Aalto University
School of Engineering

MEC-E5003

FLUID POWER BASICS

Study Year 2020

Hydromechanics

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

Lecture themes

Flow rate – Pure joy?

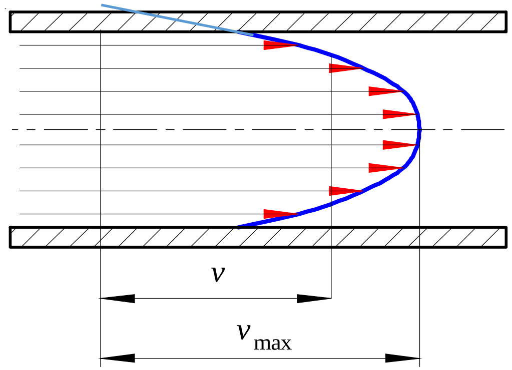
Pressure in system – Constant or what?

Efficiency – What is that?

Power – Forms of

Pressure losses induced by flow

$$\tau = \eta \frac{dv}{dy}$$



Flow induced pressure losses are categorized to losses occurring in

- straight flow channels of constant cross-sectional area
- complex flow channels (direction and/or velocity of the flow changes)

Total pressure loss of a system is a sum of these

In straight flow channels of constant cross-sectional area

$$\Delta p = \lambda \cdot \frac{l}{d} \cdot \frac{\rho}{2} \cdot v^2$$

- pipe length *l*
- pipe diameter *d*
- flow velocity *v*

λ = friction factor

For laminar flow $\lambda = \frac{64}{Re}$

