Industrial Control - Flow measurement

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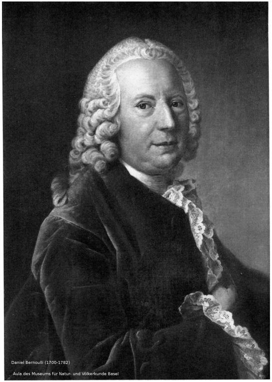
MŰEGYETEM 1782

Two lectures

Objectives of the lectures

1. Present the flow metering applications and related industrial practice.
2. Describe the quantities related to flows and fluids.
3. Understand the features determining the behavior of flowing material, study the major laws predicting the flow (viscosity, Reynolds number, Newton's viscosity law, continuity law, Bernoulli law)
4. Explain the measurement principles, their advantages and disadvantages and the conditions of their applicability.

Contents



Daniel Bernoulli (1700-1782)

Contents

Introduction

Material transfer

1. high pressure steam to turbine
2. liquid oxygen/natural gas into pipeline system/reservoir
3. blood, solutions for therapy
4. crude oil to refinery
5. fuel/gas to engine
6. beer/wine/whiskey for bottling

Measurement of flow is required

1. for accounting
2. for control and regulation
3. for monitoring

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Introduction

What is required to determine the flow?

Specific flow conditions + Measurement principle + Calculations

Flow conditions depend on

- fluid (water, oil, natural gas, steam, beer, etc.) characteristics (viscosity, density)
- environmental conditions (pressure, temperature)
- mechanical configuration around the fluid (pipe geometry, pipe surface ruggedness, orifices)
- interaction of the above features (temperature dependent viscosity, flow profile depending on surface quality, etc.)

Remark

For simplicity: we consider flow in pipes (almost) exclusively.

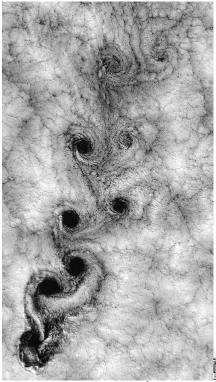
Introduction

What is required to determine the flow?

Specific flow conditions + Measurement principle + Calculations

Measurement principle

- Volume displacement meters
- Pressure difference (DP)
- Temperature difference (DT)
- Phase difference in vibration
- Frequency difference (DF)
- Vortex count
- Doppler shift
- etc.



Introduction

What is required to determine the flow?

Specific flow conditions + Measurement principle + Calculations

Results of calculations

- instantaneous volumetric flow rate over the given pipe cross section $[m^3/h]$
- instantaneous mass flow rate over the given pipe cross section $[kg/s]$
- instantaneous density inside a pipe cross section $[kg/m^3]$
- instantaneous fluid velocity $[m/s]$
- totalized volume flown over a cross section $[m^3]$
- totalized mass flown over a cross section $[kg]$

Calculations depend on the measurement principles and apply under some flow conditions.

Introduction

1. The volume of compressible fluids (hence the volumetric flow) is specified at standard pressure and temperature (STP) in so called normal cubic meters (Nm^3).
2. The STP values are specified in standards which may be different for different organizations and/or countries. The value in Nm^3 has no meaning if it is not paired with STP.
3. For a given meter, the STP values must be verified and set according to the metering contract/location as calculations may be different for different markets, countries and regions.
4. The gas technological normal state in Hungary is (MSZ2373 and ISO13443): 101325 Pa (1 atm) and 288,15 K (15°C - world average temperature) - the heating value of a cubic meter of natural gas is also given for that value (e.g. in natural gas service contracts).
5. STP according to IUPAC: 100000 Pa and 0°C
6. STP according to NIST (USA): 101325 Pa and 20°C

Introduction

Market size of flow sensors

- Report from 2020.
- Intelligent meter: sensors + embedded processing electronics
- Global market in 2020: 7030 M USD
- An average of 7.2% growth rate during the years 2021-2027
- Region with the highest expected growth rate: APAC
- Measurement principle with the highest expected growth rate: ultrasonic, vortex, Coriolis

Contents

Description of flowing fluid

Physical quantities 1

- v - flow speed $[m/s]$
- ρ - density $[kg/m^3]$

Physical quantities 2

- p - pressure $[Pa = \frac{N}{m^2} = \frac{kg}{m \cdot s^2}]$
- T - temperature $[°C]$

Remarks

- Fluid mechanics is the branch of physics that studies the mechanics of fluids (liquids, gases, and plasmas) and their behavior if forces are applied.
- Fluid mechanics also deals with the interactions between the fluid and the border elements constraining the flow (pipe wall, wing, orifice plate, etc.).
- In a given flow configuration and in the general case v, ρ, p, T are both time and location dependent.

