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

Fluid – Does it matter which?

Viscosity – How and why?

Flow – What is it needed for?

Is there a connection between pressure and flow?

Hydrodynamics

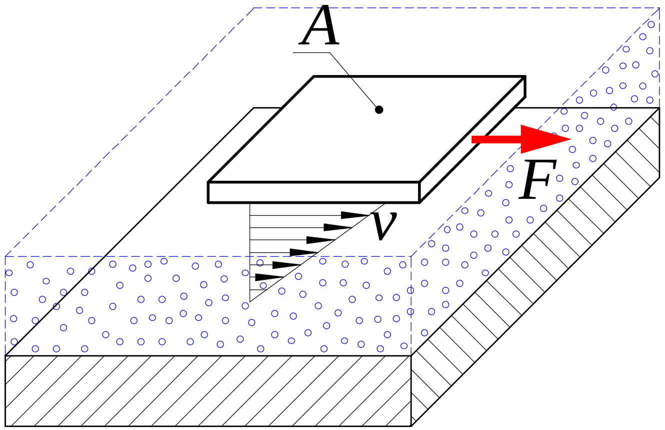
Flowing fluid under internal and external load
- mass
- internal and external friction
- compressibility

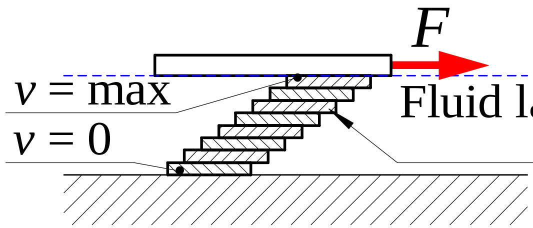
(well, not necessarily all of these in every case…)

Viscosity

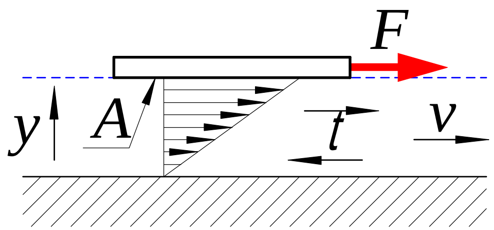
The shear force F and shear stress τ depend on

- (dynamic) viscosity η
- velocity gradient





Fluid layer approximation
shear stress



Continuous velocity distribution

$$F = h \times A \times \frac{v}{y}$$

$$t = h \times \frac{dv}{dy}$$

Newtonian fluid: viscosity indepen-dent of shear rate

Viscosity factor h represents the properties of fluid, “tenacity”

Dynamic viscosity h

Unit [Pa×s]

