PRESSURE MEASUREMENT

The analysis of an applied force by a fluid (liquid of gas) on a surface

Pressure is generally defined as a force that acts uniformly over a defined area. There are several types of pressure and ways to measure them.

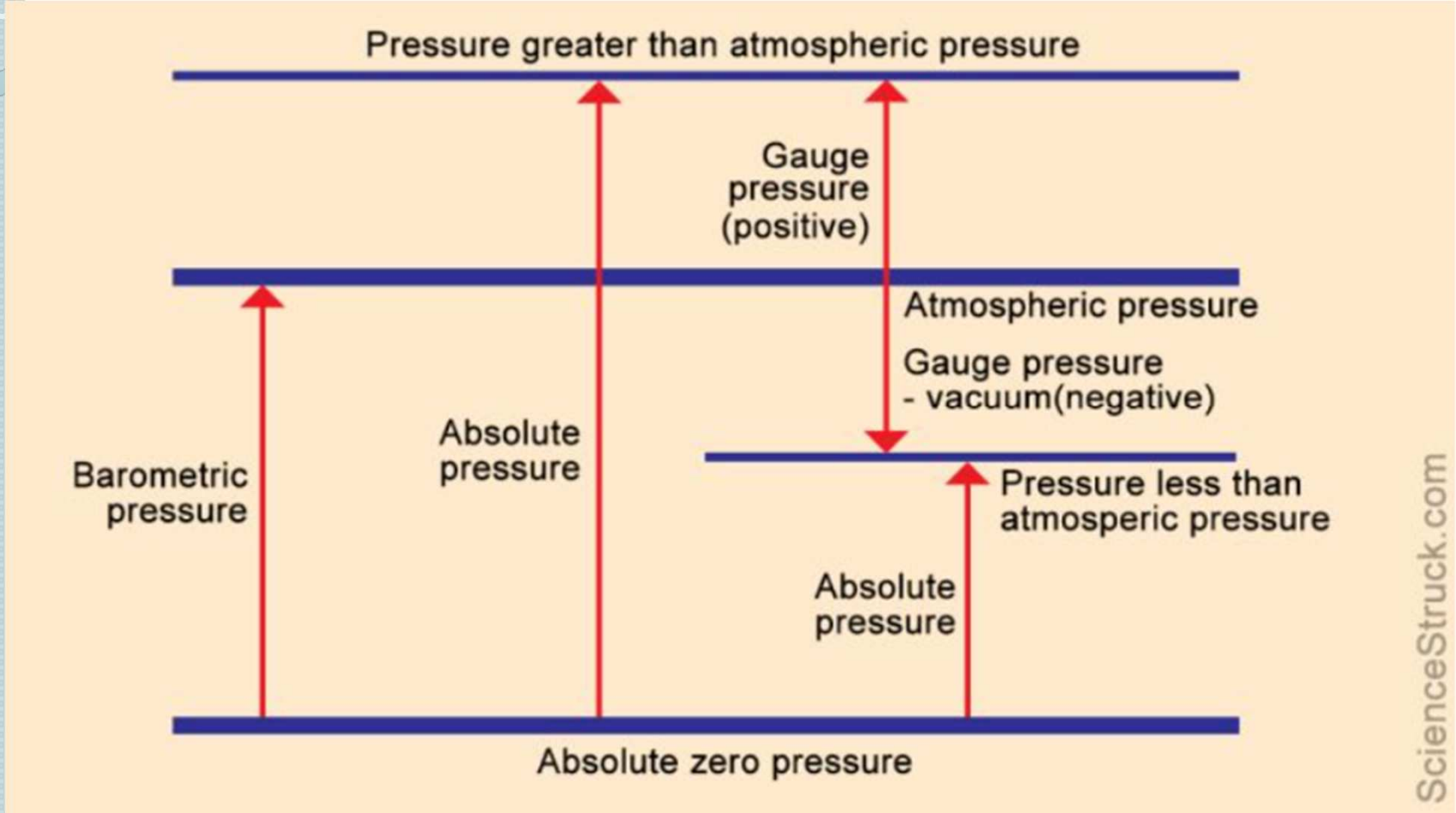
Pressure definition

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

- Absolute pressure
  - It is zero-referenced against a perfect vacuum, using an absolute scale, so it is equal to gauge pressure plus atmospheric pressure.
- Atmospheric pressure (Barometric pressure)
  - It is created by the weight of the atmosphere which surrounds the earth up to a height of approx. 500 km. Up to this altitude, its magnitude decreases continuously.
  - Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather.