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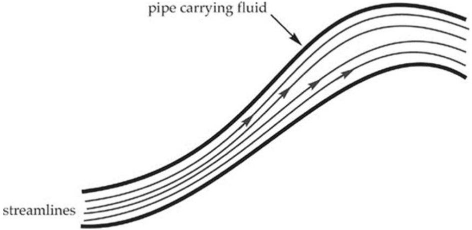
Description of the flow

Static flow

v, ρ, p, T are steady in time (may still vary depending on the location).



Flow of incompressible fluids

A fluid is incompressible if its density is constant in the volume considered, hence $\frac{D\rho}{Dt} = 0$ (total derivative as ρ may depend on T and p).

Mass conservation law

Formulation with words

Mass cannot be created and it cannot disappear. Considering a volume V delimited by the surface A, the density changes because of the difference of quantities flowing in and out. (The density of incompressible fluids cannot change, hence the inflow and outflow are identical.)

Formulation with equation

Observe that the quantity flowing across an infinitesimal surface dA can be calculated as $\rho \cdot v \cdot dA$. Then

$$-\int_V \frac{\partial \rho}{\partial t} dV = \int_A \rho \cdot v \cdot dA$$

Its differential form reads

$$\frac{D\rho}{Dt} + \rho \nabla v = 0$$

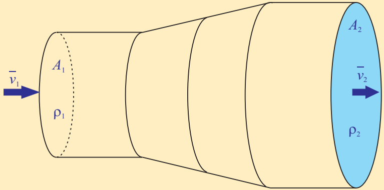
Mass conservation law

Mass conservation

From the previous slide:

$$-\int_V \frac{\partial \rho}{\partial t} dV = \int_A \rho \cdot v \cdot dA$$

In a pipe width changing diameter



(diffusor element)

Supposition

The average velocities on the inflow and outflow surfaces are $\bar{v}_1$ and $\bar{v}_2$, respectively. The flow is stationary.

Mass conservation in the pipe

Let us examine the pipe section between the surfaces A_1 and A_2. In this case $\rho_1 \bar{v}_1 A_1 = \rho_2 \bar{v}_2 A_2$

Corollary ($A_i = r_i^2 \pi$)

For incompressible fluids, the flow velocity changes as the square of the pipeline diameters: $\bar{v}_2 = \bar{v}_1 \frac{D_1^2}{D_2^2}$

Rigid bodies and fluids: an important difference

Friction and viscosity

- Shear stress (load) causes reversible deformation in the flexibility region for rigid bodies. The linear approximation to describe the relationship between the load and deformation is called the Hooke law, (with the Young modulus). This phenomenon is used to measure force and pressure. The Young modulus is characteristic to the stiffness of the material (it is a tensor in the general case).
- Fluids also deform but this deformation is not reversible. The stiffness of fluid is zero in general.
- For fluids, the relationship exists between the load and the **rate** of deformation (shear).

On border surfaces: sticking law

The relative velocity on the border surface between the rigid body (e.g. pipe wall) and the fluid is zero.

Newton's law of viscosity

Observation

- Water flows "better" compared to honey or toothpaste. The water said to be less viscous.
- Viscosity is different of density. (No flow is needed to define density.)

By words

Viscosity is the internal friction coefficient of a flowing fluid. The fluid "resists" against the relative velocity (shear) of its layers. This implies that the maintenance of flow requires external force as well.

Newton's law of viscosity

By expression

Suppose that the flow velocity of a fluid layer (of surface A) is v and the velocity changes in a direction perpendicular to it, denoted as y. To maintain the velocity gradient in the fluid, a force is required whose expression is

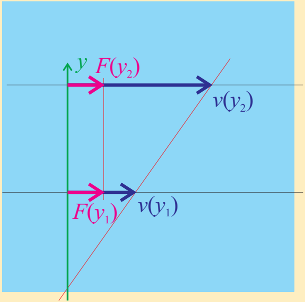
$$F = \mu A \frac{\partial v}{\partial y} \tag{1}$$

The coefficient μ is referred to as dynamical viscosity of the material.

Remark

The expression (1) is defined in laminar flow conditions

Illustration (1DOF)



Unit

The unit of the dynamic viscosity μ is $[kg/ms]$

Newton's law of viscosity

Remarks

This is a linear approximation. A fluid is said to be Newtonian if this linear approximation holds.

