Design and Modeling of Fluid Power Systems
ME 597/ABE 591 - Lecture 2

Dr. Monika Ivantysynova
MAHA Professor Flud Power Systems

MAHA Fluid Power Research Center
Purdue University

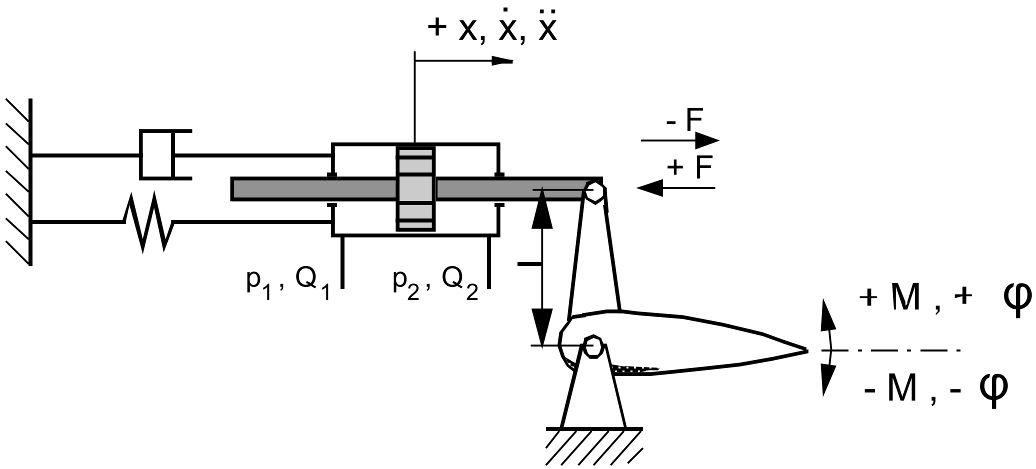
Contents

Fluid Power System Design

- Choose max operating pressure
- Size the hydraulic motor
- Calculate flow requirement
- Select type of control, in case of valve control select type and size of control valve
- Select pump size based on flow requirement and speed of prime mover
- Calculate required line diameter
- Add additional components like pressure relief valve, logic elements, filter, reservoir, accumulators

Fluid Power System Design

Example



Aileron Actuation System:

angle	φ	=	$\pm 25°$
max. velocity	$\dot{\varphi}_{max}$	=	60 °/s
- „ - during flight	$\dot{\varphi}_{max\ Flight}$	=	25 °/s
max. hinge moment	M	=	± 1800 Nm
lever arm	l	=	45 mm
max. force during flight	$F_{max\ Flight}$	=	35 kN

Fluid Properties

Properties of Fluids

- Density
- Compressibility
- Viscosity

Change of density with pressure

Change of density with temperature

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: $\rho = \frac{m}{V}$ and $\rho = f(p,T)$

Change of fluid volume with pressure and temperature: $V = f(p,T)$

$$dV = \left(\frac{\partial V}{\partial p}\right)_T \cdot dp + \left(\frac{\partial V}{\partial T}\right)_p \cdot dT$$

$$\rho_{oil} \approx 870\ \text{kg} \times \text{m}^{-3}$$

Isothermal coefficient of compressibility

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

Bulk modulus is defined as reciprocal of compressibility coefficient

$$K = \frac{1}{\beta_p}$$

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

Fluid Properties
Bulk modulus

Fluid can be compressed isothermally or isentropically (adiabatic process)