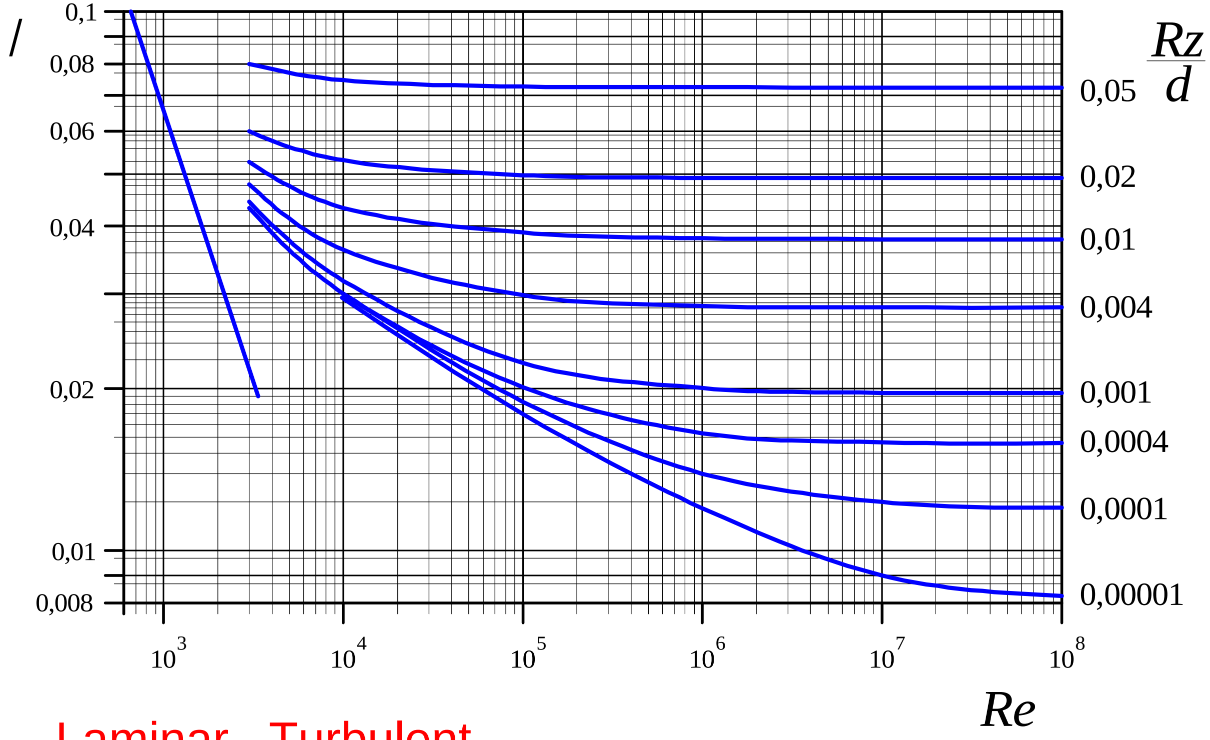
For turbulent flow Moody diagram

Reynolds number

Re=vD/ν

- velocity *v*
- pipe diameter *D*
- kinematic viscosity *ν*

Moody diagram



Relative roughness

Roughness

Seamless hydraulic pipe

0.01 – 0.04 mm

Hot rolled pipe

0.05 – 0.10 mm

Hydraulic hose

0.02 – 0.03 mm

$Re < 2300$ Laminar

$2300 < Re < 4000$

$Re > 4000$ Turbulent

Laminar friction factor

$\lambda_{lam} = 64/Re$

Use **Moody chart** or Approximation below for **turbulent friction factor**

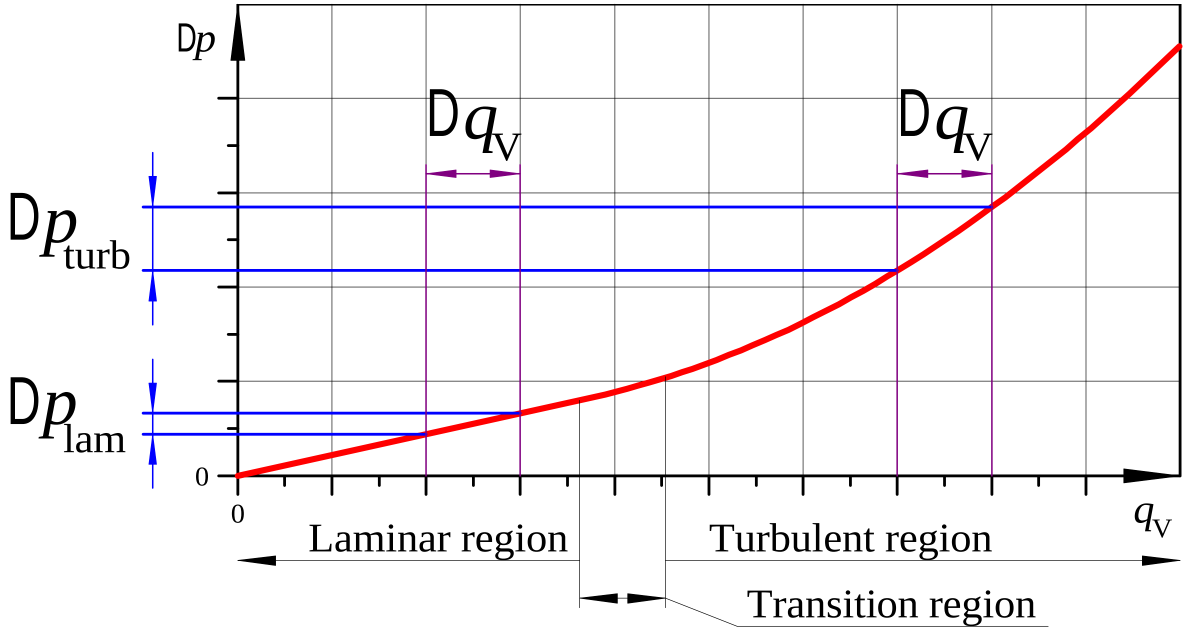
$$\lambda_{\mathrm{turb}} = \frac{6.4}{\left[ln(Re) - ln\left(1 + 0.01Re\ \varepsilon(1 + 10\sqrt{\varepsilon})\right)\right]^{2.4}}$$

Avci, A & Karagoz, I. A Novel Explicit Equation for Friction Factor in Smooth and Rough Pipes

There are many approximations for friction factor but the one above includes also relative roughness parameter ε (= R_z/d).

