Sensors
How to measure fluid flow properties ?

Amélie Danlos, Florent Ravelet

DynFluid Laboratory, Arts et Métiers ParisTech

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Introduction

To resolve a fluid dynamics problem, we must calculate different fluid properties as:

- density
- viscosity
- temperature
- pressure
- flow rate
- velocity

Sensor definition: it is a device which changes a physical quantity into a workable quantity (often electric signal).

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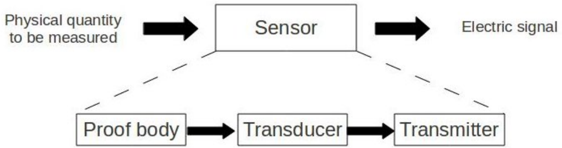

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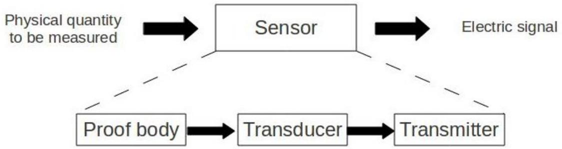


Sensor definition: it is a device which changes a physical quantity into a workable quantity (often electric signal).

Proof body = mechanical element which reacts selectively to measurable variable
$\Rightarrow$ to convert this variable into a measurable physical quantity
Transducer = it translates proof body reactions into an electric quantity
Transmitter = it permits to amplify, to filter the output signal for its transmission on a distance

Introduction

According to the sensor type, signal may be:

- **Analogical:** linked by a continuous law to the measured quantity (current or voltage)
- **Numerical:** electric pulses transmitted to computer systems
- **Logical:** All-or-nothing signal

Outline

- Density = physical quantity which characterizes material mass per unit volume (also called *specific weight*)

$$\rho = \frac{m}{V}$$

where m is the mass of the homogeneous matter occupying the volume V.

- Unit: $[\rho] = M.L^{-3}$
- **Be careful !** density≠relative density
Relative density is the ratio of the density of a substance to the density of a given reference material (water for solids and liquids and air for gases) and is also called *specific gravity*.
Relative density is <u>dimensionless</u> !
- Density varies with pressure and temperature:

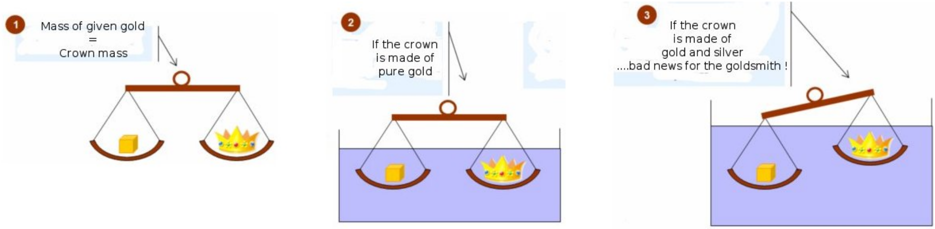
increasing pressure = increasing density
increasing temperature = decreasing density

An exception: Water !
Maximal density at $T = 3.98^\circ C$ and ice density is weaker than liquid density

How to measure density ?

Archimedes' discovery

The Syracuse king Hiero weighed out a precise amount of gold, and commanded a goldsmith to fashion out of the gold a wreath worthy of the gods. But he heard rumours that the goldsmith had replaced some of the gold that Hiero had given him, with an equal weight of silver to make the crown.



DynFluid Fluid Dynamics Laboratory

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Measurement Methods

- Pycnometer
- Densimeter
- Coriolis flowmeter

Pycnometer

=laboratory tool used to measure density of a liquid or solid product (considering temperature)
This name comes from the Greek puknos, meaning "density". This tool is also called *pyknometer* or *specific gravity bottle*.

Density determination of liquids:
The pycnometer is a glass flask with a close-fitting ground glass stopper with a capillary hole through it. This fine hole releases a spare liquid after closing a top-filled pycnometer and allows for obtaining a given volume of measured and/or working liquid with a high accuracy.

Mass measurements of pycnometer before and after filling permit to calculate density.
Calibration with distilled water.

Glass pycnometer
50mL

Steel pycnometer
50mL or 100mL

Pycnometer

Density determination of liquids:

Measurements of :

1. Mass of pycnometer full of studied liquid: M_L
2. Mass of pycnometer full of water: M_w
3. Mass of pycnometer empty and dry: M_e

Then, the liquid mass contained in pycnometer is : $m_L = M_L - M_e$
And the water mass contained in pycnometer is : $m_w = M_w - M_e$
Density can be deduced:

$$d_L = \frac{m_L}{m_w} = \frac{\rho_L}{\rho_w}$$

$$\rho_L = \rho_w \frac{m_L}{m_w}$$

Pycnometer

Density determination of solids:

Measurements of :

1. Mass of pycnometer full of water and solid (outside): M_1
2. Mass of pycnometer full of water and solid (inside): M_2
3. Mass of pycnometer empty and dry: M_e

Then, the solid mass is : $m_s = M_1 - M_e$
And the water mass occupying the same volume is : $m_w = M_1 - M_2$
Density can be deduced:

$$d_L = \frac{m_s}{m_w} = \frac{\rho_s}{\rho_w}$$

$$\rho_s = \rho_w \frac{m_s}{m_w}$$

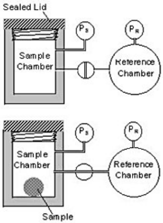
Pycnometer

Use conditions

- Delicate and expensive
- The pycnometer must be clean and dry before the initial weighing.
- When full, there should be no air bubbles in the bulb or capillary of the pycnometer, and no air space at the top of the capillary.

Pycnometer

Density determination of solids: **Gas pycnometer**



Used gas: Helium

When the valve is closed: $P_s\left(V_s - V_X\right) + P_r V_r = nRT$

with: V_x: the unknown sample volume

R: the gas constant

When the valve is opened: $P_{sys}\left(V_s + V_r - V_X\right) = nRT$

Then, $V_x = \frac{P_{sys}(V_s+V_r)-P_s V_s-P_r V_r}{(P_{sys}-P_s)}$

Hydrometer

= instrument used to measure the density of liquid products.

A float is made of a cylindrical stem and a bulb weighted with lead shot or mercury. The studied liquid is placed in a glass cylinder before the stem with the bulb is introduced. Based on Archimedes' principle, the lower the density of the substance, the farther the hydrometer will sink.

Hydrometers are used in many industrial applications:

- petroleum industry
- chemistry
- pharmacology
- drink industry
- cosmetics

Hydrometer

Hydrometer is submitted to two forces:

- Weight: $\mathbf{P} = m\mathbf{g}$
- Buoyancy: $\mathbf{F_A} = \rho V \mathbf{g}$

At equilibrium: $\mathbf{P} = -\mathbf{F_A}$
Then, ρ can be calculated.

Dasymeter

= instrument used to measure the density of gases.

