



INSTRUMENTATION MAINTENANCE

MEASUREMENTS IN INSTRUMENTATION

TRAINING MANUAL
Course EXP-MN-SI020
Revision 0

INSTRUMENTATION MAINTENANCE

MEASUREMENTS IN INSTRUMENTATION

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1. OBJECTIVES

The purpose of this course is to enable a would-be instrument engineer to understand the basics of instrumentation on a predominantly oil industry site.

By the end of the course, within the field of measurements in instrumentation, the participant must:

- ✦ Be familiar with the various pressure measurement principles,
- ✦ Be familiar with the various fluid flows,
- ✦ Be familiar with the international system measurement units (SI),
- ✦ Know the principle of buoyancy,
- ✦ Be able to make unit conversions.
- ✦ Be familiar with an instrument's measurement signals.
- ✦ Be able to distinguish measurement units.
- ✦ Know how to measure an electrical quantity with a multimeter.
- ✦ Know how to calculate volume and surface area.

2. PHYSICAL QUANTITIES

2.1. PRESSURE AND RELATIVE UNITS

In industry, fluids are practically always used under pressure to some extent: whether as a source of energy to actuate manufacturing machinery, to be conveyed in pipes over sometimes considerable distances or to be stored at reduced volume.

It is readily understandable that it is important to be able to measure the pressure as accurately as possible for the rational fluid use.

2.1.1. Definition of pressure

By definition, pressure is the force exerted by a fluid perpendicular to a surface over the unit surface area. Expressed in international system units (SI), pressure is equivalent to Newtons per metre squared. Pressure is expressed in Pascal (Pa).

A Pascal is the uniform pressure which, acting on a flat surface of one metre squared, exerts perpendicular to this surface a total force of one Newton.

We deduce the following relation from this:

$$P = \frac{F}{S} \quad P \text{ in Pa (Pascal)} \quad F \text{ in N (Newton)} \quad S \text{ in m}^2$$

2.1.2. The units of pressure

In the international metric system (SI), the unit of pressure is therefore the **Pascal** (Pa): a pressure of 1 Pascal corresponds to a force of 1 Newton exerted on a surface of 1 m².

Hence: **1 Pa = 1 N / 1 m²**

The unit for practical purposes is the **bar**

1 bar = 10⁵ Pa **1 mbar = 100 Pa = 1 hPa**

The Anglo-Saxon Unit is the *psi* (pounds force per square inch: lbf / in²)

1 psi = 6894 Pa # 69 mbar **1 bar = 14.5 psi**

1 atm = 101,325 Pa (atm = atmosphere)

1 mmHg = 1 torr = 133 Pa (mmHg = millimetres mercury)

Pressure units	Pa	bar	Kgf/cm ²	atm	cm water	mm Hg	psi
1 Pa	1	10 ⁻⁵	1.02 10 ⁻⁵	0.9869 10 ⁻⁵	1.02 10 ⁻²	7.5 10 ⁻³	1.451 10 ⁻⁴
1 bar	10 ⁵	1	1.02	0.9869	1.02 10 ³	750	14.51
1 kgf/cm ²	98 10 ³	0.980	1	0.968	1.02 10 ³	750	14.51
1 atm	101,325	1.013	1.033	1	1033	760	14.70
1 cm water	98	98 10 ⁻⁵	10 ⁻³	0.968 10 ⁻³	1	0.735	0.01422
1 mm Hg (torr)	133.33	13.33 10 ⁻³	1.36 10 ⁻³	1.315 10 ⁻³	1.36	1	0.01934
1 inch Hg	3.386	33.86 10 ⁻³	0.03453	0.03345	34.53	25.4	0.4910
1 psi	6895	6.89 10 ⁻²	0.07032	0.068	70.3	51.75	1

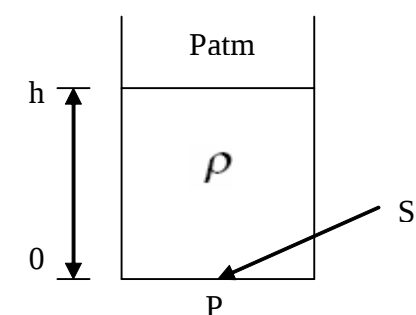
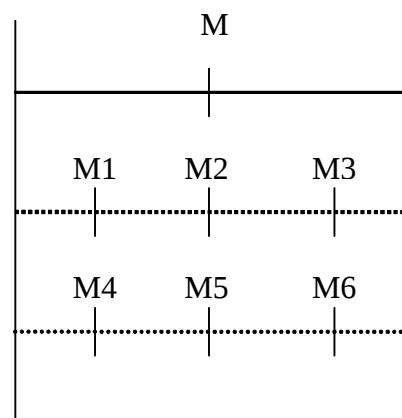
Table 1: Table of correspondence between pressure units

2.1.3. Pascal's law

The pressure at a point in a fluid in equilibrium is constant over the whole horizontal surface S denoted by M.

In this case: $P_{M1} = P_{M2} = P_{M3}$ and $P_{M4} = P_{M5} = P_{M6}$ but $P_{M1} \neq P_{M4}$

For an incompressible fluid (liquid), the pressure variation between two levels is proportional to the head difference between these same levels.



$$P = F / S$$

$$\text{Mass } m = \rho \times V$$

$$\text{Volume } V = S \times h \text{ hence } P - P_{\text{atm}} = \rho \times g \times h$$

$$\text{Pascal's law tells us: } P = \rho \times g \times h$$

P : relative pressure (Pa)

H : fluid head in (m)

ρ : density of fluid (kg/m³)

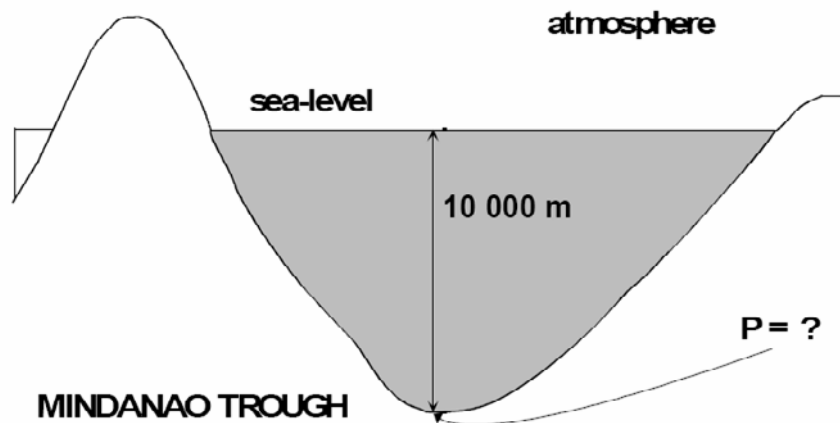
g : acceleration of gravity (m/s²)

Note:

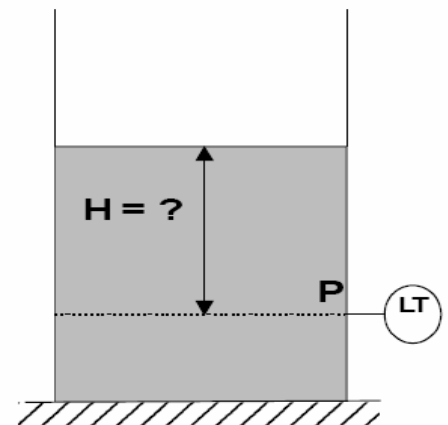
- ⊕ The volume of liquid or shape of the contents make no difference
- ⊕ But any pressure there may be above the surface of the liquid needs to be taken into account.

2.1.4. Exercises

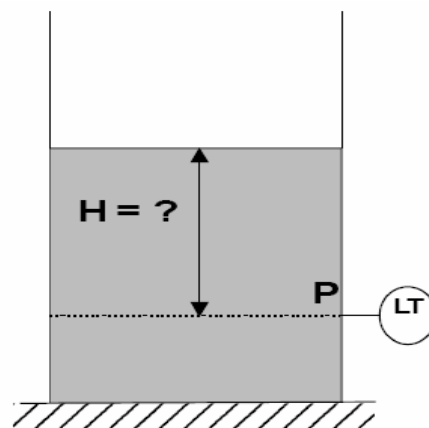
1. We want to know the pressure exerted on the MINDANAO TROUGH. To do so we know that the depth is 10,000 m and the density of water, which is 1000 kg / m^3 .



2. The tank contains water at a density of 1000 kg / m^3 . The instrument measures a pressure of **0.60 bar**, what is the liquid head?



3. The tank contains a fluid with a density of **$950 \text{ kg} / \text{m}^3$** ; the instrument measures a pressure of 0.6 bar.
What would be the liquid head?



4. Convert 10 mm Hg into mbar?

5. Convert 19 psi into bar?

6. Convert 2.5 m into bar?

2.1.5. The various types of pressure

2.1.5.1. Atmospheric pressure

This represents the pressure exerted by the layer of air surrounding the Earth under the action of gravity.

This pressure varies with latitude, altitude and meteorological conditions.

Example:

When you watch the weather forecast on the television after the national news, you will see that the presenter always uses Hectopascal (hPa); this is atmospheric pressure.

Mean atmospheric pressure at sea level, subject to $g = 9.81 \text{ m/s}^2$, is equal to 760 mmHg or 101,325 Pa, 1013.25 hPa or 10.332 mWC.

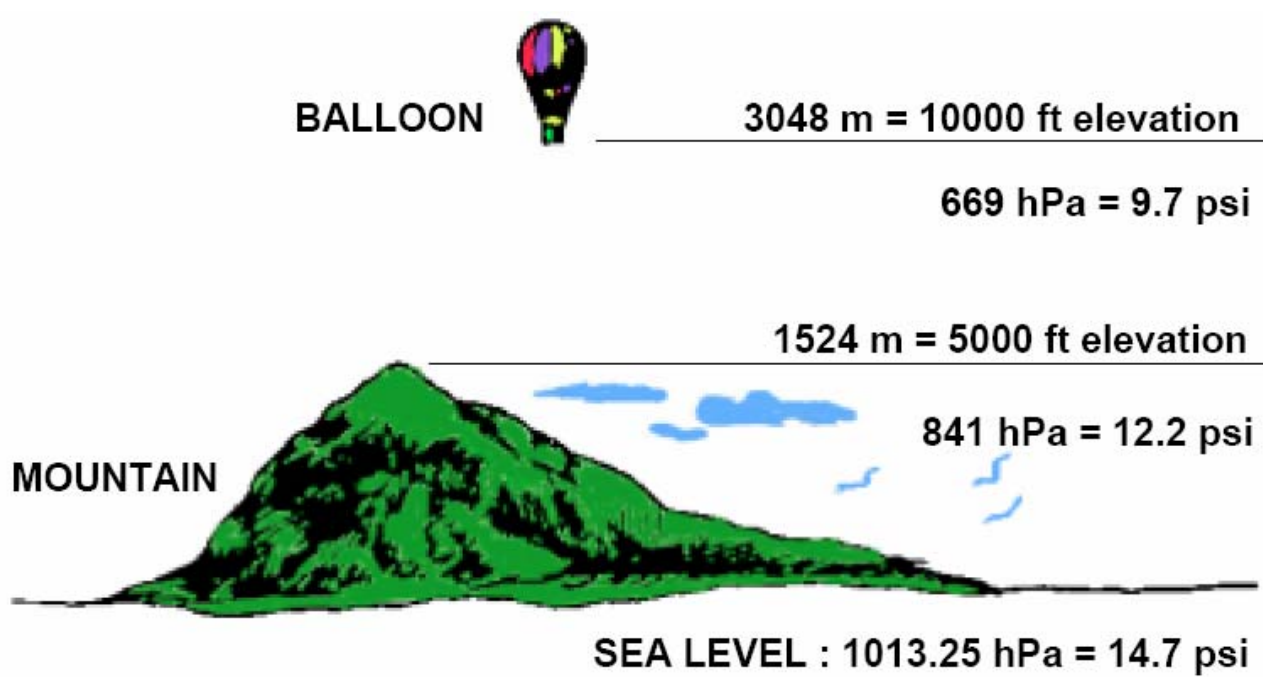


Figure 1: Atmospheric pressure variations

Note that this helps understand why we say that atmospheric pressure decreases with altitude: up a mountain, there is a smaller air column overhead.

At sea level, the human body can withstand a pressure of 1 kilogram per centimetre squared. This means that the average human being can withstand around a tonne of air! Fortunately, our internal pressure pushes outward to balance the air pressure.

At an altitude of 5000 metres, the pressure is half that at sea level.

It is lighter, but that also means that there is half the oxygen as in the same volume of air, and so mountaineers tackling the Himalayas need oxygen cylinders!

Atmospheric pressure is measured with a barometer.

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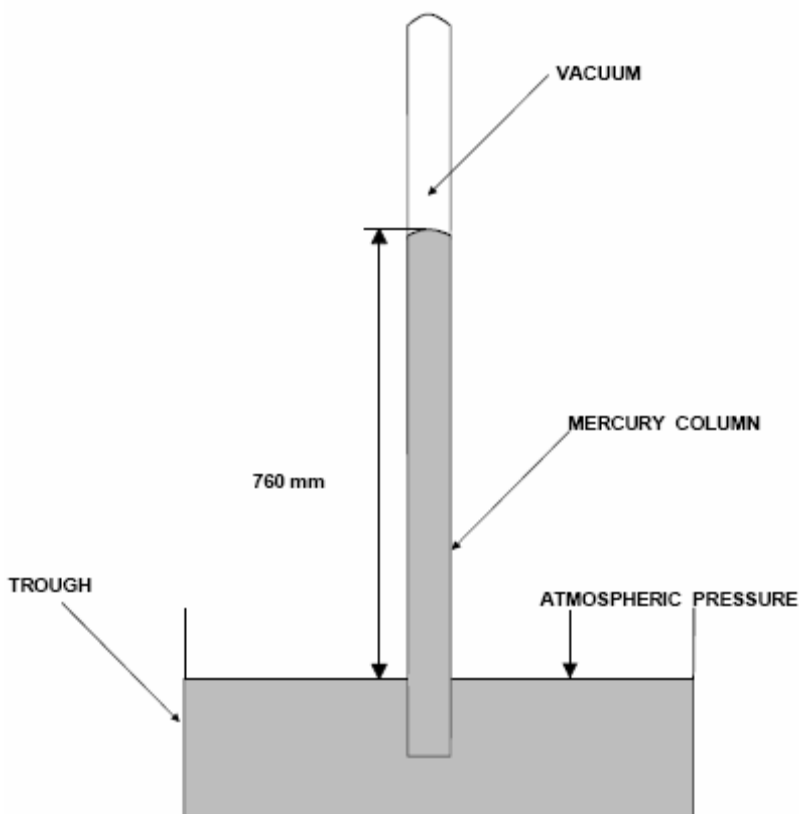


Figure 2: An aneroid barometer

The atmospheric pressure value can also be measured with the TORRICELLI barometer.

TORICELLI's experiment

A tube of mercury was completely filled, plugged with a finger to prevent air from entering, and inverted over a trough, also filled with mercury.



It was observed that the tube did not empty fully into the trough, but that a column of mercury - of **76 cm (= 760 mmHg or 1013.25 mbar)** – remains in the tube.

Figure 3: Torricelli's tube or mercury barometer

There are two precisely mutually compensating forces acting on the bottom surface of the tube: the weight of the column, which tends to pull down the mercury into the trough, and the force exerted by the air, which presses on the liquid and prevents the mercury column from emptying.

This force exerted by the air per unit surface area is **atmospheric pressure**.

If the mercury is replaced by water, the force exerted by air on the tube base is equal to the weight of a **10 m column** (1 bar = 10 WC). Hence it was the physical rather than the technological constraint that fountain engineers were up against.

The Academy of Sciences would pay tribute to Torricelli by baptising his invention with the name *Torricelli's barometer*.

Meanwhile, Pascal was also interested in the concept of *atmospheric pressure*: in particular he took measurements with the barometer at different altitudes.

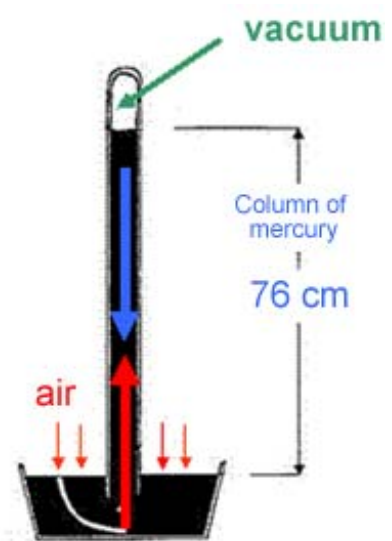
Both have given their name to a pressure unit: **the torr** (which equates to a mercury column height of 1 mm), and the **Pascal** (atmospheric pressure is close to 100,000 Pa).

2.1.5.2. Vacuum

A vacuum is a pressure below atmospheric pressure.

When the mercury in the tube drops into the trough, *what is actually there above the column?* **A vacuum**: to better understand what a vacuum is, we need to try to analyse what pressure is. Like temperature, it is a way of finding an average measurement on our scale of what is happening at microscopic level in matter.

Figure 4: Vacuum



In a gas such as air, the molecules (in this case N_2 and O_2) are isolated. No interactions are established between them, unlike with liquids and even more so with solids.

They move at high velocity (330 m/s in air at 25°C): but on the other hand, they collide extremely frequently: 10 billion times per second at ambient temperature. If we consider the boundary surface between the gas and liquid (e.g. the water or mercury column), the pressure is the force exerted by the molecules colliding on each unit of surface area.

If we keep the same number of molecules in the same volume and lower the temperature, the molecules will go less quickly, and there will be fewer collisions: the pressure will drop. If we reduce the number of molecules in the same volume, the pressure will also drop, since they will have less opportunity to collide.

We talk about a “vacuum” when the pressure is below atmospheric pressure, but this covers a wide range, from the depressions responsible for bad weather to the interstellar vacuum.

If you go into a physics laboratory or visit large-scale facilities such as particle accelerators, you will see huge grey metal enclosures surrounded with pumps, to evacuate them, i.e. suck out all the molecules (N_2 , O_2 , steam) and go down to pressures from 1 million to 1 trillion times lower than atmospheric pressure.

To what end? Precisely to avoid collisions between particles accelerated up to close to light velocity and residual gas molecules.

Figure 5: Example of vacuum pump



At this velocity and this energy, each collision with a residual molecule is “fatal” for the particle.

And it is the collisions between particles that the researchers are interested in, not those between particles and residual molecules!

2.1.5.3. Relative pressure

This is a pressure with real atmospheric pressure as its reference. Relative pressure is the most frequently used, since most pressure sensors subject to atmospheric pressure give a relative measurement.

Relative pressure is always positive, but may also be negative (in a vacuum).

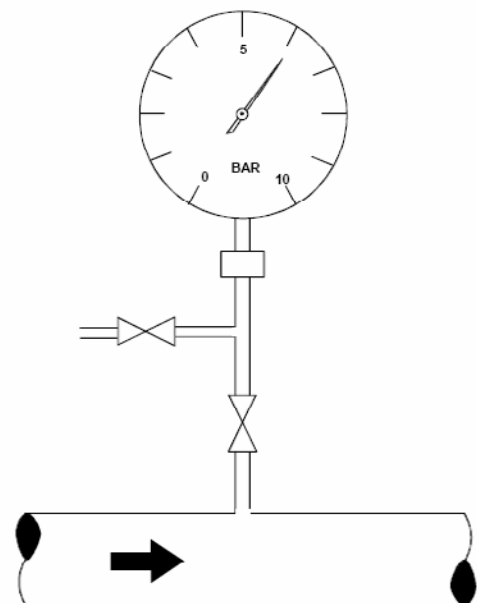
$$P_{\text{relative}} = P_{\text{measured}} - P_{\text{atmospheric}}$$

Example:

On all instrumentation air manifolds in the oil industry we make a relative pressure measurement of 6 bar in order to check for an air leak at different times.

So this measurement is made either by relative pressure gauges or relative pressure sensors

Figure 6: Relative pressure measurement



2.1.5.4. Absolute pressure

Absolute pressure is the sum of relative pressure and atmospheric pressure.

The start point of this pressure is zero. The zero point is of course **absolute vacuum**: as we approach this point we talk about **high vacuum**.

We can often add 1 bar (1013.25 mbar) to relative pressure to make it an absolute pressure, but we should remember that the exact quantity to add is the atmospheric pressure at the point where the measurement is made when we need the absolute pressure.

This justifies the presence of a barometer in the instrumentation workshop, particularly if gases are used in operations.

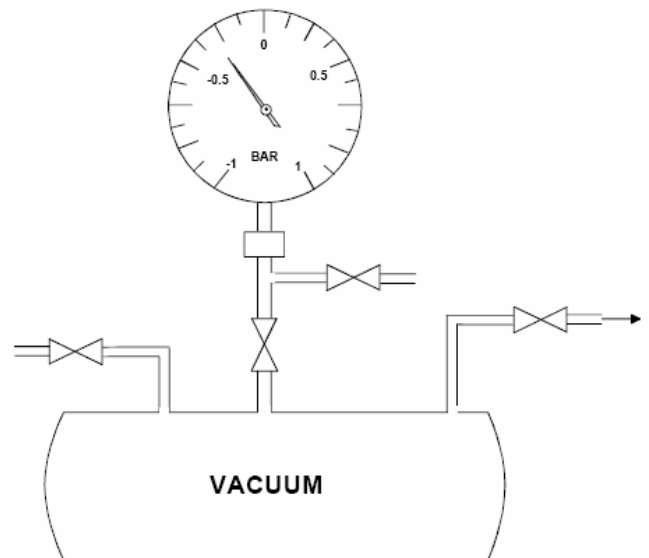
Example:

In this tank there is one part under pressure, and we measure with a pressure gauge at relative pressure – **0.2 bar relative**.

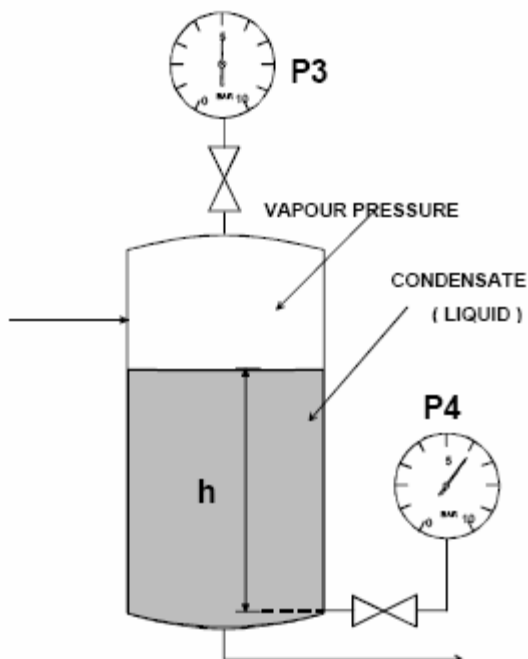
This means that the pressure is 0.2 bar less than atmospheric pressure. If on the day of this measurement, there is an atmospheric pressure of 1012 mbar, then we have an absolute pressure inside the tank of: $1012 - 200 = 812$ mbar.

$$P_{\text{abs}} = 812 \text{ mbar}$$

Figure 7: Absolute pressure measurement



2.1.5.5. Differential pressure



This designates the difference between two pressures. Its measurement is independent of the temperature and atmospheric conditions.

Differential pressure may be used as a level and flow measurement.

Example:

The pressure difference between P3 and P4 will be proportional to the liquid head in the reservoir (Pascal's law).

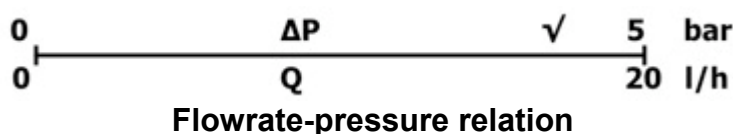
$$P_{\text{differential}} = P4 - P3$$

Figure 8: Example of level measurement with differential pressure

The method of deducing the flowrate from the differential pressure is very common for instrument engineers.

- ✚ The orifice plate, Pitot tube and Venturi use this method
- ✚ Differential pressure measurement is a very good indicator of filter clogging, for example.

The flowrate Q is proportional to the square root of the pressure difference P . So we can represent the relation between flowrate and measured pressure difference.



Hence the relation: $Q = k \times \sqrt{\Delta P}$

Any flowrate and pressure units can be used, as long as the coefficient K is calculated with these units.

For commonplace calculations and for instrumentation maintenance, it is not essential to understand how two pressure measurements made on the circumference of a pipe (i.e. the outside of the main fluid vein) can be used to find out the flowrate.

But it is an interesting question, and diaphragm measurements are so commonly used that it is good to have an idea of how it works.

2.1.6. Pressures related to fluid circulation

There are three sorts of pressure considered when a fluid is circulating in a pipe:

- ✚ **Static pressure,**
- ✚ **Dynamic pressure,**
- ✚ **Total pressure.**

2.1.6.1. Static pressure

Static pressure is the pressure of the fluid at rest in a pipe. In other words, it is the relative excess pressure or depression created by the action of a pump or fan.

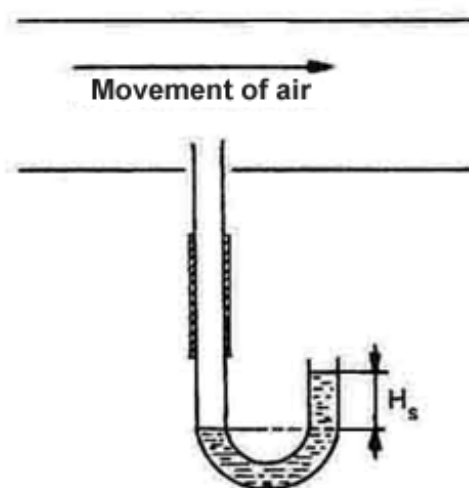
At zero flow, the value of this pressure is the same at any point of the pipe cross-section.

Static pressure is measured perpendicular to the direction of air movement.

Figure 9: Example of static pressure measurement with a U pressure gauge on the pipe

Depending on the position of the measurement (discharge or suction), the static pressure may be greater or less than atmospheric pressure.

Measured pressures are actually pressure differences between the static pressure of the liquid and atmospheric pressure. They are therefore relative pressures.



2.1.6.2. Dynamic pressure

Dynamic pressure is also known as kinetic energy.

It is a pressure due to the fluid velocity in the pipe. It acts on the orifice of a tube placed in the direction of the current (most often a Pitot tube or an annubar probe), by increasing the static pressure by a value proportional to the square of the fluid velocity.

Hence the relation: $P_{dynamic} = P_{dy} = \rho \times \frac{v^2}{2}$

P_{dy} : dynamic pressure in Pa

ρ : density in kg/m^3

v : fluid velocity in m/s

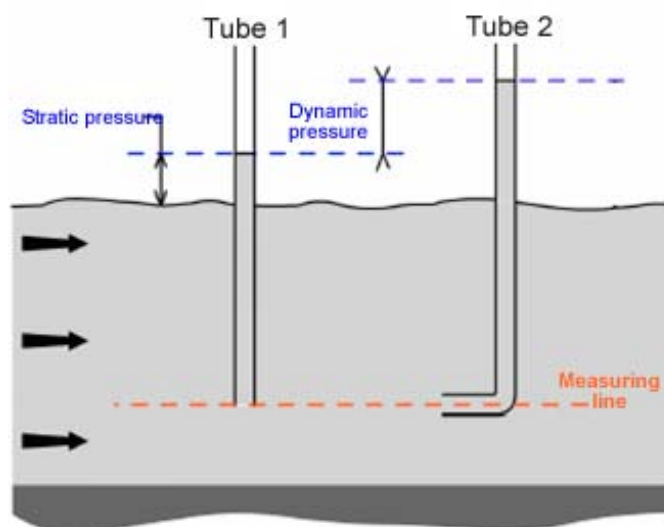
Therefore we can determine the velocity by measuring dynamic pressure, hence

the formula below: $v = \sqrt{\frac{2 \times P_{dy}}{\rho}}$

The dynamic pressure of a flowing liquid can be expressed in metres liquid or in bar.