If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. For example, when a car drives up a mountain, the (gauge) tire pressure goes up because atmospheric pressure goes down. The absolute pressure in the tire is essentially unchanged.

Pressure definition



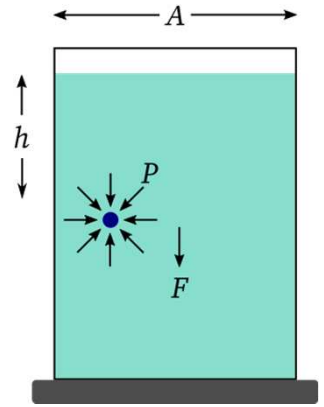
Pressure definition

- Gauge pressure (positive) = Overpressure
  - It is zero-referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure.
- Gauge pressure (negative) = Vacuum pressure
  - Negative signs are usually omitted.
  - To distinguish a negative pressure, the value may be appended with the word "vacuum" or the gauge may be labelled a "vacuum gauge".
- Differential pressure $\Delta p = p_1 - p_2$
  - difference in pressure between two points in a process

$$p = \rho \cdot g \cdot h$$

Hydrostatic pressure

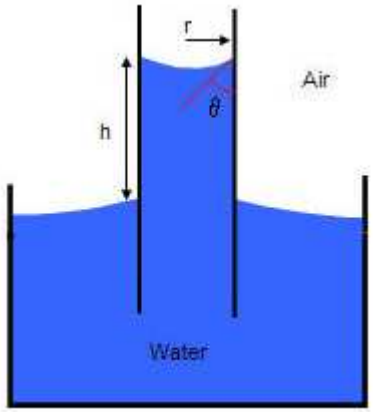
- The pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity. Hydrostatic pressure increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above.



Physical Chemistry. Hydrostatic Pressure [online]. ©2019. Available from: https://chemistrygod.com/hydrostatic-pressure

Capillary Pressure

- Pressure difference across the interface between two immiscible fluids arising from the capillary forces. These capillary forces are surface tension and interfacial tension.

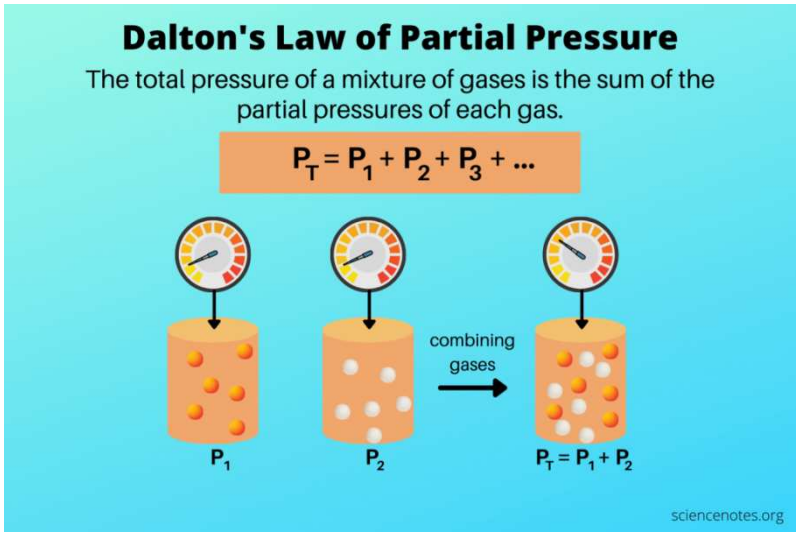


IHS Harmony. Capillary Pressure [online]. ©2020. Available from: https://www.ihsenergy.ca/support/documentation_ca/Harmony/content/html_files/reference_material/general_concepts/capillary_pressure.htm

Dalton´s Law of **Partial Pressure**

$$P = p_1 + p_2 + \cdots + p_n = \sum_{i=1}^{n} p_i$$

- In a mixture of gases, each constituent gas has a partial pressure which is the notional pressure of that constituent gas if it alone occupied the entire volume of the original mixture at the same temperature.
- The total pressure of an ideal gas mixture *P* is the sum of the partial pressures of the gases in the mixture p_i

