Aalto-yliopisto
Sähkötekniikan korkeakoulu

Flow rate measurement

ELEC-E5710 Sensors and Measurement Methods

Why is flow rate measurement needed?

- Provides knowledge required in industry and municipal engineering
- Knowing momentary flow rate of gases and liquids
  - Essential for process control, optimization and security
- Knowing the time integral of a flow rate which is the amount passing through
  - Important to balance calculations in facilities and subprojects

Basic concepts of fluid mechanics

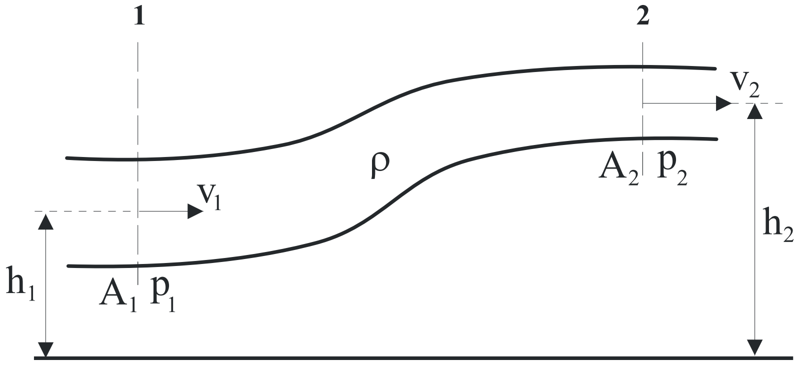
- Flowing can be divided in several different ways
  - Frictionless (ideal fluid) and frictioned flow
  - Laminar and turbulent
  - Compressible and incompressible
- Important properties of the measured medium:
  - viscosity, temperature, pressure, corrosiveness, solid particles

Basic concepts of fluid mechanics

1. Flow rate $q = \frac{dx}{dt}$
2. Volume flow rate $q_v = q \cdot A = \frac{dV}{dt}$
3. Mass flow rate $q_m = \rho q_v = \frac{dm}{dt}$

- Conservation of energy applied to fluid mechanics is called Bernoulli's principle:

$$\rho g h + p + \frac{1}{2}\rho v^2 = \text{constant}$$



- Volume flow rate continuity:

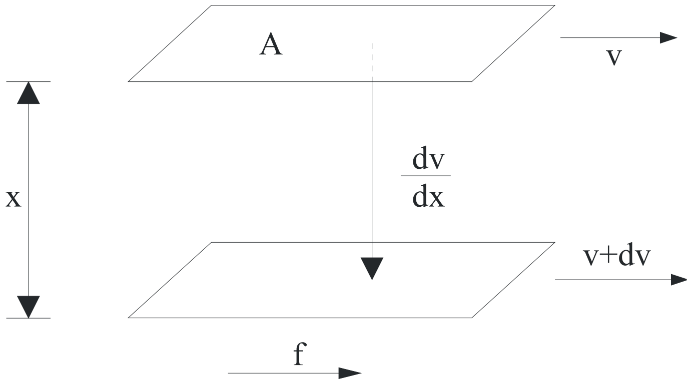
$$A_1 v_1 = A_2 v_2$$

Basic concepts of fluid mechanics

- Viscosity μ represents the internal friction of the material which is generated by velocity gradients in the observed system

- Force maintaining the velocity gradient $f = \mu A \left(\frac{dv}{dx}\right)$

  A = area of the intersecting layers
  dv/dx = velocity gradient

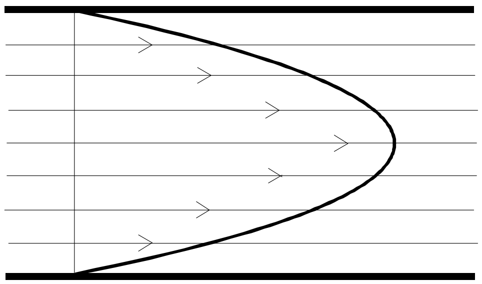


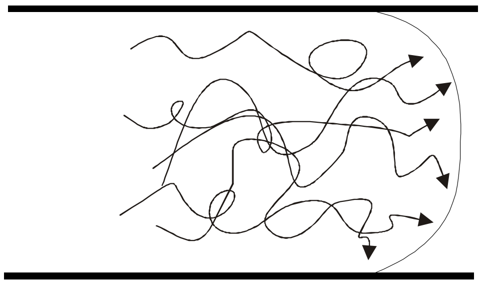
- SI unit of the viscosity
  $Ns/m^2 = Pa \cdot s$