Its value is generally very low (< 1% total pressure) at normal flow velocities.

Figure 10: Example of dynamic pressure measurement with a pitot tube



Note:

In the case of significant acceleration of a liquid in a convergent tube, we observe a very high increase in kinetic energy, and therefore an equivalent decrease in static pressure.

The latter may even drop below atmospheric pressure, and this phenomenon is used in ejectors.

2.1.6.3. Total pressure

Total pressure is the sum of static and dynamic pressures.

$$P_{\text{total}} = P_{\text{static}} + P_{\text{dynamic}}$$

2.1.7. Relation between the various pressure types

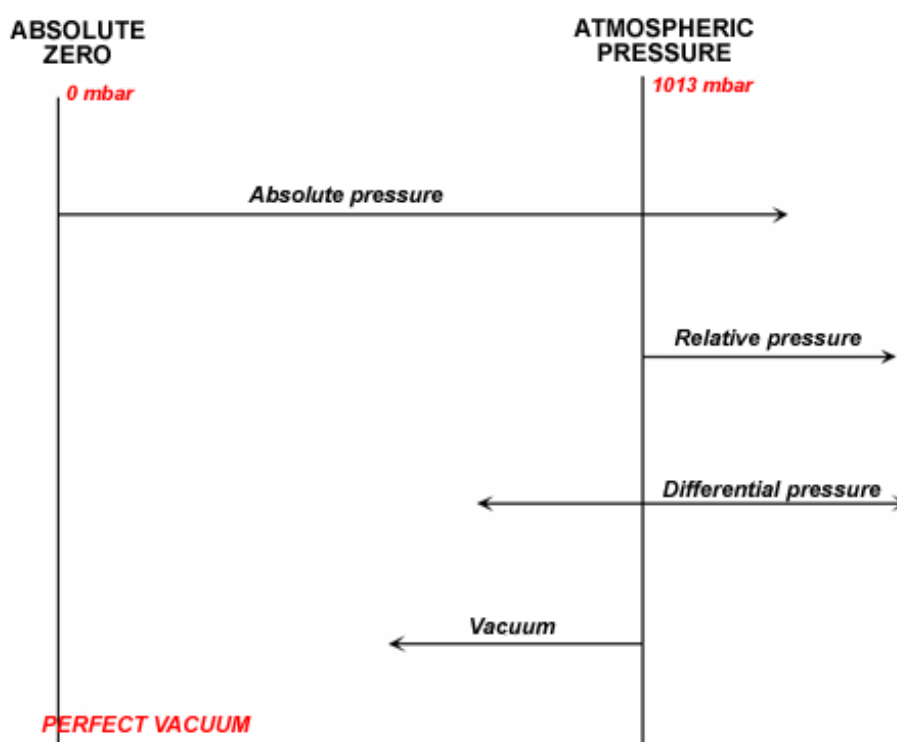


Figure 11: Pressure measurement scales

2.2. LEVEL MEASUREMENT: BUOYANCY

This measurement principle is used for plunger or torque tube level measurements (see sensors and transmitters course).

The resultant of the forces exerted by a fluid on an object immersed in this fluid is vertical, upward and equal to the weight of the volume of fluid displaced.

This resultant is known as **the buoyancy**:

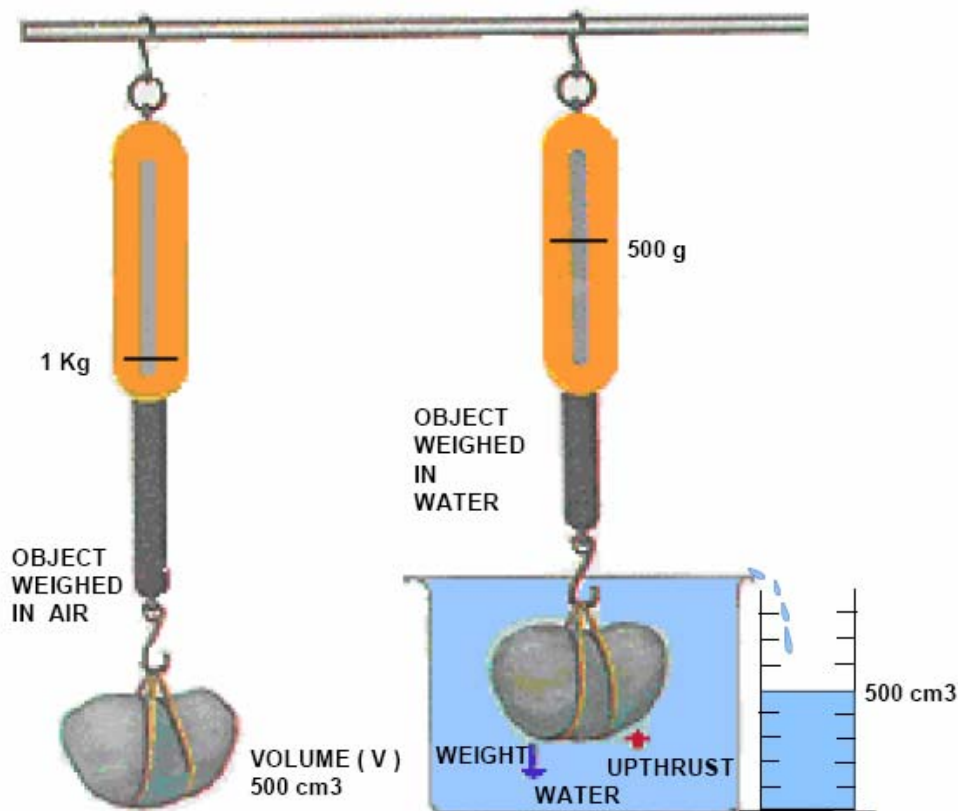


Figure 12: Schematic of buoyancy

Buoyancy (Force F) = volume of fluid displaced x fluid density x acceleration of gravity

$$F = V \times \rho \times g$$

F : force F in Newton (N)

V : volume displaced in m^3

ρ : density in Kg/m^3

g : gravity = $9.81 m/s^2$

Due to this buoyancy, any object immersed in a liquid is lighter than its actual weight

Apparent weight of an object = actual weight – buoyancy : $P_a = P_r - P_A$

If buoyancy > actual weight: the object floats,
If buoyancy < actual weight: the object sinks,
If buoyancy = actual weight: the object is in equilibrium in the liquid,

The Archimedes principle applies to gases, but since their density is low, they often produce negligible buoyancy.

Example:

A diver weighs 90 kg equipped for a volume of 95 litres. In the water he will be subjected to an upward thrust of 95 kg.

His **apparent weight** in the water will be -5 kg (he will float). To be able to submerge he will need to take at least 5 kg of ballast.

If he takes 7 kg of ballast, he will have an **apparent weight** of 2 kg (he will submerge).

Application to diving: ballast calculation, bringing up objects, stabilisation.

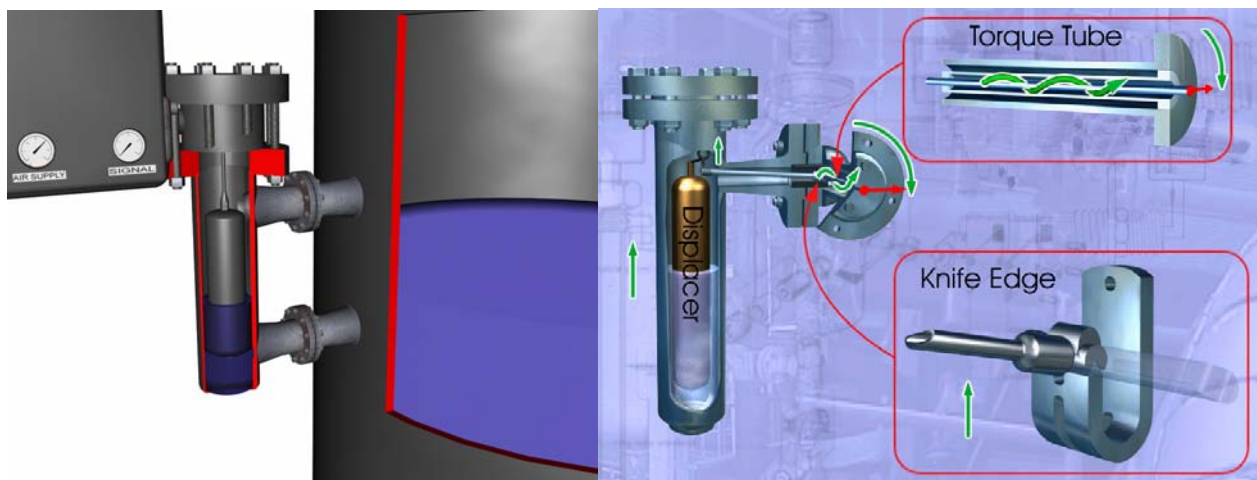


Figure 13: Example of level measurement using buoyancy

The plunger in the tube is subjected to buoyancy, and transmits its displacement via a transmission lever, enabling the level to be measured, as this is proportional to the displacement of the plunger in the tube.

NB: The fluid density must be constant, since it greatly influences the measurement. If the density varies constantly, there will be a risk of considerable measurement errors.

There is more information in the “Sensors and Transmitters” course.

2.3. FLOWRATE MEASUREMENT: FLUIDS IN MOTION

2.3.1. General points

A fluid can be considered to be formed by a number of material particles, which are very small and free to move in relation to each other. So a fluid is a continuous, deformable material medium, which is not rigid and is able to flow. Fluids are often distinguished into liquids and gases.

The liquids and gases usually studied are isotropic, mobile and viscous. The physical property that enables the two to be distinguished is compressibility.

- ✚ Isotropy means that the properties are identical in all spatial directions.
- ✚ Mobility means that they do not have a specific shape, and that they adopt the shape of the vessel containing them.
- ✚ Viscosity characterises the fact that any change in shape of a real fluid is accompanied by resistance (friction).

2.3.2. Volume Forces and Surface Area Forces

As with any mechanics problem, solving a fluid mechanics problem involves defining the material system S, the fluid particles inside a closed surface area limiting S.

The general principles and theorems of mechanics and thermodynamics are applied to this system:

- ✚ principle of conservation of mass.
- ✚ fundamental principle of dynamics.
- ✚ principle of conservation of energy

2.3.3. Definitions

The **flowrate** is the quotient of the quantity of fluid passing through a straight section of pipe by the time taken.

2.3.3.1. Mass flowrate

If Δm is the mass of fluid passing through a straight pipe section in time Δt , by definition the mass flowrate is: $Q_m = \Delta m / \Delta t$ (unit: $\text{kg} \cdot \text{s}^{-1}$)

2.3.3.2. Volume flowrate

If ΔV is the volume of fluid passing through a straight pipe section in time Δt , by definition the volume flowrate is: $Q_v = \Delta V / \Delta t$ (unit: $\text{m}^3 \cdot \text{s}^{-1}$)

2.3.3.3. Relation between Q_m and Q_v

The density is given by the relation: $\rho = \Delta m / \Delta V$ hence: $Q_m = \rho \times Q_v$

Note: Liquids are incompressible and can hardly be expanded (constant density); we then talk about **isovolume flows**.

For **gases**, the density depends on the temperature and pressure. At low velocities (limited pressure variation) and constant temperatures we find isovolume flow.

2.3.3.4. Steady flows

A flow state is said to be **steady** if the parameters characterising it (pressure, temperature, velocity, density, ...) have a constant value over time.

2.3.4. Equation of conservation of mass

2.3.4.1. Definitions

- ✦ **Stream line:** In steady state, a stream line is the curve along which a fluid element moves. A stream line is tangential at each of its points to the fluid velocity vector at this point.
- ✦ **Flow tube:** All the stream lines based on a closed curve.
- ✦ **Flow vein:** Flow tube with a small surface element DS for a base. This base tube cross-section DS is small enough for the fluid velocity to be the same at all its points (uniform distribution).

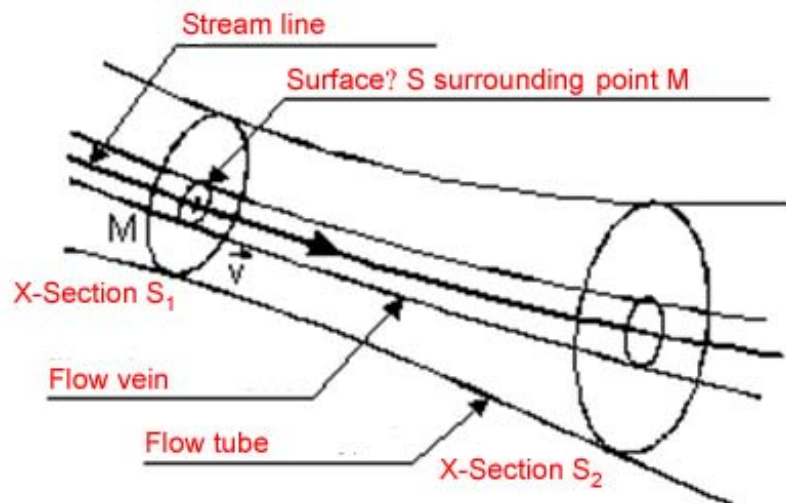


Figure 14: Principle of a fluid moving in a pipe

2.3.4.2. Conservation of flowrate

Let's take a flow tube between two cross-sections S_1 and S_2 (see figure above).

For the infinitely small time interval Δt the mass D_{M1} of fluid passing through section S_1 is the same as the mass D_{M2} passing through section S_2 .

$$Q_{M1} = Q_{M2}$$

At steady state, the mass flowrate is the same through all straight sections of the same flow tube.

In case of **isovolume flow** ($\rho = \text{Cst}$):

$$Q_{V1} = Q_{V2}$$

At steady state, the volume flowrate is the same through all straight sections of the same flow tube

2.3.4.3. Expressing flowrate as a function of velocity

The volume flowrate is also the quantity of liquid occupying a cylindrical volume with base S and length v , equal to the length covered in the time unit by a particle of fluid passing through S .

This gives the important relation: **$Q_V = v \times S$**

2.3.4.4. Mean velocity



Figure 15: Mean velocity

In general the velocity v is not constant over the section S of a flow tube; we say that there is a **velocity profile** (due to friction forces). The mass or volume flowrate is obtained by integrating the relation above:

In a straight pipe section S , the **mean velocity** v_m is the term for the velocity where: $v_m = Q_v / S$

The mean velocity v_m is the apparent uniform velocity through section S providing the same flowrate as the actual velocity distribution.

If the flow is isovolume, this mean velocity is inversely proportional to the area of the straight cross-section.

$$Q_v = v_{1m} \times S_1 = v_{2m} \times S_2 = Cst$$

This is the **equation of continuity**.

The smaller the cross-section, the greater the mean velocity.

$$v_1 / v_2 = S_2 / S_1$$

2.3.5. Bernoulli's theorem

Observations: A ping-pong ball can remain suspended in an angled air jet.
A sheet of paper is sucked up when you blow on it.

Conclusion: The pressure of a fluid decreases as its velocity increases.

2.3.5.1. The steady flow theorem in an incompressible fluid

A *perfect fluid* is a fluid with *friction-free flow*.

Take a steady isovolume flow of a perfect fluid between sections S_1 and S_2 , between which there is no hydraulic machine (no pumps or turbines).

Let m be the mass and V the volume of fluid passing through section S_1 between times t and $t + \Delta t$. In this time the same mass and same volume of fluid passes through section S_2 . The entire phenomenon is as if this fluid had changed from position (1) to position (2).

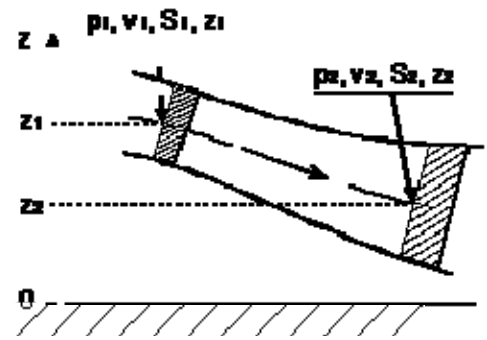


Figure 16: Steady flow in an incompressible fluid

By applying the theorem of kinetic energy to this fluid between times t and $t + \Delta t$ (the kinetic energy variation is equal to the sum of the work of external forces: weights and pressing forces), we obtain:

$$\rho \frac{v^2}{2} + \rho g z + p = Cst$$

p : static pressure

$\rho g z$: gravity pressure

$\rho \frac{v^2}{2}$: kinetic pressure.

All the terms are expressed in Pascal.

By dividing all the terms of the relation above by the product g , we write all the terms in the dimension of a height (pressures expressed in metres fluid column).

$$\frac{v^2}{2g} + z + \frac{p}{\rho g} = H = Cst$$

H : Total head

$\frac{p}{\rho g}$: Pressure head

z : Measured dimension

$\frac{v^2}{2g}$: Kinetic head

$z + \frac{p}{\rho g}$: Piezometric head.

2.3.5.2. Case of flow without work exchange

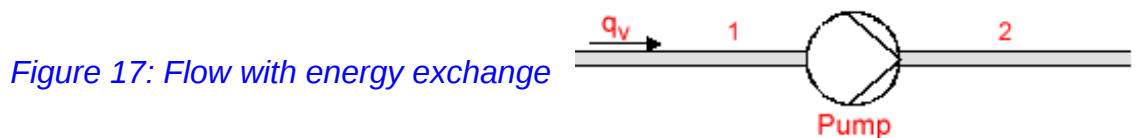
If in a perfect fluid flow there are no machines (pump or turbine) between points (1) and (2) of the same stream line, the Bernoulli relation can be written under one or other of the forms below:

$$\frac{1}{2} \rho (v_2^2 - v_1^2) + \rho g (z_2 - z_1) + (p_2 - p_1) = 0$$

$$\frac{1}{2g} (v_2^2 - v_1^2) + (z_2 - z_1) + \frac{p_2 - p_1}{\rho g} = 0$$

2.3.5.3. Case of flow with energy exchange

If the fluid passes through a hydraulic machine, it exchanges energy with this machine in the form of work DW in time Dt.



The power P exchanged is $P = \frac{\Delta W}{\Delta t}$ (P in watt (W), W in joules (J), t in second(s)).

$P > 0$ if the energy is received by the fluid (e.g.: pump);

$P < 0$ if the energy is supplied by the fluid (e.g.: turbine).

If the volume flowrate is q_v , the Bernoulli relation will be written:

$$\frac{1}{2} \rho (v_2^2 - v_1^2) + \rho g (z_2 - z_1) + (P_2 - P_1) = \frac{P}{q_v}$$

2.3.6. Application of Bernoulli's theorem

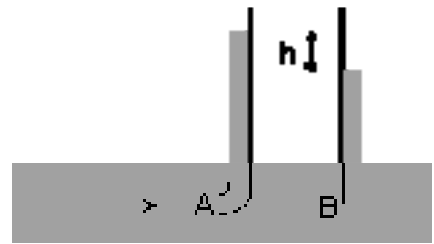
2.3.6.1. Pitot Tube

Take a liquid with steady flow in a pipe and two tubes immersed in the liquid, one emerging at A opposite the current, and the other at B along the stream lines, with both ends at the same height.

At point B, the liquid has the same velocity v as in the pipe, and the pressure is the same as that of the liquid $p_B = p$.

At A, the end point, the velocity is zero, and pressure is p_A .

Figure 18: Pitot Tube



Using Bernoulli's theorem:

$$p_B + \frac{1}{2} \rho v^2 = p_A \text{ and } \frac{1}{2} \rho v^2 = \rho g h$$

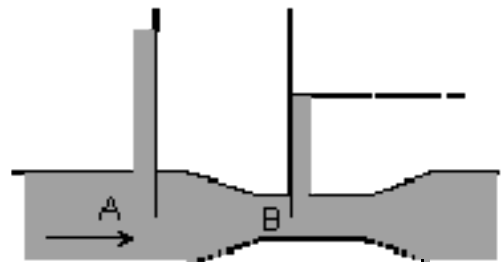
By measuring the level difference h in the liquid in the two tubes, we can deduce the fluid flow velocity v .

2.3.6.2. Venturi phenomenon

A pipe with main cross-section S_A has a bottleneck at B, where its cross-section is S_B .

A fluid's velocity increases in a bottleneck, so its pressure decreases: $v_B > v_A \Rightarrow p_B < p_A$

Figure 19: Venturi phenomenon



In this case the Bernoulli theorem is written:

$$p_A + \frac{1}{2} \rho v_A^2 = p_B + \frac{1}{2} \rho v_B^2 = p_C + \frac{1}{2} \rho v_C^2$$

Under the equation of continuity, $v_B S_B = v_A S_A = q_v$ so $v_B > v_A$ so $p_A > p_B$

$$p_A - p_B = \frac{1}{2} \rho \left(\frac{1}{S_B^2} - \frac{1}{S_A^2} \right) q^2 = k q^2$$

The pressure difference across the ends of the Venturi tube is proportional to the square of the flowrate; this is applied in flowrate measurement (pressure-reducing parts).

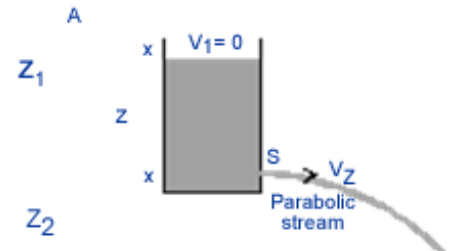
We could also mention water aspirators, sprayers...

2.3.7. Liquid flow contained in a tank

2.3.7.1. Torricelli's theorem

Take a tank fitted with a small orifice on its base, with cross-section s and a stream line from the surface at point (1), arriving at the orifice at point (2).

Figure 20: Torricelli's theorem



By applying Bernoulli's theorem between points (1) and (2),

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

$p_1 = p_2 = \text{atmospheric pressure}$ and $v_1 \ll v_2$ hence $v_2 = \sqrt{2g z}$

The flow velocity is the same as freefall velocity between the free surface and the orifice, regardless of the liquid density.

2.3.8. The difficulty of measuring gases

2.3.8.1. General points

Gas flowrates are measured the same as liquid flowrates: either by directly measuring volumes, or by multiplying a transit cross-section by the corresponding velocity (velocity measured directly or indirectly).

In both cases, we can obtain a volume per time unit; therefore we need to specify at what pressure and temperature it was measured.

Gas flowrates pose serious problems for instrument engineers.

The definition of flowrate "flow quantity per time unit" is of course the same for liquids and gases; the problem is how to express a quantity of gas?

2.3.8.2. Perfect gas law

A quantity of gas occupying a volume V_1 at pressure p_1 and temperature T_1 can also occupy a volume V_2 at pressure p_2 and temperature T_2 , and so on.

So we get the relation: $\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2} = \frac{p_3 \times V_3}{T_3} = \text{etc...}$

In this relation, P and T are absolute values (bar absolute and degrees Kelvin)
This relation is invariably true for perfect gases.

To compare two volumes of gas (which is bigger, and which smaller?), we need these volumes to be at the same pressure and temperature.

Volume measurements can be made under any conditions, with p and T stipulated as 'references'.

These 'references' can be process mean operating values (example: 30 bar and 350°C) or 'conventional' values (e.g.: 1.013 bar and 15°C) or standardised values: 1.013 bar, 0°C.

The volumes under standardised conditions (1.013 bar, 0°C) are expressed as "**normal metres cubed**" or "**standard cubic metres**": **Nm³**

2.3.8.3. The perfect gas equation

The experiments of Boyle and Mariotte demonstrated that at a temperature T (°C) the product of pressure p_T and volume V_T of a gas is a constant, as long as two conditions are satisfied: the temperature must be '*sufficiently high*' and the pressure '*sufficiently low*'.

This means firstly that the volume of the gas' constituent particles may be neglected, and secondly that these particles are free from mutual interactions.

The gas is said to be '**perfect**', obeying the relation:

$$p_T \times V_T = \text{constant}$$

The physicist GAY-LUSSAC also established by experiment that the volume of an '*uncompressed*' gas maintained at constant pressure has linear variation with temperature T (°C):

$$V_2 = V_1 (1 + \alpha_P \Delta t)$$

α_P : expansion coefficient

$\Delta t = t_2 - t_1$.

If we modify the temperature of a gas and maintain its volume constant, we observe that its pressure also has linear variation with temperature (Charles' law)

$$p_2 = p_1 (1 + \alpha_V \Delta t)$$

α_V : tension coefficient.

Precise measurements have demonstrated that α_P and α_V only differ very little for ordinary gases. We can treat them as equal for perfect gases, writing $\alpha_P = \alpha_V = \alpha$

If we select temperature $t_1 = 0^\circ\text{C}$ we can write the following relations:

$$V = V_0(1 + \alpha_t)$$

$$p = p_0(1 + \alpha_t)$$

Where V_0 and P_0 are volume and pressure at 0°C .

We note that we can arrive at a particular temperature $t = \theta = -(1 / \alpha)$ at which volume and pressure would be zero.

This ideal gas would be formed of material points with no interaction, confirming the conditions for a perfect gas stated above.

This particular temperature θ is the lowest with a physical meaning.

It is known as 'absolute zero' and precise measurements have provided the value:

$$\theta = (-273.16 \pm 0.01)^\circ\text{C}$$

$T = |\theta| + t$ defines a new, so-called absolute temperature scale (which we will look at in the temperature chapter of this course), which is expressed in Kelvin.

Hence the relations become:

$$p = p_0 \alpha_T \text{ or } p / T = Cst$$

$$V = V_0 \alpha_T \text{ or } V / T = Cst$$

So we can summarise in a single equation, known as the '**perfect gas equation**':

$$p V / T = Cst$$

If the quantity of gas is equal to one mole, the constant is that of a perfect gas:

$$P V = R T$$

$$R = 8.314 \text{ Joule.}(\text{°})^{-1}.\text{mole}^{-1}$$

And for any quantity of gas we can write: $p V = n R T$

n : number of moles

R : Perfect gas molar constant

$$R = 8.32 \text{ J mol}^{-1}\text{K}^{-1}$$

2.3.8.4. Calculating a volume of gas in standard cubic metres

“Express in Nm³” a volume V_1 at temperature T_1 and pressure P_1 means that we need to calculate what the volume would be at P_N (1.013 bar) and T_N (273 Kelvin)

Hence the relation:

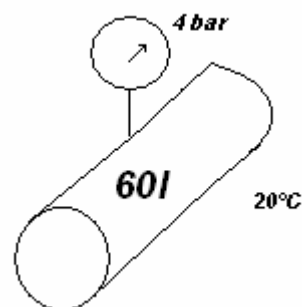
$$V_N = 269.33 \times V_1 \times \frac{P_1 (\text{bar abs})}{T_1 (\text{Kelvin})}$$

2.3.8.5. Application

Volume

What is the quantity of gas contained in a 60 l tank when the pressure indicated by the pressure gauge is **4 bar relative**, and ambient temperature is **20°C**.