Isothermal bulk modulus K

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

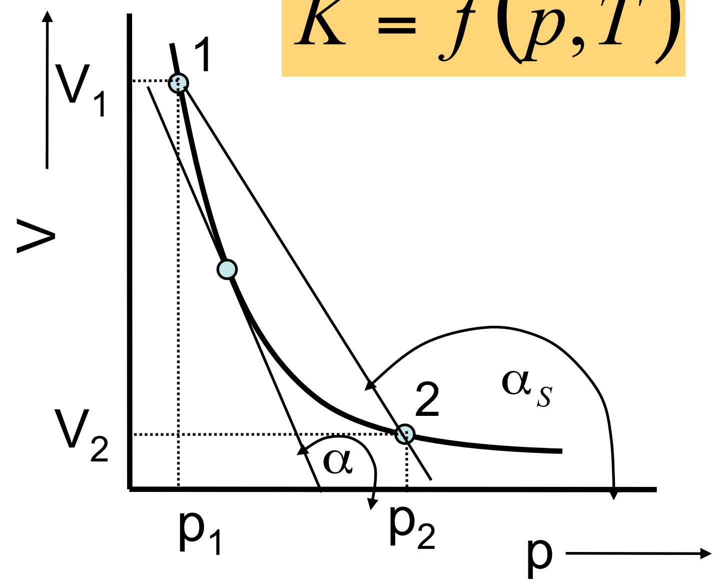
$$\ln V_2 - \ln V_1 = -\frac{1}{K} \cdot (p_2 - p_1)$$

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

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

Adiabatic bulk modulus K_A

$$K = f(p, T)$$



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 entrapped air

Due to entrapped 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

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

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 entrapped 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:

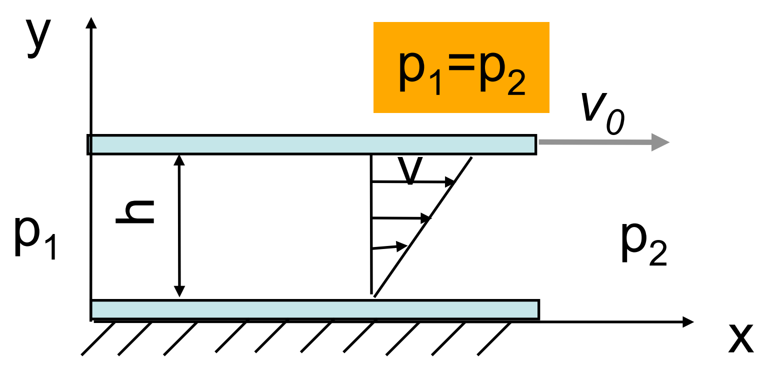
$$\frac{V}{K^*}\cdot dp = \frac{V}{K}\left(1 + \frac{V_{Air}}{V}\cdot\frac{K}{p}\right)\cdot dp \quad \Rightarrow \quad \boxed{\frac{K^*}{K} = \frac{1}{1 + \frac{V_{Air}}{V}\cdot\frac{K}{p}}}$$

Example: Calculate how the bulk modulus of the fluid – air mixture with 0.5% undissolved 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]

$$\mu = f(p,T) = \mu_0 \cdot e^{\alpha_p \cdot p - k_T \cdot (T - T_0)}$$

α_p and k_T are empirical constants for a given fluid, whereas $\alpha_p = f(T)$

Typical values for mineral oil:

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

$$k_T = 0.036\ \mathrm{K}^{-1} \div 0.057\ \mathrm{K}^{-1}$$

Viscosity of a real fluid

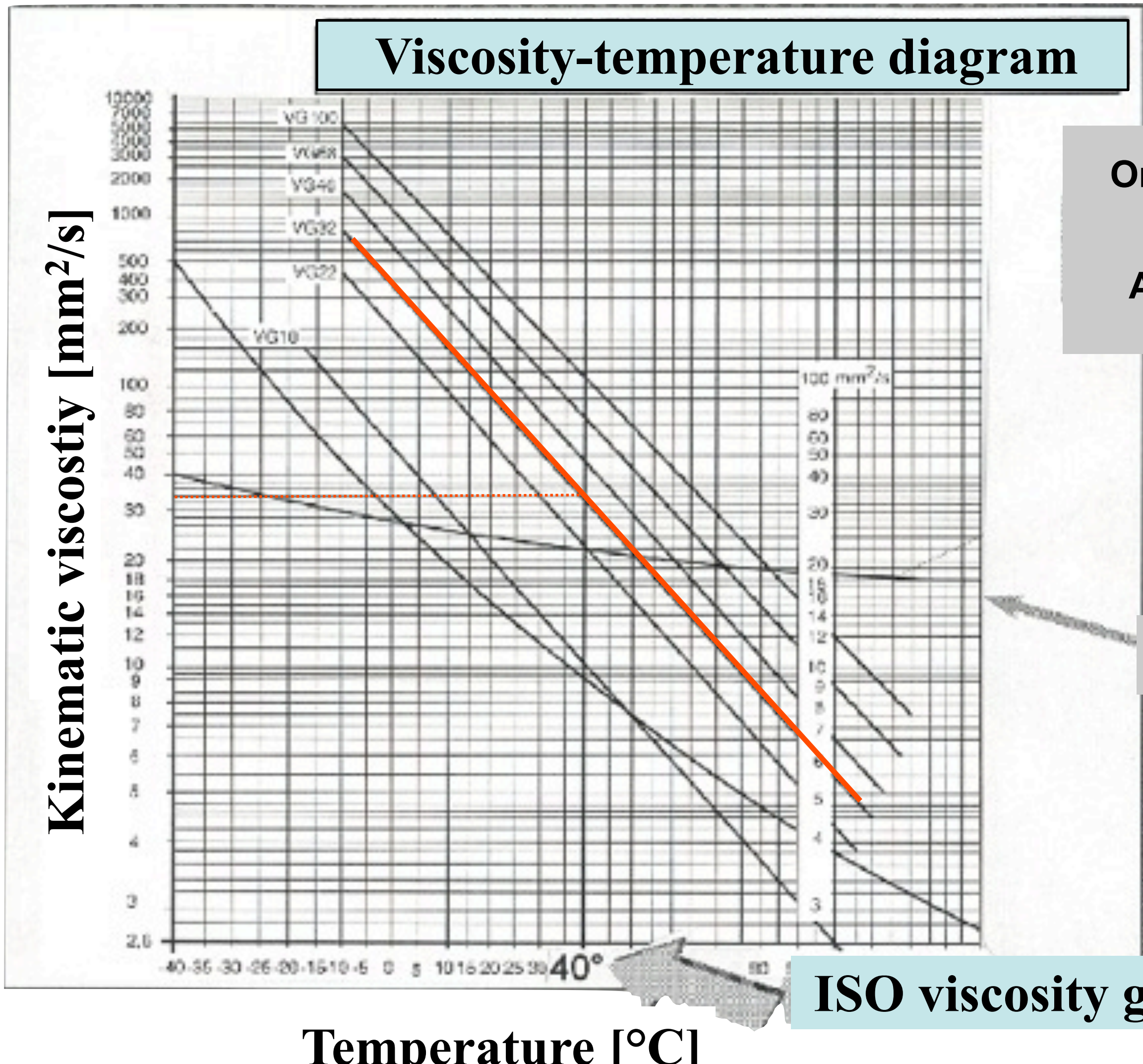
Kinematic viscosity

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



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 HL
  - reduce foaming
  - improve lubricity HLP
  - increase viscosity index HV

- Fire resistant fluids
  - oil – water emulsions (20% H_2O) - HFA
  - water in oil emulsion (about 40% H_2O) - HFB
  - Polymer solutions with H2O - HFC
  - water free synthetic fluids (Phosphate ester) - HFD

- Biodegradable fluids
  - Vegetable oil base HTG
  - Polyglycol base HPG
  - Synthetic ester HE