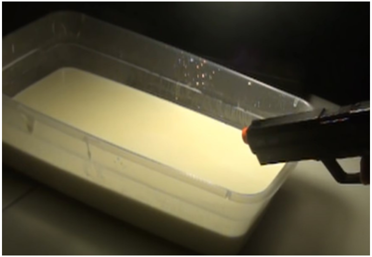
Kinematic viscosity

$$\nu = \frac{\mu}{\rho}$$

Its unit is m^2/s or St (Stokes).
$1\ St = 1cm^2/s$.

Fluidity

Fluidity is the reciprocal of viscosity.



Euler, Navier, Stokes and Bernoulli

Euler equation (frictionless and incompressible case)

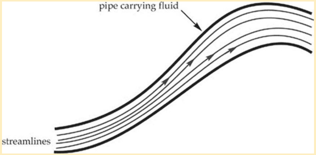
The friction is neglected, the fluid is incompressible. At a given point, the acceleration of the fluid depends on the pressure gradient and on the direction of some force field (if any, e.g. gravity field).

$$\frac{dv}{dt} = g - \frac{1}{\rho}\nabla p$$

Streamline

The streamline over a given point is the integral curve of the velocity field v, hence it is a line whose tangent vector coincides with the velocity vector of the fluid at that point.

Streamlines



Euler, Navier, Stokes and Bernoulli

Navier-Stokes equation (with friction, incompressible case)

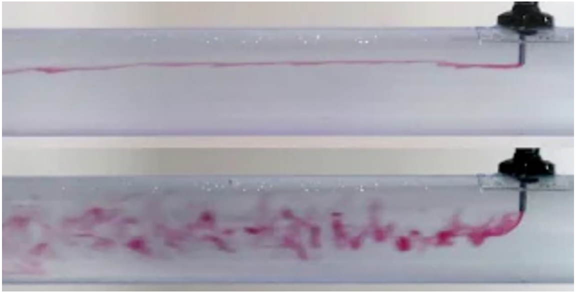
The fluid is incompressible. The acceleration of the fluid at a given point depends on the pressure gradient, on the external force field (e.g. gravity field) and on the velocity gradient.

$$\frac{dv}{dt} = g - \frac{1}{\rho}\nabla p + \nu \nabla^2 v$$

Remarks

1. As the speed increases, the flow becomes turbulent (irregular).
2. For regular flow, the viscous friction forces dominate and they obstruct the formation of turbulent flows (eddies).
3. Low velocity is preferred in industrial practice as turbulent flow causes losses and low velocity requires low power (cheaper) pumps.

Laminar and turbulent flow



- Friction losses are high in irregular flow hence such flow conditions are avoided in industrial practice.
- Some meters create eddies using some obstacles put into the way of the flow which create turbulent flow in a pipeline section on purpose.
- There is no stationary flow in the neighborhood of turbulent flow.
- Turbulent flow may be created at low flow velocity as well.

Reynolds number

By words

The Reynolds number is specific to a flow configuration and has no dimension. Its value tells the type of flow that can be expected for a given configuration: e.g. turbulent of laminar.

By expression (in pipes)

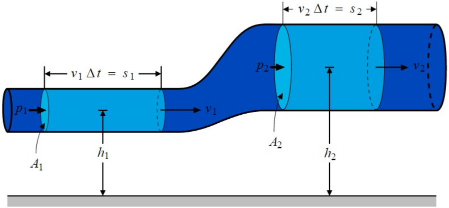
The Reynolds number is the ratio between the inertial and viscous friction forces (see also the Navier-Stokes equation). For flow in pipes (of a diameter d) it is defined as

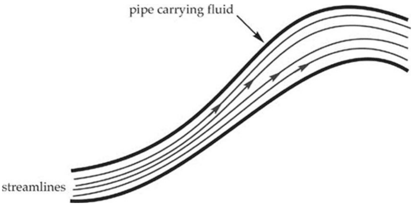
$$Re = \frac{\rho v d}{\mu} = \frac{\rho v d}{\rho \nu} = \frac{v d}{\nu}$$

Experience

For flow in pipes, turbulence is created if $Re > 2900$ and the flow is laminar if $Re < 2300$. This is an approximation.

Euler, Navier, Stokes and Bernoulli (continued)





Bernoulli equation

Using the previous assumptions, the following holds in each point along a streamline.

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = C \qquad \frac{v_1^2}{2} + \frac{p_1}{\rho} + gh_1 = \frac{v_2^2}{2} + \frac{p_2}{\rho} + gh_2$$

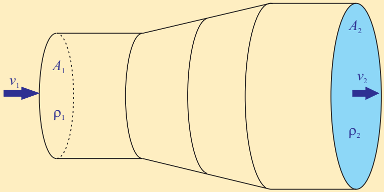
Bernoulli equation in pipelines

Bernoulli equation

From the previous slide:

$$\frac{v_1^2}{2} + \frac{p_1}{\rho} + gh_1 = \frac{v_2^2}{2} + \frac{p_2}{\rho} + gh_2$$

For the case with changing diameter



(horizontal diffusor element)

Assumption

The flow is stationary, the fluid is incompressible (ρ is constant), the internal friction is neglected.