In straight flow channels of constant cross-sectional area

$$\Delta p = \lambda \cdot \frac{l}{d} \cdot \frac{\rho}{2} \cdot v^2$$



In complex flow channels (direction and/or velocity of the flow changes)

Minor losses

$$\Delta p = \zeta \cdot \frac{\rho}{2} \cdot v^2$$

Dynamic pressure

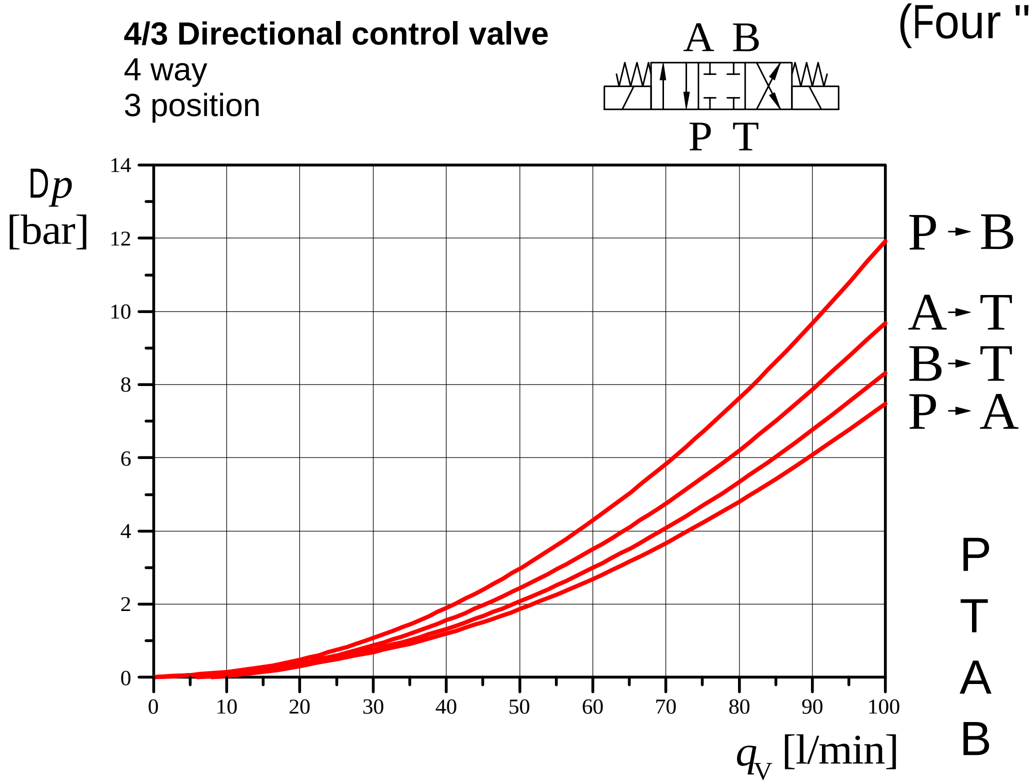
$1/2\ \rho v^2$

ζ = loss factor, resistance coefficient

Numerical value for ζ from tables or characteristic curves

Characteristic curve

This valve can be interpreted as
- four orifices:
PA - PB - AT - BT
(Four "control edges").



P	pump
T	tank
A	actuator's A interface
B	actuator's B interface

Converting known pressure loss to another operating point

$$\Delta p_2 = \left(\frac{q_{V,2}}{q_{V,1}}\right)^2 \cdot \Delta p_1$$

If flow rate changes

$$\Delta p_2 = \frac{\rho_2}{\rho_1} \cdot \Delta p_1$$

If density changes

Effect of viscosity
Approximation for common valves

$$\Delta p_2 \approx \left(\frac{\nu_2}{\nu_1}\right)^{0,25} \cdot \Delta p_1$$

Attention!
For a pure orifice the viscosity has no effect

Total pressure loss of system

$$\Delta p_{\mathrm{t}} = \sum_{i=1}^{N1} \lambda_i \cdot \frac{l_i}{D_{\mathrm{H},i}} \cdot \frac{\rho_i}{2} \cdot v_i^2 + \sum_{j=1}^{N2} \zeta_j \cdot \frac{\rho_j}{2} \cdot v_j^2$$

pipes + minor losses

Significance of individual loss components?