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

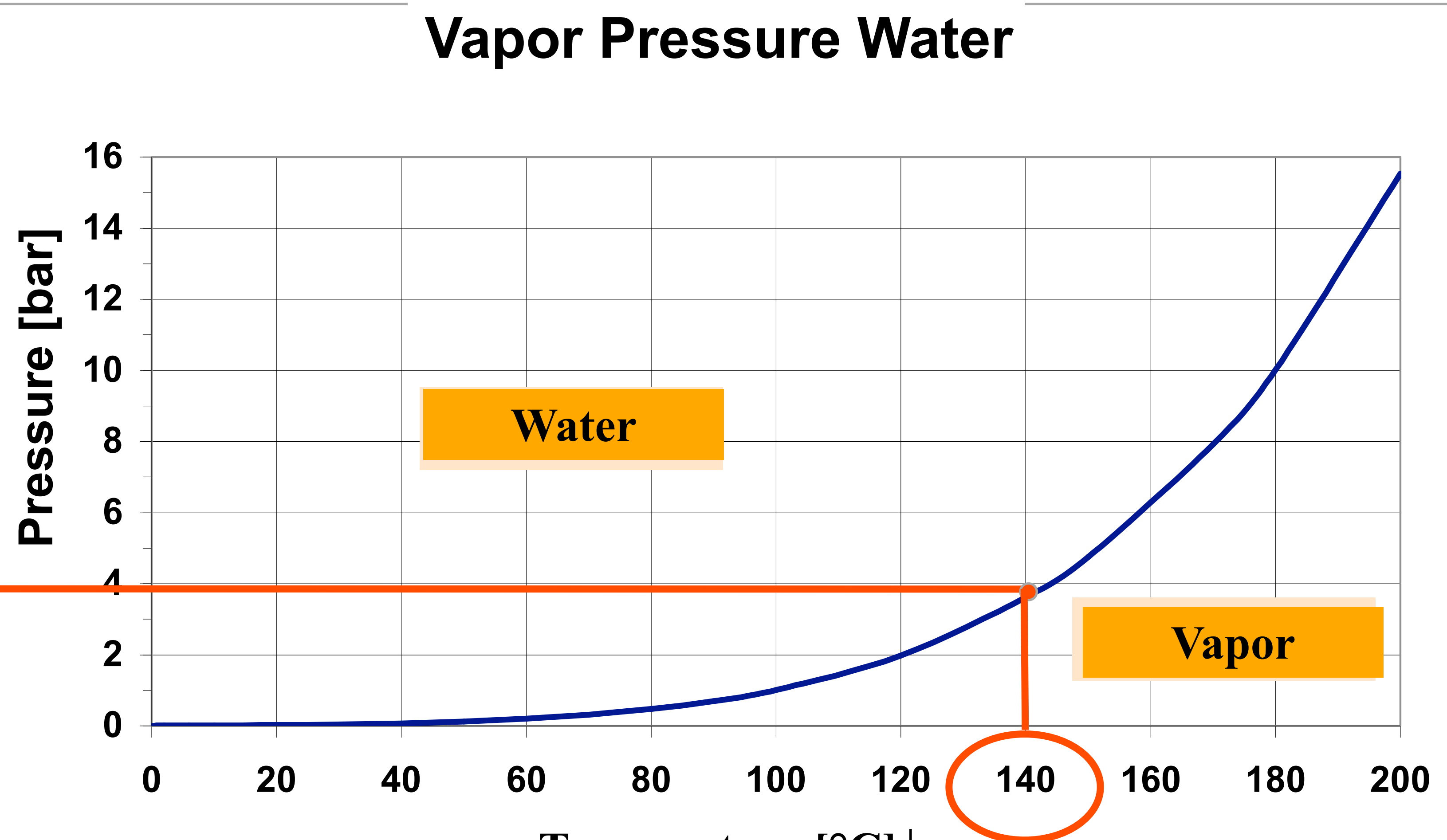
50% higher bulk modulus

Higher stiffness

Air –release ability 30times better

→ but **Higher vapor pressure**

Vapor Pressure of Water



$p_{V\ H2O}$=0.1133 bar @ 50°C

$p_{V\ mineral\ oil}$= 0.053Pa = 0.53 µbar @ 50°C

Fluid Properties

Thermal properties

Specific heat c [J/kg ·K]

Thermal conductivity λ [W/m ·K]

Solubility of gas

Henry's law

Cavitation