Bernoulli equation

Since $h_1 = h_2$ and $\rho_1 = \rho_2 = \rho$

$$\frac{v_1^2}{2} + \frac{p_1}{\rho} = \frac{v_2^2}{2} + \frac{p_2}{\rho}$$

$$\sqrt{v_1^2 - v_2^2} = \sqrt{\frac{2(p_2 - p_1)}{\rho}}$$

Bernoulli equation in pipelines

Bernoulli equation

Since $h_1 = h_2$ and $\rho_1 = \rho_2 = \rho$, we will use the previous results:

$\frac{v_1^2}{2} + \frac{p_1}{\rho} = \frac{v_2^2}{2} + \frac{p_2}{\rho}$ and $\sqrt{v_1^2 - v_2^2} = \sqrt{\frac{2(p_2 - p_1)}{\rho}}$

Remarks

1. The above equation shows the relationship between the change of flow velocity and the **pressure difference** (if assumptions hold)
2. Methods to measure pressure are known and it is simple. One may calculate the pressure from the height of a fluid column ($p_i = \rho g h_{p,i}$ similarly to the Toricelli pipe), hence

$$\sqrt{v_1^2 - v_2^2} = \sqrt{2g(h_{p,2} - h_{p,1})}$$

where ρ is not present. In practice, the pressure is measured thanks to the generated deformation so the knowledge of ρ is necessary.

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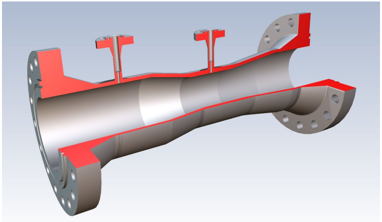
Venturi pipe

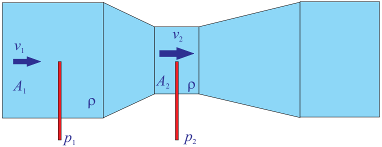
Giovanni Battista Venturi
(1746-1822)

Remark

All is understood to study the basic tool of flow measurement: the Venturi pipe.

Venturi pipe





Assumptions

1. Stationary flow
2. Incompressible fluid
3. Neglected internal friction (small viscosity)
4. An average flow velocity for the cross sections can be given

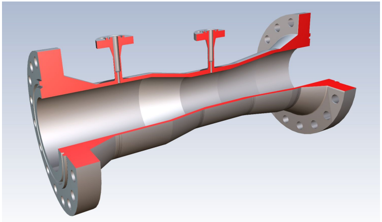
Equations

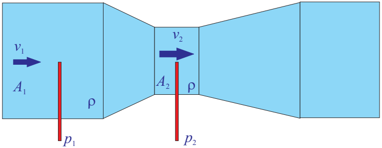
Bernoulli and continuity principle:

$$v_2^2 - v_1^2 = \frac{2(p_1 - p_2)}{\rho}$$

$$A_1 v_1 = A_2 v_2$$

Venturi pipe





Equations (continued)

Isolate v_2 or v_1 and get

$$v_2 = \frac{A_1}{\sqrt{A_1^2 - A_2^2}} \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

$$v_1 = \frac{A_2}{\sqrt{A_1^2 - A_2^2}} \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

The volumetric flow - q_v

We use that $q_v = A_1 v_1 = A_2 v_2$

$$q_v = \frac{A_1 A_2 \sqrt{2}}{\sqrt{\rho(A_1^2 - A_2^2)}} \sqrt{p_1 - p_2}$$

Venturi pipe - remarks

The DP principle

The flow speed is proportional to the square root of the pressure difference, and inversely proportional to the square root of the density.

$$q_v \propto \sqrt{\Delta p}$$

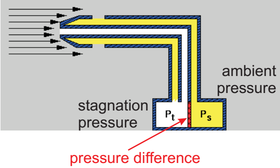
Important **limitations**

1. In the case of the Venturi pipe (and also for other types of DP based volumetric flow meters) the velocity is determined in reality for a given point or for a small cross section.
2. Calibration is needed to determine the average velocity and volumetric flow over the entire pipe cross section.
3. The DP based method allows to determine the mass flow only if the value of the density is known.

Pitot tube

The device

The Pitot tube is another device to measure flow velocity based on pressure difference. It is widely used by the aeronautic industry.