Figure 21: Volume of gas



$$V_1 = 60 \text{ l} = 0.06 \text{ m}^3$$

$$P_1 = 4 + 1 = 5 \text{ bar abs}$$

$$T_1 = 20^\circ\text{C} = 293 \text{ K}$$

$$V_N = 269.33 \times 0.06 \times (5 / 293)$$

So the volume of gas V_N is 0.275 Nm³

Flowrate

What is the flowrate value in Nm³ per hour of 420 m³/h under a pressure of 12 bar absolute and temperature 70°C?

$$T_1 = 70^\circ\text{C} = 343 \text{ K and } Q_N = 269.33 \times 420 \times (12 / 343), \text{ so the flowrate is } \underline{3957 \text{ Nm}^3/\text{h}}$$

2.3.8.6. Gas density

Since volume is a factor, the density of gases varies with pressure and temperature: if a gas has density ρ_1 at P_1 and T_1 , at P_2 and T_2 it will have density:

$$\rho_2 = \rho_1 \times \frac{T_1}{P_1} \times \frac{P_2}{T_2}$$

2.3.9. Fluid flow conditions

Experiments demonstrate that a fluid moving in a conduit (e.g.: a pipe) may flow in parallel sections (laminar flow), or that there may be a certain mixture of the fluid (which we call turbulent flow).

We describe these two types of flow in the simplest scenario, i.e. a straight conduit with a circular effective section, in other words a pipe. The figure below represents the two types of flow, according to the velocity profile.

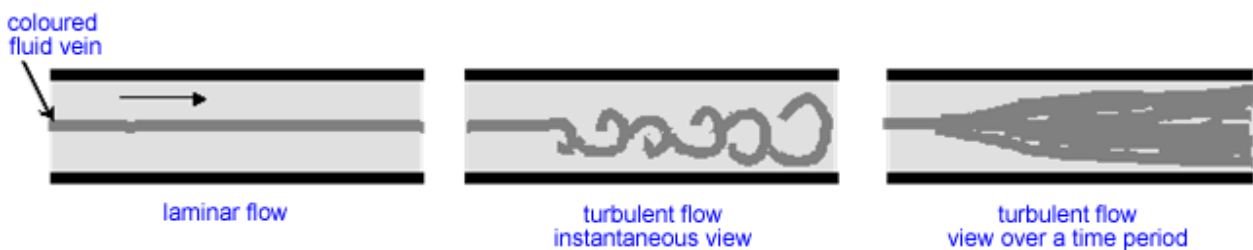


Figure 22: Fluid flow states

In **laminar flow**, the fluid acts as if it was moving in a concentric set of overlapping thin cylinders. Due to the fluid viscosity, the cylinder near the wall is stationary, while the one in the centre of the pipe is moving at greater velocity. There is no mixing between the fluid layers, and there is no velocity pulsing.

Turbulent flow is characterised by randomly mixed fluid layers. Due to this mixture, the distribution of velocities is much more uniform along the transversal section of the conduit. The mixing has a positive effect on heat transfer.

On the other hand, the mixing is manifested by velocity and pressure pulsing. These pulsations may be transferred to the whole pipe system and the equipment, and cause vibrations.

The flow type (laminar or turbulent) depends on the fluid properties (viscosity and density), its velocity and the geometry of the conduit it is flowing through.

Below are the conditions promoting **laminar flow**:

- ⊕ The dynamic viscosity is high (friction forces oppose mixing),
- ⊕ The density is low (a given volume of fluid contains less kinetic energy to overcome friction),
- ⊕ The velocity is low (there is less kinetic energy to overcome friction),
- ⊕ The conduit width is low (the proximity of the walls makes mixing more difficult, i.e. transverse movement in the conduit).

Most fluids (water, steam, compressed gases) have low viscosity, and normally flow in relatively wide conduits, at high velocity.

Furthermore, they often change flow direction (e.g.: in a pipe bend or around the tubes in a heat exchanger), which promotes mixing of layers.

Reynolds demonstrated that the parameter determining whether flow is laminar or turbulent is a **non-dimensional number known as the Reynolds number (Re)**, given by:

$$\text{Re} = \frac{\rho v D}{\eta} \text{ or } \text{Re} = \frac{V D}{\nu}$$

ρ : fluid density

V : mean velocity

D : conduit diameter

η : fluid dynamic viscosity

ν : kinematic viscosity $\nu = \eta / \rho$

Experimentation shows that:

If Re < 2000: the state is LAMINAR

If 2000 < Re < 3000 the state is intermediate

If Re > 3000 the state is TURBULENT

These values must be considered as orders of magnitude, with the transition between flow types made progressively

2.3.10. Head losses

The law of conservation of energy is universally applied. We have demonstrated that the various types of energy in a flowing fluid may be transformed into different forms. So what is a head loss?

Viscosity causes friction in the fluid, as well as between the fluid and pipe walls. The effect of this friction is to convert part of the fluid's pressure energy into motion, and increase the fluid and pipe temperature.

This phenomenon may be critical for the operation of certain equipment parts.

For instance a boiler feed pump should not be run with a discharge valve closed. Agitation of the feed water in the pump would produce so much heat due to friction, that the pump would be destroyed if it ran like that for too long. In certain cases, damage may arise in less than a minute.

The extent of energy/head losses due to friction depends on several factors.

Here are the main factors:

- ⊕ The fluid velocity
- ⊕ Its flow mode
- ⊕ Its viscosity
- ⊕ The static pressure difference at 2 points.

The effect of velocity is important, because in a turbulent flow, friction losses increase by the square of velocity. For example, if the velocity doubles, the head loss quadruples.

The source of the pressure difference $p = p_1 - p_2$ between two points (1) and (2) of a hydraulic circuit is:

- ⊕ Fluid friction on the pipe inner wall; this is known as **regular or systematic head loss**.
- ⊕ The flow resistance caused by transit accidents (bends, expanding or shrinking section, regulating parts, etc.); these are **accidental or extraordinary head losses**.

The problem of calculating these head losses calls on the following main values:

- ⊕ The fluid characterised by its density ρ and its kinematic viscosity ν .
- ⊕ A pipe characterised by its section (shape and dimension) - generally circular - (diameter D), its length L and roughness k (mean height of wall asperities).

These elements are connected by values such as mean flow velocity v or flowrate q and Reynolds number Re , which play a vital role in calculating head losses.

2.3.11. Systematic head losses

This kind of loss is caused by interior friction, which occurs in liquids; it is found in **smooth** pipes as well as **rough** pipes.

Between two points separated by a length L , in a pipe with diameter D there is a pressure loss p . expressed as follows:

$$\Delta p = \lambda \frac{\rho v^2}{2} \frac{L}{D} \text{ (Pa)} \quad \text{and} \quad \Delta h = \lambda \frac{v^2}{2g} \frac{L}{D} \text{ (mFC)}$$

Head loss expressed in metres fluid column (mFC) is a dimensionless coefficient known as **linear head loss coefficient**.

Head loss calculation is based entirely on determining the coefficient λ

2.3.11.1. Case of laminar flow $Re < 2000$

In this case we can demonstrate that the coefficient is solely dependent on the Reynolds number **Re** - the state of the surface is not a factor - and is therefore not dependent on **k** (mean height of pipe asperities), or on the nature of the pipe.

$$\lambda = 64 / Re \text{ where } Re = V D / \nu$$

It can be immediately seen that **h** is proportional to the velocity **V** and therefore the flowrate **q**, as well as the kinematic viscosity.

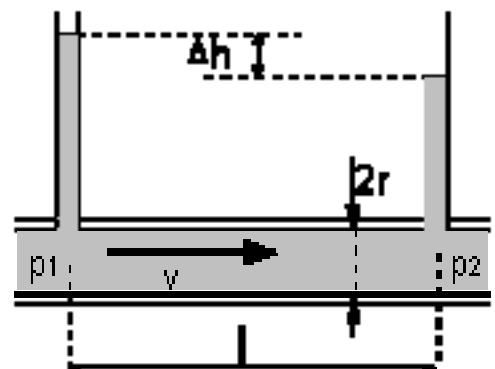
2.3.11.2. Poiseuille's law

With **laminar flow** in a horizontal cylindrical conduit, the volume flowrate of a fluid is given by:

$$q_v = \frac{\pi r^4}{8 \eta l} (p_1 - p_2)$$

Figure 23: Poiseuille's law

q_v: volume flowrate ($m^3 \cdot s^{-1}$),
r: internal radius (m),
η: fluid dynamic viscosity ($Pa \cdot s$),
l: length between points (1) and (2) (m),
p₁ and p₂: fluid pressure at points (1) and (2) (Pa).



2.3.11.3. Case of turbulent flow $Re > 3000$

The flow phenomena are much more complex and the head loss coefficient is derived from experimental measurements. This is what explains the diversity of old formulae that were proposed for its determination.

In turbulent state, the surface condition is a factor, and the higher the Reynolds number **Re** the more its influence increases. All work in this field has demonstrated the influence of roughness, and there have been subsequent efforts to find how the coefficient varies as a function of Reynolds number **Re** and pipe roughness **k**.

Colebrook's formula is currently considered as being the one that best represents the flow phenomena in turbulent state.

It is presented in the following form:

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left(\frac{k}{3.7D} + \frac{2,51}{\text{Re} \sqrt{\lambda}} \right)$$

The direct use of this formula, due to its implicit form, would require calculation by successive approximations; in practice we also employ graphic representations (charts).

To simplify the relation above, we can try to determine whether the flow is **hydraulically smooth** or **rough** to evaluate the predominance of the two terms between brackets in the **Colebrook relation**.

Note: We often employ simpler empirical formulae valid for particular cases and in a certain Reynolds number area, for example:

✚ **Blasius formula**: (for smooth pipes and $\text{Re} < 10^5$):

$$\lambda = 0.316 \text{ Re}^{-0.25}$$

2.3.12. Accidental head losses

As demonstrated experimentally, in many cases head losses are roughly proportional to the square of velocity, so we have adopted the following form of expression:

$$\Delta p = K \frac{\rho V^2}{2} \text{ (Pa)} \text{ and } \Delta h = K \frac{V^2}{2g} \text{ (mFC)}$$

K is known as **extraordinary head loss coefficient** (dimensionless).

This coefficient is primarily determined by experiment.

2.4. DENSITY

Density (sometimes referred to as specific gravity) is another basic property of fluids.

Density is defined as being the mass (m) of a volume unit (V). Its basic unit is the kg/m^3 .

Mathematically, we get the following relation: $\rho = m / V$

For all practical purposes, liquids are assumed to be incompressible, i.e. pressure has no effect on their volume or density. Although that is not absolutely true, these modifications are negligible. However, we cannot ignore the effect of temperature on the density of liquids, as liquids expand and contract as the temperature changes.

Both pressure and temperature influence the density of gases.

- ⊕ If the temperature is kept constant and the pressure increased, the density increases.
- ⊕ If the pressure is kept constant and the temperature increased, the density decreases.

2.5. VISCOSITY

2.5.1. The phenomenon

2.5.1.1. Observations

Water, oil and honey flow in different ways: water flows fast, but with vortices; honey flows slowly, but regularly.

A skydiver falls at constant velocity, contrary to the law of free fall.

The pressure of a real liquid decreases along a pipe it is flowing through, even if it is horizontal and of uniform cross-section, contrary to Bernoulli's theorem.

2.5.1.2. Conclusion

In a **real fluid**, the contact forces are not perpendicular to the surface elements on which they are exerted. Viscosity is due to these **friction forces** opposing the fluid layers sliding over each other.

The phenomena due to fluid **viscosity** only occur **when these fluids are in motion**.

2.5.2. Kinematic and dynamic viscosity

2.5.2.1. Velocity profile

Under the effect of interaction forces between fluid molecules and interaction forces between fluid molecules and wall molecules, each fluid molecule does not flow at the same velocity. **We say that there is a velocity profile.**

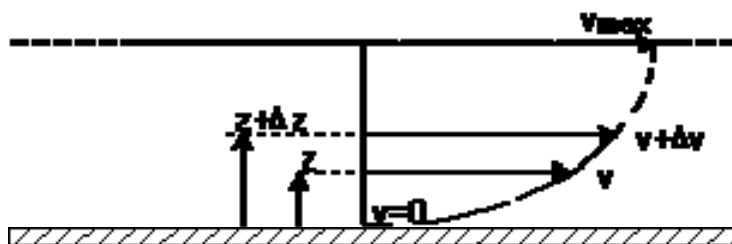


Figure 24: Velocity profile in a fluid in motion

If we use a vector to represent the velocity of each particle in a straight section perpendicular to the overall flow, the curve at the ends of these vectors represents the velocity profile.

Fluid motion can be considered as the resultant of fluid layers sliding over each other.

The velocity of each layer is a function of the distance z from this curve to the fixed plane:
 $v = v(z)$.

2.5.2.2. Dynamic viscosity

Let's take two contiguous fluid layers Dz apart. The friction force F exerted on the surface separating these two layers opposes one layer sliding over the other. It is proportional to the difference in velocity between the layers, i.e. Δv , their surface area S , and inversely proportional to Dz :

$$F = \eta S \frac{\Delta v}{\Delta z}$$

The proportionality factor **is the dynamic viscosity coefficient** of the fluid.

Dimension: $[\eta] = M \cdot L^{-1} \cdot T^{-1}$.

Unit: In the international system (SI), the unit of dynamic viscosity is **the Pascal second** (Pa s) or **Poiseuille** (PI):

$$1 \text{ Pa} \cdot \text{s} = 1 \text{ PI} = 1 \text{ kg/ms}$$

Other units (not legally recognised):

- ✦ We can also find in tables of numeric values the viscosity coefficient in an *old system of units (CGS)*: the unit is the Poise (Po); $1 \text{ PI} = 10 \text{ Po} = 1 \text{ daPo} = 10^3 \text{ cPo}$.
- ✦ The viscosity of industrial products (oils in particular) is expressed by means of *empirical units*: degree ENGLER in Europe, degree Redwood in the UK and degree Saybolt in the USA.

2.5.2.3. Kinematic viscosity

A number of formulae contain the ratio of dynamic viscosity to density.

This ratio is known as **kinematic viscosity**: $\nu = \eta / \rho$

Dimension: $[] = \text{L}^2 \cdot \text{T}^{-1}$.

Unit:

- ✦ In the international system (SI), the unit of viscosity has no particular name: (m^2/s).
- ✦ In the CGS system (not legally recognised), the unit is the Stokes (St): $1 \text{ m}^2/\text{s} = 10^4 \text{ St}$

2.5.2.4. Influence of temperature

Fluid	η (Pa·s)
water (0°C)	1.787×10^{-3}
water (20°C)	$1.002 \cdot x 10^{-3}$
water (100°C)	$0.2818 \cdot x 10^{-3}$
olive oil (20°C)	$\gg 100 \cdot x 10^{-3}$
glycerol (20°C)	$\gg 1.0$
H ₂ (20°C)	$0.860 \cdot x 10^{-5}$
O ₂ (20°C)	$1.95 \cdot x 10^{-5}$

The viscosity of liquids decreases greatly when the temperature rises.

There is no accurate relation binding η and T .

Unlike the viscosity of liquids, *gas viscosity increases with temperature.*

2.5.3. Measuring viscosity

2.5.3.1. Ostwald viscometer

A spherical ball drops slowly in a well calibrated tube containing the viscous liquid. We measure the time t taken for the ball to cover a certain distance, to demonstrate that dynamic viscosity η is proportional to the time t : $\eta = K \cdot t$

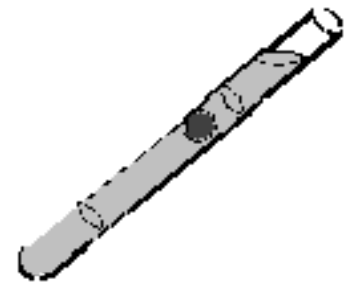
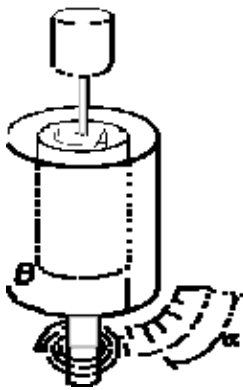


Figure 25: Ostwald viscometer

2.5.3.2. Rotary viscometer or Couette viscometer



A solid cylinder (A) rotates at constant velocity in a liquid contained in a cylindrical vessel (B); this is mobile on its axis of rotation, driven by the liquid. A spring exerting a torque after turning through angle α keeps (B) in equilibrium.

We can demonstrate that dynamic viscosity η is proportional to the angle α : $\eta = K \cdot \alpha$

Figure 26: Rotary viscometer

Applications:

Propulsion by an aeroplane or boat propeller is possible due to the viscosity of air or water.

Because of its viscosity, the pressure of a real fluid decreases as it flows through a pipe; this sometimes means introducing pumps at regular distances along the pipe.

Viscometers are used in particular in laboratories.

2.6. TEMPERATURE

Temperature is practically omnipresent! *Phew... it's so hot! Brrr... We're shivering down here! Are you ill? Take your temperature. Above the norm for the season... Put your hat on, it's not warm. Put the heating on, it's going to freeze tomorrow.*

In a car: coolant, oil, brakes, cylinder head temperature, etc.

Aeroplanes too: external, cabin, engine stages, fuel, hold, equipment, brakes temperature, etc.

In a number of everyday situations, the concept of temperature is present. We no longer pay it any attention as it has become such a regular, common and “transparent” phenomenon.

But what actually is temperature? According to the definition taken from an encyclopaedic dictionary, “temperature is a quantity manifesting the sensation of heat or cold”

This still leaves us a bit short, especially since temperature is one of the physical quantities that we most often need to measure. Furthermore, can we talk about a measurement? We can sometimes read in scientific literature that temperature is not a measurable quantity. If there is no measurement, what we do is takes references of temperature.

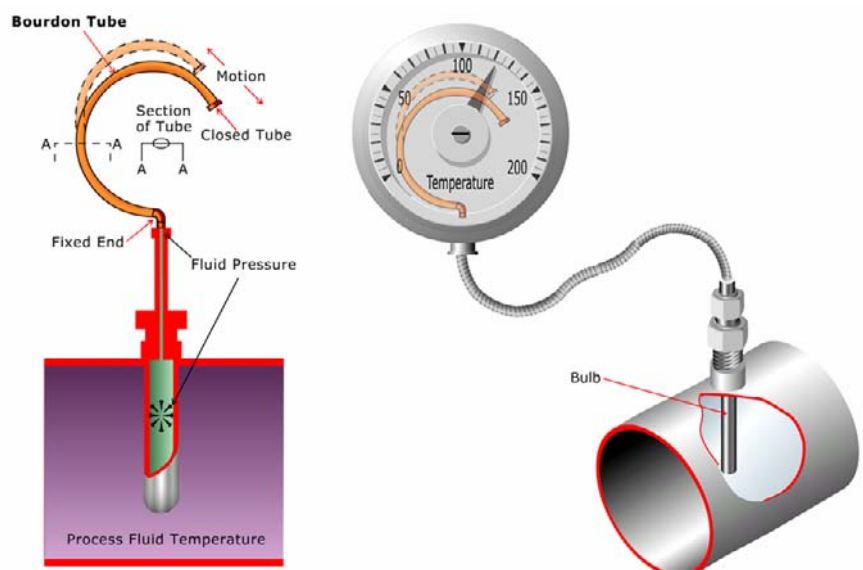
2.6.1. From referencing to measurement

It has long been known that any variation in temperature causes modifications to the physical characteristics of materials, and it is this phenomenon that we use to make thermometers.

Temperature:

- ✚ Expands solids,
- ✚ Expands liquids,

Figure 27: Example of liquid expansion thermometer



- ✦ Expands gases (e.g.: mercury thermometer),

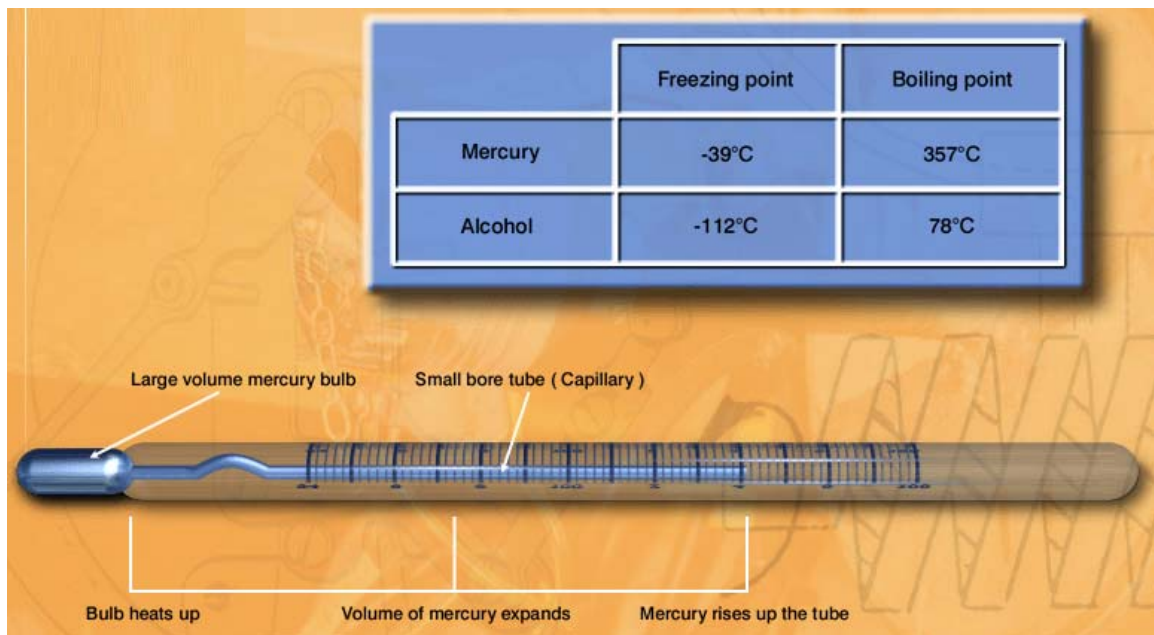


Figure 28: Example of gas expansion thermometer (e.g. mercury)

- ✦ Changes the pressure of gases (legal thermometer),
- ✦ Influences electromagnetic radiation of objects (optical infrared pyrometer),

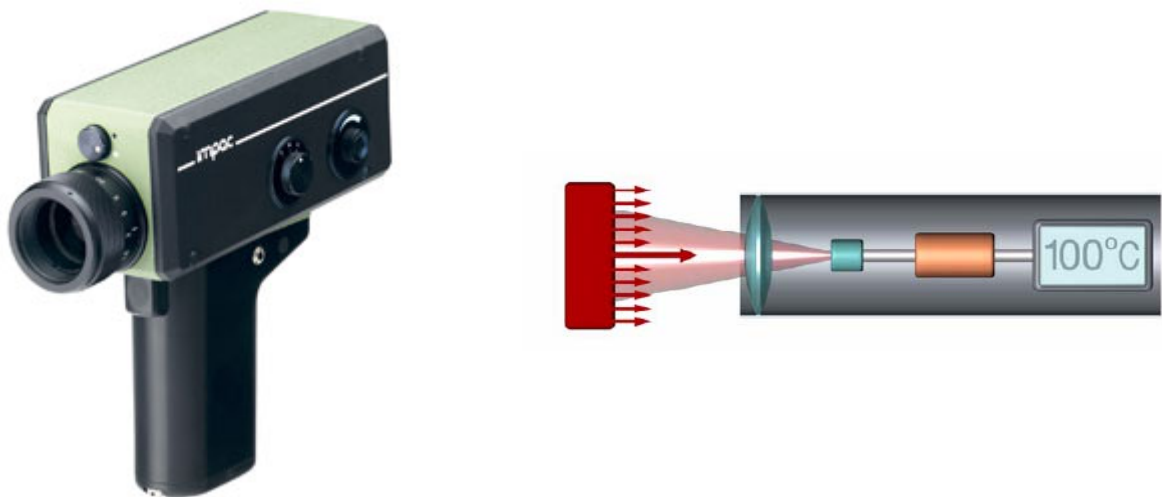


Figure 29: Example of optical infrared pyrometer

- ✦ Varies the velocity of sound (acoustic thermometer),
- ✦ Modifies an electrical resistance value (thermocouple thermometer),

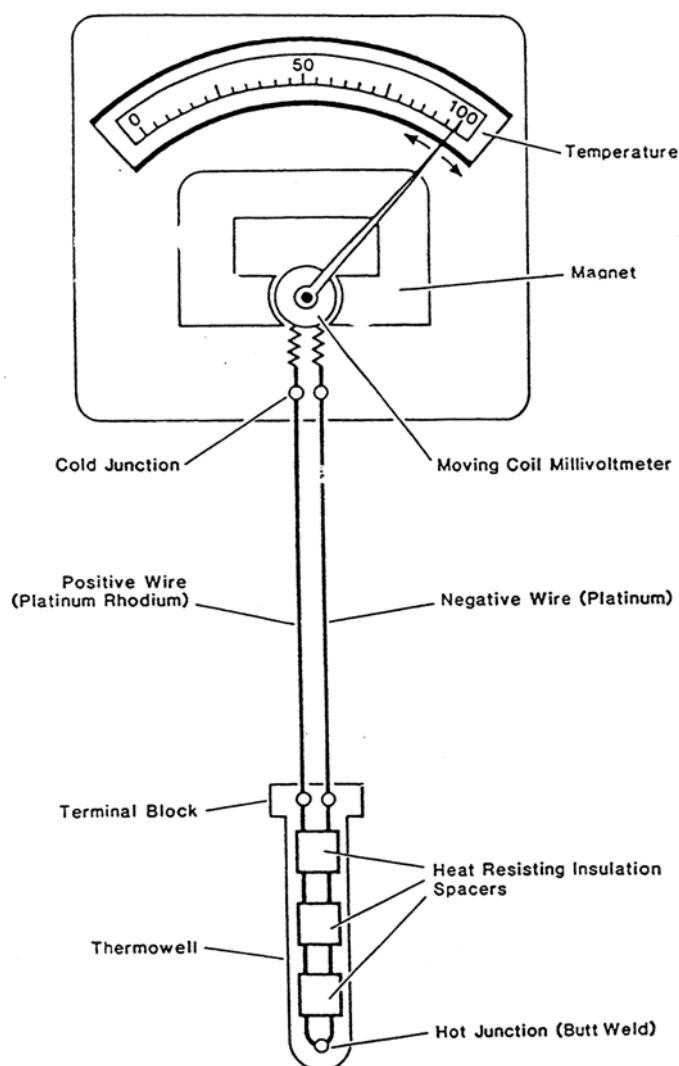


Figure 30: Example of thermocouple thermometer

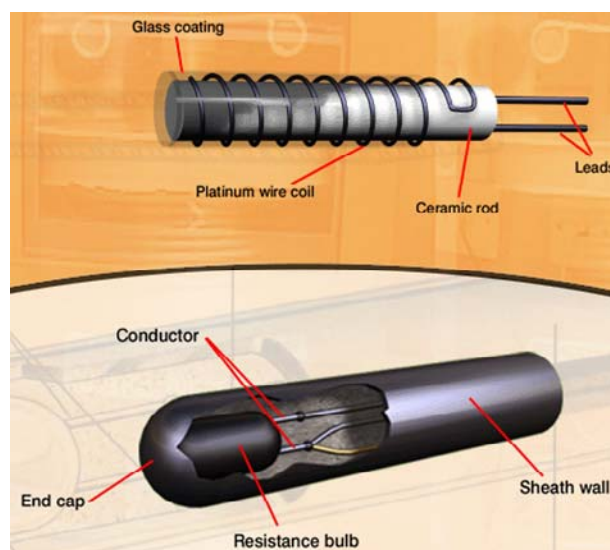
- ✚ Measures an electrical resistance value (platinum resistance thermometer),

Figure 31: Example of platinum resistance

- ✚ Modifies quartz oscillation frequency (quartz thermometer),

As you can see, we are spoilt for choice.