- Small viscosity – well running material
  - E.g. viscosity of water: 1.0 mPa·s, lubricating oil: 1000–3000 mPa·s

Basic concepts of fluid mechanics

- Laminar flow
  - Particles move parallel
  - Slower movement on the sides
    - Profile of the flow rate
- Turbulent flow
  - Turbulence in the flowing material
  - Disturbs several measuring instruments





Basic concepts of fluid mechanics

- Reynolds number = inertial force of mass / viscous force

$$\mathrm{Re} = \frac{\rho v_s^2 / L}{\mu v_s / L^2} = \frac{\rho v_s L}{\mu}$$

v_s average flow rate

L specific length of the flow e.g. diameter of a circular tube

μ viscosity of the flow medium (=friction)

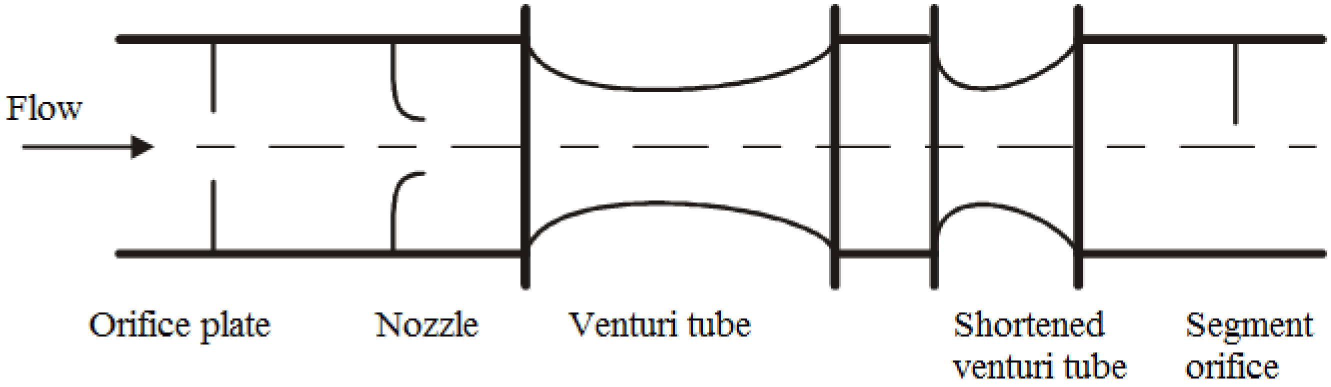
ρ density of the flow medium

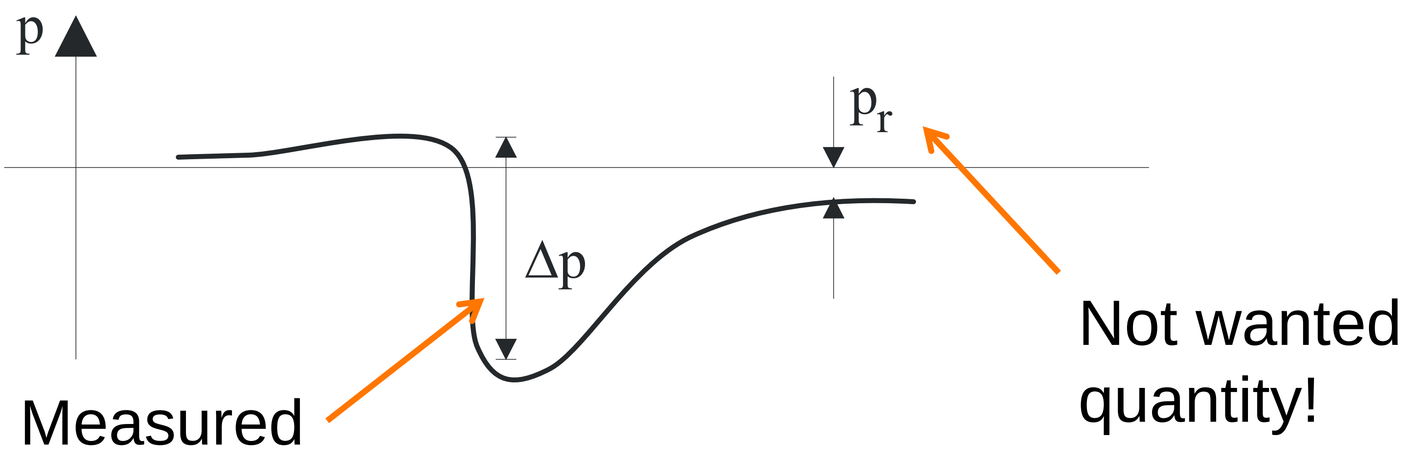
- With small Re the flow is laminar
- The transition from laminar to turbulent flow is indicated with a critical Re
- Re_{crit} depends on the flow configuration. In a tube, with circular cross section, Re_{crit} = 2300