Remark

The velocity of the air is measured in one direction and in one point. This can be improved with multiple openings in multiple directions. It may be frozen under bad weather conditions. Freezing of multiple pipes caused the AF447 disaster.

Orifice DP flow meters

The device

Instead of the complicated construction of the Venturi pipe, the diffusion is realized by an orifice plate. The ratio of diameters is defined as: $\beta = \frac{d}{D}$.

Orifice DP flow meters

Remarks

- The pressure is not measured along the center line but close to the walls.
- Thanks to the orifice, the effective flow diameter of the pipe is reduced.
- For higher flow velocities, turbulence may occur thanks to the orifice plate. Nozzles are applied to reduce turbulent flow.
- For small flow values (desirable for small friction losses) the pressure difference is small but that reduces precision.
- Sediments may modify the geometry of the orifice.

Compressible fluids

The DP measurement principle can be applied for compressible fluids as well ($\rho = f(p$, no longer constant). The Bernoulli equation reads (in horizontal pipe):

$$\frac{v_1^2}{2} - \frac{v_2^2}{2} + \int_{p_1}^{p_2} \frac{dp}{\rho} = 0$$

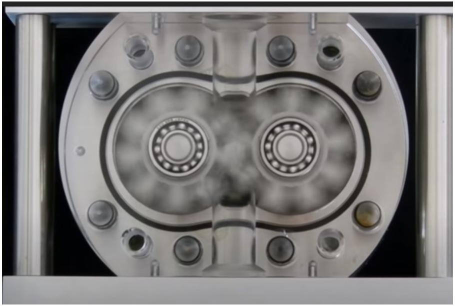
Contents

Volume counters - gear and helical meters

Measurement principle

- The fluid enters into spaces with known volume and it is transferred to the meter output. The number of transferred unit volumes is used to calculate the flow.
- The counting is usually realized on a rotating axis using incremental encoders.
- The work necessary to move the mechanism is realized by the fluid.
- Only for incompressible fluids.
- High precision is provided as the unit volumes can be created with great repeatability.
- Some versions can work as (dosage) pumps as well.
- Sensitive to pollution.

Volume counters - gear and helical meters



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The Coriolis force

Well known from previous studies (physics)

The force acting on a body that moves in a rotating frame w.r.t. to an inertial reference is proportional to its velocy and to its mass.

Using equation

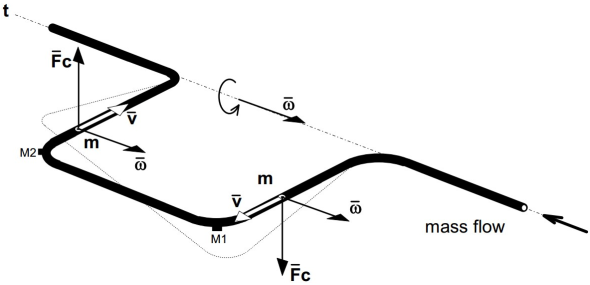
$$F_C = 2m(\omega \times v),$$

ahol

- ω - vector of instantaneous rotational velocity
- v - instantaneous velocity vector
- m - mass of the moving body

Gaspard-Gustave de Coriolis
(1792-1843)

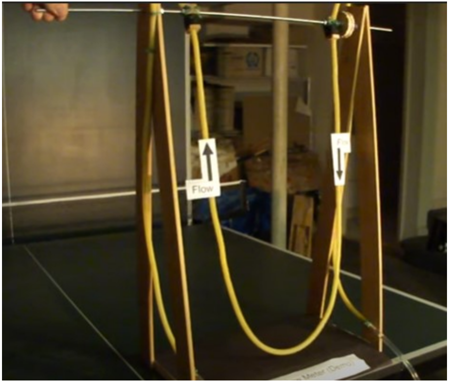
Coriolis forces in oscillating pipes



Study of the forces $v \neq 0$

- No Coriolis force is applied in the section parallel to the axis of rotation.
- The largest amount of Coriolis force is created in the pipeline sections perpendicular to the axis of rotation.
- The Coriolis forces will deform the pipe.

Coriolis forces in oscillating pipes



Study of the forces $v \neq 0$

- Two pipe sections are vibrated in opposite phase.
- Motions are measured at dedicated pick-up points.

Pipe forms and vibration modes

Considerations

1. Coriolis forces are bigger as flow velocity increases (the cross section is reduced resulting in energy loss)
2. Two pipe sections with identical forms are vibrated in opposite directions so that no vibration exits to the outside world.
3. The meter is fixed in a way so that no external vibration affects the pick-ups.
4. In multi-phase fluids (e.g. liquids with gas bubbles) the internal friction due to the displacement of the phase delimiting layers dissipates the oscillation energy.
5. The viscosity does not influence the measurement principle.