1 cP = 10^{-3} Pa·s

Kinematic viscosity n

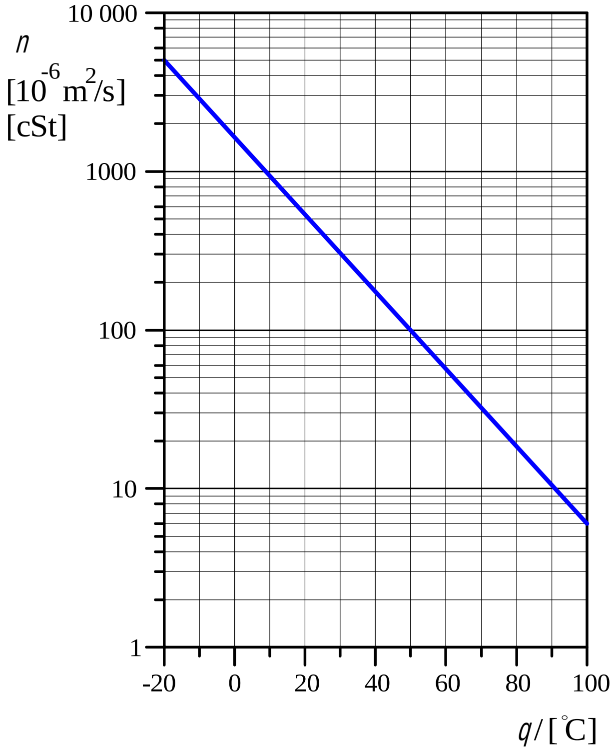
$$n = \frac{h}{r}$$

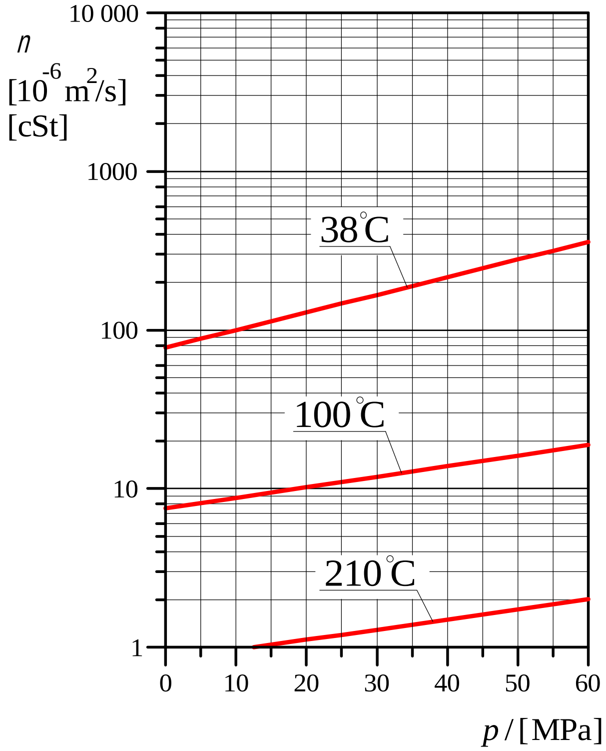
Unit [m^2/s]

1 cSt = 10^{-6} m^2/s

Temperature and pressure dependence of viscosity

Kinematic viscosity





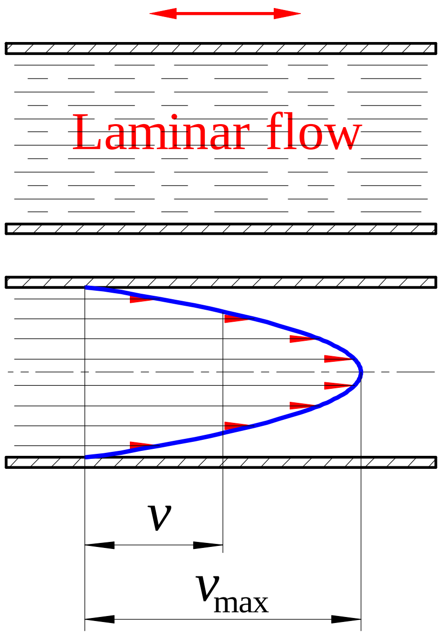
Impact of viscosity

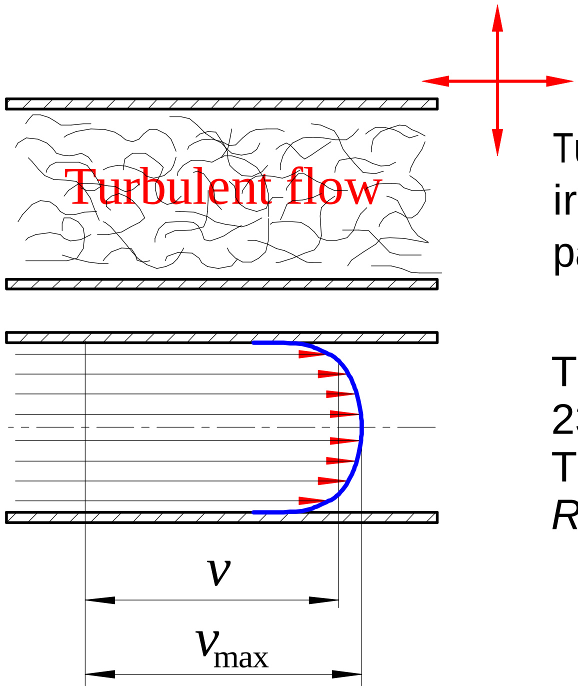
Viscosity affects

- flow induced resistance inside the system
- internal and external leaks of the system
  ® system efficiency
- lubrication of components
  ® reliability and life span of the system

Flow and flow types

Laminar flow
fluid moves
in layers





Turbulent flow
irregular movement of
particles (chaotic)

Laminar when
Re < 2300

Transitional flow
2300 < *Re* < 4000
Turbulent flow
Re > 4000

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

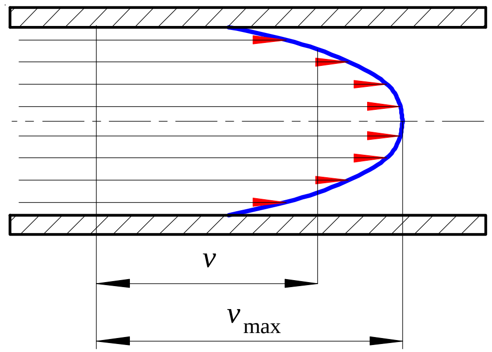
In laminar pipe flow
$v_{average} = 1/2 v_{max}$
Parabolic velocity
profile