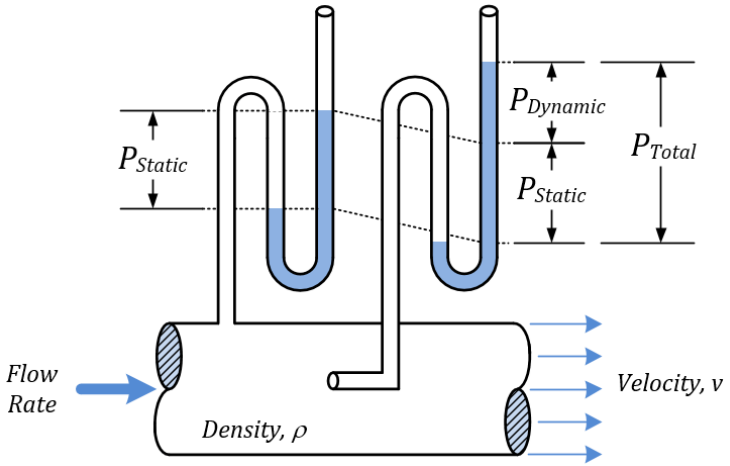


E.g. The total air pressure is about 101 kPa, of which the partial pressure of oxygen is about 21 kPa, the partial pressure of nitrogen is about 80 kPa

Helmenstine A. Dalton´s Law of Partial Pressure [online]. ©2022. Available from: https://sciencenotes.org/daltons-law-of-partial-pressure-definition-and-examples/

Static and dynamic pressure

- **Static pressure** is uniform in all directions, so pressure measurements are independent of direction in an immovable (static) fluid.
- Flow, however, applies additional pressure on surfaces perpendicular to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called **dynamic pressure**.



Pipe-Flo. Static Preessure vs. Stagnation Pressure[online]. Available from: https://pipe-flo.com/static-pressure-stagnation-pressure/

Units of Pressure

Laurila H. It´s a jungle out there [online]. ©2017. Pressure units and pressure unit Available from: https://blog.beamex.com/pressure-units-and-pressure-unit-conversion

Units of Pressure

Blaise Pascal

(1623 - 1662) – One of the basic laws of hydrostatics – **Pascal´s law (Pascal´s principle)**.

A pressure change at any point in a confined incompressible fluid is transmitted throughout the fluid such that the same change occurs everywhere.

- ✓ **Pascal**
- ✓ **Bar**
- ✓ **Torr**
  1 torr = 1 mm Hg = 1 mm mercury column
- ✓ **Atmosphere**
- ✓ **Barye**
  Acoustic wave pressure unit. It is marked **ba**.
- ✓ **Psi**
  (pound per square inch)
  1 psi = 1 lb_f/in^2 ≈ 6 894.757 Pa

The unit used depends on the pressure instrument, the industry, and a country's preferences and measurement standards.

Evangelista Torricelli

(1608 - 1647) - He introduced the term „atmospheric air pressure“

Atmosphere

- **Standard atmosphere (atm)**

  1 atm = 760 Torr = 101 325 Pa (exactly)
  = 0.1 MPa (approximately)

  1 atm = 1.0332 27 at

  – It is approximately equal to Earth's average atmospheric pressure at sea level
  – The standard atmosphere was originally defined as the pressure exerted by 760 mm of mercury at 0 °C and standard gravity (g_n = 9.80665 m/s^2)

- **Technical atmosphere (at)**

  1 at = 735.52 Torr = 98 066.5 Pa (exactly)
  = 0.1 MPa (approximately)

  1 at = 0.967 84 atm

  – A kilogram-force per centimetre square (kgf/cm^2), often just kilogram per square centimetre (kg/cm^2), or kilopond per centimetre square.