A sphere with a known density is weighed in vacuum and then weighed immersed into the studied gas. Density of gas can be obtained as:

$$\frac{\text{density of sphere}}{\text{density of gas}} = \frac{\text{weight of sphere}}{\text{weight of sample} - \text{weight of immersed sample}}$$

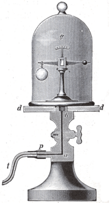


Fig. 109. Baroskop. (Apparat zum Nachweise des Auftriebes der Luft)

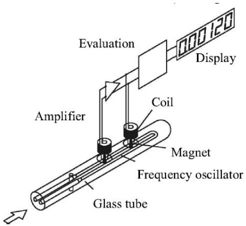
Oscillating U-tube

= instrument used to measure the density of gases and liquid products.

The liquid or gas sample is filled into a U-shaped glass tube which behaves as a spring. The tube is electronically excited into undamped oscillation (at the lowest possible amplitude). The eigenfrequency of the tube depends on the sample mass. As the volume of sample is known, density can be determined with:

$$\rho = A\tau^2 - B$$

where A and B are the instrument constants which are determined by calibrating the Oscillating U-tube with 2 substances of the precisely known densities ρ_1 and ρ_2 (reference substances are often air and water).



Outline

- = measure of the resistance of a fluid which is being by either shear or tensile stress
- If the flow has a low viscosity, its movement is easy.
- Viscosity describes an inner resitance to flow (measure of fluid friction).
- A fluid which has no resistance to shear stress is an ideal or inviscid fluid.
- A flow consists of layers which move at different velocities. The fluid viscosity arises from the shear stress between each layer.
- Shear stress:

$$\tau = \frac{F}{A}$$
$$F = \mu A \frac{\partial u}{\partial y}$$

  where:
  μ: dynamic viscosity
  $\frac{\partial u}{\partial y}$: shear deformation
  A: area of a fluid layer

- Viscosity is a tensorial quantity that can be decomposed into 2 independant components:
  - *Shear viscosity* (the most important one): it is the ratio between the pressure exerted on the surface of a fluid, in the lateral or horizontal direction, to the change in fluid velocity as you move down in the fluid
  - *Volume viscosity* (also called bulk viscosity or second viscosity): it becomes important only for such effects where fluid compressibility is essential

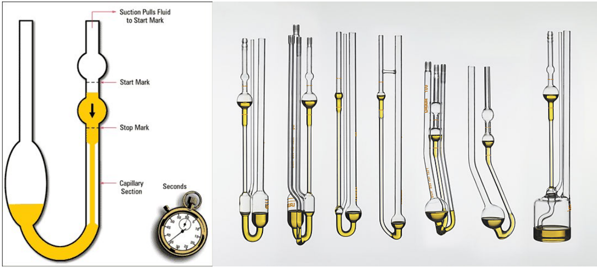
- Viscosity coefficients
  - *Dynamic viscosity* (also called absolute viscosity): μ (Unit: *Pa.s*, Poiseuille)
  - *Kinematic viscosity*: $\nu = \frac{\mu}{\rho}$ (Unit:$cm^2.s^{-1}$, Stokes)
- There are different forms of viscosity:
  - Newtonian: fluids which have a constant viscosity (as water and most gases)
  - Shear thickening: viscosity increases with the rate of shear
  - Shear thinning: viscosity decreases with the rate of shear
  - Thixotropic: becomes less viscous over time when shaken, agitated...
  - Rheopectic: becomes more viscous over time when shaken, agitated...
  - Bingham plastic: behaves as a solid at low stresses but flows as a viscous fluid high stresses.
  - Magnetorheological fluid: when it is submitted to a magnetic field, it becomes a viscoelastic solid.
- Effect of temperature on viscosity:
  - For a liquid: $\mu = \mu_0 \frac{1}{1+\alpha T+\beta T^2}$ where μ_0 is the viscosity at 0 °C
  - For a gas: $\mu = \mu_0 \sqrt{\frac{T}{T_0}} \frac{1+S/T_0}{1+S/T}$ where S is a characteristic constant of the gas

Viscosity measurement

- **Viscometers**
- **Rheometers**

U-tube viscometer (Oswald viscometer)

Movie



- This glass capillary viscometer consists of a U-shaped glass tube vertically positioned in a controlled temperature bath.
- In one arm of the U, there is a capillary with a bulb and one other bulb is situated on the other arm. Studied liquid is drawn into the upper bulb by suction, before flowing down through the capillary into the lower bulb.
- Two marks (one above and one below the upper bulb) indicate a known volume. A chronometer permits to determine the time taken for the level of liquid to pass between these marks.

U-tube viscometer (Oswald viscometer)

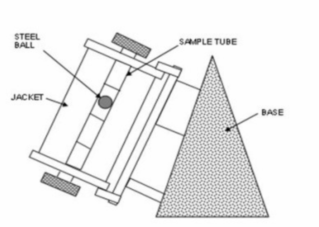
- This time is proportional to the dynamic viscosity μ:

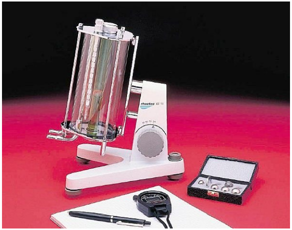
$$\mu_2 = \frac{\mu_1 \rho_2 t_2}{\rho_1 t_1}$$

μ_1: absolute viscosity of water
t_1: time of water flow
ρ_1: water density
μ_2: absolute viscosity of liquid
t_2:time of liquid flow
ρ_2: liquid density

- Accuracy:1%

Falling sphere viscometer





- The fluid is placed stationary in a vertical glass tube in which a sphere of known size and density moves. Under some conditions, the sphere reaches terminal velocity measured by the time taken to pass two marks on the tube. Electronic sensing can be used for opaque fluids.
- The terminal velocity, the size and the density of the sphere, and the liquid density permit to calculate the fluid viscosity using the Stoke's law.
- If the sphere is falling in the viscous fluid by their own weight, then a terminal velocity (also called setting velocity) is reached when the frictional force combined with the buoyant force exactly balance the gravitational force.