Reynolds number $Re = \frac{v \cdot D_H}{\nu}$

- mean velocity
- (hydraulic) diameter
- kinematic viscosity

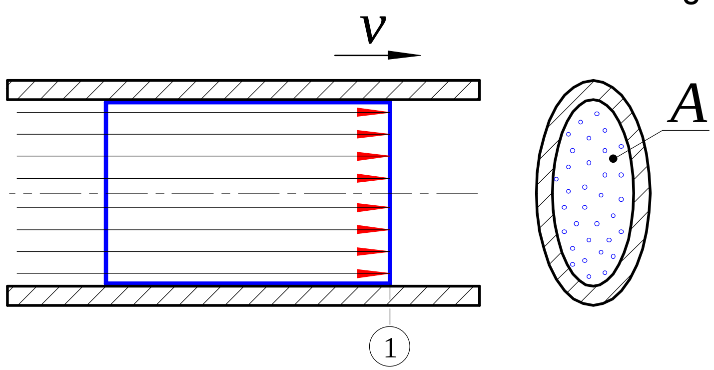
Flow rate

Actual flow profile



Simplified flow profile

Plug flow



$$\Delta V = A \cdot l = A \cdot v \cdot \Delta t$$

$$\frac{dV}{dt} = \dot{V} = A \cdot v$$

$$q_V = A \cdot v$$

Flow rate and average flow velocity

Continuity equation

Simplifying assumption

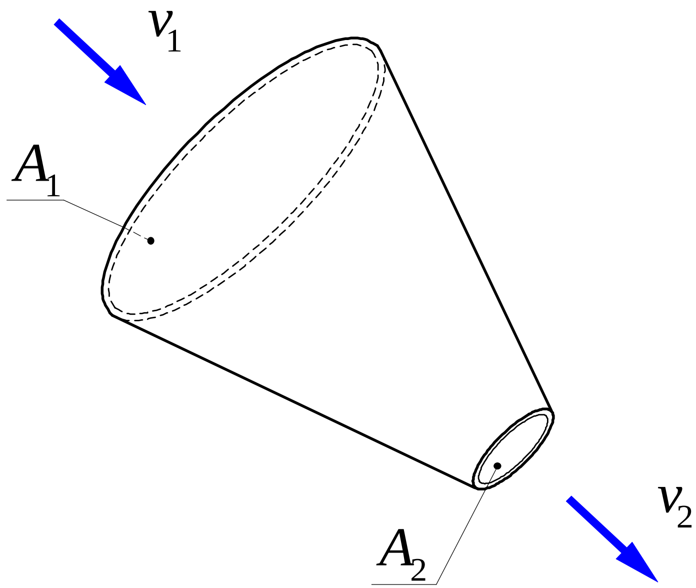
$$\dot{m} = \frac{\mathrm{d}m}{\mathrm{d}t} = \text{constant}$$

If density does not change

$$q_\mathrm{V} = A_1 \cdot v_1 = A_2 \cdot v_2$$

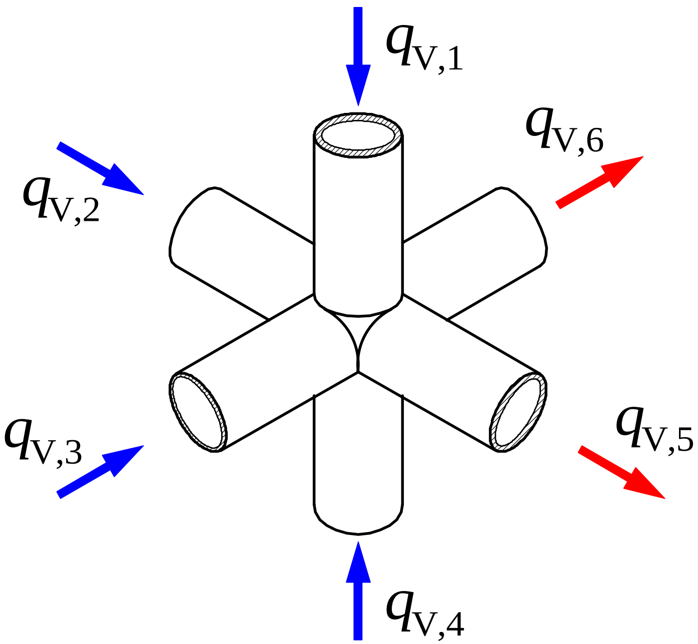
Unit [m^3/s]

1 l/min = 1/60000 m^3/s Engineering unit [l/min]



In reality: $q_\mathrm{m} = \rho \cdot \dot{V} + V \cdot \dot{\rho}$ mass flow rate

Division and joining of flow



We assume that the volume of intersection is zero ⇒ no fluid is stored in it.