For each of these different types of local temperature measurement, we also have temperature measurements using sensors and transmitters (see 'Sensors and Transmitters' course).



2.6.2. Thermometric scales

Based on the heat variations of one of the physical characteristics of a given material, we can define a reference temperature scale and find the equality of two temperatures.

However this type of scale is completely arbitrary, as it is linked to a particular property of a particular object: so it cannot provide a meaning for the temperature value, and therefore cannot be used to measure it.

Fortunately, the arrival of thermodynamics made it possible to resolve the situation and define temperature scales with a universal character.

In developing some considerations relating to the second principle of thermodynamics, **Lord Kelvin** established the **absolute thermodynamic temperature** which today bears his name. At the same time he proved the existence of **absolute zero**, the same for all objects.

Thanks to thermodynamics, absolute temperature represents something other than a simple sensation of heat or cold. For example, the ratio of two thermodynamic temperatures is equal to the ratio of heat quantities.

If we work with perfect gases at constant volume, the ratio of two temperatures is equal to the ratio of two pressures (Boyle and Mariotte law). There are a variety of possible examples.

This means that any temperature can be defined from a **reference temperature**. Hence temperature, initially something purely subjective, has acquired the status of a measurable quantity, connected to most physical quantities.

A few melting points of metals	
+ 231°C: Tin	≈ 1535°C: Soft iron
+ 419°C: Zinc	≈ 1554°C: Palladium
≈ 660°C: Aluminium	≈ 1755°C: Platinum
+ 961°C: Silver	≈ 1800°C: Titanium
+ 1064°C: Gold	≈ 3180°C: Carbide and titanium
≈ 1084°C: Copper	≈ 3410°C: Tungsten
Gas combustion temperatures	
≈ 1850°C: Natural gas + air	≈ 3650°C: Hydrogen + fluorine
≈ 2850°C: Natural gas + oxygen	≈ 4550°C: Cyanogen + oxygen
≈ 3200°C: Acetylene + oxygen	≈ 5000°C: Butynedinitrile + oxygen

Electrical furnace heating temperatures, according to the type of resistor used	
$\approx 1200^{\circ}\text{C}$: Nickel-chromium	$\approx 2800^{\circ}\text{C}$: Pressurised graphite
$\approx 1600^{\circ}\text{C}$: Platinum	$\approx 3200^{\circ}\text{C}$: Pressurised tungsten

Table 2: Some notable temperatures

In spite of this, we needed to wait to finally have a legal definition of the unit of temperature.

The triple point of water was selected as the fundamental fixed reference point, with an allocated temperature of **273.16 K**.

The Kelvin became the temperature unit (symbol K) rather than the degree Kelvin ($^{\circ}\text{K}$); it is the fraction of $1 / 273.16$ of the thermodynamic temperature of the triple point of water.

State	T_{90} / K	$T_{90} / ^{\circ}\text{C}$
Triple point of hydrogen	13.8033	-259.3467
Boiling point of hydrogen at a pressure of 33321.3 Pa	17.035	-256.115
Boiling point of hydrogen at a pressure of 101,292 Pa	20.27	-252.88
Triple point of neon	24.5561	-248.5939
Triple point of oxygen	54.3584	-218.7916
Triple point of argon	83.8058	-189.3442
Triple point of mercury	234.3156	-38.8344
Triple point of water	273.16	0.01
Melting point of gallium	302.9146	29.7646
Freezing point of indium	429.7485	156.5985
Freezing point of tin	505.078	231.928
Freezing point of zinc	692.677	419.527
Freezing point of aluminium	933.473	660.323
Freezing point of silver	1234.93	961.78
Freezing point of gold	1337.33	1064.48
Freezing point of copper	1357.77	1084.62

Table 3: Table of fixed temperature reference points

2.6.3. Units

2.6.3.1. Degree Fahrenheit

The first scale to be *universally* recognised was that of **Gabriel Fahrenheit**, a Dutchman who at the start of the 18th Century made mercury thermometers that could provide reliable and repetitive temperature measurements.

His scale was based on two points:

- ✦ The low point represented the lowest temperature that Fahrenheit could reproduce, which he named "zero degrees". It was produced by a mixture of ice and salt. This temperature is equivalent to around -17.8°C .
- ✦ The high point represented the temperature of human blood, which he named "96 degrees". This temperature is equivalent to around 35.5°C .

Why 96 and not 100 degrees? Doubtless because many British units used base 12, and the metric system was in its infancy. In any case, a Fahrenheit thermometer in melting ice indicates 32°F , and 212°F when water boils.

2.6.3.2. Degree Celsius

In 1741 the Swedish physicist **Anders Celsius** (1701-1744) built a mercury thermometer which marked 0 degrees at the freezing point of water and 100 at the boiling point, and which was used from 1742 to 1750 in the Uppsala Scandinavian observatory. In 1745, Linne presented to the Swedish Academy of Sciences a mercury thermometer with an ascending centigrade scale, with zero the freezing point of water.

At the same time, the perpetual secretary of the Academy of Fine Arts in Lyon, Jean-Pierre Christin (1683-1755), was having the Lyon craftsman Pierre Casati build a mercury thermometer with an ascending centigrade scale, which he presented on 19 March 1743 to the public assembly of this academy.

The Swedish thermometer and the Lyon thermometer would only have been restricted in use if the French Revolution had not given the modern world the metric system, and if the Weights and Measures Commission, created by the Convention, had not decided in 1794 that "the thermometer degree shall be the hundredth part of the distance between the end point of ice and that of boiling water". In October 1948, by decision of the 9th Weights and Measurements Conference, the degree centigrade adopted the name degree Celsius.

2.6.3.3. Kelvin

William Thomson, known by the name of Lord Kelvin, made a lasting contribution to thermodynamics. After the S. Carnot's essay on heat and the experimental work of J. Joule, the first law of thermodynamics could be stated, and in 1850, R. Clausius was able to assert the principle that heat could not of its own accord pass from a cold object to a warm object.

Thomson demonstrated, based on the Carnot system, that it was possible to define an operating temperature scale, independent of the properties of the system used. This led to the establishment of the "absolute" thermometric scale, or Kelvin scale.

We should note that the Kelvin must not be used with the word degree, or with the ° symbol; we say "a Kelvin", rather than a degree Kelvin.

2.6.3.4. Degree Rankine

The Rankine scale (°R) is simply the transposition to degrees Fahrenheit of the Kelvin absolute temperature scale. It was given its name in honour of a pioneer of thermodynamics, William John Macquorn Rankine (1820-1872). The °R is equal to the temperature in °F + 459.67.

2.6.3.5. Degree Réaumur

As a reminder, **René Antoine Ferchault de Réaumur** (1683-1757) came to invent in around 1730 the alcohol thermometer that bears his name, due to the inaccuracy of the measurements employed. Although this was later supplanted by the Celsius thermometer, it was a remarkable advancement for the 17th Century. Its scale was fixed in 1732 at zero degrees for the melting point of ice and 80 degrees for the boiling point of spirit of wine (alcohol).

For a certain period, the Réaumur thermometer designated instruments where the boiling point of water was at a division between 80 and 100 degrees Réaumur. This observation in 1772 led the Genevan physicist Jean-André Deluc (1727-1817) to propose a division into 80 parts of the basic interval of the Réaumur thermometer in the countries that had adopted it.

French makers gradually standardised their scale in line with this proposal, but the renown left behind by Réaumur was so great that it was his name that was given to it. Its use continued to the very start of the 20th Century in Southern Germany, Spain, Russia and South America.

2.6.4. The relations between temperature scales

2.6.4.1. The Celsius scale

This is the most used temperature scale in everyday life. One of the big advantages of this scale is that the difference between two temperatures has the same value in degrees Celsius (°C) or in Kelvin (K).

The two fixed points of this scale are:

- ⊕ The equilibrium temperature between the liquid phase and solid phase of water: **reference 0°C**,
- ⊕ The equilibrium temperature between the liquid phase and gaseous phase of water: **reference 100°C**.

Note: the triple point of water (273.16K) is at 0.01°C.

$$T \text{ (K)} = t \text{ (°C)} + 273.15$$

2.6.4.2. The Fahrenheit scale

This scale is still used in Anglo-Saxon countries.

The two fixed points are as follows:

- ⊕ The equilibrium temperature between the liquid phase and solid phase of water: **reference 32°F**,
- ⊕ The temperature between the liquid phase and gaseous phase of water: **reference 212°F**.

A difference of 1°F is 5/9 K, and therefore 5/9°C.

There is also the absolute Rankine scale, which is to the Fahrenheit scale what the Kelvin scale is to the Celsius scale.

The unit °F is equal to the unit °R. We can switch between scales by a simple arithmetic adjustment:

$$T \text{ (°R)} = t \text{ (°F)} + 459.67$$

2.6.5. Correspondence between scales

There are many formulae to be used:

- Between **Kelvin** (K) and **Rankine** (°R)

$$T (K) = 5 / 9 T (°R)$$

$$T (°R) = 9 / 5 T (K)$$

- Between **Celsius** (°C) and **Kelvin** (K)

$$T (K) = t (°C) + 273.15$$

$$t (°C) = T (K) - 273.15$$

- Between **Fahrenheit** (°F) and **Rankine** (°R)

$$T (°R) = t (°F) + 459.67$$

$$t (°F) = T (°R) - 459.67$$

- Between **Fahrenheit** (°F) and **Kelvin** (K)

$$T (K) = 5 / 9 (t (°F) + 255.4)$$

$$t (°F) = 9 / 5 (T (K) - 255.4)$$

- Between **Celsius** (°C) and **Fahrenheit** (°F)

$$t (°C) = 5 / 9 (t (°F) - 32)$$

$$t (°F) = 9 / 5 (t (°C) + 32)$$

2.6.5.1. Summary of temperature scale correspondences

	Kelvin	Celsius	Centi grade	Fahren heit	Rankine
Absolute zero	0	-273.15		-459.67	0
Melting point of water	273.15	0	0	32	491.67
Vaporisation point of water	373.125	99.975	100	212	671.67

Table 4: Summary table of temperature scale correspondences

3. MEASUREMENT

3.1. FOREWORD

A “**measurement**”, as seen by an instrument engineer, is derived from a device of variable adjustment difficulty, the installation of which, always a delicate matter, provides a more or less representative value of the actual condition of the physical quantity measured.

A “**measurement**”, as seen by the operator, is correct if it indicates the desired value, and is doubtful otherwise, and so the operator will call on the instrumentation maintenance service.

The specialist, more objective, knows that the value indicated represents what is measured with a certain accuracy (+/- 1% for example), but there is still a certain probability that the value indicated is completely different to the true value (for example if the device remains locked at one indication, +/-1% is no longer of any meaning).

In conclusion, a measurement is never exact, since it requires:

- ✚ An operator
- ✚ A method
- ✚ A device
- ✚and each is a source of errors

The measured quantity will only be known “with a degree of approximation” known as the measurement **uncertainty**

3.2. USEFUL VOCABULARY

Measuring:

A set of operations for the purpose of determining the value of a quantity.

Measurand:

A quantity subjected to measurement (e.g.: a pressure, temperature, level, etc.).

Influencing quantity or interference

This is a quantity that is not being **measured**, but which influences the value of the **Measurand** or the indications of the measuring instrument.

Examples: Ambient temperature, frequency of a measured alternating electrical voltage, atmospheric pressure, storm, electrostatic / magnetic field, etc.

Sensitivity

This is the quotient of increase in response by a measuring instrument by the corresponding increase in input signal.

$$S = \Delta y / \Delta x$$

Examples:

- ⊕ A 100 mm recorder (width of paper), full scale 125°C: sensitivity is (100 / 125) = **0.8 mm/°C**
- ⊕ A transmitter ΔP with input scale 10 - 60 mbar, standard electrical output (4 – 20 mA): the sensitivity is (20 - 4) / (60 - 10) = **0.3 mA/mbar**

Mobility

A measuring instrument's ability to respond to small variations in input signal value.

E.g.: mobility 1 / 10°C

Note: Sensitivity and mobility are often confused since mobility corresponds to what used to be known as "sensitivity".

Mobility threshold

The slightest variation in input signal that causes a perceptible variation in the response of a measuring instrument.

NB: The mobility threshold may depend, for instance, on noise (internal or external), friction, damping, inertia or quantification.

E.g.: If the smallest load variation resulting in a perceptible movement of the needle of a balance is 90 mg, the balance's mobility threshold is 90 mg.

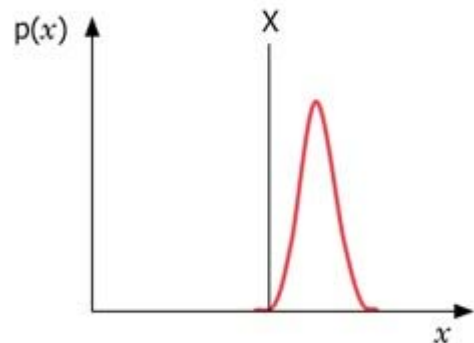
Repeatability of a measuring instrument

Ability of a measuring instrument, under determined conditions of use, to give very similar responses upon repeated application of the same input signal.

NB: The conditions of use defined are normally as follows:

- ✦ Repetition over a short time period,
- ✦ Used in the same place under constant ambient conditions,
- ✦ Variations due to the observer kept to a minimum.

Figure 32: Repeatability of a measurement

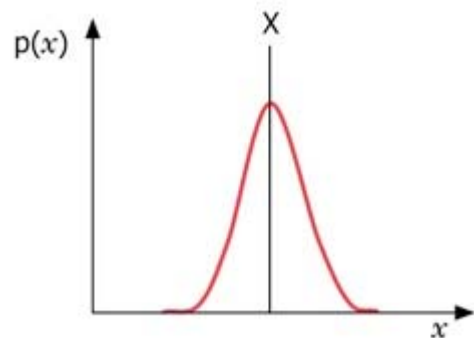


Trueness of a measuring instrument

Ability of a measuring instrument to give indications free from bias error.

Note: Laboratory equipment is true but too fragile to be repeatable; some old devices are repeatable but too rough to be true.

Figure 33: Trueness of a measurement



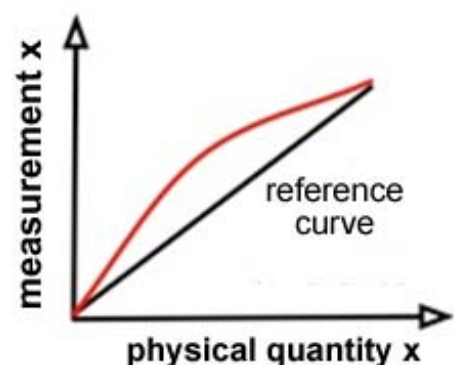
Linear scale

Scale on which the length and value of each division are linked by a constant proportionality coefficient along the scale.

NB: A linear scale with constant division values is known as a regular scale.

Note: a measurement by an instrument must be like the reference curve in the figure above. The curve in red represents a measurement with a **linearity error**.

Figure 34: Linear scale

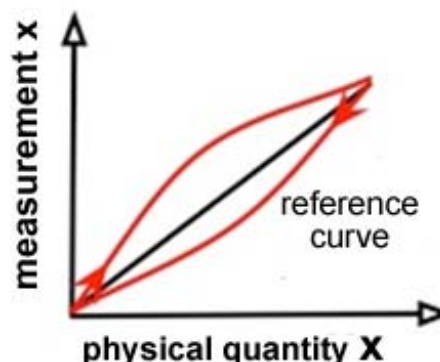


Hysteresis

Property of a measuring instrument with a response to a given input signal dependent on the sequence of previous input signals.

NB: Although hysteresis is normally considered to be related to the quantity to be measured, it may also be related to interference.

Figure 35: Hysteresis



Accuracy

Closeness of agreement between the result of a measurement and the actual value of the quantity measured.

Accuracy class

Class of measuring instruments that satisfy certain metrological requirements intended to keep errors within specified limits.

NB: An accuracy class is normally indicated by a number or symbol adopted by convention, and denoted class index.

The accuracy class of measuring instruments is stated in manufacturers' specifications. Here is an example for a variable section flowmeter

Flow %	Accuracy class				
	1	1.6	2.5	4	6
	Total error as % of measurement				
100	1.000	1.600	2.500	4.000	6.000
90	1.028	1.644	2.569	4.111	6.167
80	1.063	1.700	2.656	4.250	6.375
70	1.107	1.771	2.768	4.429	6.643
60	1.167	1.807	2.917	4.667	7.000
50	1.250	2.000	3.125	5.000	7.500
40	1.375	2.200	3.438	5.500	8.250
30	1.583	2.533	3.958	6.333	9.500
20	2.000	3.200	5.000	8.000	12.000
10	3.250	5.200	8.125	13.000	19.500

Figure 36: Example of accuracy class

3.3. ERRORS AND UNCERTAINTIES

3.3.1. Systematic error

This is a component of measurement error which, over several measurements of the same measurand, remains constant or varies predictably.

Systematic errors and their causes may be known or unknown.

3.3.2. Accidental error

This is a component of error which, over several measurements of the same measurand, varies unpredictably.

Examples:

- ✦ Mechanical friction on the pivot of a needle means that over start repetitions, the indications differ slightly.
- ✦ The observer absent-mindedly mistakes the gauge reading or measuring device indication

3.3.3. From error to uncertainty

Measurement uncertainty is an estimated maximum accidental error that might occur in the measurement.

***NB:** Measurement uncertainty generally consists of several components. Some may be estimated based on the static distribution of the results of measurement series, and may be characterised by experimental standard deviation. Estimates of other components can only be based on experience and other information*

3.3.4. Absolute and relative uncertainty

Absolute uncertainty is the probable discrepancy ΔX between the approximate value and true value.

Absolute uncertainty is therefore of the same nature as the physical quantity measured, and must be expressed with the same unit.

E.g.:

$U_{\text{measured}} = 45 \text{ V}$, $\Delta U = 1 \text{ V}$, hence the true value = $45 \text{ V} \pm 1 \text{ V}$

Relative uncertainty is the quotient of absolute uncertainty by the measured value; $\Delta X/X$ expressed as a percentage: It represents the measurement accuracy.

E.g.: $\Delta U / U = (1 / 45) = 2.2\%$

3.3.5. Calculating uncertainty

To put a figure on measurement uncertainty, manufacturers specify the device class.

- ✚ Accuracy class: measuring instrument class satisfying certain metrological requirements intended to keep errors within specified limits.
- ✚ It gives in % maximum deviation the potential uncertainty on a particular reading.

E.g.:

A pressure transmitter: class index 1.5, maximum deviation 1050 mbar, the reading is 600 mbar.

So $\Delta P = (1.5 / 100) * 1050 = 15.75$ mbar i.e. $P_{\text{True}} = 600 \text{ mbar} \pm 16 \text{ mbar}$

4. MEASUREMENT SIGNALS

Signals to be processed may come from a great variety of sources, but most are electrical signals or have been converted into electrical signals using sensors and transmitters (microphones, retinas, or thermal, optical, pressure, position, speed, acceleration sensors, and in general for any physical or chemical quantities).

We can primarily distinguish the analogue signals produced by various sensors, amplifiers, digital/analogue converters; digital signals from computers, terminals, a reading on a digital medium or digitisation by an analogue-digital converter.

Without digitising signals, the processing can be carried out by analogue electronic circuits or also optical systems (optical signal processing).

It is increasingly performed by digital signal processing, using computers, on-board micro-processors, specialised micro-processors known as DSP, reconfigurable circuits (FPGA) or dedicated digital components (ASIC).

There are several particular branches of signal processing, according to the nature of the signals considered.

In particular:

- ✦ Speech processing (or sound generally) for analysis, compression and voice recognition
- ✦ Processing of images for analysis, restoration and compression of fixed images
- ✦ Processing of video for analysis and compression of video sequences
- ✦ Signal processing may have a variety of purposes:
 - ✦ Detecting a signal
 - ✦ Estimating quantities to be measured on a signal
 - ✦ Encoding, compression of signal for storage and transmission
 - ✦ Improving quality (restoration) under physiological criteria (for listening and viewing).

The processing of a signal depends on the end purpose. In particular, the concepts of signal and noise are subjective, they depend on what the user is interested in.

We use various measurements representative of signal quality and the information content:

The ratio of signal over noise, a concept very frequently used, but ambiguous since it all depends on what is considered as a signal and as noise.

The Effective Number of Bits (ENOB), which is a measurement of analogue-digital conversion quality.

Fisher information, useful in particular for estimating parameters. This is the information on a parameter or pair of parameters (Fisher information matrix).

Entropy, a quantity derived from statistical physics and information theory (work by Shannon), used in encoding operations. It is a measurement of the signal's "intrinsic" information.

4.1. WHAT IS AN INSTRUMENT?

It is a device sensitive to a physical quantity: its input.

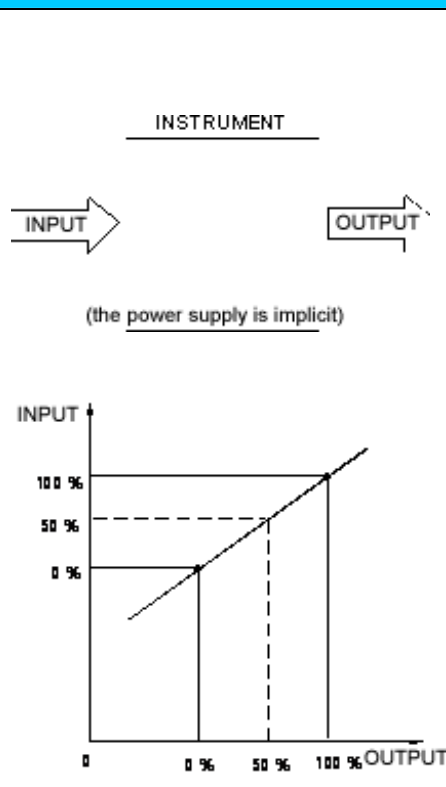
Variable inputs	INSTRUMENT	Variable outputs
Pneumatic	 The diagram illustrates an instrument's function. It shows an 'INPUT' arrow entering a box labeled 'INSTRUMENT' and an 'OUTPUT' arrow exiting. Below this, a note states '(the power supply is implicit)'. A graph plots 'INPUT' on the vertical axis against 'OUTPUT' on the horizontal axis. The vertical axis has markings for 0 %, 50 %, and 100 %. The horizontal axis has markings for 0, 0 %, 50 %, and 100 %. A straight line passes through the origin (0,0) and the point (100%, 100%). Dashed lines indicate that at 50% input, the output is 50%, and at 100% input, the output is 100%.	Pneumatic
Standard signal: 200 – 1000 hPa 3 – 15 psi		Standard signal: 200 – 1000 hPa 3 – 15 psi
Electrical		Electrical
Standard signal: 4 – 20 mA Current intensity: mA Voltage, pd, emf: 1 – 5 V, mV Frequency: Hz Resistance: R (Ω) Inductance: L (H) Capacitance: C (F)		Standard signal: 4 – 20 mA Current intensity: mA Voltage, pd, emf: 1 – 5 V, mV Frequency: Hz Resistance: R (Ω) Inductance: L (H) Capacitance: C (F)
Process		Process
Quantities measured: P, L, T, F...		Correcting variable: Q_v
		Mechanical
		Needle rotation: $\Delta\theta$ Pen movement: Δx Stem, disc, valve movement: Δy

Table 5: Instrument

It can modify its output in a predetermined, measurable way when its input is varied.

All instruments require an energy supply of the same kind as their output (electrical, pneumatic).

This supply must be provided separately or by means of the output signal:

- ✦ External supply (24 VDC or 230 VAC) is provided either by a filtered stabilised supply or by an intrinsic safety isolation device,
- ✦ The current loop supply (4 - 20 mA) is provided by an automaton or a control system.

The calibration of an instrument determines the precise correspondence between input and output within a given measuring range (MR):

For each input value there is a corresponding output value (and vice-versa).

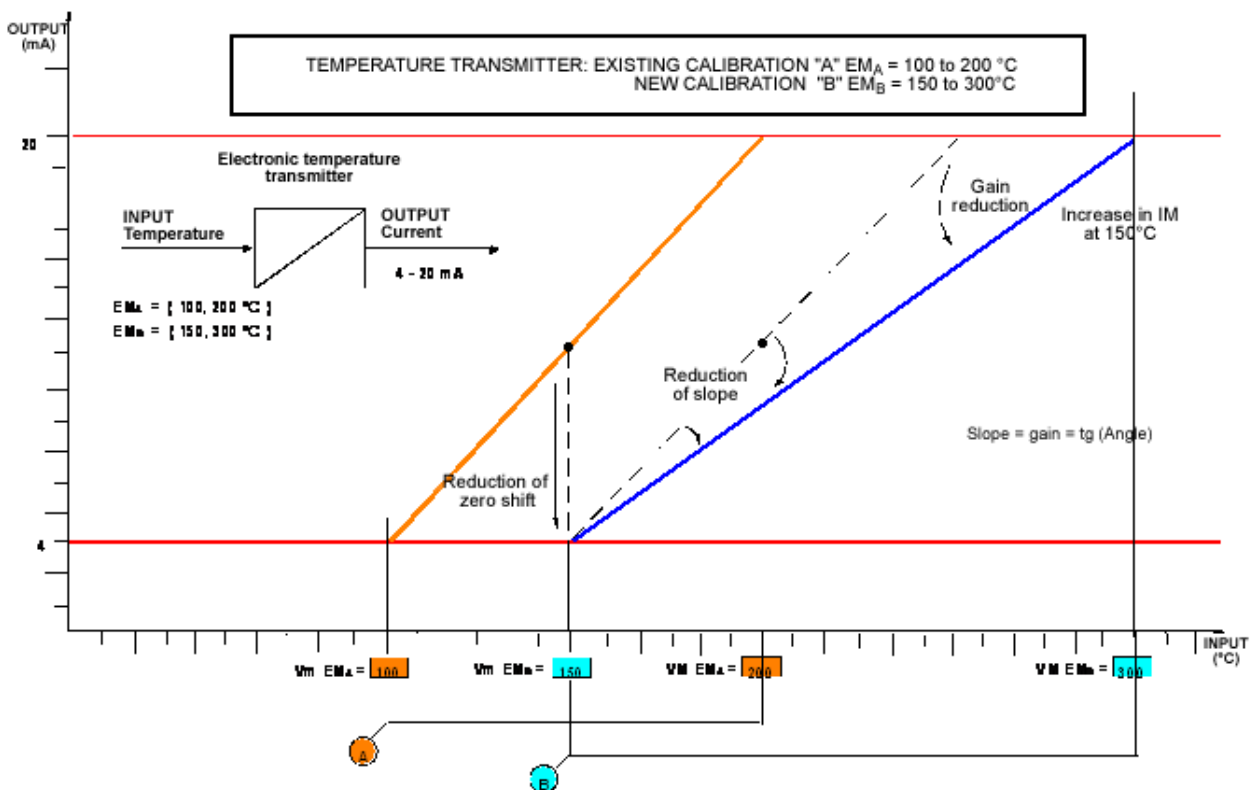


Figure 37: Influence of settings on the measuring signal

The representative theoretical curve for this relation is a straight line.