Falling sphere viscometer

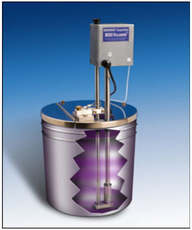
- Terminal velocity is v:

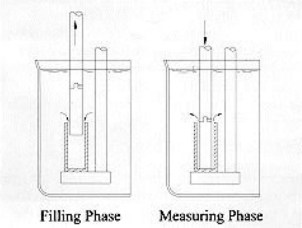
$$v = \frac{2}{9}\frac{R^2 g(\rho_p - \rho_f)}{\mu}$$

R: Stokes radius of the sphere
g: gravitational acceleration
ρ_p:sphere density
ρ_f: fluid density
μ: dynamic fluid viscosity

- Accuracy:$1 - 2\%$

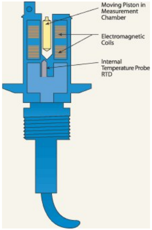
Falling piston viscometer (also called Norcross viscometer)





- A piston is periodically raised by an air lifting mechanism, drawing the studied fluid through the gap between the piston and the wall of the cylinder.
- Piston is held up for a few seconds, then it falls by gravity expelling the sample out through the same gap that it comes in, creating a shearing effect on the measured liquid.
- Particularly sensitive for measuring thixiotropic liquids.
- **Advantages:**
  - Low manitenance and longevity
  - Not affected by flow rate or external vibrations

Oscillating piston viscometer (Electromagnetic viscometer)

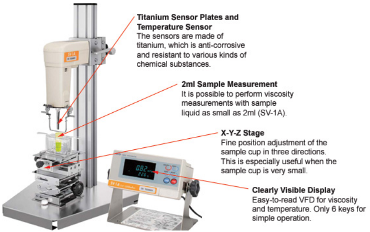


- **Advantages:**

- Adapted to small and micro-sample viscosity
- Can measure gas viscosity
- Accuracy: 1%

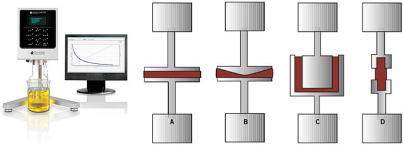
- The sensor comprises a measurement chamber and magnetically influenced piston.
- The sample is introduced into the thermally controlled measurement chamber where the piston resides. Electronics drive the piston into oscillatory motion within the measurement chamber with a controlled magnetic field. A shear stress is imposed on the liquid (or gas) due to the piston travel and the viscosity is determined by measuring the travel time of the piston.
- The construction parameters for the annular spacing between the piston and measurement chamber, the strength of the electromagnetic field, and the travel distance of the piston are used to calculate the viscosity according to Newton's Law of Viscosity.

Vibrational viscometer



- 2 thin sensor plates are driven with electromagnetic force at the same frequency by vibrating at constant sine-wave vibration in reverse phase like a tuning fork.
- The driving electric current, which is exciting force, will be detected as the magnitude of viscidity produced between the sensor plates and the sample fluid. The coefficient of viscosity is obtained by the correlation between the driving electric current and the magnitude of viscidity.
- The higher the viscosity is, the larger the damping imposed on the resonator is.

Rotational viscometer



- The torque required to turn an object in a fluid is a function of the fluid viscosity. A rotational viscometer measures the torque required to rotate a disk or bob in a fluid at a known speed.
- This viscometer defines the exact volume of a sample which is to be shared within a test cell. The torque required to achieve a certain rotational speed is measured and plotted.
- Different types of rotational viscometers:
  "cup and bob" viscometers = "Couette" or "Searle" systems: the rotating cup is preferred in some cases because it reduces the onset of Taylor vortices, but is more difficult to measure accurately.
  "cone and plate" viscometers: use a cone of very shallow angle in bare contact with a flat plate. The shear rate beneath the plate is constant to a modest degree of precision and deconvolution of a flow curve. A graph of shear stress (torque) against shear rate (angular velocity) yields the viscosity is.

Bubble viscometer

- Bubble viscometers are used to quickly determine kinematic viscosity of known liquids such as resins and varnishes
- The time required for an air bubble to rise is directly proportional to the viscosity of the liquid, so the faster the bubble rises, the lower the viscosity.

Rheometers

- Rheometers are used for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than it is the case for a viscometer.
- Measure the way in which a liquid, suspension or slurry flows in response to applied forces.
- 2 different types of rheometers:
  - Rotational or shear rheometers: control the applied shear stress or shear strain
  - Extensional rheometers: apply extensional stress or extensional strain.

Types of shear rheometers

Pipe or capillary, Rotational cylinder, Cone and plate, Linear shear

Types of extensional rheometers

Rheotens, CaBER, FiSER, Sentmanat, Acoustic, Falling plate, Capillary / Contraction flow

Outline

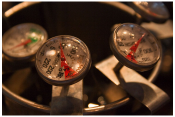
- The temperature of a substance typically varies with the average speed of the particles that it contains, raised to the second power; that is, it is proportional to the mean kinetic energy of its constituent particles. Formally, temperature is defined as the derivative of the internal energy with respect to the entropy.
- Some of the world uses the Celsius scale ($^\circ$) for most temperature measurements. It has the same incremental scaling as the Kelvin scale used by scientists, but fixes its null point, at $0^\circ C = 273.15K$, the freezing point of water.
- Fahrenheit scale for common purposes is a historical scale on which water freezes at $32^\circ F$ and boils at $212^\circ F$.

Temperature measurement

- Thermometer
- Thermocouple
- Thermistor
- Resistance thermometer

Thermometer

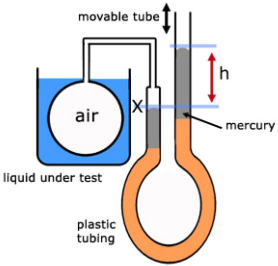
Thermometric materials



- Thermometric materials thermometers rely on the constitutive relation between pressure and volume and temperature of their thermometric material. For example, mercury expands when heated.
- A thermometric material must have three properties:
  1. Its heating and cooling must be rapid.when a quantity of heat enters or leaves a body of the material, the material must expand or contract to its final volume or reach its final pressure and must reach its final temperature with practically no delay.
  2. Its heating and cooling must be reversible. The material must be able to be heated and cooled indefinitely often by the same increment and decrement of heat, and still return to its original pressure and volume and temperature every time.
  3. Its heating and cooling must be monotonic.

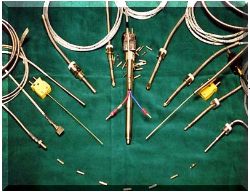
Thermometer

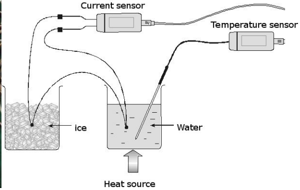
Constant volume thermometry



- The temperature of the liquid depends on the gas pressure in the bulb.
- A constant volume gas thermometer is composed of a bulb filled with a fixed amount of a dilute gas that is attached to a mercury manometer. A manometer is a device used to measure pressure. When the temperature of an ideal gas increases, that there is a corresponding increase in pressure.

Thermocouple





- A thermocouple is a device consisting of two different conductors (usually metal alloys) that produce a voltage proportional to a temperature difference between either end of the pair of conductors.When two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, there is a continuous current which flows in the thermoelectric circuit (Seebeck effect).
- Thermocouples are a widely used type of temperature sensor for measurement and control and can also be used to convert a temperature gradient into electricity.
- In contrast to most other methods of temperature measurement, thermocouples are self powered and require no external form of excitation. The main limitation with thermocouples is accuracy and system errors of less than one degree Celsius can be difficult to achieve.

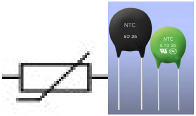
Thermocouple

- Any junction of dissimilar metals will produce an electric potential related to temperature. Thermocouples for practical measurement of temperature are junctions of specific alloys which have a predictable and repeatable relationship between temperature and voltage. Different alloys are used for different temperature ranges.
- Normally the cold junction is maintained at a known reference temperature, and the other junction is at the temperature to be sensed.