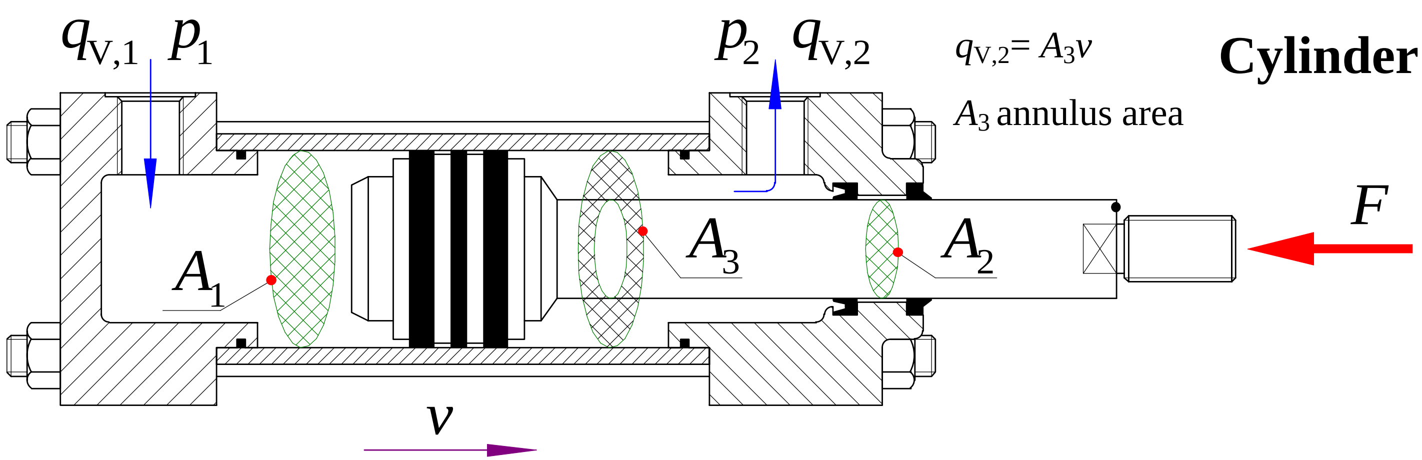
Fluid can be "stored" in "volumes" like pipes, cylinder chambers and accumulators ⇒ the amount of fluid stored affects the pressure.

Kirchhoff's I law

$$q_{V,1} + q_{V,2} + q_{V,3} + q_{V,4} = q_{V,5} + q_{V,6}$$

Flow: An application example

Stationary flow case:
- flow rate does not change
- piston velocity does not change
- pressures (p_1, p_2) do not change



Continuity equation

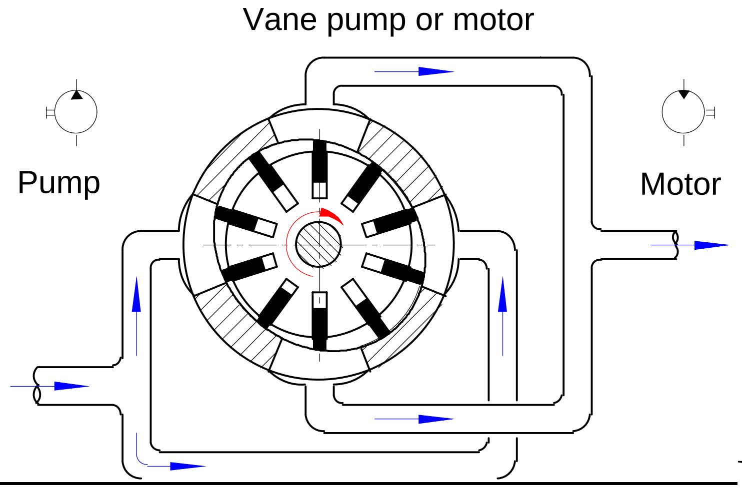
$$q_{V,1} = A_1 v$$

Flow demand

$$q_{V,1} = A_1 v$$

What will happen if $q_{V,1}\ ^{1}\ A_1 v$?

Flow rate: An application example



Pump

Motor

Produced flow —— Flow demand

$$q_{V,p} = n_p \times V_{g,p}$$

$$q_{V,m} = n_m \times V_{g,m}$$

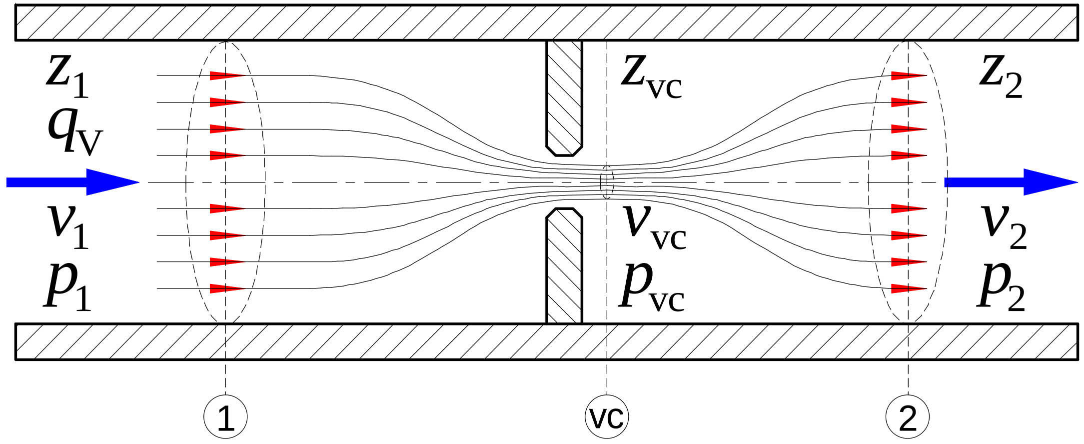
1. Rotational speed
2. Swept volume (displacement)

No leakage! Theoretical!