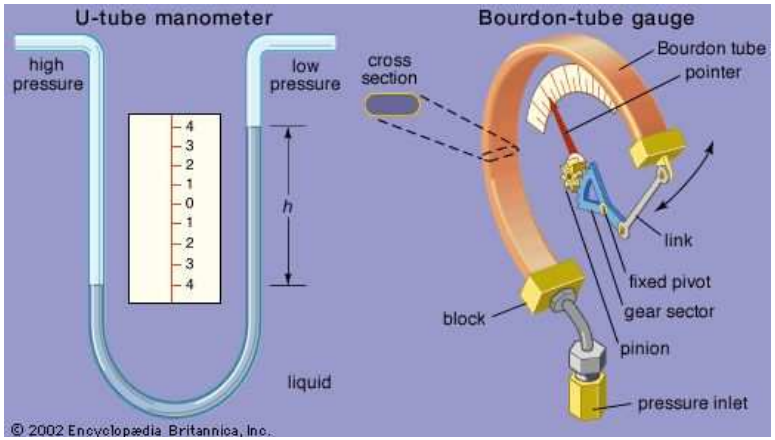
Principles of pressure measurement

- Instruments used to measure and display pressure in an integral unit = PRESSURE METERS or MANOMETERS or PRESSURE GAUGES or VACUUM GAUGES
- Pressure gauges uses pressure sensing elements for measuring applied pressure
- Any physical event that is affected by the pressure can be used to measure pressure.
- The pressure sensing elements deforms elastically under pressure, which helps in measurement.

Types of pressure gauge (manometer)

- Based on
  - Pressure sensing elements
  - Magnitude of the measured pressure
  - Time variability of the measured pressure
  - Required measurement accuracy.

Santora M. What is a pressure gauge? Sensors & Gauges [online]. Available form: https://www.fluidpowerworld.com/what-are-gauges/



Pressure gauge instrument. Encyclopaedia Britannica [online]. Available form: https://www.britannica.com/technology/pressure-gauge

Types of pressure gauge (manometers)

according to the functional principle:

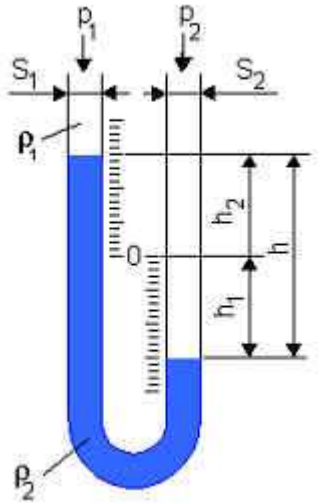
- Hydrostatic
- Aneroid (mechanical)
- Piston (deadweight tester)
- Electronic pressure instruments

HYDROSTATIC GAUGES

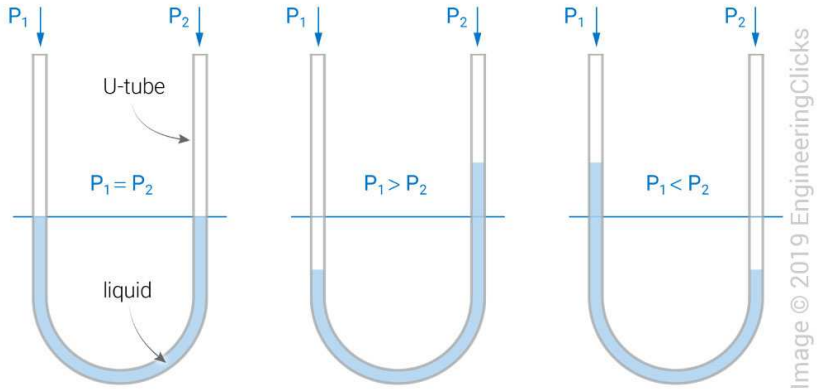
Fluid Head—Manometers, U-tube manometers

- The effect of hydrostatic pressure is used
- The measure of pressure is the **height of the fluid column *h***
- Typically, the liquid is mercury because of its high density
- They are independent of the type of gas being measured
- They have poor dynamic response

$$p = h \cdot \rho \cdot g$$



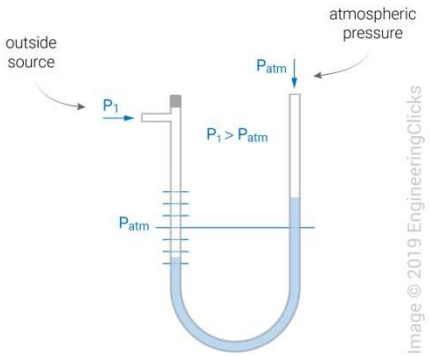
http://www.e-automatizace.cz/ebooks/mmv/tlak/tlak_tlakomery_kapalinove.htm