This straight line may be modified by zero and MR adjustments:

- ✦ zero adjustments = offset = line shift.
- ✦ Measuring Range adjustments = gain = slope = line rotation.

In reality, non linearity, hysteresis and drift convert this straight line into a greater or lesser surface area, according to their influence.

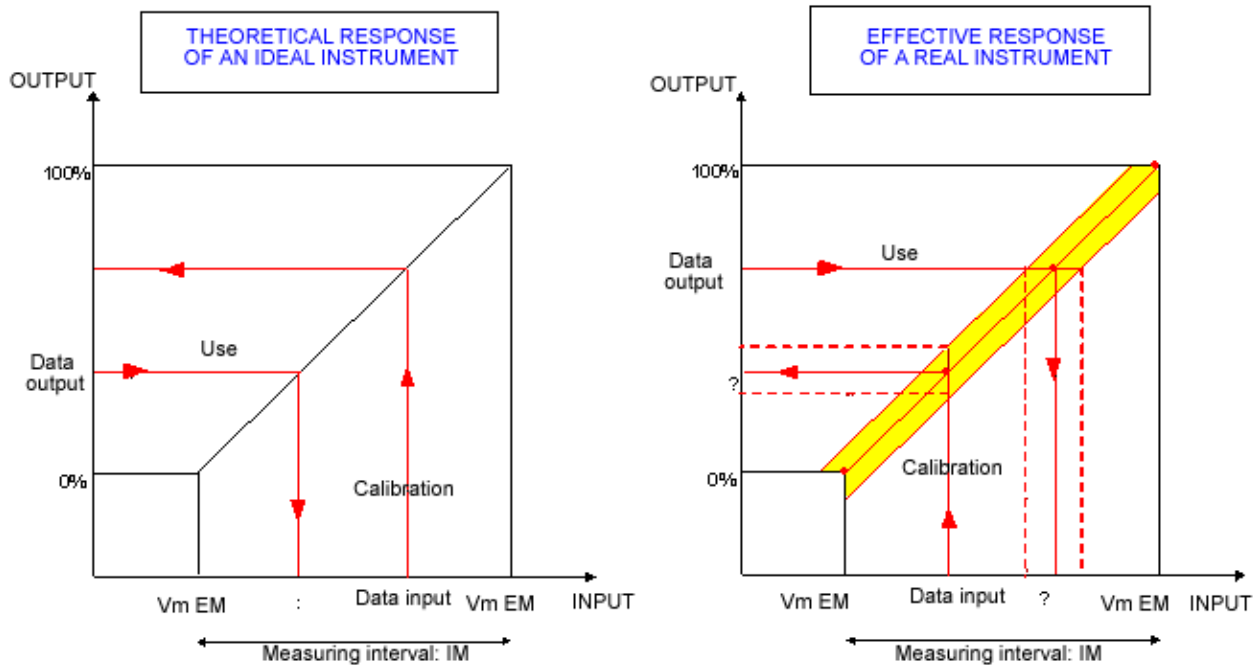


Figure 38: Comparison between a measuring instrument's theoretical and actual response

An instrument's response may be different from a line: parabola, exponential...

An additional element needs to be used to linearise this response.

The graphs below show how the parabolic signal from a ΔP transmitter can be "linearised" by adding a square root extractor between the transmitter and receiver (indicator, recorder, regulator...).

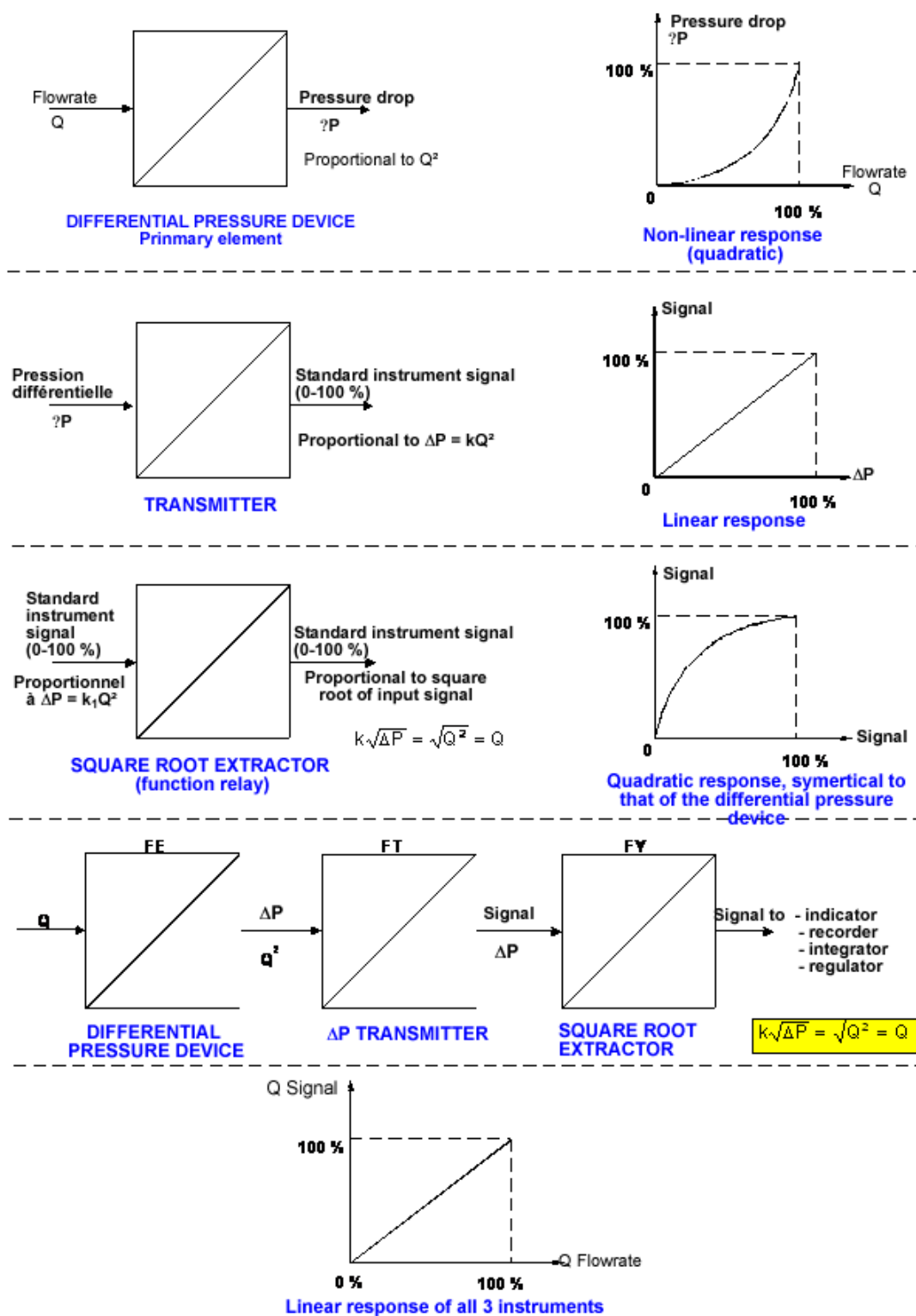


Figure 39: Behaviour of different measurement signals

4.2. WHAT IS AN INSTRUMENT SIGNAL?

A signal is a physical quantity (current, pressure) circulating between the elements of a loop.

The value of a signal can be used to determine the value of the quantity producing it, if its measurement range (MR) is known.

For a given instrument:

- ⊕ Output signal = 0 % $\Rightarrow$ instrument input = MR minimum value (MR mv).
- ⊕ Output signal = 100% $\Rightarrow$ instrument input = MR maximum value (MR MV).

The essential relation enabling simple conversion is proportionality

In general to abstract the units, input and output are expressed in %.
(Or better yet: between 0 and 1)



Figure 40: Instrument signal proportionality

4.3. DIFFERENT SIGNAL TYPES

Sensors supply measurement signals (mV, ΔP , frequencies, ΔR , etc.) too low to be usable.

These signals are amplified and converted to conventional signal form (electrical or pneumatic) by the associated transmitter, and are proportional to the measurement signals

4.3.1. *Pneumatic signals*

Represented by air or gas pressure of between 3 and 15 psi, or 200 and 1000 hPa.

These signals require an air or gas supply:

- ✦ 100 psi or 7 bar at the header,
- ✦ 20 psi or 1.4 bar for the instrument.

Most pneumatic instruments have become obsolete since their use is restrictive:

- ✦ Instrument air or gas clean, dry, oil-free,
- ✦ Distance between instruments as low as possible,
- ✦ Costly transmission tubes,
- ✦ Problems of leaks...

However, certain instruments are difficult to replace:

- ✦ I/P converters,
- ✦ Pneumatic or electro-pneumatic positioners,
- ✦ Pneumatic safety systems (well head cabinets),
- ✦ Electro-pneumatic system (SOV).

4.3.2. *Electrical signals*

Represented by a **low voltage direct current**, with the current offering the advantage of remaining the same at any point of a current loop.

The current varies between 4 and 20 mA.

The supply may be:

- ✦ 24 VDC, in two-wire configuration,
- ✦ 110 / 220 VAC, in four-wire configuration

The receivers are connected in series with the transmitter in the current loop, generally across the terminals of a standard resistor (250Ω).

This resistor can have several receivers connected in parallel

The signal can be measured and each receiver removed without interrupting the current loop.

The total resistance (receivers + lines) must always remain less than or equal to the transmitter's charging resistance (value given by the manufacturer)

The advantages of the 4-20 mA signal are substantial:

- ✚ Enables far longer distances than with pneumatic.
- ✚ No risk of leaking.
- ✚ No additional dead time.
- ✚ Less maintenance

In hazardous zones, using electrical devices requires special precautions, protection by intrinsic safety isolation devices or explosion proof enclosures, manufacturer's certification of the apparatus concerned.

4.3.3. Signal conversion

These conversions must be carried out with relations of proportionality maintained.

For example:

$$5.6 \text{ mA} = 10 \% = 4.2 \text{ psi}$$

$$11 \text{ psi} = 66.7\% = 10.67 \text{ mA} = 3.67 \text{ V}$$

Value of a signal in %:

$$Y\% = 3 + Y/100 \times 12 \text{ psi}$$

$$Y\% = 200 + Y/100 \times 800 \text{ hPa}$$

$$Y\% = 4 + Y/100 \times 16 \text{ mA}$$

Converting a measurement into a signal:

We have a measurement X and want to calculate the corresponding signal Y.

$$\text{Ratio } R = (X - \text{MRmv}) / (\text{MI})$$

- ✚ For a pneumatic transmitter:

$$Y = (3 + 12 \times R) \text{ psi}$$

$$Y = (200 + 800 \times R) \text{ hPa}$$

- ✚ For an electronic transmitter:

$$Y = (4 + 16 \times R) \text{ mA}$$

Converting a signal into a measurement

We have a signal Y and want to calculate the corresponding measurement X.

$$\text{Ratio } R = (Y_{\text{mA}} - 4) / 16$$

$$= (Y_{\text{psi}} - 3) / 12 = (Y_{\text{hPa}} - 200) / 800$$

$$X = MR_{\text{mv}} + R \text{ (MI)}$$

4.3.4. Transmission rules

4.3.4.1. Transmission of electric signals

Use shielded twisted pairs to limit:

- ✚ Mutual inductions between conductors
- ✚ Electromagnetic interference (induced currents).

The cable ducts and supports must:

- ✚ Include instrument cables only (0.5 m between high and low voltage),
- ✚ Avoid the proximity of electric motors with high voltage devices (1.5 m).

The cable shielding must be earthed at just one end to prevent earth loops:

- ✚ For skin temperature measurements by TC or RTD at the unit side,
- ✚ For others at the machinery room end,
- ✚ Lightning protection barriers must be installed at the end of the cables to protect instruments in certain regions.

4.3.4.2. Pneumatic signal transmission

The connections need to be checked up periodically to detect any leaks.

- ✦ tube blockage or accumulation of liquid are possible in case of instrument air or gas outside of specifications.
- ✦ if the line distance is greater than 100 m, and for valves with big servomotors, relays (boosters) need to be used to minimise dead times.

4.3.4.3. Signal calculations

Certain signals can be combined in different ways, such as:

- ✦ Adding flowrate signals, to obtain an overall flowrate signal,
- ✦ Gas volume flowrate signal, multiplied by pressure signal and divided by temperature signal to obtain a mass flowrate signal.

4.3.4.4. Digital transmitters

Generate an output signal in the form of binary words, and are equipped with a fieldbus

These words generally comprise 12 bits, i.e. 2 exhibiting 12 or 4096 different values, i.e. a resolution of $1 / 4096 = 0.025 \%$ (see '**automated system logics**' course)

They have certain advantages:

- ✦ Better accuracy (measuring external influences),
- ✦ A single line for several transmitters (in case of a network),
- ✦ Two-way communication (parameter reading & configuration) from an Operator station / micro-console,
- ✦ Option of checking other components of the measuring loop (sensors, transmitters & receivers),
- ✦ On-line diagnostics options,
- ✦ Quicker measurement response.

Drawbacks: the communication protocols are not standardised (HART, PROFIBUS, SMART, etc.)

The most commonly used protocol is the **HART** protocol.

The transmitter associated with the sensor supplies two types of electrical signals:

- ✦ A 4-20 mA analogue signal, replacing the pneumatic signal
- ✦ A 4-20mA digital signal, improving the electronics of the sensor-transmitters used for converting the conventional analogue signal into a digital signal. Analogue-digital converters and vice-versa are therefore built into the transmitter.

To avoid the analogue signal deteriorating, the digital signal superimposed over the analogue signal is frequency encoded

4.4. ANALOGUE AND DIGITAL

Analogue and digital are two processes for data transmission and storage.

Analogue originated with the beginnings of electricity, whereas **digital** is a recent product of the IT age. A signal is analogue if its information is represented by the variation of a physical quantity.

The concept of analogue is used in contrast with that of digital. A physical quantity such as an electrical voltage, a position in space, a certain height of a liquid, etc., are analogue values.

Of course, they can be measured and therefore represented by digits, but these will have to be accompanied by the value designation for correct comprehension.

The difference, in terms of result, between an analogue system and a digital system lies principally in the **information accuracy**. In fact, in an analogue transmission, the information received is measured. It is therefore subject to possible accuracy errors.

In a digital transmission, the information received is detected (or not). So the information is recovered identically with no loss of accuracy, unless the detection fails.

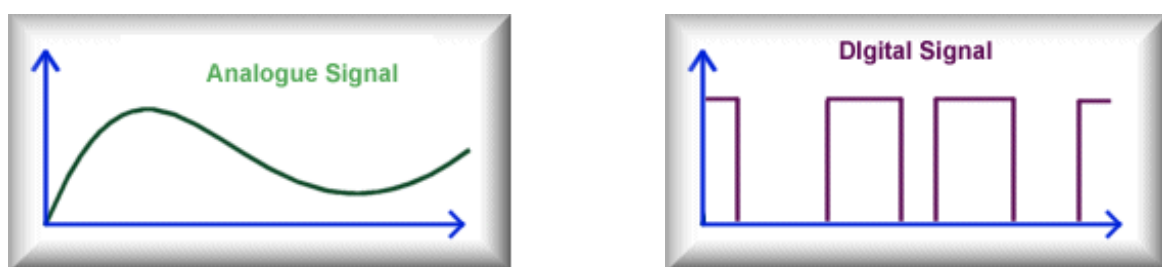


Figure 41: Appearance of analogue signal and digital signal

The word **digital** is most often used in IT and electronics, especially if the information is converted to binary format, as in digital audio or digital photography.

These kinds of data carrying signals can transmit two types of electronic or optical pulses: *logic 1* (pulse present) or *logic 0* (pulse absent).

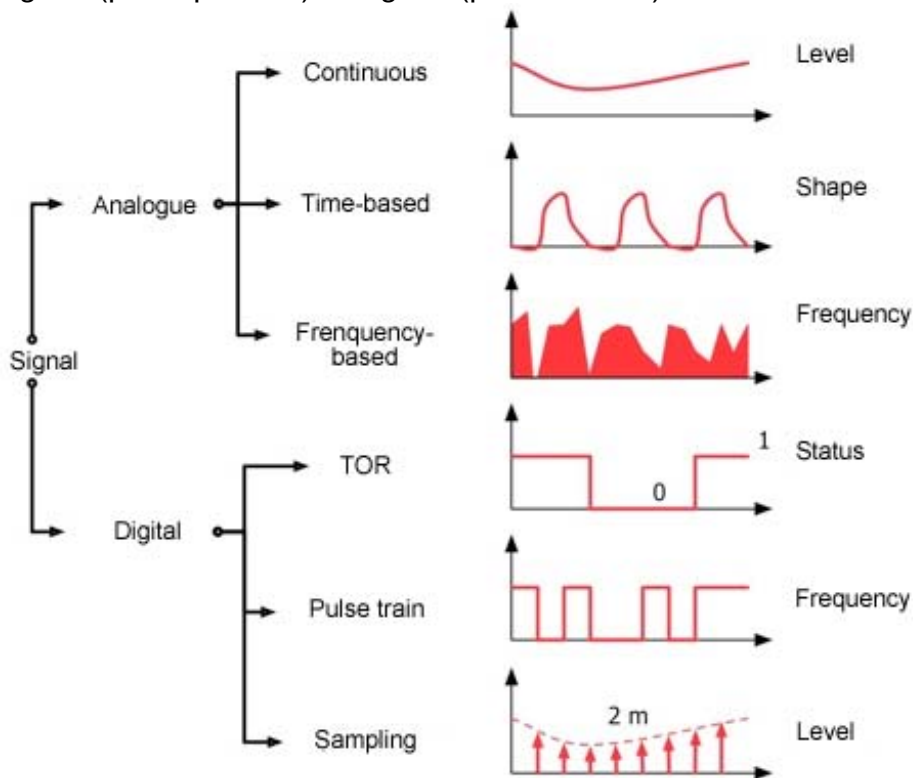


Figure 42: Signals

4.4.1. Analogue-Digital Conversion

The new generation of sensor-transmitters converts the electrical signal from the sensor into a digital signal in the transmitter part before being reconverted into an analogue signal from the transmitter output, to be directed towards the receiver (e.g.: DCS, PLC, etc.).

Since natural signals are nearly all continuous signals and digital circuits only handle discrete data, these signals first need to be converted before digital processing can be applied to them. This conversion is known as **discretisation** or **digitisation**; it is performed by an analogue-digital converter.

This operation comprises two actions:

- ✚ sampling, which converts the continuous medium signal into a discrete medium signal (a sequence of values);
- ✚ quantification, which replaces the continuous values by discrete values

An Analogue-Digital Converter (ADC) is an electronic assembly whose function is to generate a digital value (encoded in several bits) from an analogue value, proportional to this input analogue value.

This will most often involve electrical voltages.

There are several solutions for converting an analogue signal into a digital signal – they are classified here in the order slowest to fastest.

- ⊕ Dual slope converter,
- ⊕ Single slope converter,
- ⊕ Successive approximation converter,
- ⊕ Sigma Delta converter,
- ⊕ Flash converter,

4.4.1.1. Dual slope converter

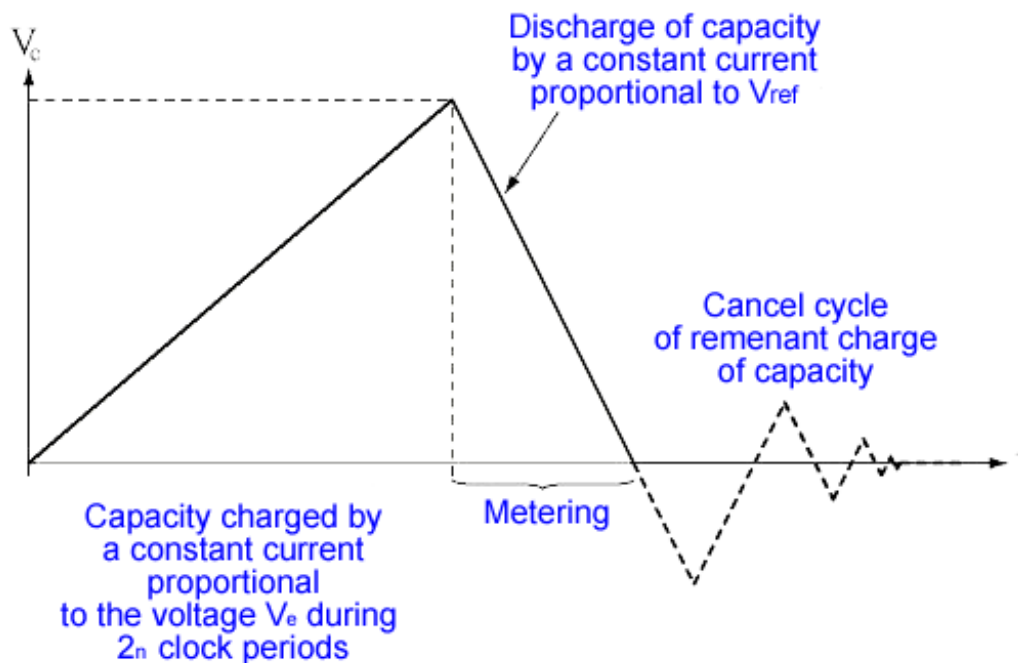


Figure 43: Dual slope converter operation

This development from single slope converters makes it possible to cope with the natural drift in the constituent components.

It works based on comparison between a reference and the signal for conversion.

The conversion works in 3 steps:

1. A capacitor is charged with a current proportional to the signal to be converted for a fixed time (the counter's complete count time);
2. The capacitor is then discharged, with a constant current derived from the reference voltage, until the voltage across its terminals is cancelled out. When the voltage reaches zero, the counter value is the result of the conversion;
3. Finally the voltage across the capacitor terminals is cancelled out by a convergent series of charges and discharges (the objective being to fully discharge the capacitor so as not to distort the next measurement). This is generally known as the relaxation phase.

These converters are particularly slow (tenths of a millisecond per cycle, and sometimes hundreds), but are highly accurate (over 16 bits). They have little time and temperature drift.

4.4.1.2. Single ramp converter

A voltage ramp is generated using a counter and a digital-analogue converter.

A comparator stops the counter when the voltage created by the ADC reaches the voltage to be converted. The counter will then indicate the result over N bits, to be stored or processed.

These converters have the same performance in terms of stability as successive approximation converters, though they are distinctly slower than the latter. In addition their conversion time, which changes with the voltage to be converted, makes it a little-used tool.

4.4.1.3. Successive approximation converter

Very close in terms of composition to single slope converters, successive approximation converters (also known as bit weighing) use a process of comparison to convert an analogue voltage into digital.

A sequencer (generally called SAR, or Successive Approximation Register) coupled to an ADC generates an analogue voltage, which is compared to the signal to be converted.

The result of this comparison is then introduced into the SAR, which will take it into account, to continue the process of comparison, until completion.

The converter performs its conversion by positioning the most significant bit (MSB) first and gradually dropping to the LSB.

Successive approximation converters have conversion times of around ten microseconds, with resolutions of approximately a dozen bits.

4.4.1.4. Sigma Delta converter

This type of converter is based on the principle of over-sampling an input signal.

A comparator is generally used to convert over one bit (i.e. 0 or 1) the difference (delta) between the input signal and the result of conversion (0 = smallest, 1 = biggest).

The result of comparison is then entered into a filter known as the decimator, which adds up (sigma) the input signal samples. This means calculating the integral of the difference between the input and output.

This creates a feedback system (the output loops back to the input), which makes the integral value of the signal to be converted fluctuate around a reference value (the result of conversion).

The comparator's digital output is over 1 bit at high frequency (sampling frequency), which is filtered by the decimator which increases the number of bits by reducing the sampling pseudo- frequency. The benefit of this type of converter lies in its high potential output resolution (16, 24, 32, 64 bits or even more) for input signals of moderate bandwidth.

These converters are well suited to converting analogue signals derived from sensors with an often low bandwidth (for example audio signals).

Sigma/Delta converters are, for example, used in CD players.

4.4.1.5. Flash converter

The principle is to generate 2^N analogue voltages by means of a voltage divider with $2^N + 1$ resistors. The 2^N voltages obtained across the terminals of each resistor are then compared in 2^N comparators with the signal to be converted.

A combination logic unit connected to these comparators will give the result coded over N bits in parallel. This conversion technique is very quick, but costly in terms of components, and therefore used for critical applications such as video.

Flash converters have conversion times of below a microsecond, but a fairly low accuracy (of around ten bits). This converter is often very expensive.

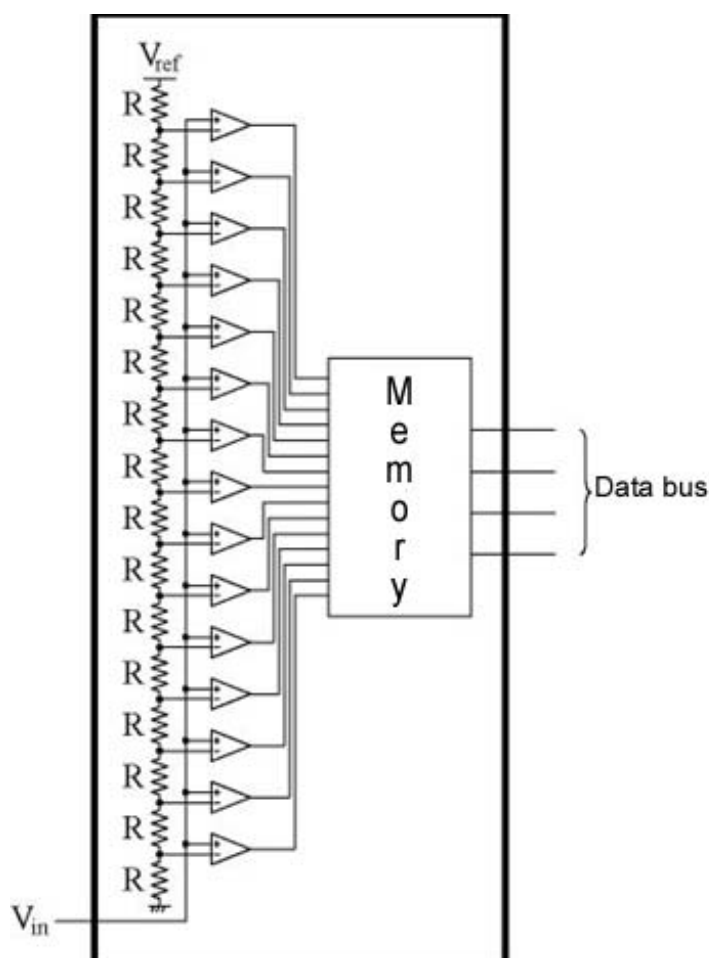


Figure 44: Structure of a flash converter

4.4.1.6. Sampling

Sampling consists of converting an analogue signal (continuous) into a digital signal (discrete) by capturing values at regular time intervals (here time should be taken in the broad sense, and applies to any signal).