Meters for pressure difference

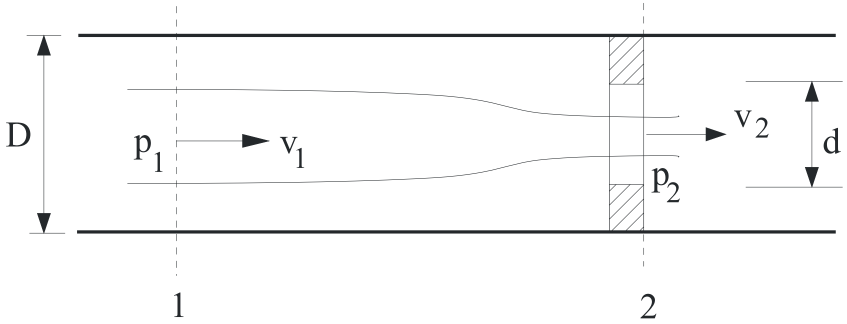
- Most common type of flow rate meters
- Very suitable for measuring the flow of liquids, gases and steams
- Can be divided into two classes:
  - Meters based on throttling device
    - Orifice plate
    - Flow nozzle
    - Venturi tube
  - Meters based on stagnation pressure
    - Pitot tube
    - Target flow measurement

Throttling device





Throttling device



Bernoulli's principle: $p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$

Continuity of the flow rate: $q_v = \frac{1}{4}\pi D^2 v_1 = \frac{1}{4}\pi d^2 v_2$

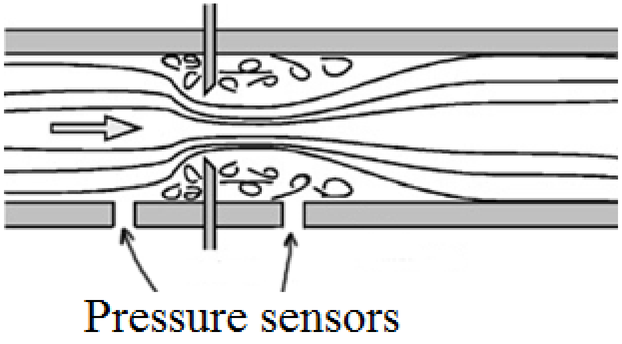
$$\Rightarrow v_1 = \sqrt{\frac{2\Delta p}{\rho[(D/d)^4 - 1]}}$$

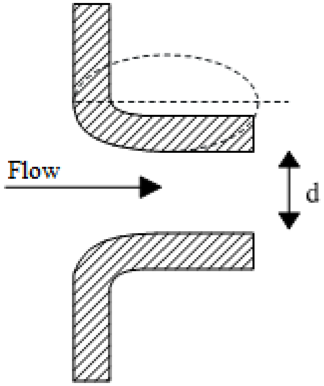
$$q_v = \frac{1}{4}\pi D^2 \sqrt{\frac{2\Delta p}{\rho[(D/d)^4 - 1]}} = \pi E D^2 \beta^2 \sqrt{\frac{\Delta p}{8\rho}},$$

where $E = \frac{1}{\sqrt{1-\beta^4}}$ is approaching factor, and $\beta = \frac{d}{D}$