Thermocouple

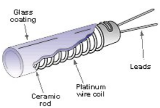
Type	Temperature range °C (continuous)	Temperature range °C (short term)	Tolerance class one (°C)	Tolerance class two (°C)	IEC Color code	BS Color code	ANSI Color code
K	0 to +1100	−180 to +1300	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 1000 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 1200 °C			
J	0 to +750	−180 to +800	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 750 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 750 °C			
N	0 to +1100	−270 to +1300	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 1000 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 1200 °C			
R	0 to +1600	−50 to +1700	±1.0 between 0 °C and 1100 °C ±[1 + 0.003×(T − 1100)] between 1100 °C and 1600 °C	±1.5 between 0 °C and 600 °C ±0.0025×T between 600 °C and 1600 °C			Not defined.
S	0 to 1600	−50 to +1750	±1.0 between 0 °C and 1100 °C ±[1 + 0.003×(T − 1100)] between 1100 °C and 1600 °C	±1.5 between 0 °C and 600 °C ±0.0025×T between 600 °C and 1600 °C			Not defined.
B	+200 to +1700	0 to +1820	Not Available	±0.0025×T between 600 °C and 1700 °C	No standard use copper wire	No standard use copper wire	Not defined.
T	−185 to +300	−250 to +400	±0.5 between −40 °C and 125 °C ±0.004×T between 125 °C and 350 °C	±1.0 between −40 °C and 133 °C ±0.0075×T between 133 °C and 350 °C			
E	0 to +800	−40 to +900	±1.5 between −40 °C and 375 °C ±0.004×T between 375 °C and 800 °C	±2.5 between −40 °C and 333 °C ±0.0075×T between 333 °C and 900 °C			
Chromel/AuFe	−272 to +300	n/a	Reproducibility 0.2% of the voltage; each sensor needs individual calibration.				

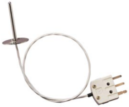
Thermistor



- A thermistor is a type of resistor whose resistance varies significantly with temperature, more so than in standard resistors.
- Thermistors differ from resistance temperature detectors (RTD) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals.
- Two types of thermistors: if the resistance increases with increasing temperature, the device is called a positive temperature coefficient (PTC) thermistor, or posistor, on the other hand, if the resistance decreases with increasing temperature, the device is called a negative temperature coefficient (NTC) thermistor.

Resistance thermometer





- Resistance thermometers, also called resistance temperature detectors or resistive thermal devices (RTDs), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature.
- Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core. The element is usually quite fragile, so it is often placed inside a sheathed probe to protect it. The RTD element is made from a pure material whose resistance at various temperatures has been documented.
- As they are almost invariably made of platinum, they are often called platinum resistance thermometers (PRTs).
- At temperatures above $660^\circ C$ it becomes increasingly difficult to prevent the platinum from becoming contaminated by impurities from the metal sheath of the thermometer.

Outline

- =is the force per unit area applied in a direction perpendicular to the surface of an object

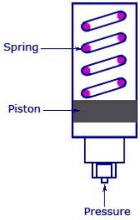
$$P = \frac{F}{A}$$

  F: normal force
  A: surface area on contact

- The force is considered towards the surface element, while the normal vector points outward.
- The pressure, as a scalar, has no direction. It is the force given by the previous relationship to the quantity that has a direction, not the pressure.
- SI unit: pascal (Pa), $[P] = M.L^{-1}.T^{-2}$
- Pressure is a measure of potential energy stored per unit volume measured.
- Because pressure is commonly measured by its ability to displace a column of liquid in a manometer, pressures are often expressed as a depth of a particular fluid (cm of water, mm of mercury). The most common choices are mercury (Hg) and water; water is nontoxic and readily available, while mercury's high density allows a shorter column (and so a smaller manometer) to be used to measure a given pressure.

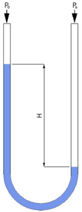
- The pressure exerted by a column of liquid of height h and density ρ is given by the hydrostatic pressure equation $P = \rho g h$. Fluid density and local gravity can vary from one reading to another depending on local factors, so the height of a fluid column does not define pressure precisely.
- **Absolute pressure** is zero-referenced against a perfect vacuum, so it is equal to gauge pressure plus atmospheric pressure.
- **Gauge pressure** is the pressure relative to the local atmospheric or ambient pressure. It is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.
- **Differential pressure** is the difference in pressure between two points.
- **Static pressure** is uniform in all directions. Flow, however, applies additional pressure on surfaces perpendicular to the flow direction, while having little impact on surfaces parallel to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called **dynamic pressure**.
- An instrument facing the flow direction measures the sum of the static and dynamic pressures; this measurement is called the **total pressure** or **stagnation pressure**.
- Dynamic pressure is used to measure flow rates and airspeed.

Piston type pressure transducer



- The input pressure moves the piston accordingly and causes the spring to be compressed. The piston position will be directly proportional to the amount of input pressure exerted.
- Applications: tire-pressure gauges
- Accuracy: $2 - 5\%$

Liquid column (also called Manometer)



- Liquid column gauges consist of a vertical column of liquid in a tube whose ends are exposed to different pressures. The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube.

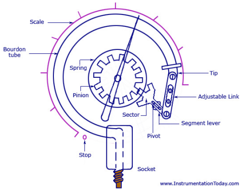
$$x = \frac{p_a - p_0}{g\rho}$$

- The U-shaped tube half-full of liquid, one side of which is connected to the region of interest while the reference pressure (which might be the atmospheric pressure or a vacuum) is applied to the other.

Bourdon tube

Movie 1

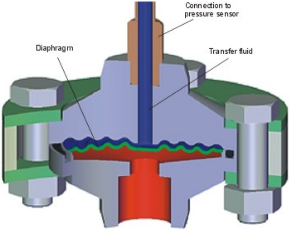
Movie 2

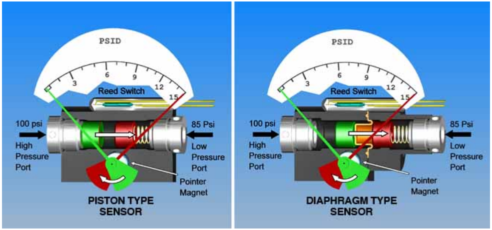


Bourdon Tube Pressure Gauge

- It is an elastic type pressure transducer.
- Cross-sectional tubing when deformed in any way will tend to regain its circular form under the action of pressure.
- Very high range of differential pressure measurement
- In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link which is usually adjustable.
- Accuracy: 0.1%

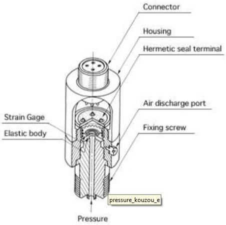
Diaphragm pressure transducer

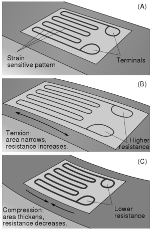




- A diaphragm pressure transducer is used for low pressure measurement.
- Metallic diaphragms are known to have good spring characteristics and non-metallic types have no elastic characteristics. Thus, non-metallic types are used rarely, and are usually opposed by a calibrated coil spring or any other elastic type gauge.
- When a force acts against a thin stretched diaphragm, it causes a deflection of the diaphragm with its centre deflecting the most.