This step is required in order to record, analyse and process a signal by computer, since computers can only process numbers. We need to distinguish sampling from quantification, but these are both necessary steps in the digitisation of a signal.

The frequency at which the values are captured is the sampling frequency, also known as the sampling rate, expressed in Hz. For instance, an audio CD contains musical data sampled at 44.1 kHz (44,100 samples per second).

An analogue signal by definition has infinite accuracy, both in terms of time and value.

Sampling, to enable an exact signal definition in terms of time to store it digitally, will reduce this signal to a sequence of discrete points. This has two distinct consequences:

Only the information present on the point of capture is recorded; all the rest is lost.

Intuitively, you can realise that if the sampling frequency is very low the acquisitions will be highly spaced, and therefore if the original signal has details between two capture positions, they will not be recorded.

For this reason the sampling frequency must be well chosen, big enough to correctly retrieve all the information carried by the analogue signal, at least the useful information, without being excessive and wasting storage space.

Shannon's theorem asserts that all signal frequencies less than half the sampling frequency are correctly retrieved.

In practice, however, we find that the harmonic frequencies of the sampling frequency are favoured, and that there are numerous losses.

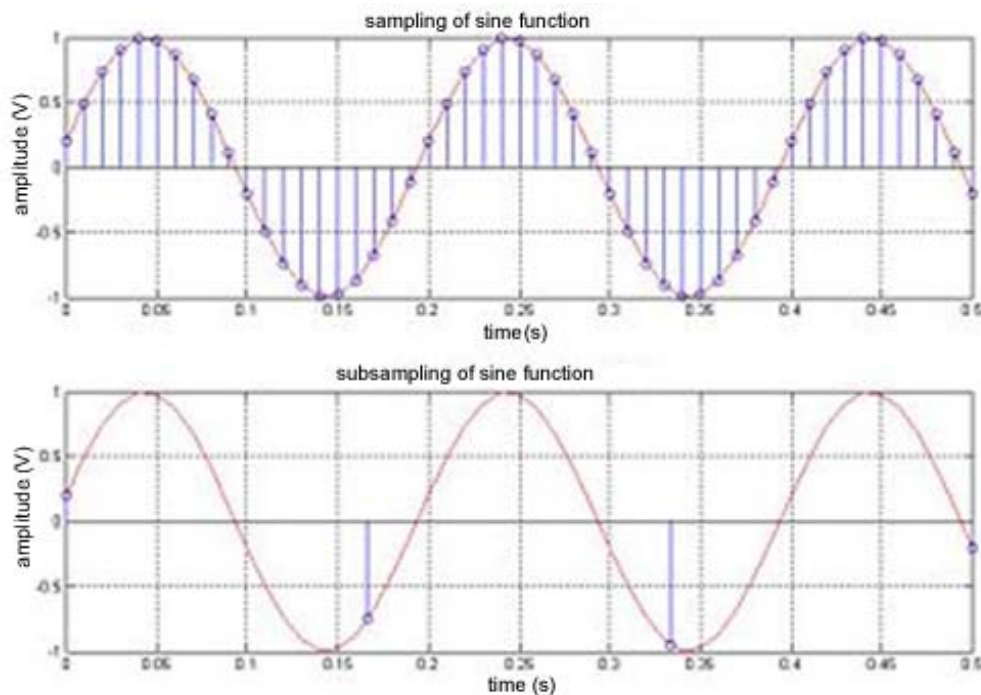


Figure 45: Sampling

Frequencies greater than half the sampling frequency introduce a spectral overlap also known as aliasing.

To convince ourselves of this, let's try to imagine an analogue signal with very short and large impulses, like the grooves on a vinyl disc. These impulses represent an addition of high frequencies to the basic signal.

If the capture point falls on a sound portion, the impulse is ignored, but if the capture point falls in the middle of the impulse, the value at this precise point will be recorded, thereby introducing an artefact in the recording, since this value will be considered to be the average value for its interval.

To prevent this type of disturbance, we generally perform low-pass frequency filtering before the sampling operation itself, known as the anti-aliasing filter, where the cut-off frequency will theoretically be equal to the highest correctly retrieved frequency, i.e. half the sampling frequency.

In practice, things are completely different. It is of course necessary for frequencies greater than half the sampling frequency to be greatly attenuated (for a good filter, -50 dB).

But the anti-aliasing filter size (purely analogue) will have a so-called greater or lesser attenuation band according to the filter order. The figure above illustrates the problem.

The attenuation band is between 20 kHz and 22.05 kHz. The problem is that a linear analogue filter with an order greater than 8 is difficult to operate (filters with switched capacities are simpler).

It is simpler to slightly increase the sampling frequency.

The filter can also be a **band-pass**; for instance if we want to sample an FM radio source, in which case the sampling frequency must be double the bandwidth, rather than the cut-off frequency, of this filter.

If we take the particular case of a CD, with sampling frequency set at 44.1 kHz, *Shannon's theorem* asserts that we must not exceed a recorded frequency of 22,050 Hz.

In reality, if the sampled frequency gets very close to the sampling frequency, we cannot avoid an interference effect generating undesirable interference noise. There are several potential methods for preventing this.

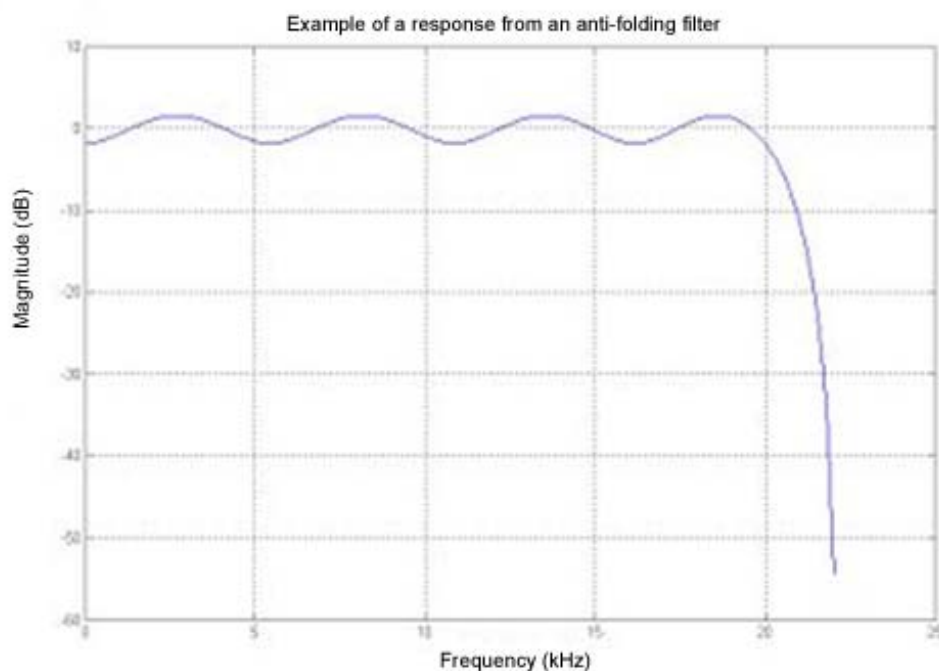


Figure 46: Example of anti-aliasing filter

The simplest consists of deliberately cutting off the frequencies in excess of 20 kHz, instead of cutting at 22, before sampling, using for example an anti-aliasing filter. In this way we avoid the “danger” zone. Another method consists of “correcting” the data in real time to adapt it to the sampling frequency (for example Super Bit Mapping developed by Sony).

In many cases, filtering is naturally carried out in the acquisition, via the imperfection of the capturing systems.

Let's take the example of a CCD sensor: its function is to convert the light it receives into a light intensity value.

It does not receive an infinitely small spot of light which would mathematically correspond to a discrete point and physically to a photon – this is physically impossible - but it receives a greater or smaller area of light, and its physical properties mean that an analogue intensity value is given at the output, equating to a sort of weighted average of all the light spots received.

It may very well pay greater consideration to the centre of its reception area than the periphery, or even vice-versa, and the output will change accordingly.

However, most sensors will act similarly to a **low-pass filter**, thereby avoiding the need to filter the *analogue signal*.

4.4.2. Electronic filters

A filter is an electronic circuit that performs a processing operation on a signal. In other words, it attenuates certain signal components while letting others through. An example familiar to the public is the audio equaliser.

A filter modifies (or filters) certain parts of an input signal in the field of time and frequency.

Any real signal can be considered as comprising the sum of sinusoidal signals (infinite if necessary) at different frequencies; the function of the filter is to modify the phase and amplitude of these components.

We can classify filters based on their transfer function method or the behaviour of the passive elements making up the filter.

The most common filters are one of the following four types: low-pass, high-pass, band-pass or band ejector.

A **high-pass** filter only lets through frequencies above a given frequency, known as the cut-off frequency, and attenuates the others (low frequencies).

In other words, it “lets through high”: it is a bass attenuator for an audio signal. It could also be known as a **bass stop**.

A low-pass filter only lets through frequencies below its cut-off frequency. It is a treble attenuator for an audio signal. It could also be known as a treble stop.

A **band-pass** filter only lets through a certain frequency band (and attenuates everything above or below). It is commonly used in radio, TV receivers, etc. to isolate the signal that we want to capture.

A rejector filter, also known as a trap filter, bell filter or band-stop filter is a complement of the band-pass.

It attenuates a range of frequencies. This may be useful for reducing certain types of interference for example.

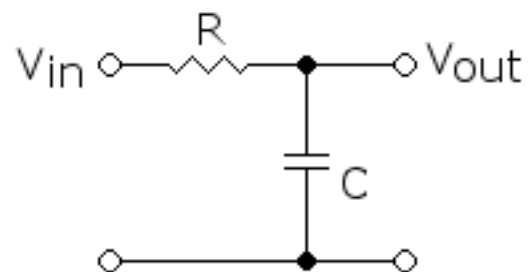
Technically, a filter may be made in different forms: passive, active or digital

4.4.2.1. Passive filters

A passive filter is characterised by the exclusive use of passive components (resistors, capacitors, coupled or uncoupled coils). Consequently, their gain (power ratio between output and input) may not exceed 1. In other words, they can only partly attenuate the signals, but not amplify them.

The simplest designs are based on RC, RL, LC circuits or an RLC circuit. But it is of course possible to increase the complexity of the filter (and the number of components).

Figure 47: Passive filter structure



The fewer components there are, the trickier it will be to be selective: the attenuation will be gradual.

With more components, we can expect more abrupt frequency cut-off, with less contact with neighbouring frequencies.

Passive filters are rarely subject to saturation phenomena (except for some cases of coils with core); which explains for instance their use in speaker enclosures.

Furthermore they may be present in all frequency ranges (which explains their use in certain high frequency circuits as in radio for example).

However, it will be difficult for the same circuit to cover on its own a very wide frequency range, since the choice of a type of coil or capacitor depends on the frequency. It is feasible but more complex.

We can mention the example of the electrochemical capacitor: well-suited to low frequencies, it fairly quickly becomes inductive with increasing frequency (it loses its capacitive behaviour).

A coil consists of a wire, and therefore is conductive at low frequency. However, it resists the passage of high frequencies.

Capacitors do the opposite, insulating at low frequency, and conducting at high frequency.

Resistors do not select the frequencies themselves, but can define the time constants of a circuit by limiting the currents to a greater or lesser extent. So resistors determine the frequency at which the filter acts, and its attenuation.

Beyond 100 MHz: inductance coils often comprise a single sinuous wire or metal bands, and the capacitors superimposed metal bands (stubs).

For example on both opposing faces of a printed circuit.

For second order filters, i.e. those that can be described by a second order differential equation (very often linear), it is possible to define a quality factor, i.e. the ratio between their central frequency and bandwidth. NB this is only valid for a band-pass.

A filter with a very fine band for its central frequency will be considered highly selective or high quality.

The circuit is subject to more or less interference noise appearing in the signals. This depends on the components employed: very low thermal noise in resistors, fairly low noise in capacitors, but greater sensitivity to magnetic fields with coils.

For the sake of completeness, we should mention quartz filters, Surface Acoustic Wave filters (SAW), ceramic filters and mechanical filters, which also come under passive filters.

4.4.2.2. Active filters

Active filters are characterised by the use of at least one active component (e.g. transistor, operational amplifier, or other integrated circuit ...).

These filters have the advantage of being able to avoid coils which are expensive, hard to miniaturise and imperfect (loss angles, natural resonances, sensitivity to interference).

In addition they have a gain that may be greater than 1 (they can amplify).

This type of filter is well-suited to low-amplitude and low-power signals. Active filters are therefore widely used in audio amplifiers and electronic instruments of all sorts.

On the downside, unlike passive filters, they require a power supply and are limited in amplitude (saturation).

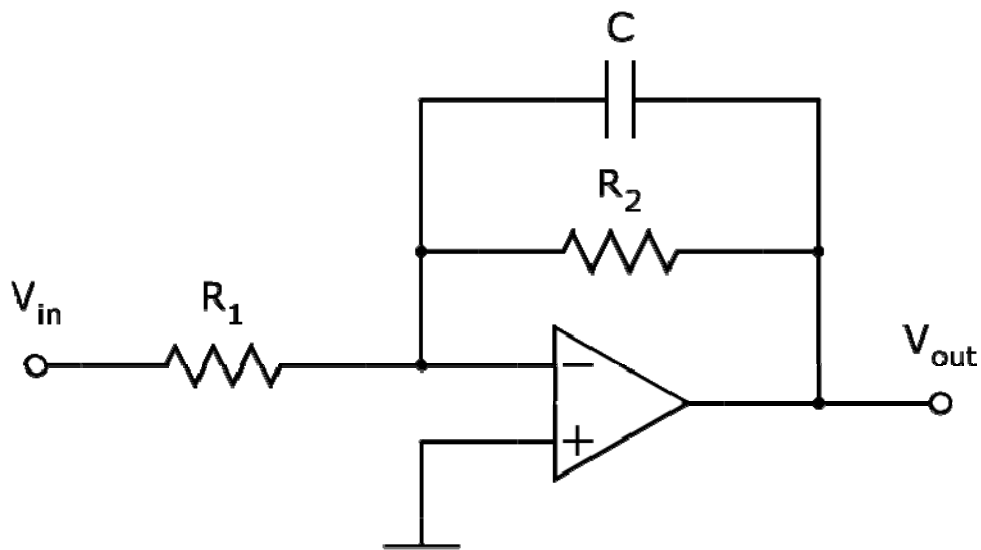


Figure 48: Active filter structure

Today they can cover wide frequency bands. Active components (as well as resistors to a lesser extent) may introduce interference noise, which, beyond a certain threshold, may be troublesome. However, this noise can often be controlled.

In this category of filters in case of necessity we can mount switched capacity filters, which are mid-way between passive and active filters.

5. MEASUREMENT UNITS

The International System of units (SI) has been obligatory in France since 1962, with the previously commonly used kilogram-force and derived units (kilogram-metre, kg/cm², etc.) now prohibited.

The SI enables considerable simplifications in calculations, and above all is an international language; it is important to use it correctly, so we need to take great care with writing the units. The writing of the unit symbols is now standardised in the same way as the system itself.

We would believe that a colleague might understand “120 km.h” as a speed, but a computer would definitely not, it needs to be written correctly: 120 km / h. The same applies for Kg and kg, m/m and mm, etc.

5.1. BASIC SI UNITS

Quantitative study of the formulae obtained by a physicist or engineer requires the use of a coherent system of units.

The international system of units – SI for short – is the system universally adopted in the field of electricity. It is based on seven basic units and two additional geometric units set out in the table below.

Quantities		SI units		Note
Name	Symbol	Name	Symbol	
Length	l, d $x, y, \dots$	metre	m	
Mass	m	kilogram	kg	not to be confused with weight
Time	t	second	s	
Electrical current intensity	I i	ampere	A	
Thermodynamic temperature	T	Kelvin	K	
Quantity of matter	n	mole	mol	
Light intensity	I_v	candela	cd	
Plane angle	$\alpha, \beta, \gamma, \dots$	radian	rad	2π (rad) = 1 complete revolution
Slid angle	Ω	steradian	sr	

Table 6: Basic units

5.2. DERIVED SI UNITS

All the other units are derived from these base units, on the basis of natural laws and geometric relations. A list of the main quantities and derived units used in electricity is given in the table below.

Quantities		Derived SI units		Relations between units
Name	Symbol	Name	Symbol	
Force	F	Newton	N	$1 \text{ N} = 1 \text{ kg m/s}^2 = 1 \text{ W s/m}$
Torque (moment of a force)	$\frac{M}{T}$	Newton-metre	Nm	
Energy, work	$\frac{E}{W}$	Joule	J	$1 \text{ J} = 1 \text{ Nm} = 1 \text{ W s}$
Power (active power)	P	Watt	W	$1 \text{ W} = 1 \text{ J/s} = 1 \text{ V A}$
Reactive power	Q	reactive volt-ampere	var	$1 \text{ var} = 1 \text{ V A}$
Apparent power	S	volt-ampere	VA	
Pressure	P	Pascal	Pa	$1 \text{ Pa} = 1 \text{ N/m}^2$
Electric charge	Q	coulomb	C	$1 \text{ C} = 1 \text{ A s}$
Voltage, potential difference	$\frac{U}{u}$	Volt	V	$1 \text{ V} = 1 \text{ W/A} = 1 \text{ J/C}$
Electrical resistance	R	Ohm	Ω	$1 \Omega = 1 \text{ V/A}$
Electrical capacity	C	Farad	F	$1 \text{ F} = 1 \text{ C/V} = 1 \text{ A s/V}$
Inductance	L	Henry	H	$1 \text{ H} = 1 \text{ Wb/A} = 1 \text{ V s/A}$
Frequency	f	Hertz	Hz	$1 \text{ Hz} = 1 \text{ s}^{-1}$
Angular frequency	ω	radian/second	rad s^{-1}	$\omega = 2\pi f$
Magnetic flux	Φ	Weber	Wb	$1 \text{ Wb} = 1 \text{ V s}$
Magnetic induction	B	tesla	T	$1 \text{ T} = 1 \text{ Wb / m}^2$
Magnetic field	H	ampere/metre	A/m	
Electric field	E	volt/metre	V/m	

Table 7: Derived SI units

5.3. PREFIXES

The main invention of the metric system proposed during the French Revolution was attaching prefixes to the units, corresponding to base 10 multiples and sub-multiples of the unit.

Take a distance above expressed in **kilometres**, abbreviated to “km”. This prefix equates to multiplying by 1000, and we can say that this distance is 37.2 km for example. In the same way, for a pencil lead with a diameter measuring 0.0005 m or 0.5×10^{-3} m, we would instead use a sub-multiple of the metre, i.e. the **millimetre**, abbreviated to “mm”, which equates to a sub-multiple of 1000, whereby this diameter is 0.5 mm.

Factor	Prefix		Example
	Name	Symbol	
10^{12}	tera	T	1 TJ = 10^{12} J
10^9	giga	G	1 GHz = 10^9 Hz
10^6	mega	M	1 MW = 10^6 W
10^3	kilo	k	1 k Ω = 10^3 Ω
10^2	hecto	h	1 hm = 100 m
10^{-1}	deci	d	1 dl = 0.1 l
10^{-2}	centi	c	1 cm = 0.01 m
10^{-3}	milli	m	1 mA = 10^{-3} A
10^{-6}	micro	μ	1 μ H = 10^{-6} H
10^{-9}	nano	n	1 ns = 10^{-9} s
10^{-12}	pico	p	1 pF = 10^{-12} F

Table 8: Prefixes

The same applies systematically to all SI units, and for much higher ratios. To form names and symbols of decimal multiples and sub-multiples of SI units, we use the prefixes given in the table above.

5.4. RULES FOR WRITING UNITS

Use of units in technical texts is governed by very strict spelling rules, defined by ISO (*International Organization for Standardization*), particularly in the choice of upper/ lower-case, punctuation and plural:

- ✦ Symbols are not followed by the dot normally used in abbreviations. So we write: “the distance d equals 12 m”.
- ✦ When its name is written entirely in letters, the unit remains unchanged. So we write: “This motor has a power of 850 watt”, i.e. without the “s” in the plural.

However, in less technical texts, the normal grammar rules take over: “This boat measures 12 metres”, with the final “s”.

5.5. “NON-STANDARD” TECHNICAL UNITS

Certain units predating the SI system are still in use, often through habit, sometimes because the SI equivalent is not as “practical”.

Quantities	Unit		Relations between units
	Name	Symbol	
Distance	Angstrom	Å	1 Å = 0.1 nm = $0.1 \cdot 10^{-9}$ m
	Nautical mile		1 nautical mile = 1852 m
	Light year	ly	1 ly = $9.46 \cdot 10^{15}$ m
Volume	litre	l	1 l = $1 \text{ dm}^3 = 0.001 \text{ m}^3$
Angle	Degree	°	1 revolution = $360^\circ = 6.28 \text{ rad}$
	Minute	′	1′ = 60″
	Second	″	60″ = 1′
Time	Minute	min	1 min = 60 s
	Hour	h	1 h = 60 min = 3600 s

Quantities	Unit		Relations between units
	Day	d	1 d = 24 h
Speed	Kilometres per hour	Km/h	1 m/s = 3.6 km/h
	Knot		1 knot = 1 nautical mile / h = 1.852 km/h = 0.5144 m/s
Angular speed	Revolutions per minute	rpm	1 s ⁻¹ = 1 rps = 60 rpm 3000 rpm * π / 30 $\approx$ 314 rad/s
Mass	Tonne	t	1 t = 1000 kg
Force	Kilo pound	kp	1 kp = 9.81 N The weight of a mass of 1 kg on Earth
Energy	Calorie	cal	1 cal = 4.1868 J Heats 1 g of water by 1°C
	Large calorie	Cal	1 Cal = 1 kCal = 1000 cal
	Kilowatthour	kWh	1 kWh = 3.6 10 ⁶ J
Power	Metric Horsepower	Hp	1 Hp = 735 W
Pressure	Bar	bar	1 bar = 100,000 Pa = 1 hPa
	Kilo per cm squared	kp/cm ²	1 kg/cm ² = 9.81 N/cm ² = 98,000 Pa $\approx$ 1 hPa
	Atmosphere	atm	1 atm = 1.03 kp/cm ² = 1.01325 hPa $\approx$ 1 hPa
Temperature	Degrees Celsius	°C	Temperature difference: 1°C = 1°K Reference: 0°C = 273.16°K

Table 9: "Non-standard" technical units

5.6. ANGLO-SAXON UNITS

Even scientific Anglo-Saxon circles have trouble sticking to the SI system, and still use the specifically British or American units. These are distinguished by the fact that units of length, mass and many others are based on multiples of 12, 16 and many others.

For example, 1 (land) mile equals 5280 feet; 3 feet are equal to 36 inches (1 foot = 12 inches).

With the engineering profession often a very international one, we should at least be aware of the existence of the units in the following table:

Quantities	Name of unit			Relations between units
	En français	In English	Symbol	
Length		mil	mil	1 mil = 0.001" = 25.4 μ m
	<i>Pouce</i>	Inch	" in	1" = 25.4 mm
	<i>Pied</i>	Foot	' ft	1' = 12" = 30.48 cm
	<i>Mille</i>	(statute) mile		1 mile = 5280' = 1609.3 m
	<i>Mille marin</i>	(nautical) mile		1 mile = 1852 m
Volume	<i>Gallon impérial</i>	Imperial gallon	UK gal	1 UK gal = 4.546 dm ³
	<i>Gallon US</i>	US gallon	US gal	1 US gal = 3.79 dm ³
Mass	<i>Once</i>	Ounce	oz	1 oz = 28.35 g
	<i>Livre</i>	Pound	lb	1 lb = 16 oz = 0.4536 kg
		Ton	ton	1 ton = 2240 lb = 1061.1 kg
Pressure	<i>Livre / pouce²</i>	Pound / square inch	lb/in ² psi	1 lb/in ² = 70.3 g/cm ² = 6.8948 kPa
Energy		British thermal unit	BTU	1 BTU = 252 kJ
Torque (*)	<i>Livre-pouce</i>	Pound-inch	lb-in	1 lb-in = 0.113 Nm
	<i>Livre-pied</i>	Pound-foot	lb-ft	1 lb-ft = 1.35582 Nm
Power	<i>Cheval</i>	Horsepower	hp	1 hp = 42.41 BTU/min = 745.7 W
Temperature	<i>Degré Fahrenheit</i>	Fahrenheit	°F	1°F = 5/9°C $\cong$ 0.56°C 0 ... 100°C equates to 32 ... 212°F

(*): For torque conversions, we need to consider gravitational acceleration $g = 9.8065 \text{ m/s}^2$, since the pound is a unit of mass and not force. Hence $1 \text{ lb-ft} = 0.13831 \text{ kgp} \cdot \text{m}$.