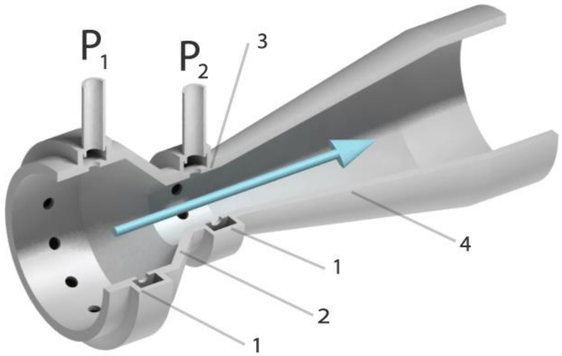
Throttling devices

- Orifice
  - The most common throttling device
  - Inexpensive, plenty of experience using it in practice
  - Can be manufactured from several different materials
    - Also for corrosive materials
  - Not suitable for fluids with large impurities
    - Risk of blocking the flow
- Nozzle
  - Advantages compared to orifice:
    - Smaller p_r
    - Lower risk of blocking the flow

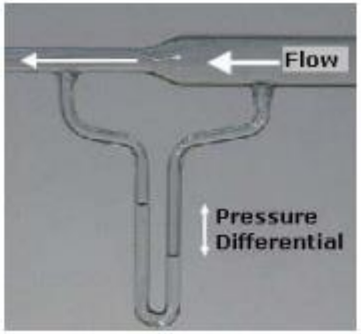


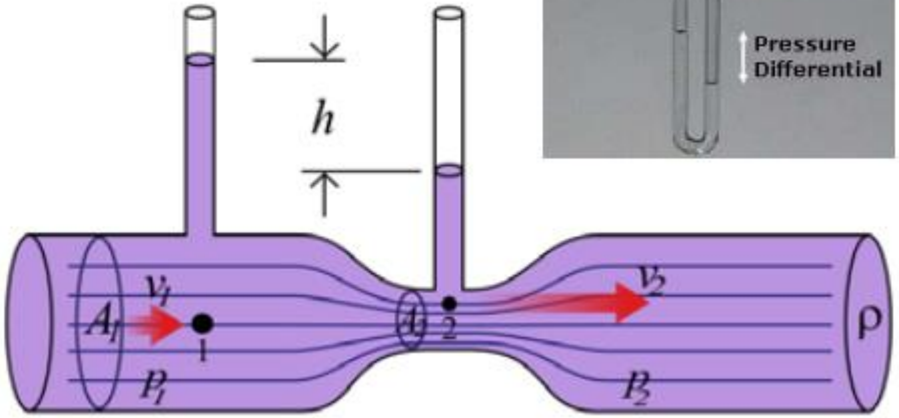


Venturi tube



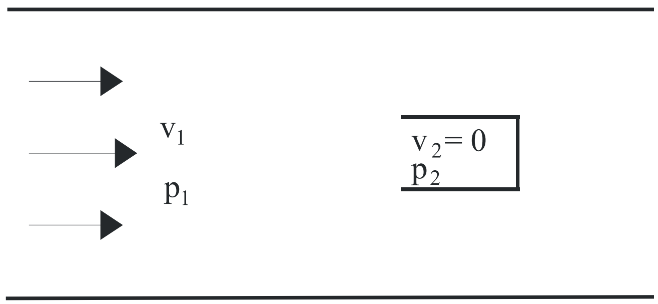
- Smaller decrease in total pressure than in the case of orifices or nozzles
- Large size
  – Entry cone taper 30°, exit cone taper 5°
  – Often a shortened version is used ("Dall tube")
- expensive





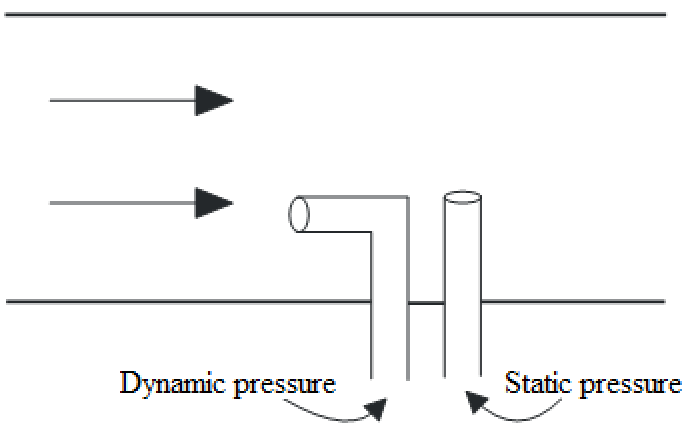
Stagnation pressure meters

- An obstacle, which has one end closed, is placed inside a linepipe
- Inside the tube shaped obstacle, there is a flow rate $v_2 = 0$
  - Dynamic pressure i.e. stagnation pressure: $p_2 = p_1 + \frac{1}{2}\rho {v_1}^2$
  - Flow rate: $v_1 = \sqrt{\frac{2}{\rho}\Delta p}$