Pressure of a system

In each point of a system the prevailing pressure builds up on
- external loading of the system
- internal loading of the system (= pressure losses)

External loading, ie., pressure demand of the actuators

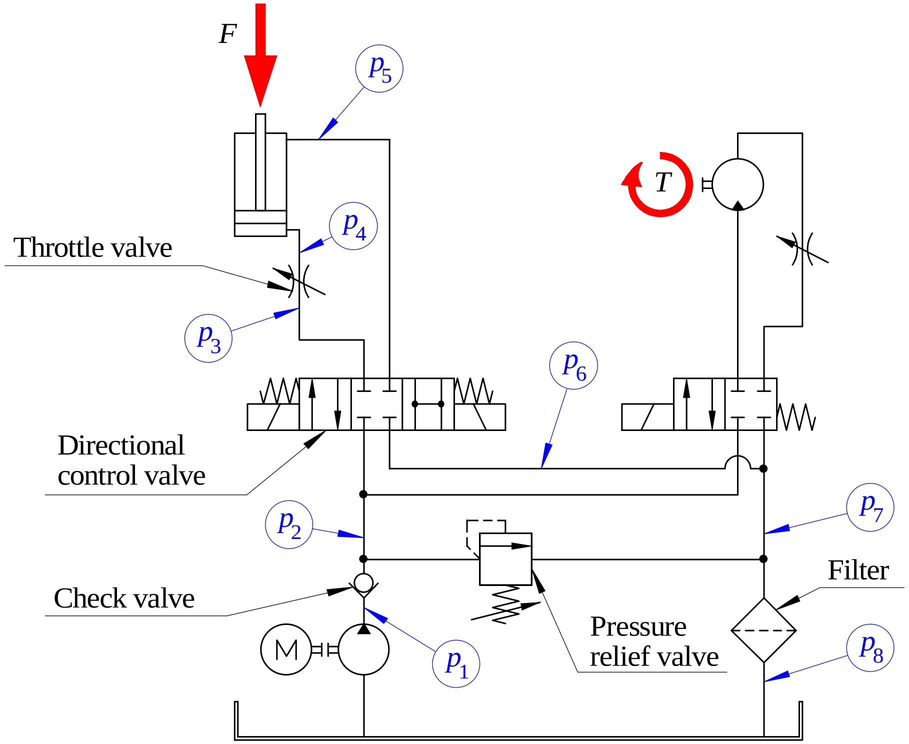
$$p_{\mathrm{ex,c}} = \frac{F}{A} \quad \text{cylinder} \qquad p_{\mathrm{ex,m}} = \frac{2\pi \cdot T_{\mathrm{m}}}{V_{\mathrm{g,m}}} \quad \text{motor}$$

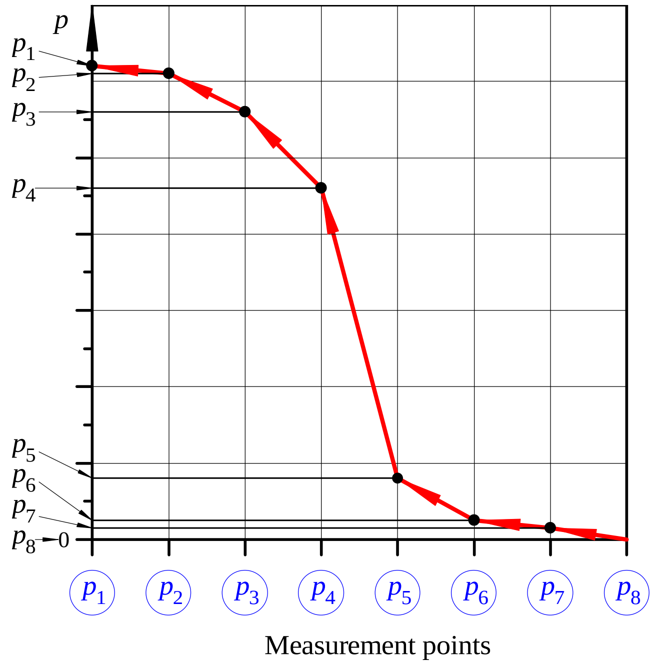
$$p_{\mathrm{ex,t}} = \sum p_{\mathrm{ex,c}} + \sum p_{\mathrm{ex,m}}$$

Internal loading, ie., flow induced pressure losses

$$\Delta p_{\mathrm{t}} = \sum_{i=1}^{N1} \lambda_i \cdot \frac{l_i}{D_{\mathrm{H},i}} \cdot \frac{\rho_i}{2} \cdot v_i^2 + \sum_{j=1}^{N2} \zeta_j \cdot \frac{\rho_j}{2} \cdot v_j^2$$