Unknown gas/fuel theft (2000 BC –)

Pipe forms and vibration modes

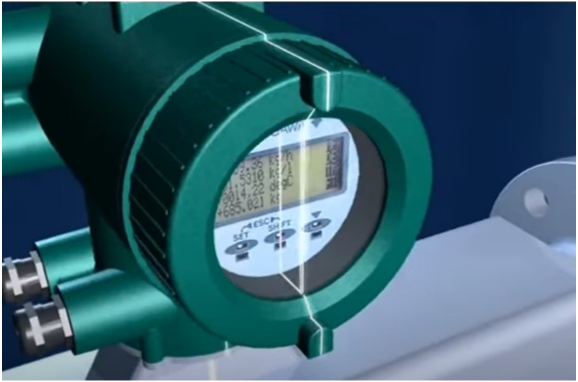
The mechanical oscillator

1. Oscillation and pick-up is realized using electromagnetic principles. Displacements are under 1 *mm*.
2. The pipe structure is approximated as a linear spring for such small deformations.
3. The pipe structure is a second order underdamped oscillator:

$$W(s) = \frac{1}{ms^2 + bs + k} = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

   where k is (essentially) the stiffness of the pipe, b is (essentially) the viscosity of the fluid and m is the vibrated mass (pipe and fluid).
4. The undamped natural frequency is $\omega_0 = \sqrt{\frac{k}{m}}$.
5. The oscillation at the (angular) frequency ω_0 requires the smallest amount of energy.

What can we measure from the vibration?



Measurable quantities

- Density - from (undamped natural) frequency
- Mass flow - from phase difference

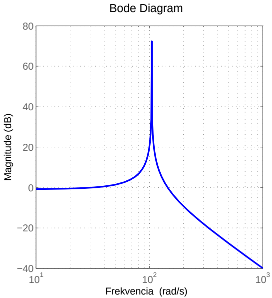
Measurement of density

$$W(s) = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{k}{m}} \qquad \omega_0 = \sqrt{\frac{k}{m}}$$

Principle

1. The stiffness k of the vibrating tube section is known (manufactured by us).
2. The mass m_{pipe} and the volume V of the pipe between the fixation points are known.
3. If the pipe oscillates with the frequency ω_0, the average density can be determined as

$$\rho = \frac{1}{V}\left(\frac{k}{\omega_0^2} - m_{pipe}\right)$$



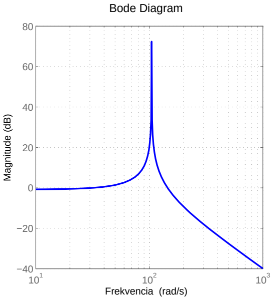
Measurement of density

How to sustain the vibration at ω_0?

This is a regulation problem. Its solution is known: PLL (with VCO).

Calculation of ω_0

1. From the signals of the pick-ups (or from the difference signal).
2. Using FFT for example.



Where did you learn the ingredients?

Signals and systems, Physics, Electronics, Electromagnetic fields, Measurement theory, Control engineering.

Measurement of mass flow

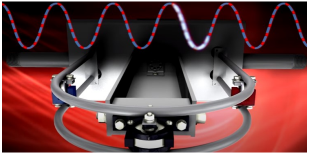
Principle

The phase difference Δt at the pick-ups is proportional to the **mass flow** $q_m \propto \Delta t$. The relationship reads

$$q_m = \frac{k(T) - \Theta\omega_0^2}{2Kd^2}\Delta t,$$

where

- k - stiffness of the pipe
- T - temperature
- Θ - inertia
- K - pipe form constant
- d - diameter



Thermal expansion

The stiffness of the pipe changes as the temperature changes, its compensation is possible if T is measured.

Coriolis mass flow meters - summary

Advantages

- "Direct" measurement of mass flow (independent of fluid consistency thanks to the measurement principle).
- Possible accuracy may be **under** $0,1\%$ relative to measured value (not to maximal flow value).

MMG Flow C-mass demonstration

MMG Flow Coriolis mass flow meters

1. flow range: 0.15 - 300 t/h
2. pressure range: 10-320 bar
3. temperature range: -40 ... 200 $^{\circ}C$
4. APEX housing (if required)

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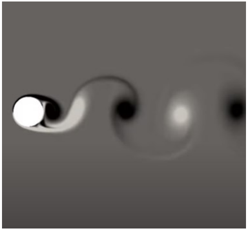
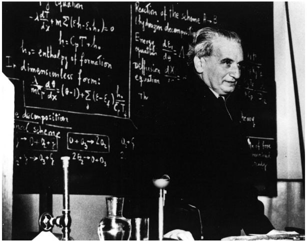
Kármán’s vortex street





vortex street generation

- Vortices are generated thanks to the pressure difference behind the bluff body.
- The energy level of the motion must be sufficient to generate vortices.
- Vortices are generated if *Re* stays in a given interval.

