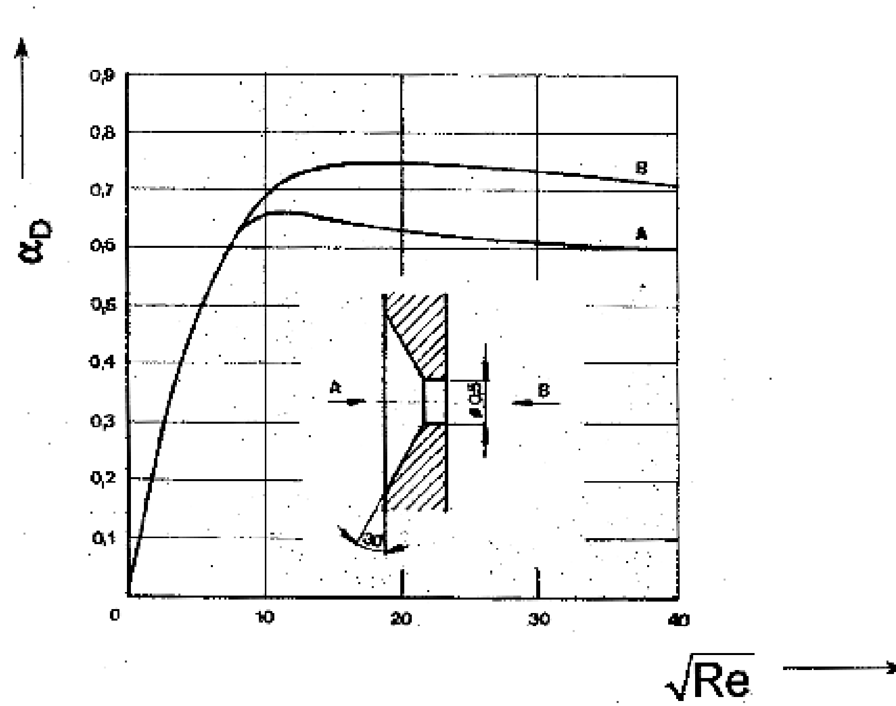
Pressure loss in hydraulic lines (pipes)

$$\Delta p_L = \sum_{j=1}^{m} \lambda_j \cdot \frac{l_j}{d_j} \cdot \rho \cdot \frac{v_j^2}{2}$$

Orifice Flow

"$_D$ ... Discharge coefficient





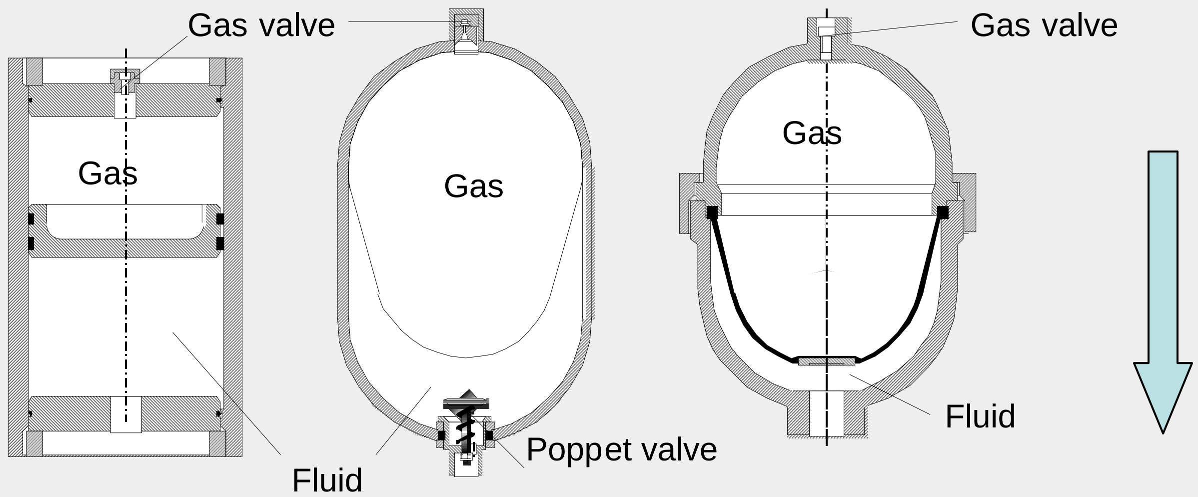
Hydraulic Accumulators

Types of hydropneumatic accumulators (gas loaded)

Piston design | Bladder design | Diaphragm design

Screwed | Welded

Weight loaded



Piston exchangeable

Bladder exchangeable

Diaphragm exchangeable

<u>Maintenance free</u>

Gas used: ***Nitrogen***, Helium, Argon, Carbon dioxide

- large
- uncommon
- piston loaded design

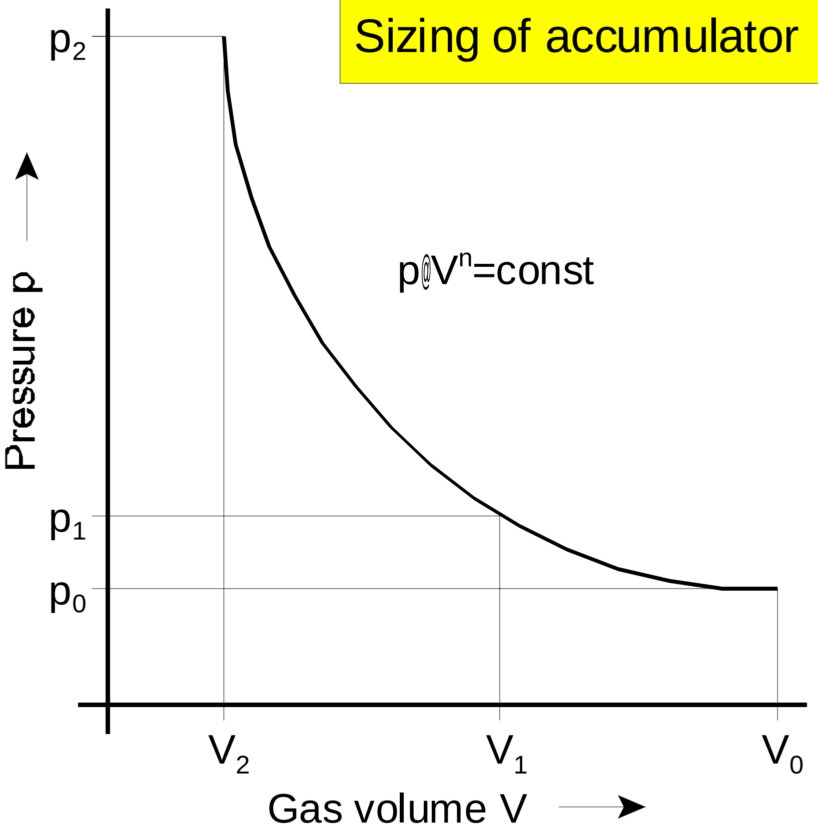
Advantage:

Maintain fluid pressure constant

Hydraulic Accumulators

Gas loaded

Sizing of accumulator & working principle



Thermodynamic process

6 adiabatic $n=1.4$

6 isothermal $n=1$

$$\Delta V = V_0 \left[\left(\frac{p_0}{p_1} \right)^{\frac{1}{n}} - \left(\frac{p_0}{p_2} \right)^{\frac{1}{n}} \right]$$

ΔV **… useable fluid volume**

V_0 **… size of the accumulator**

p_0 ... precharge gas pressure $p_0=0.9\ p_1$

V_0 ... effektive gas volume @ p_0