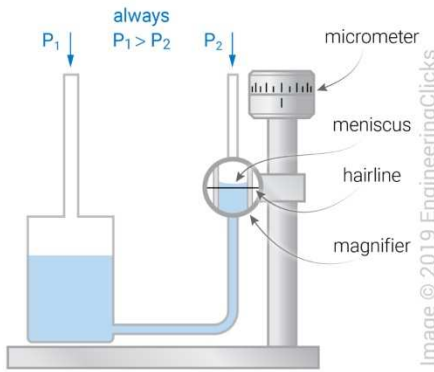
Benson M. Manometer types and working principle [online]. ©2019. Available form: https://www.engineeringclicks.com/manometer/

HYDROSTATIC GAUGES

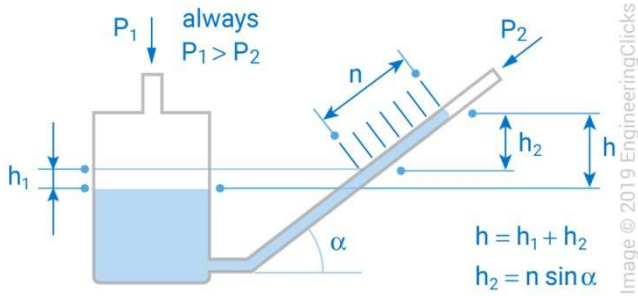
- **U–Tube manometers**
  - Most common tradition U-Tube device
  - Manometric liquid: mercury, water, alcohol, tetrachlor, oil



- **Micro manometer**
  - The micro-design is a modified version of the basic U-tube except one side of the tube has a larger cross-section
  - The structure of the U-tube it is able to measure minute pressure differences



- **Inclined manometer**
  - A gradual incline in the design allows for the measurement of minuscule pressure to extremely high levels of accuracy



Benson M. Manometer types and working principle [online]. ©2019. Available form: https://www.engineeringclicks.com/manometer/

ANEROID GAUGES
Mechanical Gauges

Aneroid gauges are based on a **metallic pressure-sensing element** that flexes elastically under the effect of a pressure difference across the element

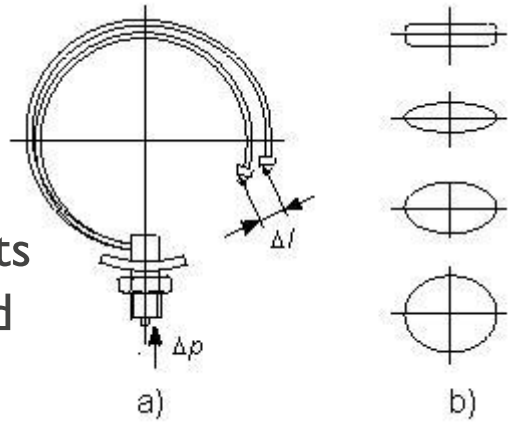
- "Aneroid" means "without fluid", and the term originally distinguished these gauges from the hydrostatic gauges
- The field of application is defined by the validity of Hooke's law
- The most commonly used pressure gauges in industry
- The deflection of the pressure sensing element may be read by a linkage connected to a needle, or it may be read by a secondary transducer.

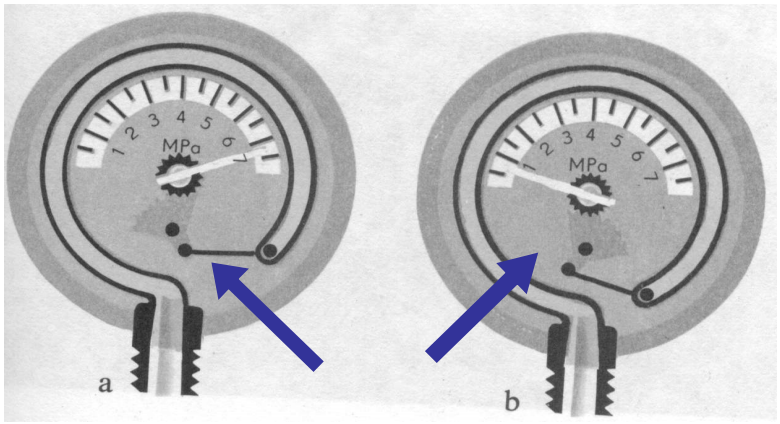
- The most commonly used pressure measuring elements are:
  - Bourdon tube
  - Diaphragm
  - Bellows