Energy equation

Flow through orifice

Flow rate remains the same



VC - Vena Contracta

Bernoulli: $p + \rho \cdot g \cdot z + \frac{\rho \cdot v^2}{2} = \text{constant}$

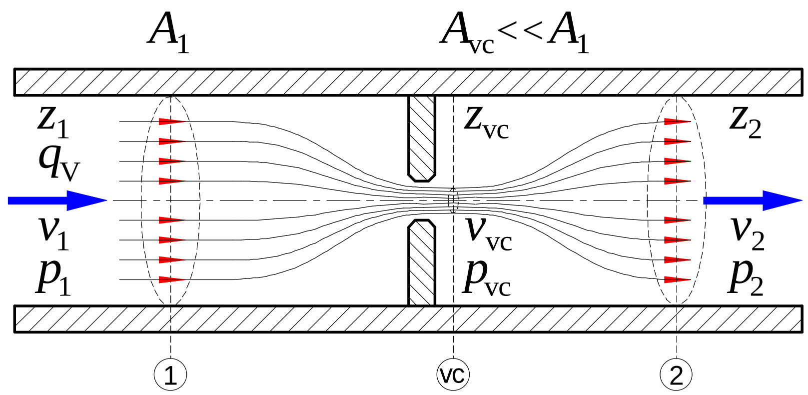
- static
- hydrostatic
- dynamic

vc =

vena contracta

diameter of flow

is the least



Using observation points 1 and vc:

$$p_1 + \rho \cdot g \cdot z_1 + \frac{\rho \cdot v_1^2}{2} = p_{vc} + \rho \cdot g \cdot z_{vc} + \frac{\rho \cdot v_{vc}^2}{2}$$

Simplification $\rightarrow$ $p_1 = p_{vc} + \frac{\rho \cdot v_{vc}^2}{2}$

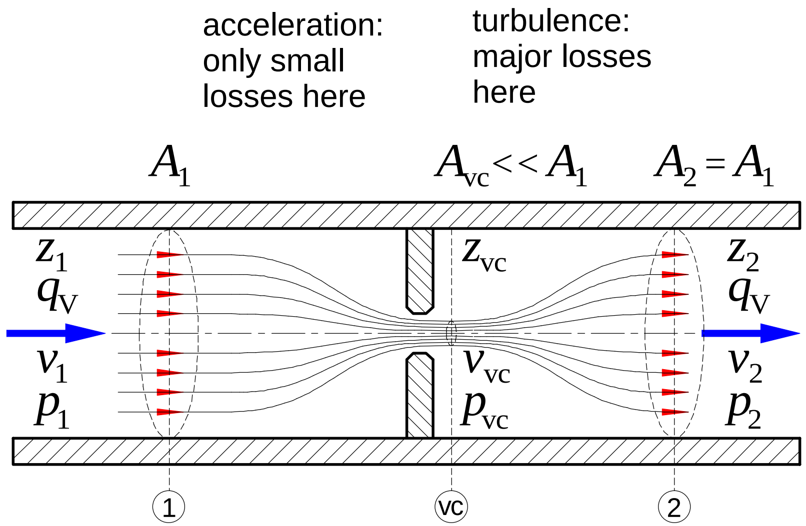
v_1 is small compared with v_{vc} also squared!

$\Rightarrow$ p_{vc} must be smaller

$$p_1 = p_{vc} + \frac{\rho \cdot v_{vc}^2}{2}$$

Flow velocity
in vena contracta

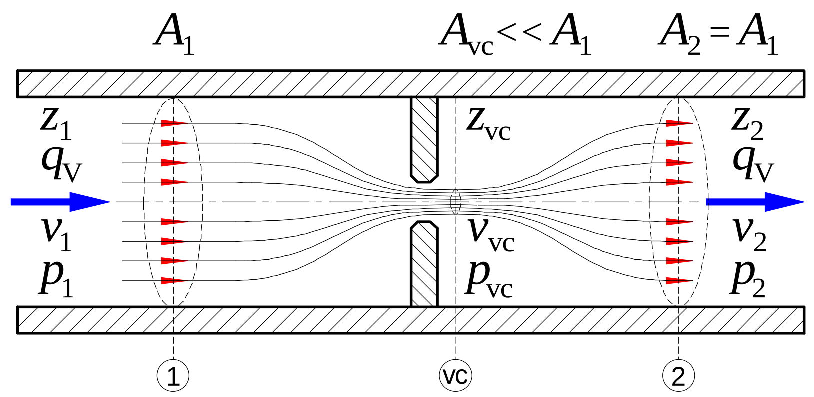
$$\Rightarrow \quad v_{vc} = \sqrt{\frac{2 \cdot (p_1 - p_{vc})}{\rho}}$$