Kármán' vortex street - singing power lines

Remarks

1. Thanks to viscosity, flow becomes regular behind the bluff body.
2. Vortices may not be generated at low energy level flow, so flow velocity may need to be increased by decreased pipe diameters.
3. Typical *Re* range required to generate a vortex street: $[47, 10^5]$.
4. Vortices resonate the bluff body.

(Magic) formula

The average flow velocity v behind a cylindrical bluff body

$$v = \frac{fd}{0,198}\left(1 - \frac{19,7}{Re}\right)^{-1},$$

where

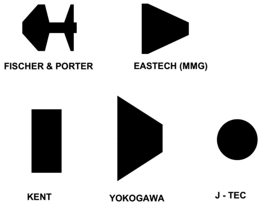
- f - vortex frequency
- d - cylindrical bluff body
- Re - Reynolds number

Hence $v \propto f$ and $q_v = Av$. Mass flow q_m is not measured.

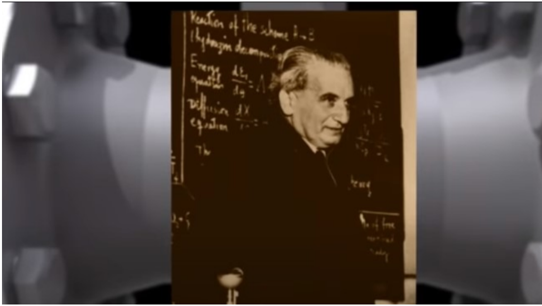
Vortex meters and bluff body

Vortex counting

Displacement of the counting stick is perpendicular to the middle line of the pipe. The displacement detection happens using piezo of optical sensors.



Popular bluff body forms



Strouhal number

In a given configuration the ratio $\frac{fd}{v}$ is defined as the Strouhal number.

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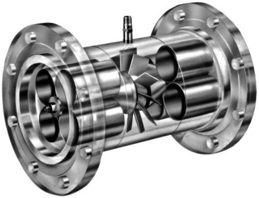
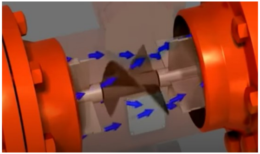
Turbine flow meters - principle of operation





Considerations

- Flow rotates turbine blades as it crosses between them.
- The configuration of blades minimizes vortex generation behind the turbine but the flow is stopped right next to the blade.
- No turbine axis friction is considered in the ideal case.

Turbine flow meters - principle of operation

Ideal behavior

If friction and viscosity are neglected, one gets

$$q_v = Kf,$$

where

- K - calibration coefficient of the meter
- f - blade frequency (proportional to angular velocity)

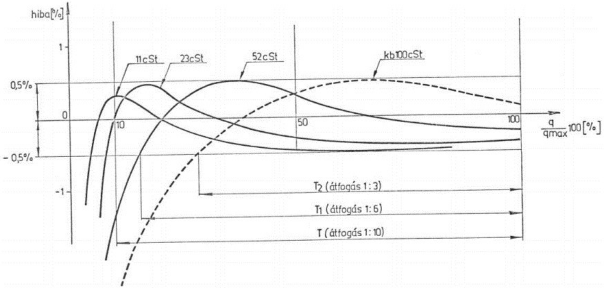
Leak flow

No blade motion is detected under some non-zero flow value q_v referred to as the leak flow.

Friction and viscosity

The effects inducing inaccuracy depend on the flow itself so the calibration coefficient depends on the flow as well.

Turbine flow meters - error of K



Remarks

- The figure shows the dependence of K on q_v for different values of kinematic viscosity.
- One needs to use the upper region of the meter's range.
- For a given viscosity, the function $K(q_v)$ is usually interpolated.

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Measurement principle

Faraday law

If a conductive fluid moves in a magnetic field with induction B and with velocity v, than a voltage is induced. If v is perpendicular to B:

$$U = v \cdot B \cdot D,$$

where D is the pipe diameter, U is the induced voltage and v is the (average) velocity.

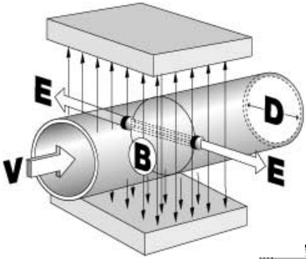
Limited applicability

Only for conductive fluids (water, blood, solutions, liquid metals).