And in the SI system: 1 metric horsepower (Hp) = 735 W (or 736 W) while 1 Imperial horsepower (HP) = 746 W

Table 10: Anglo-Saxon units

5.7. CONVERSIONS BETWEEN UNITS

5.7.1. Conversions between units of physical quantity

Pressure	Pa	kPa	bar	mbar	mm H ₂ O	mm Hg	atm	psi	inches Hg
Pa	1	0.001	10^{-5}	0.01	0.102	$7.5 \cdot 10^{-3}$	$9.869 \cdot 10^{-6}$	$1.45 \cdot 10^{-4}$	0.0002953
kPa	1000	1	0.01	10	102	7.5006	$9.869 \cdot 10^{-3}$	0.14504	0.2953
bar	10^5	100	1	1000	10200	750.06	0.9869	14.5	29.53
mbar	100	0.1	0.001	1	10.197	0.75006	$9.869 \cdot 10^{-4}$	$1.45 \cdot 10^{-2}$	0.02953
mm H ₂ O	9.806	$9.81 \cdot 10^{-3}$	$9.81 \cdot 10^{-5}$	$9.806 \cdot 10^{-2}$	1	0.07355	$9.86 \cdot 10^{-5}$	$1.422 \cdot 10^{-3}$	
mm Hg	$1.333 \cdot 10^2$	$1.333 \cdot 10^{-1}$	$1.333 \cdot 10^{-3}$	1.333	13.595	1	$1.315 \cdot 10^{-3}$	0.019337	0.03937
atm	$1.0132 \cdot 10^5$	$1.0132 \cdot 10^2$	1.0132	$1.0132 \cdot 10^3$	10132	750	1	14.695	29.9213
psi	$6.894 \cdot 10^3$	6.894	$6.894 \cdot 10^{-2}$	68.94	703.08	51.715	0.068	1	2.03802
inches Hg	3386.39	3.38639	0.0338639	33.8639		25.4	0.033421	0.491154	1

Table 11: Table of pressure units

Kinematic viscosity	m ² /s	St	cSt
m ² /s	1	$1 \cdot 10^{-4}$	$1 \cdot 10^{-2}$
St	$1 \cdot 10^{-4}$	1	$1 \cdot 10^2$
cSt (mm ² /s)	$1 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	1

Table 12: Table of kinematic viscosity units

Dynamic viscosity	Pa.s	P	cP
Pa.s	1	10	$1 \cdot 10^3$
cPa.s (P)	$1 \cdot 10^{-1}$	1	$1 \cdot 10^2$
mPa.s (cP)	$1 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	1
microPa.s	$1 \cdot 10^{-6}$		$1 \cdot 10^{-3}$

Table 13: Table of dynamic viscosity units

5.7.2. Conversions between flowrate units

Mass flowrate	kg / s	kg / h
kg / s	1	3600
kg / h	$2.778 \cdot 10^{-4}$	1
lb / s	$4.526 \cdot 10^{-1}$	$1.633 \cdot 10^3$
lb / mm	$7.560 \cdot 10^{-3}$	27.216
lb / h	$1.260 \cdot 10^{-4}$	0.4536

Table 14: Table of mass flowrate units

Volume flowrate	dm ³ /s l/s	l/h	m ³ /s	m ³ /h	cfm	ft ³ /h	UKgal/m	UKgal/h	USgal/m	USgal/h
dm ³ /s l/s	1	3600	0.001	3.6	0.118882	127.133	13.19814	791.8884	15.85032	951.019
l/h	0.000278	1		0.001	0.000588	0.025215	0.003666	0.219969	0.004403	0.264172
m ³ /s	1000	3600000	1	3600	2118.88	127133	13198.1	791889	15850.3	951019
m ³ /h	0.277778	1000	0.000278	1	0.588578	35.3147	3.66615	219.969	4.402863	264.1718
cfm	0.471947	1699.017	0.000472	1.699017	1	60	6.228833	373.73	7.480517	448.831
ft ³ /h	0.007866	28.3168		0.028317	0.016667	1	1.103814	6.228833	0.124675	7.480417
UKgal/m	0.075768	272.766	0.0000758	2.272766	0.160544	9.63262	1	60	1.20095	72.057
UKgal/h	0.001262	4.54609		0.004546	0.002676	0.160544	0.016667	1	0.020016	1.20095
USgal/m	0.06309	227.125	0.0000631	0.227125	0.133681	8.020832	0.832674	49.96045	1	60
USgal/h	0.001052	3.785411		0.003785	0.002228	0.133681	0.013878	0.832674	0.016667	1

Table 15: Table of volume flowrate units

5.7.3. Correspondence between units of length

Length	mm	cm	m	km	in	ft	yard	mile
mm	1	0.1	0.001		0.03937			
cm	10	1	0.01		0.393701	0.032808		
m	1000	100	1	0.001	39.3701	3.28084	1.09361	
km			1000	1		3280.84	1093.61	0.621371
in	25.4	2.54			1	0.083333	0.027778	
ft	304.8	30.48	0.3048		12	1	0.33333	
yard	914.4	91.44	0.9144	0.000914	36	2	1	0.000568
mile			1609.344	1.609344		5280	1760	1

Table 16: Table of units of length

5.7.4. Correspondence between units of mass

Masse	kg	tonne	lb	UK cwt	UK ton	US cwt	US ton
kg	1	0.001	2.20462	0.019684	0.000984	0.022046	0.001102
tonne	1000	1	2204.62	19.6841	0.984207	22.0462	1.10231
lb	0.453592	0.000454	1	0.008929	0.000446	0.01	0.0005
UK cwt	50.8023	0.050802	112	1	0.05	1.12	0.056
UK ton	1016.05	1.01605	2240	20	1	22.4	1.12
US cwt	45.3592	0.0453959	100	0.892857	0.044643	1	0.05
US ton	907.185	0.907185	2000	17.8571	0.892857	20	1

Table 17: Table of units of mass

5.7.5. Correspondence between surface area units

Surface	cm ²	m ²	km ²	in ²	ft ²	yd ²	hectare	mile ²
cm ²	1	0.0001		0.155	0.001076	0.0001196		
m ²	10000	1	0.000001	1550	10.7639	1.19599	0.0001	
km ²		1000000	1				100	0.386102
in ²	6.4516	0.000645		1	0.006944	0.000772		
ft ²	929.03	0.092903		144	1	0.11111	0.000009	
yd ²	8361.27	0.836127		1296	9	1	0.000084	
hectare		10000	0.01		107639	11960	1	0.0038598
mile ²			2.589987				259.08	1

Table 18: Table of surface area units

6. BASIC CONCEPTS IN ELECTRICITY

6.1. THE NATURE OF ELECTRICITY

The origin of electricity is the movement of electrical charge in matter.

Like mass, electrical charge is a property of matter, explaining the origin of certain phenomena. This means that no-one has ever directly observed an electrical charge, but that scientists have found similarities in behaviour by studying certain particles. They have asserted that these particles had a common characteristic, the properties of which matched their observations.

Unlike mass, there are two types of electrical charge, which behave as if they were mutually "opposed"; these are by convention known as positive and negative.



Figure 49: Two opposing charges attract



Figure 50: Two like charges are repelled

Opposing charges cancel each other out. This means that a particle with as much positive charge as negative charge behaves as if it had none. We say that it is electrically **neutral**

Matter is formed by chemical elements. The smallest possible quantity of an element is the atom The atom is itself formed by electrons (in yellow), protons (in red) and neutrons (in green), which act as cement between the protons.	<i>An atom seen under the microscope</i>  The atom nucleus is represented in dark blue.	Electrons are very small, negatively charged particles, which rotate around the nucleus like satellites around the Earth. Protons are positively charged.
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Electrons can be easily "torn from" the atom, and be taken into another atom. When a surface overloaded with electrons (i.e. negative) comes into contact with a surface short of electrons (i.e. positive), sparks and crackling are generated: this is electricity.

Certain substances (plastics, glass) attract light objects after these have been rubbed. You can try rubbing a balloon on your jersey and then placing it over the head of someone with short hair.

In storm clouds, violent air currents cause friction between water or ice particles. These clouds form positive and negative layers. Flashes occur inside the clouds (most often) or between the cloud and the ground. An average storm generates the electrical power of a small nuclear power station.

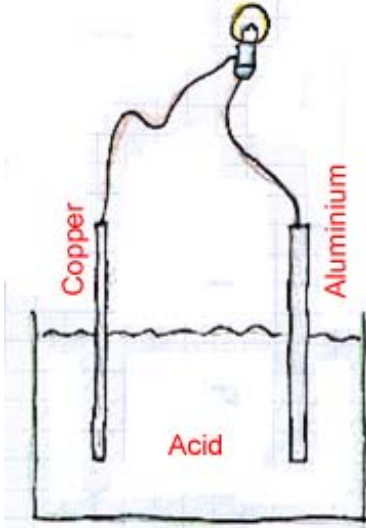
6.2. ELECTRICITY PRODUCTION

It is possible to generate movement of mobile electrons and control their direction.

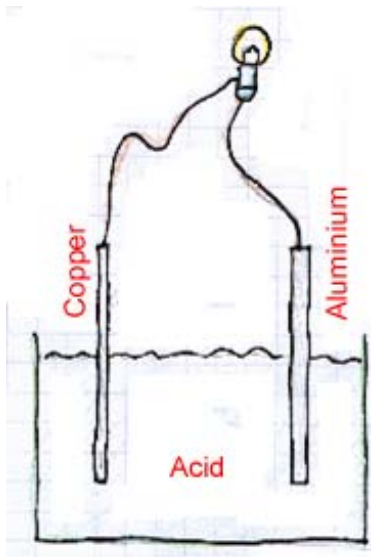
An electric current is what we call a constant flow of electrons.

A generator is what we call the element organising electron movement.

Conductors consist of atoms with at least one mobile electron which can circulate randomly between atoms.

<i>Producing electrical current by friction</i>	<i>Producing current by chemical reaction</i>
 Moving a magnet inside a wound conductive wire produces electricity	 Acid attracts electrons from the copper atoms, transmitting them to the aluminium atoms.
This is how electricity is generated in thermal power stations, with wind turbines, in hydro-electric dams, with mills, with a bicycle dynamo and in nuclear power stations	The aluminium terminal, which has an excess of electrons, is the negative terminal. The copper terminal, which has lost its electrons, is the positive terminal. This is how electricity is generated in cells and batteries.

You can make your own battery yourself:



Put a copper nail and an aluminium nail into a lemon (the lemon will be the acid represented in the diagram). Connect the two nails with electric wires.

To sense the current that you have created, place the two ends of the wire on your tongue: you will feel a slight pinch (your tongue replaces the bulb in the diagram)

6.3. STATIC ELECTRICITY

In nature, electrons carry negative charge and protons carry positive charge. Atoms, which make up ordinary material, consist of electrons moving around a nucleus comprising protons and neutrons, which are electrically neutral. Since the number of electrons is equal to the number of protons, the atom is electrically neutral overall.

When certain materials are rubbed together, the surface electrons of the atoms of one are detached, and recovered by the atoms of the other. For example, a glass rod rubbed on a silk tissue is positively charged, since its atoms lose electrons to the silk; if a balloon is rubbed on dry hair, it is charged negatively, since it captures electrons from the hair.

A plastic ruler rubbed on clothes has a negative charge. So it can attract small pieces of paper. By electrostatic induction, the ruler modifies the distribution of charge in the paper: the ruler's negative charge repels the negative charge to the other end of the piece of paper and attracts the positive charge of the paper atoms.

We talk about static electricity, since the electrical charges cannot circulate: they are trapped in insulating materials: plastic, glass and paper, which oppose circulation of charges.

6.4. VOLTAGE

The voltage U is the difference in electronic state (potential difference) between the input and output of an electric device.

The current circulates in a receiver when this electronic state difference is not zero.

Voltage is a quantity measured using a voltmeter expressed in volts (V) or millivolts (mV).

The voltmeter has a bypass connection (in parallel). The voltage between two points A and B is denoted U_{AB} .

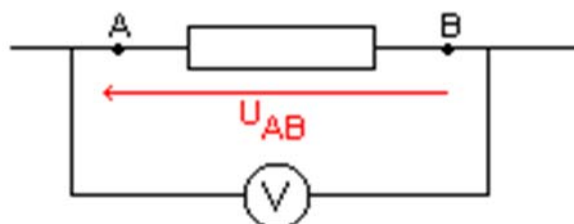


Figure 51: Voltmeter connection

The voltmeter is connected in parallel

$$U_{AB} = V_A - V_B$$

U_{AB} : Voltage between points A and B in volts (V).

V_A : electrical potential at point A in volts (V).

V_B : electrical potential at point B in volts (V).

Note: Voltage is an algebraic quantity:

$$U_{AB} = V_A - V_B$$

$$\Rightarrow U_{AB} = - (V_B - V_A)$$

$$\Rightarrow U_{AB} = - U_{BA}$$

6.4.1. Voltage measurement

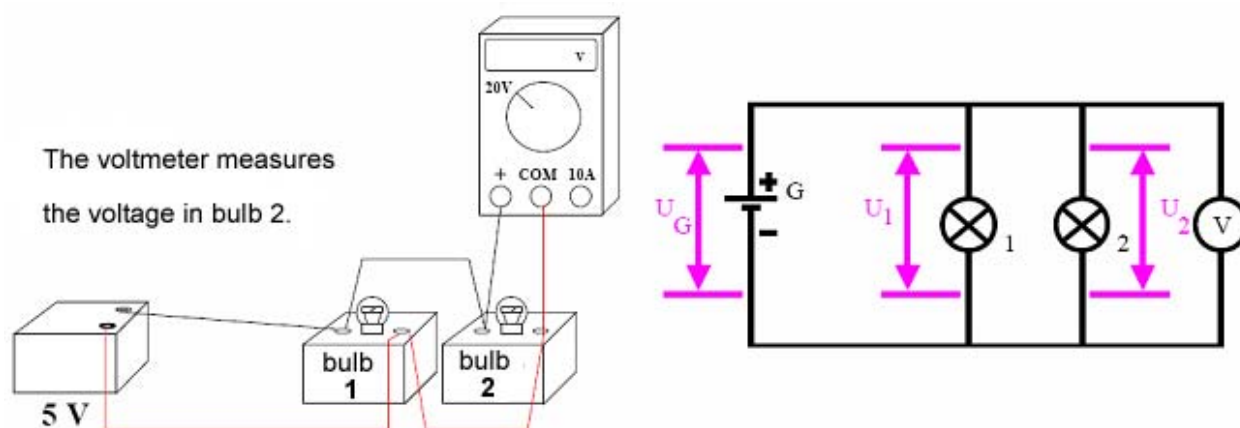


Figure 52: Example of voltage measurement in parallel configuration

The voltmeter is connected to bypass the terminals of the device whose voltage we want to measure (one wire at the device input and the other wire at the output).

The generator forces its voltage on the lamp(s).

The voltage is identical throughout: each lamp is supplied at the same voltage as that of the generator.

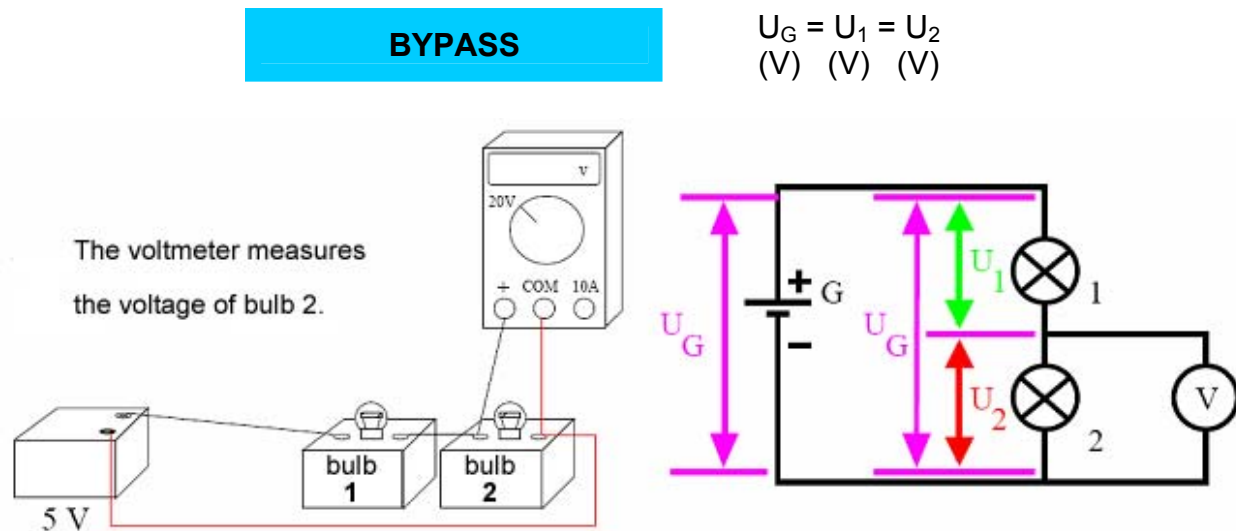


Figure 53: Example of voltage measurement in series configuration

The generator voltage across the terminals of the group of lamps. The sum of the lamp voltages is equal to the generator voltage.



If both lamps are strictly identical, each one has half the generator voltage across its terminals.

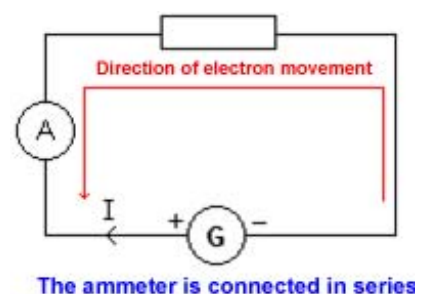
6.5. INTENSITY OF ELECTRIC CURRENT

The intensity I of an electric current is the quantity of electricity passing through an electrical device in one second.

Intensity is the number of electrons passing through an electrical device per unit time: 1A corresponds to a flow of $6.24 \cdot 10^{18}$ electrons per second.

The number of electrons leaving a device is the same as those that entered.

Figure 54: Ammeter Connection



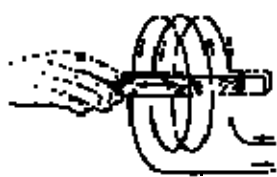
The intensity is the same at the output and input of an electrical device.

The electrical current intensity is measured using an ammeter, and is expressed in amperes (A) or milliamperes (mA).

Ammeters are connected in series.

Note: The conventional current direction is that of the circuit, outside the generator, from the positive to negative terminal.

Little Experiment: If you use a small magnet and wire in this experiment only a few electrons will move, which will only light up a small bulb slightly.



But if you rotate a very powerful magnet in a coil with tens of windings, the electron flow may become considerable, and you will see your bulb light up much more.

Figure 55: A "generator"

In "power stations", several very powerful magnets are rotated in several coils with thousands of windings, generating a large considerable electron flow.

6.5.1. Intensity measurement

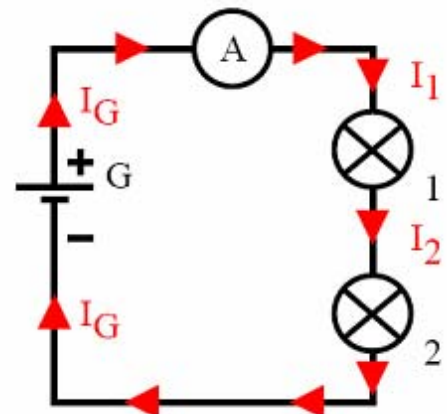
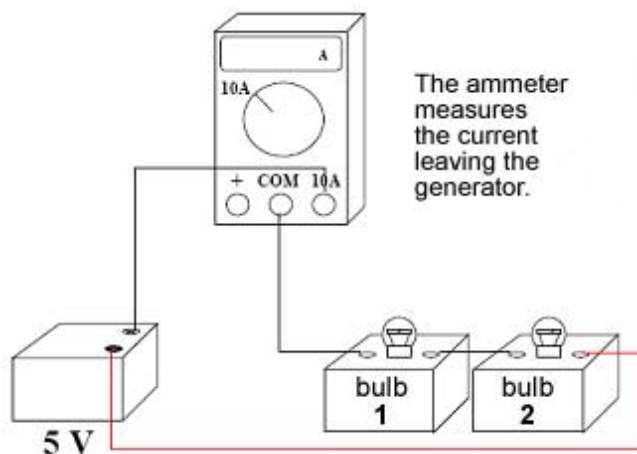


Figure 56: Example of intensity measurement in a series configuration

The intensity is the same throughout a simple or series configuration circuit.

The same current passes through the whole circuit. The current intensity is the same throughout.

SERIES

$$I_G = I_1 = I_2$$

(A) (A) (A)

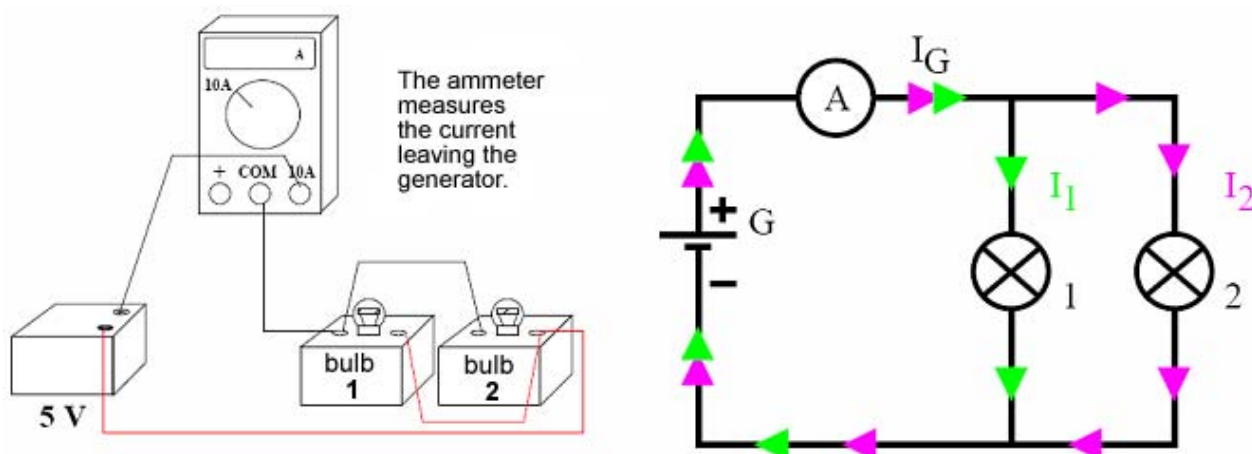


Figure 57: Example of intensity measurement in a parallel configuration

In a circuit comprising bypasses, the generator intensity is equal to the sum of the intensities of the lamps.

BYPASS

$$I_G = I_1 + I_2$$

(A) (A) (A)

6.6. ELECTRICAL CIRCUIT

An electrical circuit generally comprises the following four elements:

- ✦ **The electrical source:** This is the element supplying our circuit with the electrical current. It may be an electric battery, a generator or a current outlet as we have at home.

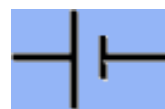


Figure 58: Electrical source

- ✦ **Conductor:** This element can carry electricity from the source to the consuming devices and vice versa. It will consist simply of electric wires.
- ✦ **Switch:** This element closes or opens an electrical circuit, thereby enabling or disabling electrical flow in the circuit. Take note: when a circuit is **open**, the electric wire will be cut off, and **electricity cannot flow**. So there is no electricity in an open circuit. However, in a closed circuit electricity circulates freely.



Figure 59: Open and closed switch

- ✦ **Consuming device:** This is the element consuming electrical energy and converting it into another energy source. For example, the light of a lamp converts electricity into light energy.

Figure 60: Consuming device



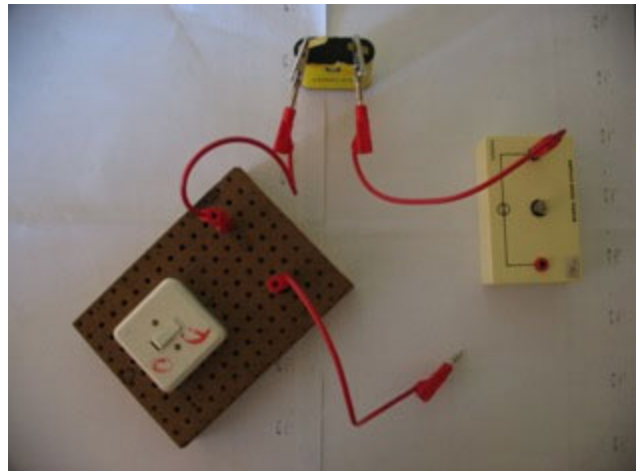
6.6.1. Open circuit

A circuit is open if *the electric current* cannot circulate.

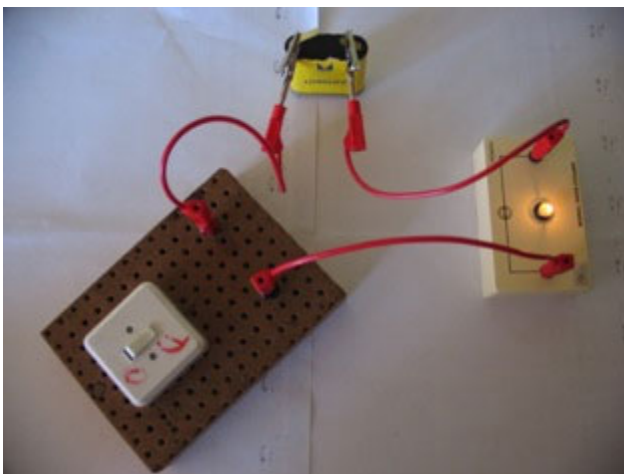
In this case, (two-pole) electrical devices are not all interconnected.

There is a "hole" in the circuit (see figure below).

Figure 61: Example of open electric circuit



6.6.2. Closed circuit



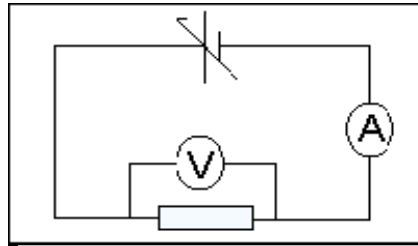
A circuit is closed if *the electric current* can circulate.

In this case, all the devices are interconnected without "holes" in the circuit.

Figure 62: Example of closed electrical circuit

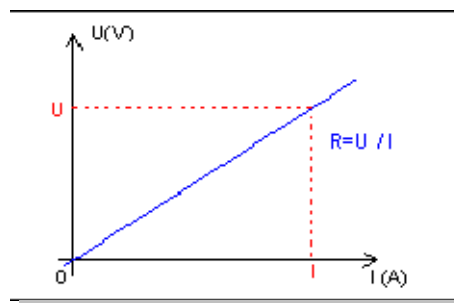
6.7. OHM'S LAW FOR AN OHMIC CONDUCTOR

We set up the circuit as opposite:



We vary the voltage across the generator terminals, and for each **voltage value U** across the terminals of the ohmic conductor, we read the **intensity I** of the electrical current passing through it.

We then plot the curve $U = f(I)$



The curve obtained is linear:

The **voltage** across the terminals of an **ohmic conductor** is proportional to the **intensity** of the current passing through it.

For example: $I = 0.1 \text{ A}$ and $U = 3 \text{ V}$
 $I = 0.2 \text{ A}$ and $U = 6 \text{ V}$
 $I = 0.3 \text{ A}$ and $U = 9 \text{ V}$

The characteristic $U = f(I)$ of an ohmic conductor is symmetric and linear. This characteristic is derived from the origin.

So we can write:

Resistance of the conductor:
in Ohms (Ω)

↓

$$\mathbf{U = R \times I}$$

↙ ↘

Voltage at the terminals of the conductor:
in Volts (V)

Current Intensity across the conductor:
in Amperes (I)

The proportionality coefficient R (which is also the slope of the characteristic) is known as the resistance of an ohmic conductor.

The voltage U across the terminals of an ohmic conductor with resistance R is equal to the product of resistance R by the current intensity I passing through it.