Flow rate $\quad q_V = A \cdot v$

$$\Rightarrow \quad q_{Vvc} = A_{vc} \cdot \sqrt{\frac{2 \cdot (p_1 - p_{vc})}{\rho}}$$

$$q_{Vvc} = A_{vc} \cdot \sqrt{\frac{2 \cdot (p_1 - p_{vc})}{\rho}}$$



Point of vena contracta is difficult to measure

- transfer latter observation point (vc) to point 2, much more meaningful
- change requires a correction factor C_q to the equation

$$\rightarrow \qquad q_V = C_q \cdot A \cdot \sqrt{\frac{2 \cdot (p_1 - p_2)}{\rho}}$$

Denote $\Delta p = p_1 - p_2$

$$\rightarrow \qquad q_V = C_q \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

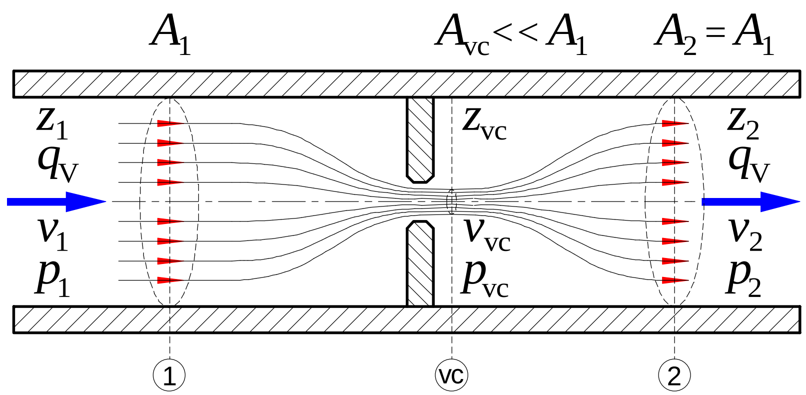
Flow coefficient C_q

According to Bernoulli $p + \rho \cdot g \cdot z + \frac{\rho \cdot v^2}{2} = \text{constant}$

pressures $p_1 = p_2$, since flow channel properties in observation points 1 and 2 are equivalent

, so why Δp?

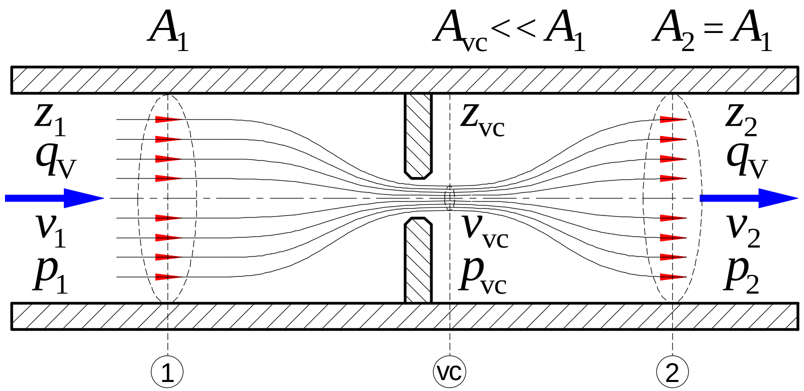
Static pressure p does not normalize (reach its original value) after energy conversion although flow channel properties normalize



An energy loss takes place and is manifested as pressure loss Δp

$$\Rightarrow \quad p_1 + \rho \cdot g \cdot z_1 + \frac{\rho \cdot v_1^2}{2} = p_2 + \rho \cdot g \cdot z_2 + \frac{\rho \cdot v_2^2}{2} + \Delta p$$