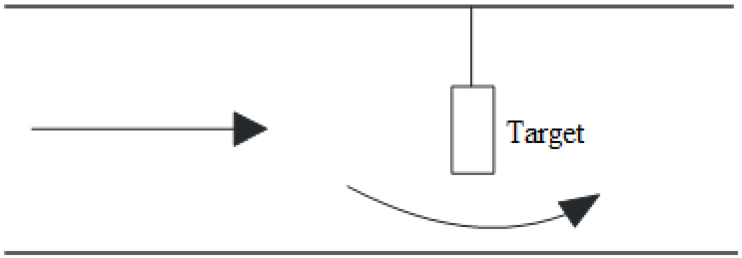
Pitot tube

- Measures both dynamic and static pressure caused by a flow
- In industry, it is used to measure pure liquids and gases. It can also be used to measure the air flow rate of airplanes



Target flow measurement

- A flow applies a force to a target and this force is measured
- Force applied to target: $F = pA = \frac{1}{2} kA\rho v^2$
  - k is the shape factor of the target, A is the area of the target
- Flows going either way can be measured
- On the other hand, it is sensitive to vibrations and shocks
- Most suitable for measuring pure liquids and gases
- Inaccuracy about ± 3 %.

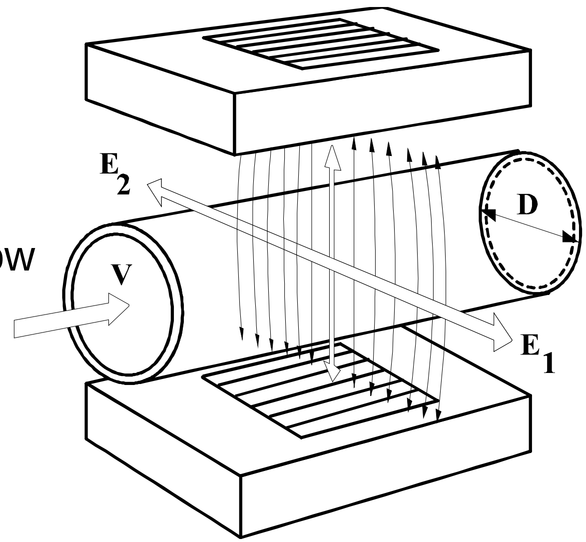


Magnetic flow rate measurement

- An induced voltage E is created in a magnetic field due to a conductive liquid moving
- If the electrodes, magnetic field and the flow channel are perpendicular:

$$E = vBD$$

- Voltage is small (mV), protection against interference is important
- Due to electrochemical potentials an alternating magnetic field is used
- Independent on the density, viscosity, temperature and flow rate profile of the measured liquid
- Does not contain moving parts → durable
- Does not disturb the flow
- Expensive
- Suitable only for conductive liquids: conductivity > 5 mS/cm



Measuring mass flow rate

- Mass flow rate can be measured with a volume flow rate meter:

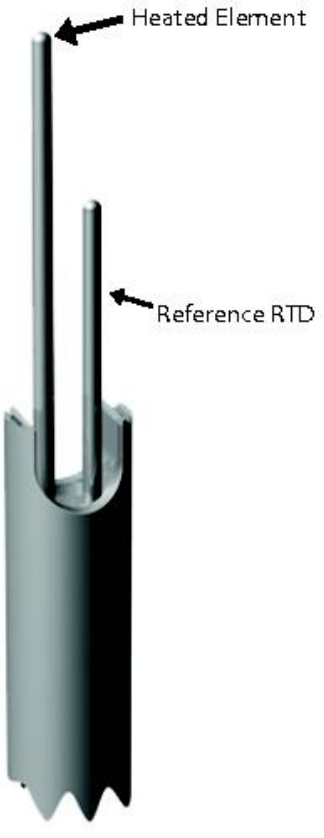
$$m = V\rho$$

  - When a constant density is assumed

- If the density of the measured medium is not constant or it contains air bubbles, the mass flow rate measured with a volume flow rate meter is not reliable!