6.7.1. Colour code

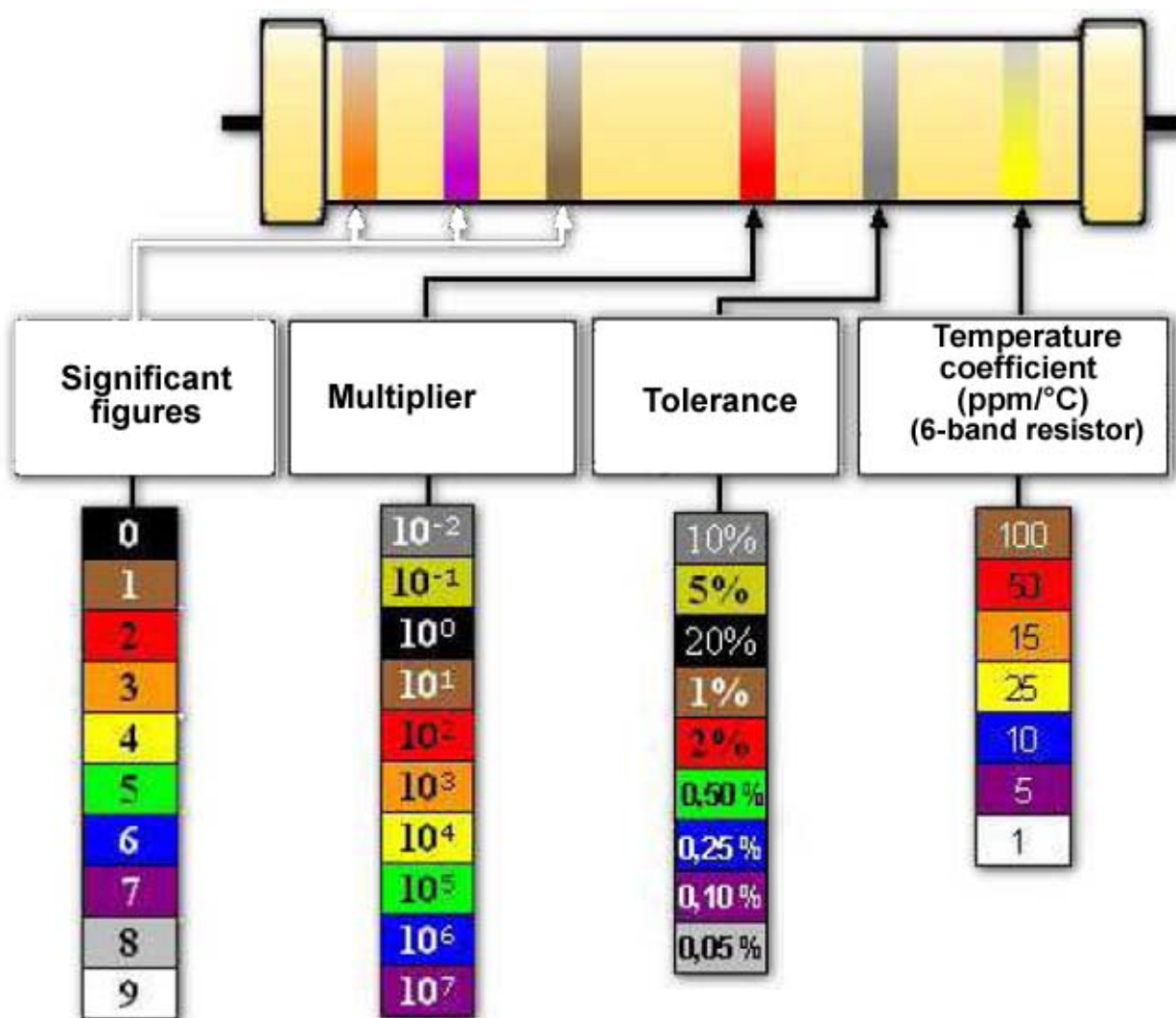


Figure 63: Description of resistor colour codes

6.7.2. Method for deciphering colour codes on a resistor

We first need to put the resistor the right way round. Generally, a resistor has a gold or silver band, which needs to be on the right. In other cases, the widest band needs to be placed on the right.

There are three types of resistors:

- ✦ **Four-band resistor:** The first two indicate the significant digits (the first indicating the tenth and the second the unit); the third gives the multiplier (the power of 10 that need to be multiplied with the significant digits); the fourth the tolerance (uncertainties over the actual resistance value given by the manufacturer);
- ✦ **Five-band resistor:** The first three indicate the significant digits; the fourth indicates the multiplier; the fifth gives the tolerance,
- ✦ **Six-band resistor:** The first four have the same meaning as 5-band resistors; the sixth is a temperature coefficient (variation in electrical conductivity with temperature).

A few examples:

	First significant digit: yellow = 4 Second significant digit: green = 5 Multiplier: orange = 3 Tolerance: silver = 10 % Resistance value: $45 \cdot 10^3 \Omega$ at 10 % i.e. 45 kΩ at 10 %
	First significant digit: red = 2 Second significant digit: violet = 7 Multiplier: brown = 1 Tolerance: silver = 10 % Resistance value: $27 \cdot 10^1 \Omega$ at 10 % i.e. 270 Ω at 10 %

Tip:

There is a mnemonic for remembering the colour code, consisting of the following phrase:

Black Beetles Running On Your Garden Bring Very Good Weather

B: Black (0) B: Brown (1) R: Red (2) O: Orange (3) Y: Yellow (4)	G: Green (5) B: Blue (6) V: Violet (7) G: Grey (8) W: White (9)
---	--

The position of the words in the phrase indicates the digit corresponding to the colour of the ring.

7. MISCELLANEOUS CALCULATIONS

7.1. CALCULATING SURFACE AREA

The square metre is the basic unit for measuring a surface area.

- ✦ It corresponds to the area of a one-metre sided square.
- ✦ It corresponds to a centiare ($1 \text{ m}^2 = 1 \text{ ca}$) or one hundredth of an are

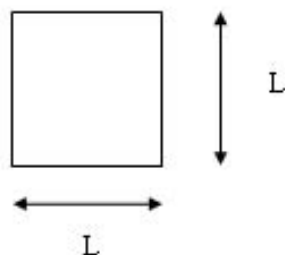
Multiples:

- ✦ Square decametre or are: ($1 \text{ a} = 100 \text{ m}^2$),
- ✦ Square hectometre or hectare: ($1 \text{ ha} = 10,000 \text{ m}^2$),
- ✦ Square kilometre: km^2 : ($1 \text{ km}^2 = 1,000,000 \text{ m}^2$).

Sub-multiples:

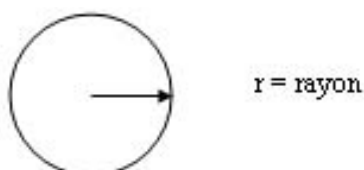
- ✦ Square decimetre: $\text{dm}^2 = (1 \text{ dm}^2 = 0.01 \text{ m}^2 = 1 \times 10^{-2} \text{ m}^2)$.
- ✦ Square centimetre: $\text{cm}^2 = (1 \text{ cm}^2 = 0.0001 \text{ m}^2 = 1 \times 10^{-4} \text{ m}^2)$.
- ✦ Square millimetre: $\text{mm}^2 = (1 \text{ mm}^2 = 0.000001 \text{ m}^2 = 1 \times 10^{-6} \text{ m}^2)$.

7.1.1. Area of a square



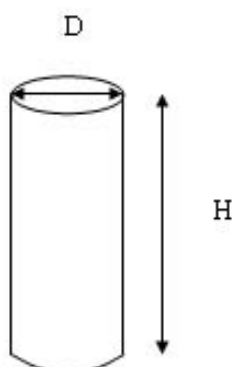
$$A = L^2 = L \times L$$

7.1.2. Area of a circle



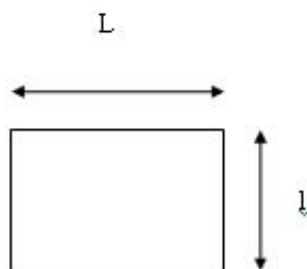
$$A = \pi \times r^2$$

7.1.3. Area of cylinder



$$A = \pi \times D \times H$$

7.1.4. Area of a rectangle



$$A = L \times w$$

7.2. CALCULATING VOLUME

The unit of volume in the international system is the **cubic metre (m^3)** and its derivatives (dm^3 , cm^3 , mm^3).

Volumes of liquid matter often have their own units (litre, pint, barrel).

The implementation of the metric system has greatly simplified the number of units of volume used, which under the old system were over twenty in number.

When we want to find out the quantity of gaseous matter (number of molecules) in a given volume, regardless of pressure and temperature, there are two correction definitions:

- ✦ the so-called normal cubic metre, expressed in $m^3(n)$ or Normal m^3 (Nm^3), which equates to a volume of gas at a pressure of 1013.25 hPa (normal atmospheric pressure, or 1 atm) and a temperature of $0^\circ C$,
- ✦ the so-called standard cubic metre expressed in $m^3(s)$, which equates to a volume of gas at a pressure of 1013.25 hPa (normal atmospheric pressure, or 1 atm) and a temperature of $15^\circ C$.

The volumes described above equate to so-called corrected volumes. A volume that does not take these corrections into consideration is said to be gross. These volumes can be found in determining gas flowrates and heating values.

In the European Union, many volumes (and masses) on consumer products are indicated as estimated quantities. They are marked as such, with a small “e”.

In mathematics, the unit of volume does not appear in the formulae. It is implicitly given by the cube unit volume.

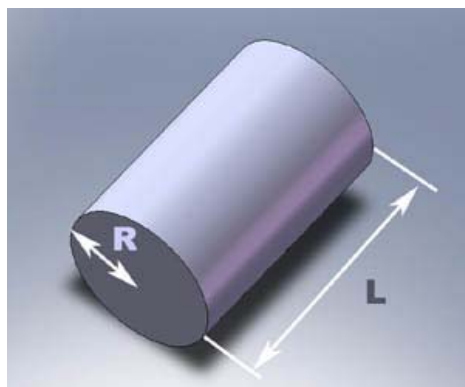
If, for example, for scale reasons, the cube unit has an edge of 2 cm, a volume of X (cube unit) equates to 8 X cm³.

7.2.1. Volume of a sphere



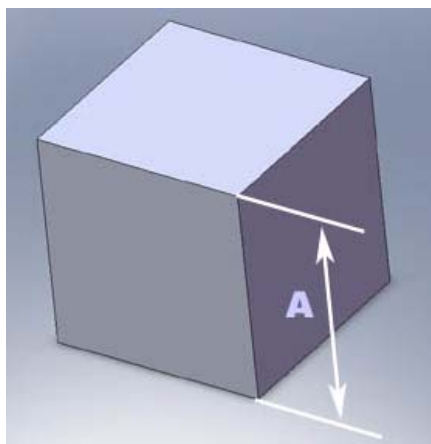
$$V = 4 / 3 \times \pi \times R^3$$

7.2.2. Volume of a cylinder



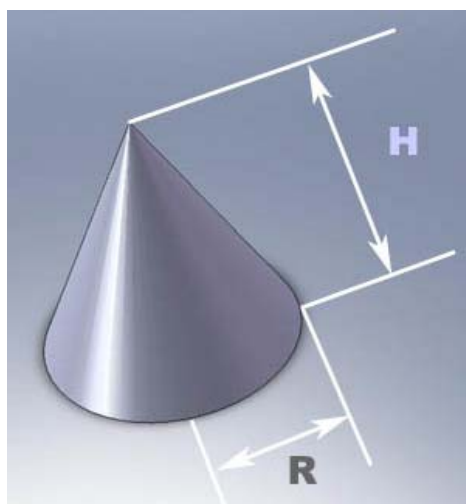
$$V = L \times \pi \times R^2$$

7.2.3. Volume of a cube



$$V = A^3$$

7.2.4. Volume of a cone



$$V = H / 3 \times \pi \times R^2$$

Use the same measurement units for H and R

8. HOW IS AN ELECTRICAL QUANTITY MEASURED?

We saw in the '*sensors and transmitters*' course that a measuring instrument is required to obtain a measurement of a process' physical quantities (pressure, temperature, flowrate, etc.).

We will now look at the measurement of 3 fundamental electrical quantities, which are voltage U , current I and resistance R .

These 3 quantities are also important for instrument engineers, since the output signal of a transmitter is a current (4-20 mA); sensors and transmitters can also have an alternating voltage supply (4 wire configuration); pT100 probes give an ohmic resistance measurement.

To do so, we have to be able to measure these electrical quantities with the flagship tool of instrument engineers, the multimeter (see '*instrumentation tools*' course).

This is an essential tool for troubleshooting.

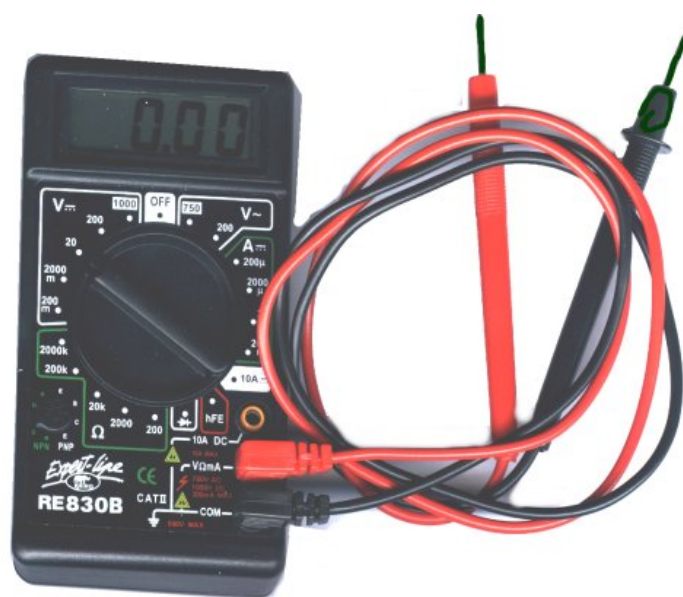


Figure 64: Multimeter

8.1. MEASURING A VOLTAGE

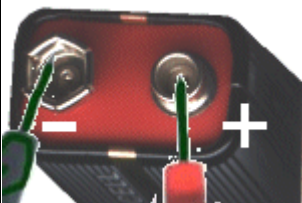
Connection: Use the black lead for the BLACK COM (-) socket and the red lead for the RED socket (+) as shown in the photo.

Our multimeter can measure direct or alternating voltages: initially we will measure the voltage of our 9 V DC battery, and then an alternating voltage, the 220 V from an outlet.



To measure DC voltages, we set the multimeter selector to this position:

We then need to set the selector to the appropriate DVC direct voltage range – in our case to the 20 V rating

	If we don't know the voltage to be measured, we need to set the rating to the highest, 1000 V, and then lower it one rating at a time to get a result on the LCD.
	With a direct voltage, there is a positive and negative pole. So we need to get the polarity right, i.e. put the red contact on the battery +, and use the black contact for the - (if you do the opposite, the voltage displayed will be negative, with a - sign)
	The display indicates the voltage of your battery, e.g.: 9.00 The measuring accuracy indicates hundredths of volts
	If you change the rating to 200 V, the display indicates 09.0 V The accuracy is now just tenths of volts – hence the importance of the rating in measurement quality.

To measure a voltage, the meter must be in parallel on a circuit.

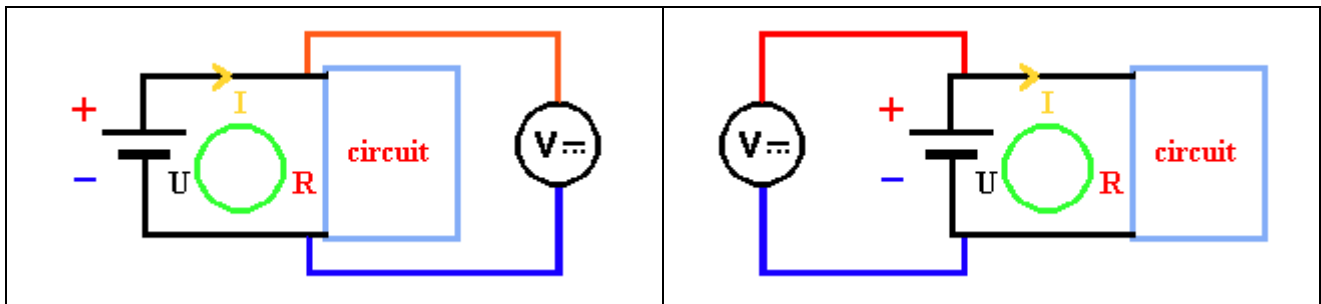
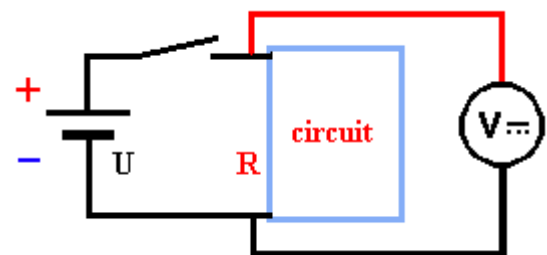


Figure 65: Parallel connection

The voltage measured in both cases is identical, since the loss in the wires is disregarded.

If the circuit is not closed as in the figure below, the voltage does not reach the circuit, voltage = 0 V.

Figure 66: Open circuit



Now let's look at the measurement in a circuit.

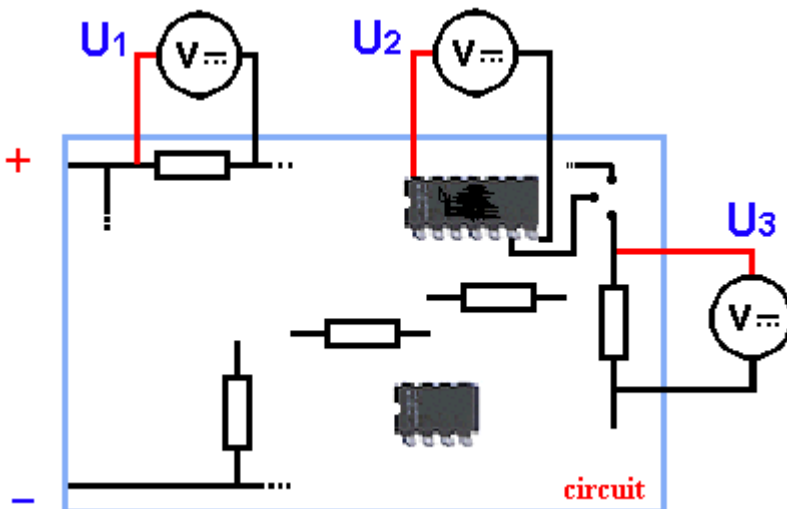


Figure 67: Measurement in a circuit

The voltage measurement in a circuit is taken parallel to the components.

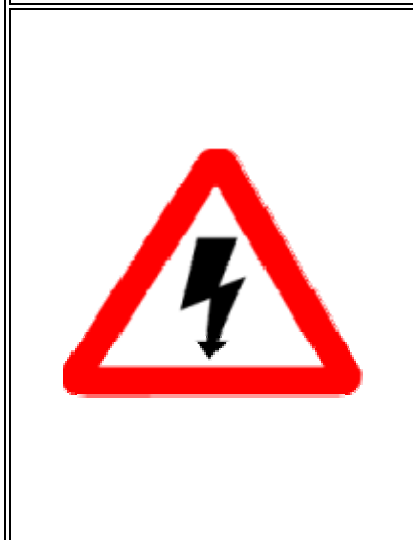
U_1 indicates the voltage across the resistor terminal, while U_2 indicates the supply voltage of the 14 pin circuit if the supply is on pins 7 and 14 and U_3 indicates the voltage across the resistor terminal.

As you can observe, a direct voltage measurement is taken primarily on resistive elements.

To measure alternating voltages, we set the selector to this position:

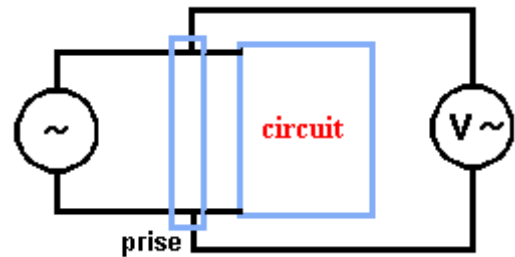


We then need to set the selector to the appropriate VAC range – in our case to the 750 V~ rating

	If we don't know the voltage to be measured, we need to set the rating to the highest, 750 V~, and then lower it one rating at a time to get a result on the LCD.
	CAUTION DANGER Any handling of live 220 V ~ is dangerous; there is a risk of electrocution. DO NOT TOUCH CONDUCTIVE PARTS Even disconnected, the end of the wire need only touch phase for your body to run the risk of acting as an earth.
	With AC voltage the direction is of little importance, so insert the red contact and black contact into the socket. The display indicates a voltage of e.g.: 220, but often this value varies between 215 and 240 V.

To measure an AC voltage the meter must be in parallel.

Figure 68: Alternating voltage measurement



8.2. MEASURING A CURRENT

This type of small multimeter can only measure DC intensities.

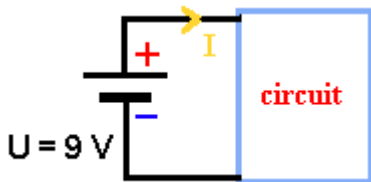


Symbol for DC ammeter:

Connection: if the intensity is low $0.2 \text{ A} = 200 \text{ mA}$, we need to use the same sockets as for voltage measurement, with the red contact in the RED socket 200 mA MAX (+); however with higher intensities we need to use the socket above, YELLOW 10 A DC for (+), with the black contact still in the BLACK COM socket (-).

An intensity is measured in series on a closed circuit (current flowing)

We will measure the current flowing in a circuit comprising a 5 mm red LED with a 470 Ohm resistor.

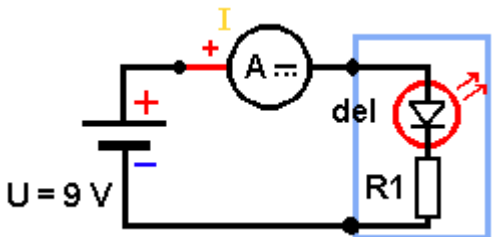
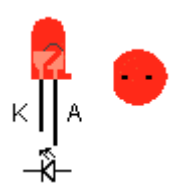
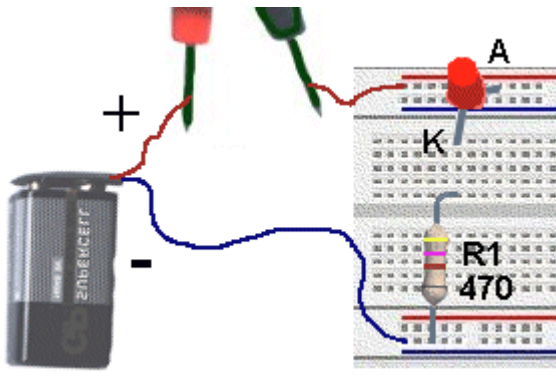


Here is a representation of our circuit.



The ammeter rating is 200 mA, with the red contact in the red socket and the black contact in the black socket.

The red contact is connected to the battery +; it is the ammeter input, and the black contact its output.

	To make an intensity measurement, the ammeter is mounted in series. So we need to open the circuit to insert the ammeter,
	In our example the circuit comprises: a 5 mm diameter red LED (diode) The longer foot of the diode is the anode, and goes to the +; the shorter foot is the cathode and will be connected on the resistor at the - We must always mount a resistor in series for an LED to work
	Resistor $R_1 = 470$ Ohms, colour code (Yellow, Violet, Brown)
	Which gives us with our test board
	The measurement indicates 15.7 mA, but everything depends on your battery, which should supply 9 Volts, and the exact value of your resistor. The resistor used actually has a tolerance of +/- 5 %, since band 4 is gold.

8.3. MEASURING A RESISTANCE

It is possible to measure resistance values with our multimeter, using the Ohmmeter function.

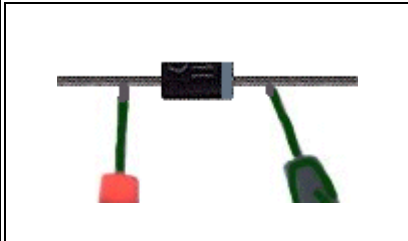
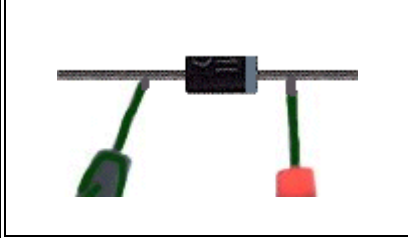
Important: any resistance measurement must be taken with the power off; the supply must be cut and if the resistance is on a circuit one foot must be detached for the measurement, so as not to measure any resistances that may be in parallel.

	Let's go back to our 470 Ohm resistor The measurement is made simply by connecting across the terminals of the resistor There is no direction, a resistor is a two-way component. We must avoid touching the terminals with our fingers, so as not to alter the reading.
	The rating to be used in our example is 2000 ohms
	The reading is 477 Ohms

8.4. MEASURING AND CHECKING A DIODE

A diode is a very commonly used two-pole electronic component, which lets through current just one way, from anode to cathode, blocking the current in the opposite direction.

To check a diode it must be disconnected from the circuit, or one of its feet detached.

	The rating to be used is the diode symbol.
	Anode A  Cathode K passing direction
	The reading is 679 mV (millivolts) in the passing direction: this value must be between 500 and 900.
	In the opposite direction the dial indicates 1: any other reading indicates a fault in the diode.

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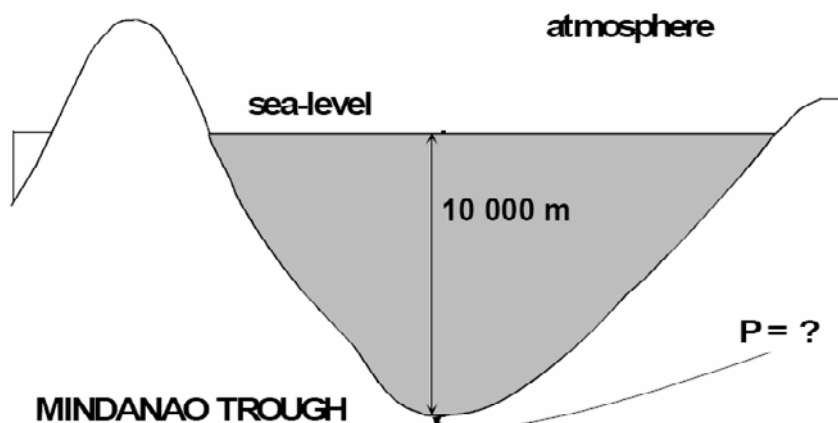
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11. EXERCISE CORRECTIONS

1. We want to know the pressure exerted on the MINDANAO TROUGH. To do so we know that the depth is 10,000 m and the density of water, which is 1000 kg / m³.

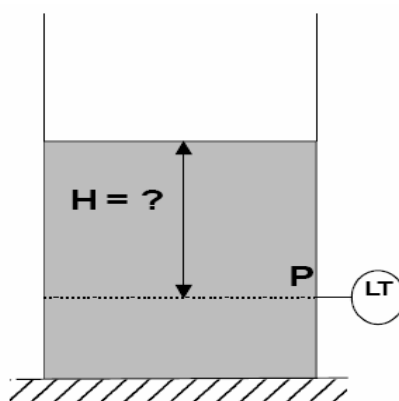


$$P = 1000 \times 9.81 \times 10000$$

$$P = 98,100,000 \text{ Pa}$$

$$P = 981 \text{ bar}$$

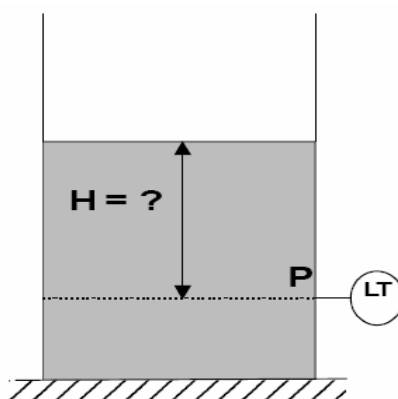
2. The tank contains water at a density of 1000 kg / m³. The instrument measures a pressure of 0.60 bar, what is the liquid head?



$$H = 60,000 \text{ Pa} / (1000 \times 9.81)$$

$$H = 6.11 \text{ m}$$

3. The tank contains a fluid with a density of **$950 \text{ kg} / \text{m}^3$** ; the instrument measures a pressure of 0.6 bar. *What would be the liquid head?*



$$H = 60000 \text{ Pa} / (950 \times 9.81)$$

$$H = 6.43 \text{ m}$$

We can see that the liquid head changes with density.

4. Convert 10 mm Hg into mbar?

We know that 760 mmHg = 1 bar = 1000 mbar: we use the rule of 3, giving us
 $10 \text{ mmHg} = (10 \times 1000) / 760$

$$10 \text{ mmHg} = 13 \text{ mbar}$$

5. Convert 19 psi into bar?

$$1 \text{ bar} = 14.5 \text{ Psi so } \underline{19 \text{ Psi} = 1.3 \text{ bar}}$$

6. Convert 2.5 m into bar?

$$\text{We know that } 1 \text{ bar} = 10 \text{ metres, so } 2.5 \text{ m} = 250 \text{ mbar}$$