Energy equation

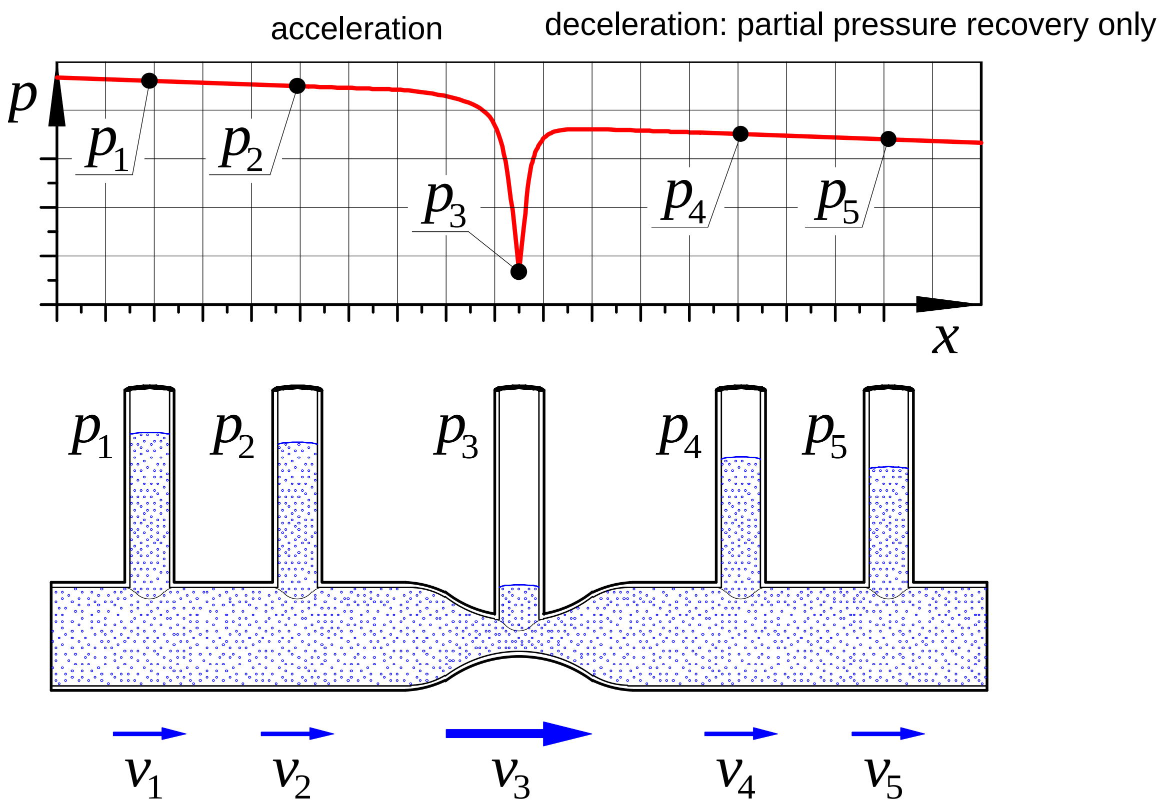


$$p_1 + \rho \cdot g \cdot z_1 + \frac{\rho \cdot v_1^2}{2} = p_2 + \rho \cdot g \cdot z_2 + \frac{\rho \cdot v_2^2}{2} + \Delta p$$

In hydrostatic systems the heads of elevation and flow velocities are typically low

$\rightarrow \quad p_1 = p_2 + \Delta p \quad$ or $\quad p_1 = p_2 + p_s$

Interconnectedness of pressure and flow

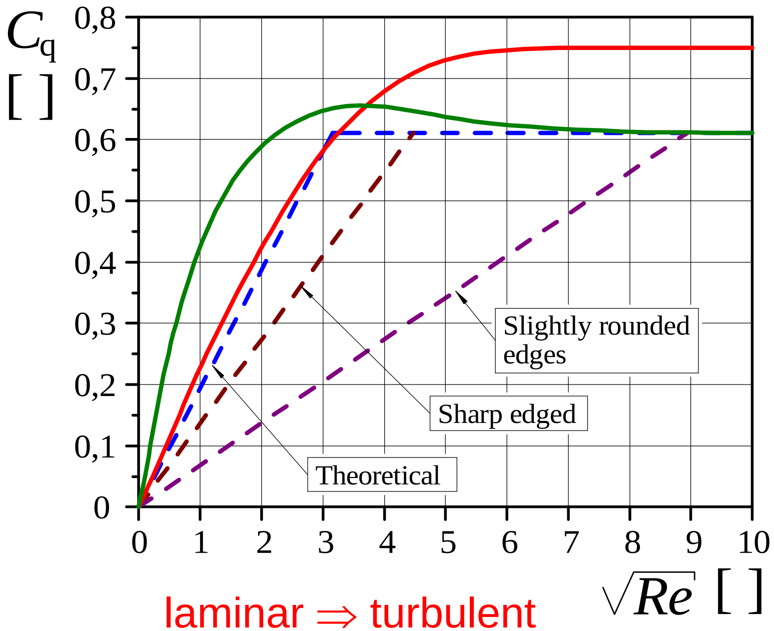


$$p_1 = p_2 + \Delta p$$

$$(\Delta p = p_1 - p_2)$$

Pressure losses in
- pipes
- orifice

At small velocities (pressure differences) also orifice flow is laminar.