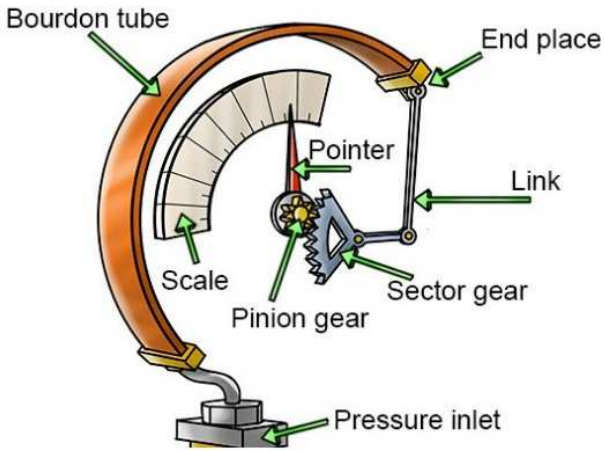
Hooke´s law - for relatively small deformations of an object, the displacement or size of the deformation is directly proportional to the deforming force or load. Under these conditions the object returns to its original shape and size upon removal of the load.
Elastic behaviour of solids.

BOURDON GAUGE – Bourdon tube

- For gauge pressure both positive and negative (from 0.6 to 7000 bar)
- A flattened tube tends to straighten or regain its circular form in cross-section when pressurized (like party horn principle)
- The most use type of mechanical gauges





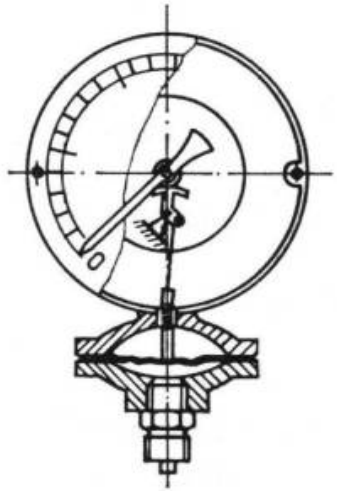


In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link that is usually adjustable.

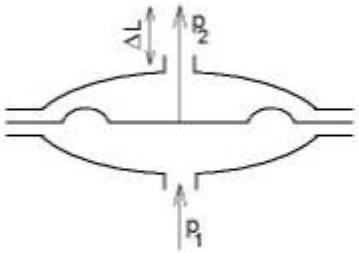
Toucan. Are water and air pressure gauges the same? [online]. Available form https://www.quora.com/Are-water-and-air-pressure-gauges-the-same

http://uprt.vscht.cz/ucebnice/mrt/F4/F4k42-tlak.htm

DIAPHRAGM GAUGE



- Use deflection of a flexible membrane that separates regions of different pressure
- The deformation of a thin diaphragm is dependent on the difference in pressure between its two faces
- The reference face can be open to **atmosphere** to measure **gauge pressure**, open to a second port to measure **differential pressure**, or can be sealed against a vacuum or other fixed reference pressure to measure **absolute pressure**.
- Ceramic and metallic diaphragms are used
- Measuring range: do 4 MPa

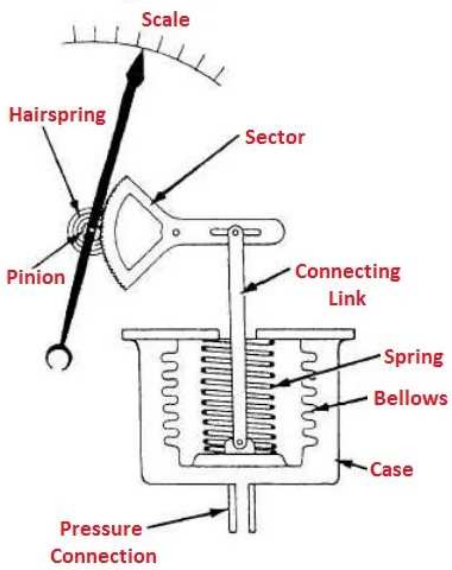


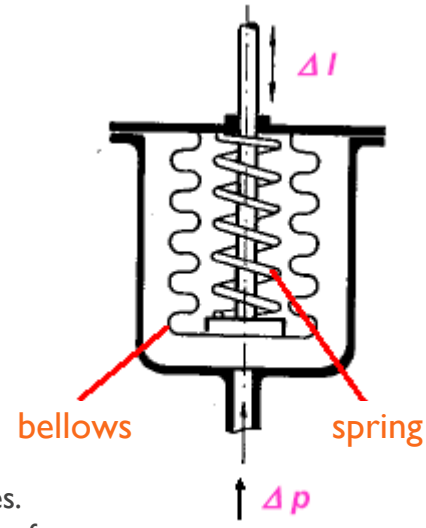
Deformační tlakoměry. [online]. Available form: http://www.e-automatizace.cz/ebooks/mmv/tlak/tlak_deformacni_tlakomery.htm