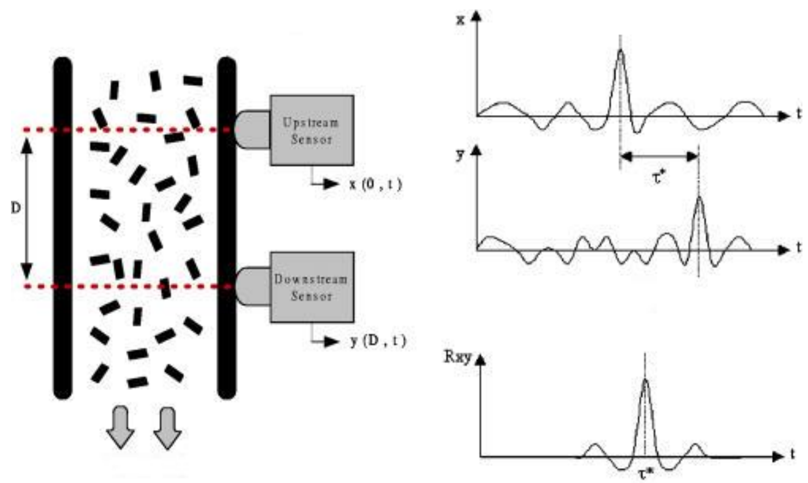
Thermic methods

- Based on a cooling effect of a flow
- A thin heated wire or film loses part of its heat to a flow
- Temperature is measured resistively and another sensor measures the temperature of the flow
- Low response time and high sensitivity
  - Suitable for measuring slow flows
- Impurities in a flow damage wires
- Applied to gas flow measurements



Cross correlation flow meter

- Based on measuring the transition time of particles flowing in a channel between two sensors
- Measuring quantity may be e.g. optical or ultrasound
  - Does not disturb the flow at all!
- Other quantities are possible too
- Suitable for measuring solid mediums because there is no need to place additional obstacles to the flowing channel



About the accuracy of flow rate measurements

- Effect of the installation point
  - A flow stabilizes after a long and straight tube
- Changes
  - Density (non-uniform material), velocity distribution
  - Electric conductivity
  - Temperature distribution (thermal expansion of the tube)
  - Flow circumstances (roughness of the surface, critical dimensions of the pressure difference instrument)
- Measured material is always different compared to material used in calibration
- Pressure variation must be considered in gas measurements

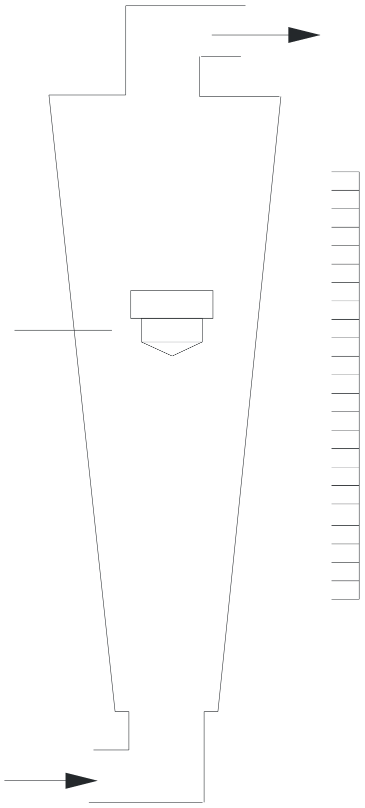
Flow rate meters with changing aperture

- Revision: aperture size of the throttling device is constant in pressure difference meters; flow rate is determined with the pressure difference between the entry and exit side
- In meters with changing aperture, the pressure stays roughly the same. The flow rate determines the aperture size

Rotameter

- Glass or metal
- Scale on the wall of a glass tube rotameter, in the case of metal rotameter scale can be e.g. magnetic
- Does not require expensive equipment → inexpensive meter
- Suitable for liquids and gases
- Also suitable for slow flows
- Movement of the float must be attenuated if the flow has much variation