Strain gauge transducer





- The conversion of pressure into an electrical signal is achieved by the physical deformation of strain gages which are bonded into the diaphragm of the pressure transducer. Pressure applied to the pressure transducer produces a deflection of the diaphragm which introduces strain to the gauges. The strain will produce an electrical resistance change proportional to the pressure.
- When an electrical conductor is stretched within the limits of its elasticity such that it does not break or permanently deform, it will become narrower and longer, changes that increase its electrical resistance end-to-end.

Outline

- Flow rate = material amount (expressed by a volume or a mass) which passes through a surface per time unit

Mass flow rate	Volumetric flow rate
$q_m = \int_\Sigma \rho \mathbf{V}.\mathbf{n} d\sigma$ $[q_m] = M.T^{-1}$	$q_V = \int_\Sigma \mathbf{V}.\mathbf{n} d\sigma$ $[q_V] = L^3.T^{-1}$

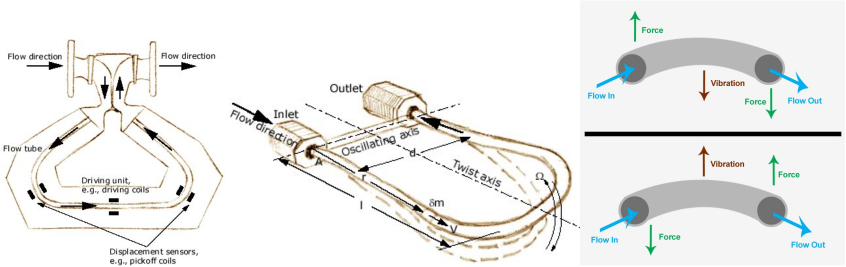
where ρ is the density of the flow passing through the surface Σ with the velocity $\mathbf{V}$.

- For liquid flows: mass flow rate (due to temperature and pressure effects on the volume)
- For gas flows: volumetric flow rate (with constant standard conditions for temperature and pressure)
- If we consider an uniform flow: $q_V = VS$ and $q_m = \rho VS$
- **Watch out !** Mass flow rate is conserved BUT volumetric flow rate is conserved only for incompressible fluid !
- A surface section variation induces a velocity variation

Mass flow meter	Volumetric flow meter
Coriolis flow meter	Magnetic flow meter
Thermal flow meter	Turbine flow meter
Ultrasonic flow meter	Ultrasonic flow meter
	Diaphragm flow meter
	Venturi meter
	Rotameter
	Pitot tube
	Target flow meter

Coriolis flow meter

= mass flow meter which permit to measure density, temperature and mass flow of gases and liquid products simultaneously.



Coriolis flow meter

Principle
Coriolis (1792-1843)

Movie



- A U-shaped tube vibrates due to an electromagnetic system. When a flow goes through the tube, the coriolis effect induces a distortion of the tube:

When the tube goes up	$\Rightarrow$	flow pushes the tube downwards
When the tube goes down	$\Rightarrow$	flow pushes te tube upwards

- Tube twist amplitude is proportional to mass flow
- Two sensors placed on each side of the tube measure vibrating tube velocity (in the inlet and the outlet of the tube): the phase shift permit to find mass flow and signal frequencies give the flow density value.

Coriolis flow meter

Mass flow:

$$Q_m = \frac{K_u - I_u \omega^2}{2Kd^2} \tau$$

Where
- K_u: tube stiffness
- I_u: tube inertia
- ω: oscillation frequency
- K: shape constant
- d: tube width
- τ: temporal shift

Characteristics

- 1 or 2 tubes
- Straight tubes: made of titanium
- Curved tubes: made of steel
- Dynamics: $1 - 50$

Advantages

- Applications: liquid, gas, liquid mixtures (no need of filtration)
- Simultaneous measurements: density, mass flow, temperature
- Measurement accuracy: 0.1%
- Dynamics: 1 — 50

Disadvantages

- Expensive tool
- No bubbles in fluid flow to have an accurate result

Thermal flow meter

- For gas and liquid flows
- Mass flow rate is deduced from variations of temperature or thermal power induced by the flow.
- Thermal flow meters have no moving elements $\Rightarrow$ strenght and reliability
- Possibility of sudden changes of pressure and flow reversal
- Usable for a large range of pressure

Different types of thermal flow meter

- **Constant temperature thermal mass flow meter**
- **Calorimetric or energy balance thermal mass flow meter**
- **Thermal dispersion gas mass flow meter**

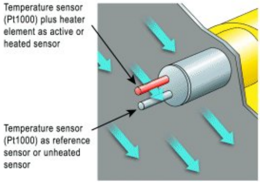
Movie

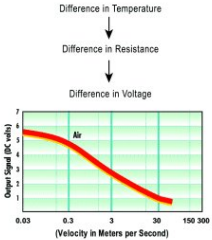
Thermal flow meter

Constant temperature thermal mass flowmeters

$$W = Q_m C_p \Delta T$$

W:Thermal power
Q_m:Mass flow rate
C_p:Heat capacity
ΔT:Temperature rise





- Two active sensors operate in a balanced state. One acts as a temperature sensor reference while the other is the active heated sensor.
- Heat loss produced by the flowing fluid tends to unbalance the heated flow sensor and it is forced back into balance by the electronics.

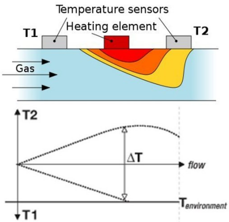
Thermal flow meter

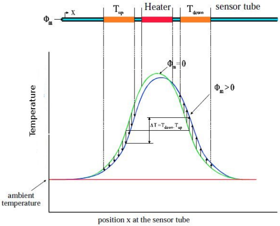
Constant temperature thermal mass flowmeters

- Heat loss increases with increasing fluid velocity.
- Fast response to fluid velocity and temperature changes.
- Turndown ratio 1000:1

Thermal flow meter

Calorimetric or energy balance thermal mass flowmeters

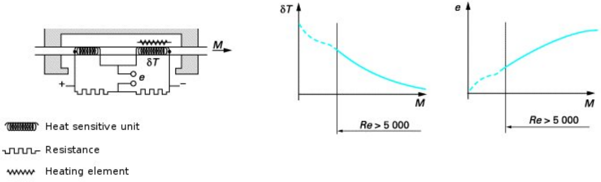




- One heating element with a constant heat input is placed in the middle of a flow tube, between two thermocouples (attached equidistant upstream and downstream of the heater).
- **The differential temperature at flowing conditions increases with increasing fluid velocity.**
- Turndown ratio 1:10