Weber S. Advantages of diaphragm pressure gauges [online]. ©2018. Available form: https://blog.wika.com/knowhow/advantages-of-diaphragm-pressure-gauges-2-solution-for-critical-media//

BELLOW GAUGE

- Pressure responsive element is made of a thin metal tube with a deep circumference when the pressure changes as the elastic elements increase or decrease
- A pointer is connected to it which indicates reading on the circular dial.
- Pressure can be applied from one side or from both sides
- It expands when the pressure increases and when the pressure is low the elastic elements in the pressure gauge are contracts
- Measuring range: to 0.4 MPa

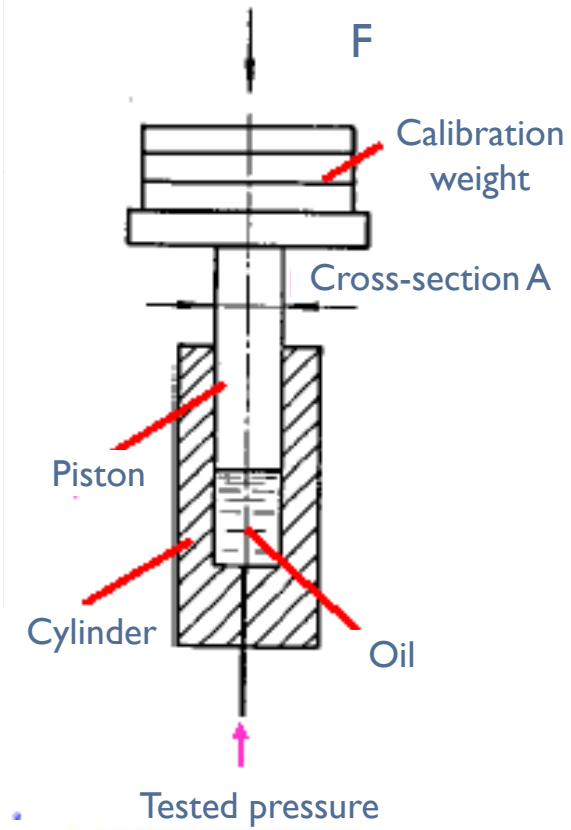




Saif M. Mechanical pressure gauges: types, working, applications, advantages. [online]. ©2020. Available form: https://www.theengineerspost.com/types-of-pressure-gauge/