Floating level sensor



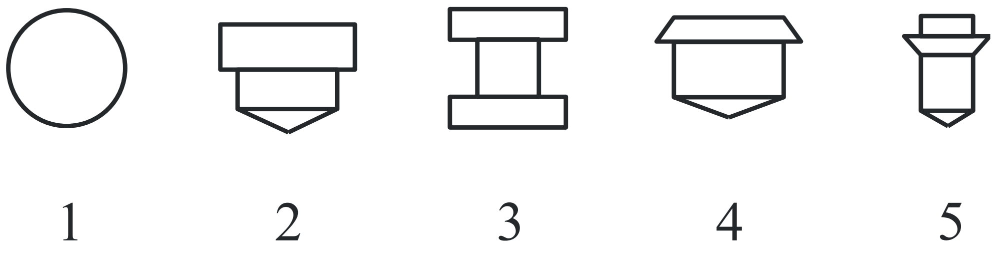
Rotameter – the shape of the float

- The shape of the float strongly affects its properties:

1. Easy to manufacture → used in small rotameters
2. General float, cone head → very durable
3. For small flows
4. Low sensitivity to viscosity
5. Sensitive to changes in viscosity

   → used as a viscosity sensor when the flow rate is constant

   → scale must be produced to each measured material



Volume counters

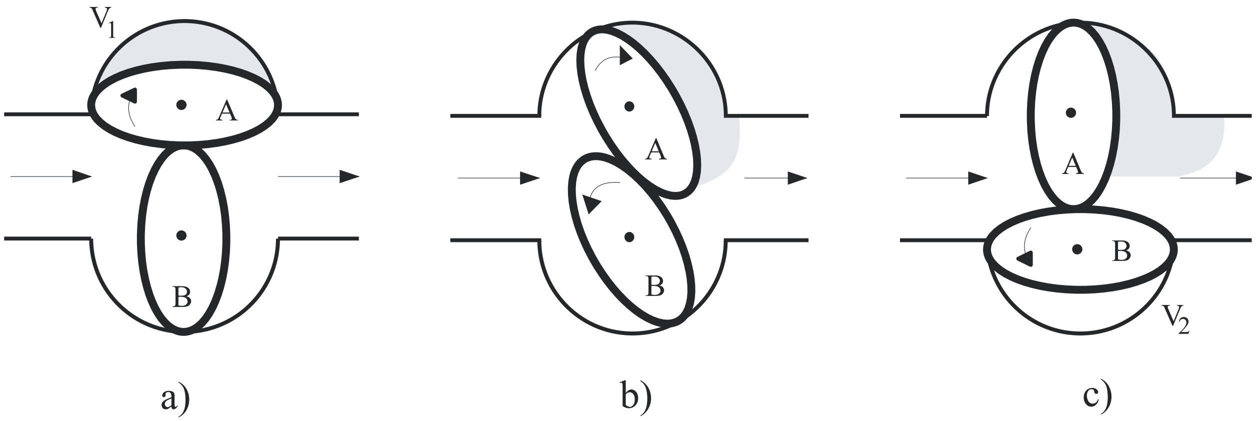
- Used in flow rate measurements of liquids
- Good accuracy