Thermal flow meter

Thermal dispersion gas mass flow meter



- A sensor tube is used with two temperature coils. As gas flows through the device, it carries heat from the upstream coil to the downstream coils.
- The temperature differential generates a proportional change in the resistance of the sensor coils. Resistance change is proportional to mass flow rate.
- It is difficult to get a strong signal using thermal mass flow meters in liquids, due to considerations relating to heat absorption.
- **Higher velocity flows result in a greater cooling effect.**

Thermal flow meter

Thermal dispersion gas mass flow meter

- Gas must be dry and free of particules
- Slow response times
- Accuracy: 5%

$$W = \alpha S \Delta T$$

W:Thermal power
S:Heating element surface
α:Convective coefficient linked to mass flow rate
ΔT:Temperature difference between upstream and downstream sensors

if $Re > 5000 \Rightarrow W = kQ_m^{0.8}\Delta T$

Ultrasonic flow meter

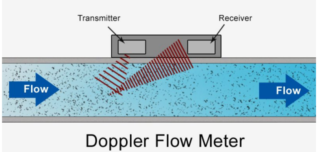
- For gas and liquid flows
- This flow meter (mass flow meter or volumetric flow meter) uses transducers to transmit and/or receive ultrasonic waves (frequency>20kHz) to measure the velocity of the fluid
- Measurement of the transit time of both signals is proportional to the flow rate
- **Advantages:**
  - Non-invasive method
  - Effect of viscosity on pipe flow rate is negligible
  - Causes negligible pressure drop (= equivalent length of a straight pipe)
- **Disadvantages:**
  - Expensive tool

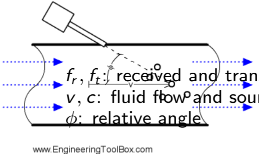
Different types of ultrasonic flow meter

- **Doppler ultrasonic flow meter**
- **Transit time ultrasonic flow meter**

Ultrasonic flow meter

Doppler ultrasonic flow meter





f_r, f_t: received and transmitted frequencies
v, c: fluid flow and sound velocities
ϕ: relative angle

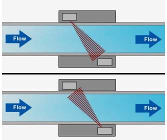
$$v = \frac{c(f_r - f_t)}{2 f_t \cos\phi}$$

- Ultrasonic waves transmitted into the fluid are reflected off particles and bubbles in the flow
- The frequency change between the transmitted wave and the received wave to measure the fluid flow velocity
- Applications: dirty liquids and slurries
- **Disadvantages:** Measurement depends on particle density, flow profile, fluid density and temperature.

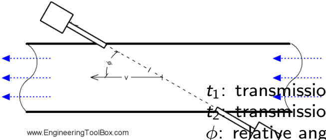
Movie

Ultrasonic flow meter

Transit time ultrasonic flow meter



Time of Flight Flow Meter



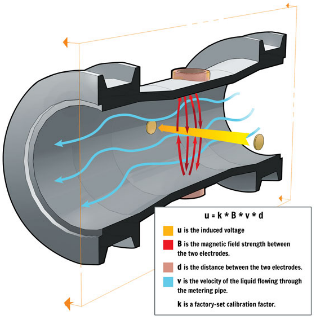
t_1: transmission time downstream
t_2: transmission time upstream
ϕ: relative angle
l: distance between sensors

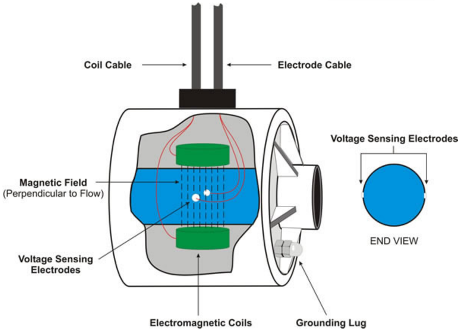
$$v = \frac{t_2 - t_1}{t_2 t_1} \left(\frac{l}{2 \cos \phi} \right)$$

- Two ultrasonic signals are transmitted accross a pipe: one traveling with the flow and the other traveling against the flow. The signal traveling with the flow is faster than the other.
- The ultrasonic flowmeter measures the transit time of both signals: difference between these two times is proportional to the flow rate.
- Applications: clean liquids and gases
- **Advantages:** Turndown ratio 20:1

Electromagnetic flow meter

Movie





- This flow meter operates on Faraday's law of electrmagnetic induction: a voltage will be induced when a conductor moves through a magnetic field.
- A pair of magnetic coils permit on induce a magnetic field in a non-magnetic pipe pipe. When a conductive fluid flows through this magnetic field, a voltage is measured by a pair of electrodes.

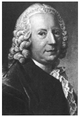
Movie

Electromagnetic flow meter

- Electromagnetic flowmeters (or Magmeters) can measure difficult, corrosive and abrasive liquids and slurries
- **Advantages:**
  It does not matter whether the flow is laminar or turbulent
  Accuracy: 0.5%
  Measurement is independant of viscosity, density, temperature and pressure
  No moving parts
  No obstruction to flow and no pressure drop
- **Disadvantages:**
  Relatively high power consumption
  Applications: only for electrival conductive fluids (as water)
  Air and gas bubbles will cause errors
  The fluid should be full in the pipe to get accurate results
  The output voltage is low and hence requires amplification

Differential pressure flow meter

- Differential pressure flow meters are the most commonly used flow measurement technique in industrial applications
- Bernoulli first established the relationship between static and kinetic energy in a flowing stream.



- As a fluid passes through a restriction, it accelerates, and the energy for this acceleration is obtained from the fluid static pressure. The pressure differential developed by the flow element is then measured: the downstream pressure is lower than the upstream pressure.
- When the flow increases, more pressure drop is created (the pressure drop is proportional to the square of the flow rate).
- This technique is used for flow of liquids and gases (relatively clean fluids but corrosive fluids can be measured too).

Differential pressure flow meter

- **Bernoulli's principle (1738)**
  Assuming a horizontal incompressible irrotational flow of an ideal fluid, along a streamline:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \qquad (1)$$

where: p: pressure
ρ: density
v: flow velocity

Assuming uniform velocity profiles in the upstream and downstream flow, the continuity equation can be expressed as:

$$Q_v = v_1 A_1 = v_2 A_2 \qquad (2)$$

where: Q_v: volumetric flow rate
A: flow area

Then, if $A_1 > A_2$:

$$Q_v = A_2 \sqrt{\frac{2\left(p_1 - p_2\right)}{\rho\left(1 - \left(A_2/A_1\right)^2\right)}} \qquad (3)$$

Differential pressure flow meter

We can also expressed this equation (3) as:

$$Q_v = C_d \frac{\pi D_2^2}{4} \sqrt{\frac{2(p_1 - p_2)}{\rho(1 - d^4)}} \quad (4)$$

with: D_2: orifice inside diameter
D_1: upstream and downstream pipe diameter
$d = \frac{D_2}{D_1}$: diameter ratio