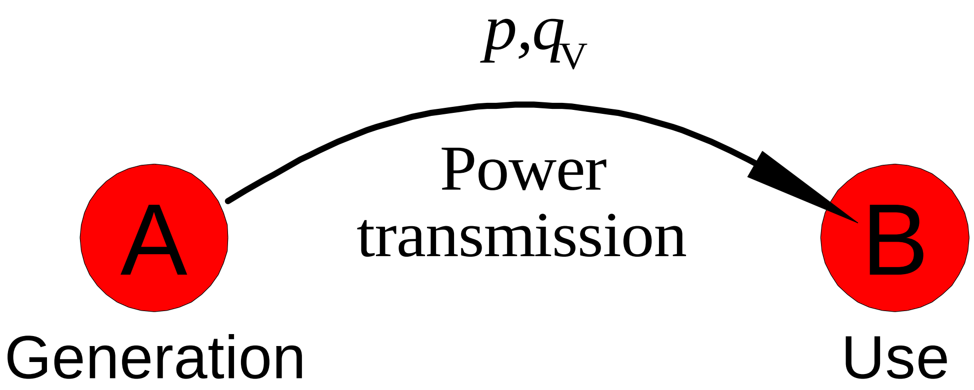
® Pressure in observation point $p_t = p_{ex,t} + \Delta p_t$





Hydraulic power and efficiency – introduction

$$P = q_V \cdot p$$



Power – Utility or Loss

$$P_{\mathrm{out}} = q_{\mathrm{V}} \cdot \Delta p$$

$$P_{\mathrm{s}} = q_{\mathrm{V}} \cdot p_{\mathrm{s}}$$

Utility:
- cylinders
- motors
- pumps

Loss:
- cylinders
- motors
- pumps
- control components
- piping
- maintenance components

Power demand of system: $P_{\mathrm{in}} = P_{\mathrm{out}} + P_{\mathrm{s}}$

Efficiency

$$P_{\mathrm{in}} = P_{\mathrm{out}} + P_{\mathrm{s}}$$

$$\eta_{\mathrm{t}} = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}$$

Total efficiency (related to power)

$\rightarrow$ $$P_{\mathrm{out}} = P_{\mathrm{in}} \cdot \eta_{\mathrm{t}}$$

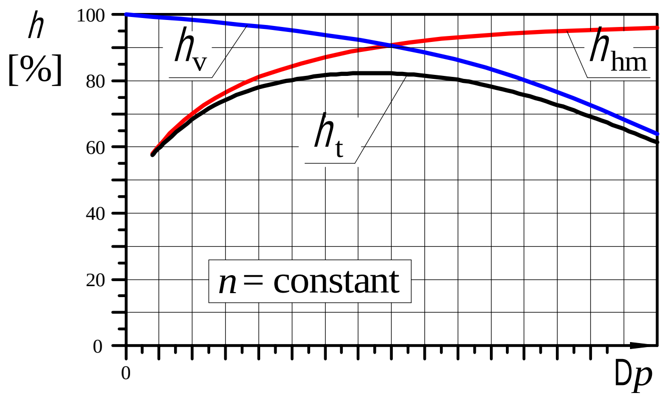
Less power out than in, $\eta_{\mathrm{t}} < 1$

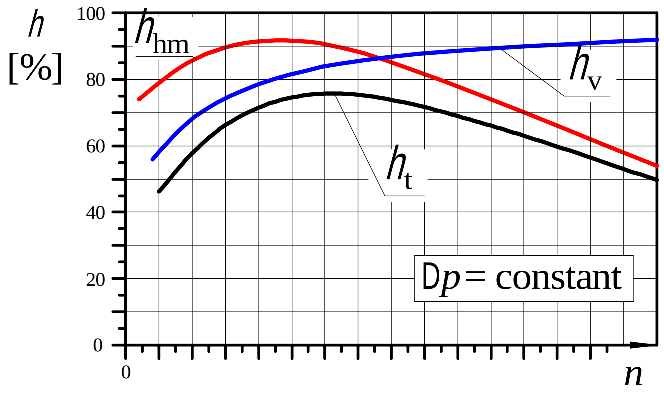
$$P_{\mathrm{s}} = P_{\mathrm{in}} \cdot (1 - \eta_{\mathrm{t}})$$