  → Used to calibrate other flow rate meters

- Trivial example: a bucket and a stopwatch

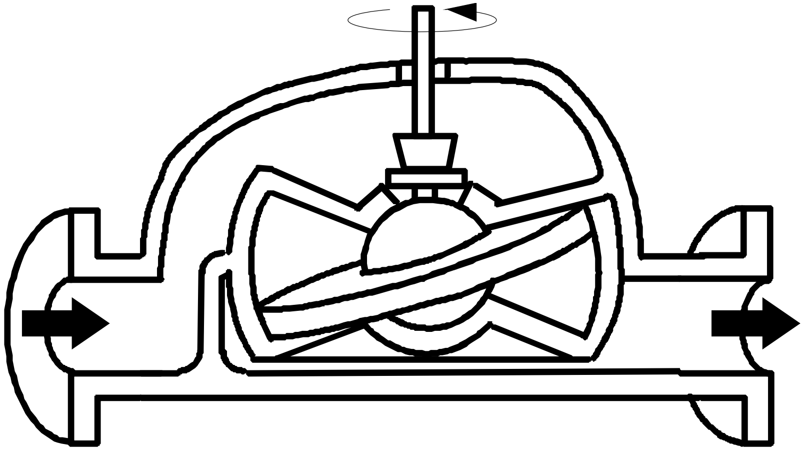
Oval wheel flow meter

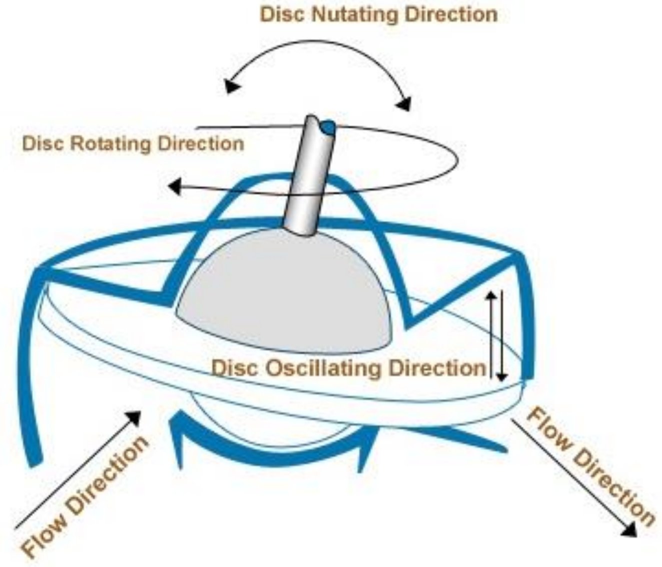
- Oval shaped cogwheels spin due to pressure difference between the entry and the exit side
- As the cogwheels spins 180°, a volume V_1+V_2 of liquid has passed through the meter
- On the negative side: sensitive to impurity particles
- Error about 0,5 %



Mutating disc flow meter

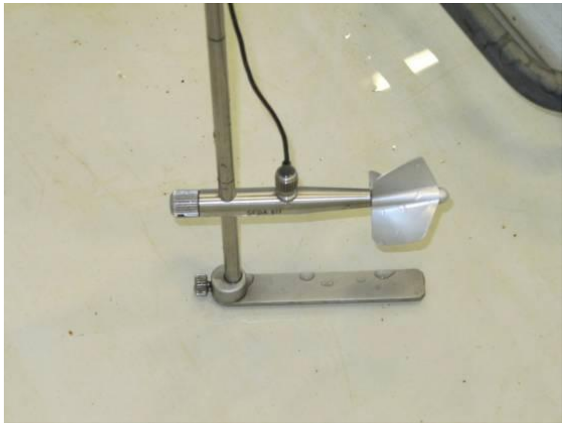
- Used as household water flow meters
- Pressure difference between the inlet and the exit side forces a circular disc to move
- A constant volume of liquid passes through the meter during every spin





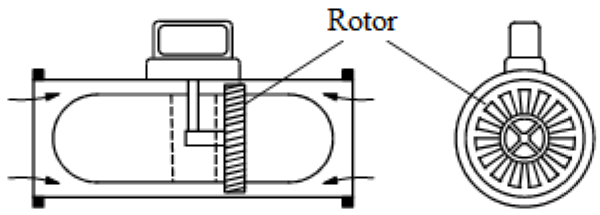
Current meter

- A rotor which contains as frictionless as possible bearing. A flow forces the rotor to rotate
- The speed of rotation of the rotor is proportional to flow rate
- The movement of the current meter is transferred electrically or mechanically to a counter

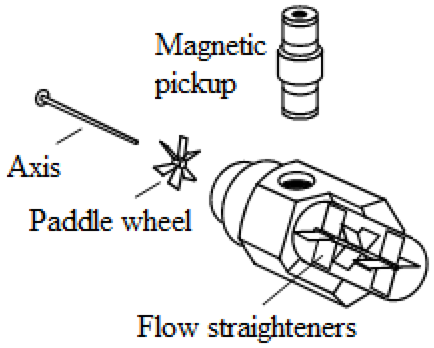


Turbine meter

- The most common type of current meters
- Specific models for gases and liquids
- Error is in the case of liquids about 0,3 %, and gases 1 %
- Turbulences may cause an error of several percent
- Contamination → suitable only for pure flows
- Fast response time → flow rate can change rapidly



Gas turbine meter



Liquid turbine meter (flow straighteners remove turbulences from the flow)

Blade wheel counter

- Commonly used in water measurements
- Flow rate is determined from the speed of rotation
- Error about 2 %