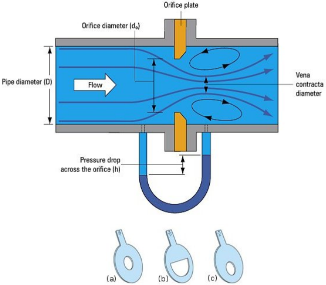
Different types of Differential pressure flow meter

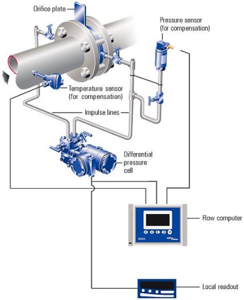
- Orifice plate flow meter
- Venturi meter
- Nozzle flow meter

Movie

Differential pressure flow meter

Orifice plate flow meter

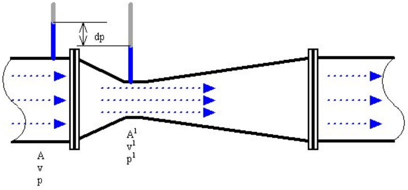




- 3 geometry types: (a) concentric, (b) segmental and (c) eccentric
- 3 methods of placing pressure taps: flange location (1 inch on each side of the plate), "vena contracta" location (1 pipe diameter upstream and from 0.3 to 0.8 pipe diameter downstream), pipe location (2.5 times nominal pipe diameter upstream and 8 times nominal pipe diameter downstream)

Differential pressure flow meter

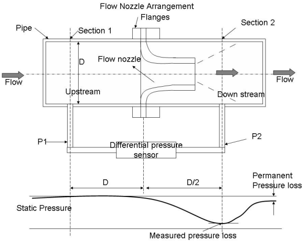
Venturi meter



- The fluid is accelerated through a converging cone of angle 15 − 20° and the pressure difference between the upstream side of the cone and the throat is measured and provides a value for the volumetric flow rate
- The flow area is minimum at the throat.
- Because of the cone and the gradual reduction, there is no "vena contracta".
- Standard value of C_d is 0.975 but this value varies noticeably at low values of Re.
- The pressure recovery is much better for the ventury meter than for the orifice plate.

Differential pressure flow meter

Nozzle flow meter



Discharge Coefficient - c_d				
Diameter Ratio	Reynolds Number - *Re*			
$d = D_2 / D_1$	10^4	10^5	10^6	10^7
0.2	0.968	0.988	0.994	0.995
0.4	0.957	0.984	0.993	0.995
0.6	0.95	0.981	0.992	0.995
0.8	0.94	0.978	0.991	0.995

- 3 different types:
  - The ISA 1932 nozzle: developed in 1932 by the Intern,ational Organisation for Standardization
  - The long radius nozzle: variation of ISA 1932 nozzle
  - The venturi nozzle: hybrid having a convergent section similar to the ISA 1932 nozzle and a divergent similar to a venturi tube flowmeter

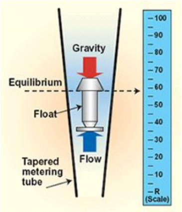
Differential pressure flow meter

Comparisons of orifice plate, ventury and nozzle flow meters

Flow meter	Applications	Turndown ratio	Pressure loss	Accuracy	Cost
Orifice plate	clean and dirty liquids slurries	5:1	medium	2 to 4%	low
Venturi meter	clean dirty and viscous liquids slurries	10:1	low	1%	medium
Nozzle	clean and dirty liquids	4:1	medium	1 to 2%	medium

Variable Area Flowmeter or Rotameter

Movie



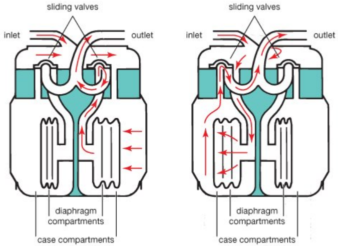
- A rotameter consists of a vertically oriented glass (or plastic) tapered tube with a larger end at the top and a metering float which is free to move within the tube.
- The float rises in the tube due to the fluid flow as the upward pressure differential and buoyancy of the fluid overcome the effect of gravity.
- The float rises until the annular area between the float and tube increases sufficiently to have a state of dynamic equilibrium.
- The flow rate is indicated by the height of the float. The tube can be calibrated and graduated in appropriate fluid units.

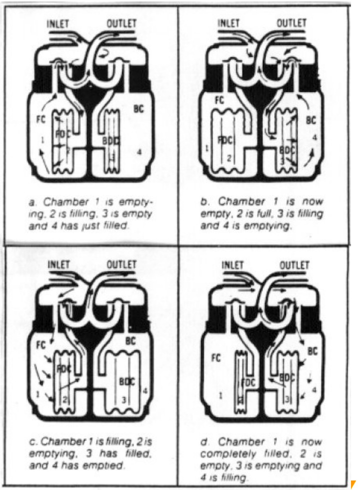
Variable Area Flowmeter or Rotameter

- Magnetic floats can be used for alarm and signal transmission functions.
- Floats are made in different shapes (spheres and ellipsoids are commonly use)
- **Advantages**
  - It requires no external power or fuel.
  - Scale is approximaly linear.
  - Low cost
  - Low pressure drop
- **Disadvantages**
  - It must always be vertically oriented with the fluid flowing upward
  - Graduations on a given rotameter will only be accurate for a given fluid at a given temperature
  - Effects of fluid density and viscosity
  - Use of transparent material
- Turndown ratio: 12:1
- Accuracy: 1%

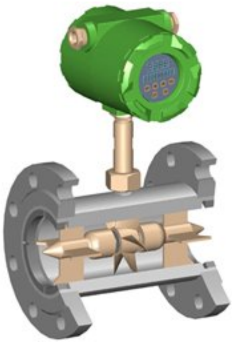
Diaphragm gas flow meter

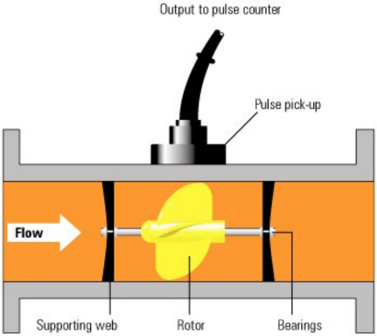
- The diaphragm flow meter consists of 2 or more chambers formed by movable diaphragms. Chambers are alternatively fill and expell gas with the flow directed by internal valves induces.
- As the diaphragms expand and contract, levers connected to cranks convert the linear motion of the diaphragms into rotary motion of a crank shaft which can drive an odometer (like counter mechanism) or can produce electrical pulses.





Turbine flow meter





- A multi-bladed rotor mounted at right angles of the flow is suspended in the fluid stream on a free-running bearing. The diameter of the rotor is slightly less than the inside diameter of the flowmetering chamber.