$$Re = \frac{vD_h}{\nu}$$

laminar ⇒ turbulent

Flow coefficient C_q

Theoretical value 0,611

$$q_V = C_q \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

laminar flow

$\Delta p \propto \eta v$ to the 1st power of *v*

turbulent flow

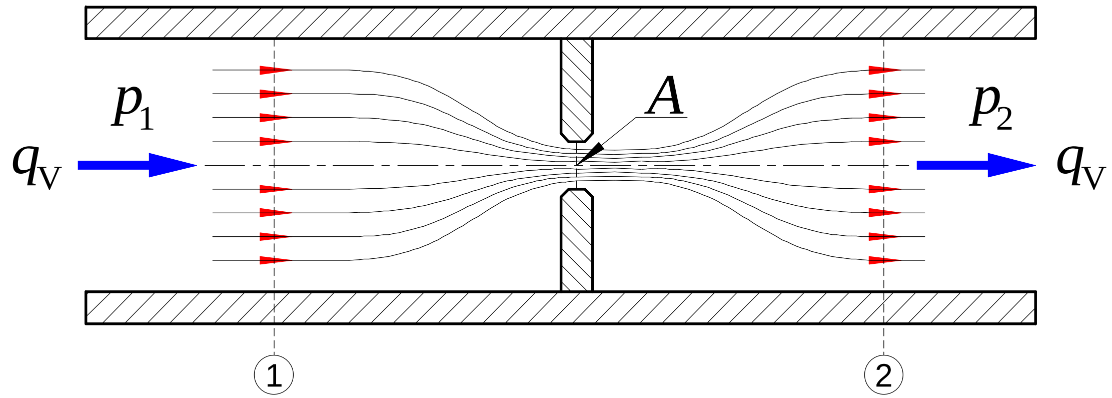
$\Delta p \propto 1/2 \rho v^2$ to the 2nd power of *v*

Flow coefficient $C_q \neq$ Discharge coefficient C_d

Flow coefficient $C_q \approx$ Velocity coefficient $C_v \cdot$ Contraction coefficient C_c

Actual velocity of Jet / Theoretical velocity   Area of Jet / Area of Orifice

So,



Pressure difference induces flow

$$q_V = C_q \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

⇔

(Flow induces pressure difference)

$$\Delta p = \frac{\rho}{2} \cdot \left(\frac{q_V}{C_q \cdot A} \right)^2$$

$1/2\rho v^2$ included

(dynamic pressure)

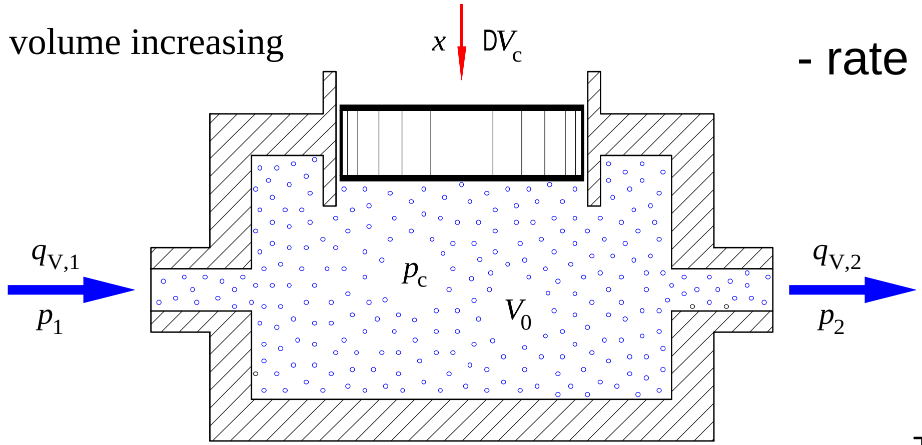
Flow and pressure in volume

Pressure induced by flow into and out of a volume

Two mechanisms to change pressure
- net flow rate $\neq 0$
- rate of change of volume $\neq 0$

$\Delta V_C > 0 \Rightarrow$ volume increasing

Throttle restricting the inflow



Throttle restricting the outflow

Thermal expansion coefficient $\approx 0.7 \cdot 10^{-3}$ 1/K (mineral oil)

Time derivative of pressure: "how fast does the pressure change" [Pa/s]

Pressure generated in volume

$$\dot{p} = \frac{K_e}{V_{0,c}} \cdot \left[\sum q_V - \dot{V}_c \right]$$

hydraulic stiffness

Integrate this to get the pressure changes

K_f bulk modulus of fluid [Pa]

V_0 fluid volume [m^3]

Fluid properties

Where do we need the information?

Density	turbulent pressure losses in orifices and losses in pipes
Viscosity	leakage, lubrication, laminar flow pressure losses
Bulk modulus	hydraulic stiffness, mechanical stiffness

Lecture themes - Recap

Do the fluid properties have impact on the system?

Flow rate, from where?

Is there any use for flow rate?

Interconnection between flow and pressure,
does it exist?