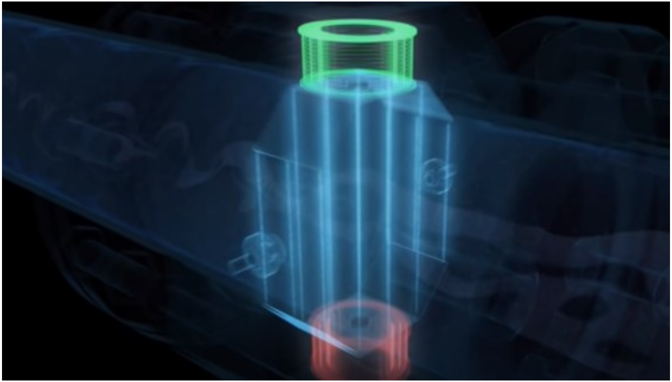
Difficulty

Generation of the field B

- Using coils and AC current.
- Using DC excitation (requires high power).



Induction meters



Remarks

- Regular cleaning of the electrodes is necessary.
- Systematic errors can be eliminated if the field is changing.

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Ultrasonic meters

Measurement principles

Ultrasonic packages (pulses) are sent into the pipe. Two measurements methods are exploited

1. Time of Flight (ToF) based measurement
2. Doppler shift based measurement.

Time of Flight

The transit time of the ultrasonic pulses (packages) is different if they travel with or against the flow.

Doppler shift

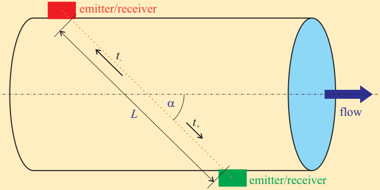
Flowing particles reflect the pulse with a frequency shift depending on their velocity. The shift is proportional to the velocity ($v \propto \Delta\omega$).

Advantage - reasons of popularity

No need to apply bluff bodies hence losses are minimal (may still result from reduced meter cross section).

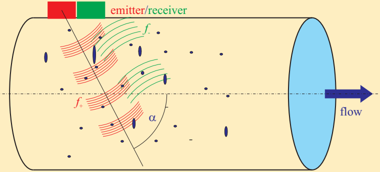
Ultrasonic meters - measurement configuration

Time of flight



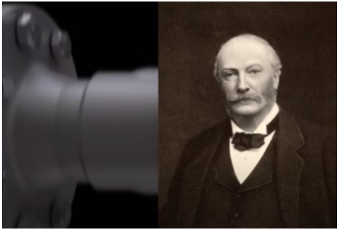
- The sound bundle is refracted when it enters and leaves the pipe wall.
- There are methods that measure the reflected waves from the pipe walls.

Doppler shift



Return waves arrive from reflective particles travelling with the flow in the pipe. No measurement is possible if no such particles are present.

Measurement using time of fligt



Remark

More than one emitter-receiver pairs can be created in the section. They usually generate and detect waves using piezoelectric principles.

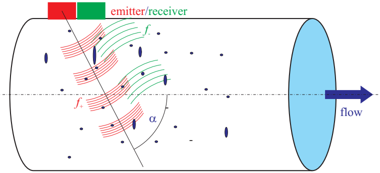
Equation

The average flow velocity

$$v = \frac{L}{2\sin\alpha}\frac{t_- - t_+}{t_- t_+} \quad q_v = A \cdot v,$$

- t_- - travelling time against the flow
- t_+ - travelling time along the flow
- α - angle between the pulse travelling direction and the flow direction
- L - distance between the emitter and the receiver

Doppler shift based measurement



Remark

Metal pipe walls may drive away a large part of the energy of the ultrasonic pulse sent from outside.

Equation

The average flow velocity over the cross section

$$v = \frac{c}{2f_+ \cos\alpha}(f_+ - f_-) \quad q_v = A \cdot v,$$

- f_- - frequency of the reflected pulse
- f_+ - frequency of the emitted pulse
- α - angle between the pulse travelling direction and the flow direction
- c - speed of sound in the fluid

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Flow measurement methods - comparison

Measured value and typical accuracy (w.r.t. the measured value)

- Turbine meter - q_v - $\pm 0,3\%$, wrong performance for small q_v and for big ν.
- Orifice meter - q_v - $\pm 0,2\%$, complex compensation calculations.
- Induction meter - q_v - $\pm 0,1\%$, only for conductive material.
- Vortex meter - q_v - $\pm 0,1\%$, makes the flow irregular.
- Coriolis - q_m $\pm 0,1\%$

Other considerations

Range (ratio of the largest and smallest measurable values), straight run section in front of the meter, null-stability, calibration, flow loss, maintenance costs, TCO (total cost of ownership).