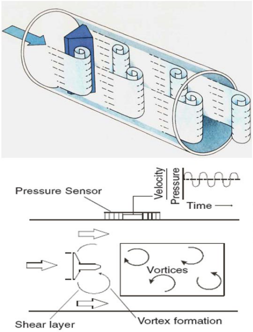
Turbine flow meter

- Rotor speed is proportional to the volumetric flow rate. The speed of rotation is determined using an electronic proximity switch mounted on the outside of the pipework, which counts the pulses.
- **Advantages**
  - Relatively low cost
  - Turndown ratio 25:1
  - Accuracy: 0.5%
- **Disadvantages**
  - Any steam pressure variations will lead to inaccuracies
  - Wet steam can damage the turbine wheel and affect accuracy
  - Low flow rates can be lost due to the insufficient energy to turn the turbine wheel
  - Viscosity sensitive
  - Fluid must be very clean

Vortex shedding flow meter

Movie

Also called Vortex flow meter or oscillatory flow meter



- A small obstruction called bluff-body is placed in the flow path. As fluid flows accross the bluff-body, small low pressure areas called vortices are created just downstream the bluff-body. The vortices trail behind the obstruction in two rolls, alternatively on each side of the bluff-body (Von Karman vortex street).

Vortex shedding flow meter

- The frequency of the vortices shift is directly proportional to flow rate. This shift is detected by a very sensitive pressure sensor.
- Volumetric flow rate is expressed as:

$$Q_v = \frac{f \pi D^3}{4St} \left(\frac{w}{D} \right) \left(1 - \frac{4}{\pi} K \frac{w}{D} \right)$$

  w: width of the bluff-body
  D: pipe diameter
  K: factor to compensate for the non-uniform profile of the pipe flow
  f: vortex shedding frequency
  St: Strouhal number

- **Advantages**
  - No moving parts
  - Low cost
  - Not much maintenance needed when used in clean flow conditions
- **Disadvantages**
  - No coorosive or dirty liquids
  - Low to medium pressure drop due to the obstruction in the flow path.

Movie

Comparison of flow meters

Flow meter	Turndown ratio	Accuracy (% of full scale)
Orifice plate flow meter	5:1	2 to 4
Venturi flow meter	10:1	1
Nozzle flow meter	4:1	1 to 2
Rotameter	12:1	1
Turbine flow meter	10:1	0.5
Diaphragm flow meter	80:1	1
Ultrasonic flow meter	50:1	0.3 to 2
Coriolis flow meter	10:1	0.1
Electromagnetic flow meter	10:1	0.5
Vortex flow meter	3:1	2.5

Comparison of flow meters

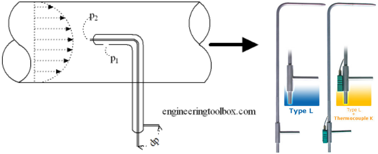
Flow meter	Low flow	High flow	High P	High T	High viscosity
DP flow meter	g/l	g/l	l	l	
Rotameter	g/l	g/l		g/l	
Turbine flow meter	g/l	l	l	l	
Ultrasonic flow meter	l	l	l	l	
Magmeter	l	l	l	l	
Vortex flow meter	l	g/l	g/l	g/l	l

g: gas
l: liquid

Outline

Movie

Pitot tube



- Pitot-static tube can measure the fluid flow velocity by converting the kinetic energy in the fluid flow into potential energy.
- This pressure measurement instrulment used to measured fluid flow velocity is widely used to determine the airspeed of an aircraft and to measure gas velocities in industrial applications.
- Measure of the local velocity at a given point in the flow stream.

Pitot tube

- A Pitot-static tube (or Prandtl tube) consists of 2 concentric elbowed tubes with 2 holes:
  - External tube opens perpendicularly to the flow. Pressure inside this tube is then equal to the ambient pressure, called static pressure.
  - Internal tube is parallel to the flow and is opened face to the flow. Pressure inside this tube is the total pressure (also called stagnation pressure) and is the sum of the static and the dynamic pressures.
- A manometer measures the pressure difference between the 2 tubes to calculate the dynamic pressure which permit to have the fluid velocity around the tube.
- Bernoulli's equation:

For an incompressible flow:

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

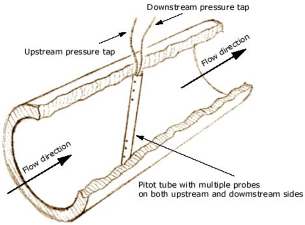
if $z_1 = z_2$ and $v_2 = 0$, then: $\frac{v_1^2}{2} + \frac{p_1}{\rho} = \frac{p_2}{\rho}$

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

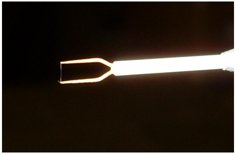
Pitot tube

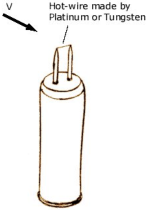
- **Advantages:**
  - Low cost
  - It can be used in wide ranges of fluid phases and flow conditions
  - Turndown ratio 10:1
- **Disadvantages:**
  - Medium to high pressure drop
  - If the velocity is low, the difference in pressures may be too small to have a good accuracy with the transducer.
  - Wrong results for clogged or pinched tubes.

Averaging Pitot tube



Hot wire anemometer

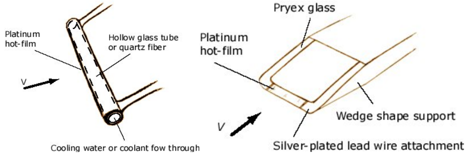




- Hot wire anemometer measures fluid velocity by noting the heat convected away by the fluid.
- The core of the anemomenter is an exposed hot wire either heated up by a constant current or maintained at a constant temperature.
  - CCA: Constant Current Anemometer
  - CVA: Constant Voltage Anemometer
  - CTA: Constant Temperature Anemometer
- The heat lost to fluid convection is a function of the fluid velocity.

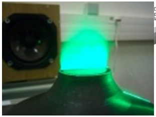
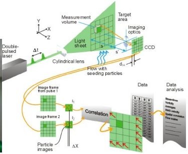
Hot wire anemometer

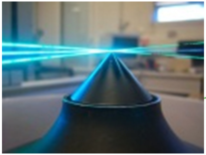
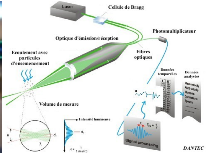
- Typically, the anemometer wire is made of platinium or tungsten and is 4 to 10μm in diameter and 1mm in length.
- **Advantages:**
  - Excellent spatial resolution
  - High frequency response ($>$ 10kHz, up to 400kHz)
- **Disadvantages:**
  - Suitable only for clean gas flow
  - It needs to be recalibrated frequently due to dust accumulation
  - High cost
- Another alternative is a pyrex glass wedge coated with a thin platinium hot-film at the edge tip.



Optical methods to measure fluid flow velocity

- 2D or 3D velocity measurements
- Image post-processing

Optical methods

- **Particle Image Velocimetry (PIV)**
- **Laser Doppler Velocimetry (LDV)**
- **Particle Tracking Velocimetry (PTV)**