Efficiency terms of hydraulic energy converting components

$$\eta_t = \eta_v \cdot \eta_{hm}$$

Pump as an example





Volumetric efficiency η_v
effect of leakages
Hydromechanical efficiency η_{hm}
effect of mechanical and flow friction

Energy converting components $P_{out} = P_{in} \cdot \eta_t$

Energy converting components

Pump : $P_{\text{out,pump}} = T \cdot \omega \cdot \eta_{\text{t}} = q_{\text{V}} \cdot \Delta p$

$\omega = 2\pi n$

Hydraulic motor : $P_{\text{out,motor}} = q_{\text{V}} \cdot \Delta p \cdot \eta_{\text{t}} = T \cdot \omega$

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

Unclear way to represent power losses!

Utility power – Power loss

System efficiency

Momentary total efficiency:

$$\eta_{\mathrm{t,mom}} = \frac{P_{\mathrm{out,mom}}}{P_{\mathrm{in,mom}}}$$

Total efficiency of work cycle:

$$\eta_{\mathrm{t,wc}} = \frac{W_{\mathrm{out,wc}}}{W_{\mathrm{in,wc}}} = \frac{\sum_{i=1}^{N} P_{\mathrm{in},i} \cdot \eta_{\mathrm{t},i} \cdot t_i}{\sum_{i=1}^{N} P_{\mathrm{in},i} \cdot t_i}$$

Hydraulic system heats up

Power loss turns into heat

$$P_{\text{s,sys}} = P_{\text{in,sys}} - P_{\text{out,sys}} = P_{\text{in,sys}} \cdot (1 - \eta_{\text{t}}) = P_{\theta}$$

System → q_{j} - Part of the heat stores in to the system thus rising its temperature

Surroundings

Part of the heat transfers to the surroundings

$$B_{\theta} = \sum_{i=1}^{N} C_{\text{U},i} \cdot A_i$$

overall heat transfer coefficient [W/(m²·K)]

heat transfer surface area [m²]

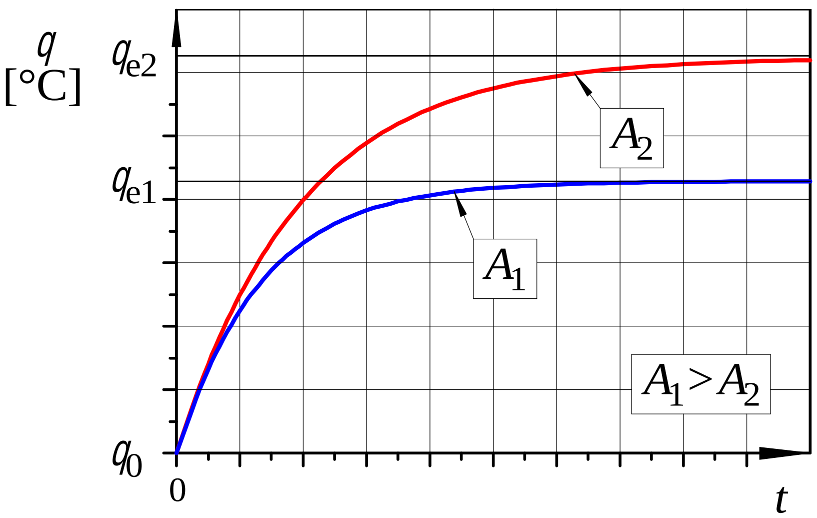
Ability to transfer heat (*B*), [W/K]

System temperature sets to a value at which

$$P_{\text{heat-transfer}} = P_{\theta} = P_{\text{s,sys}}$$

Settling time depends on time constant τ.

Effect of surface area on asymptotic temperature



$$\theta_t = \theta_0 + \frac{P_{\text{s,sys}}}{B_{\theta}} \left(1 - e^{\frac{-t}{\tau}} \right)$$

Temperature as a function of time.

$$\theta_{\text{e}} = \theta_0 + \frac{P_{\text{s,sys}}}{B_{\theta}}$$

New stationary temperature after the transient.

Ability to transfer heat (B), [W/K]

Lecture themes - Recap

Was flow rate just pure joy?

Total system pressure – Contributing factors?

System pressure – Same everywhere?

Efficiency – What story does it tell for us?

Effects of power losses on the system?