DEAD WEIGHT TESTER

PISTON-CYLINDER TYPE GAUGE

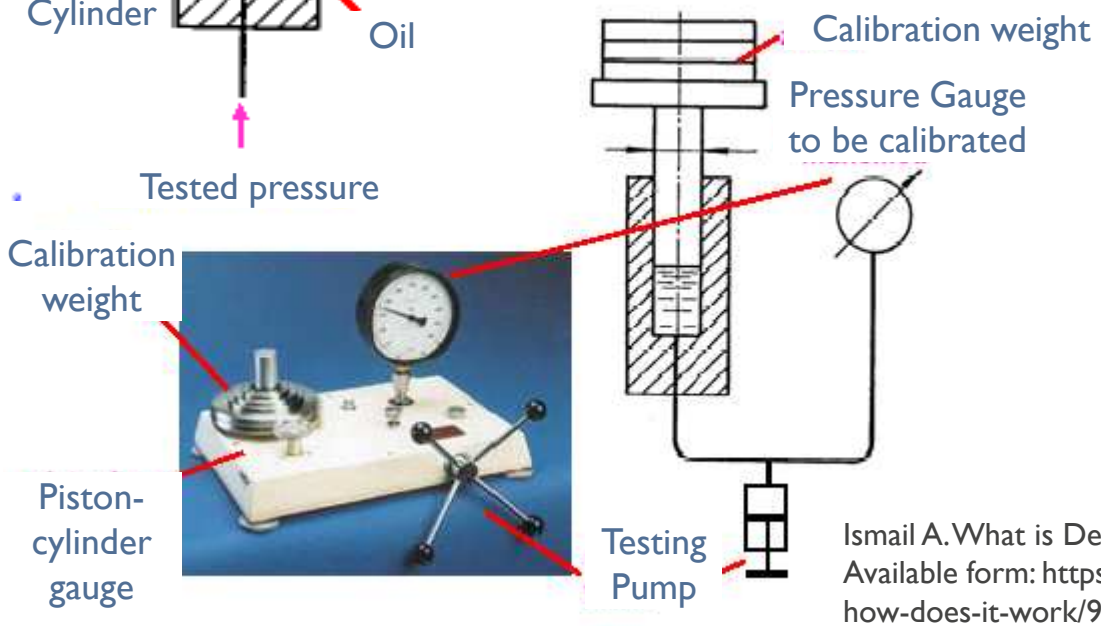


- A device that measures the weight of a force divided by the area applied to calibrate the pressure
- medium – air, water or oil
- The force of piston is compared to the force exerted by the calibrated load (by testing pump)

F – force of weight and piston

A – *area of piston*

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



- Pressure measurement is converted to force measurement
- Mainly used for calibration and verification
- Dead weight testers are very accurate and sophisticated

Ismail A. What is Dead Weight Tester. How does it work? [online]. ©2021. Available form: https://forumautomation.com/t/what-is-dead-weight-tester-how-does-it-work/9748

ELECTRONIC PRESSURE INSTRUMENTS

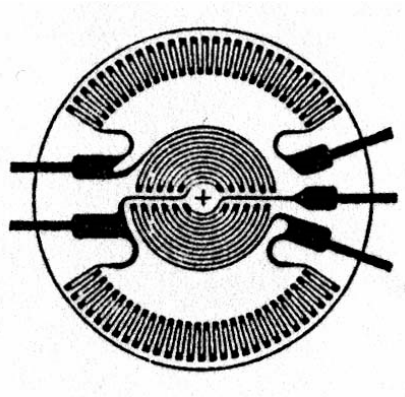
- Pressure sensors that provide an output electrical signal
- **Force collector types**
  - These types of electronic pressure sensors generally use a force collector (such a diaphragm, piston, bourdon tube, or bellows) to measure strain (or deflection) due to applied force over an area (pressure)
- Other types
  - These types of electronic pressure sensors use other properties (such as density) to infer pressure of a gas, or liquid.

- The most common force collector type:
  - Metal strain gauge
  - Capacitive
  - Piezoresistive strain gauge
  - Piezoelectric

METAL STRAIN GAUGE

Resistance strain gauge (resistance tensometer)

- Foil or thin-film strain gauge is glued or deposited onto a membrane.
- Membrane deflection due to pressure causes a resistance change in the strain gauge which can be electronically measured



Foil rosette for membrane pressure sensors

$$R = \rho \cdot \frac{l}{A}$$

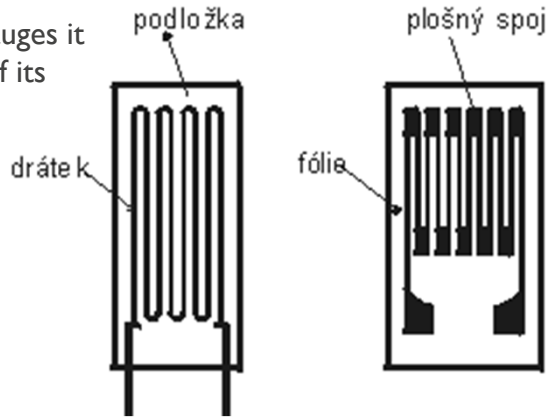
R	*wire resistance* [Ω]
ρ	*specific el. resistance (resistivity)* [Ωm]
l	*wire length* [m]
A	*perpendicular cross-sectional area* [m^2]

During stretching, the **length** of the strain gauge wire (firmly connected to the surface of the stressed object) **increases**, the **cross-section decreases** and its specific electrical **resistance changes** according to the used material - for metal strain gauges it is practically independent of deformation, ie **ρ is constant**. Only the dimensions of its conductor affect the changes in the resistance of the metal strain gauge..

Metal resistance strain gauge

- Hairpin-shaped thin resistance wires
- Foil - created by etching a metal layer

Metal resistance strain gauges usually have a **constantan** conductor (copper alloy (55%) and nickel (45%)), due to the small dependence of its resistance on temperature changes.

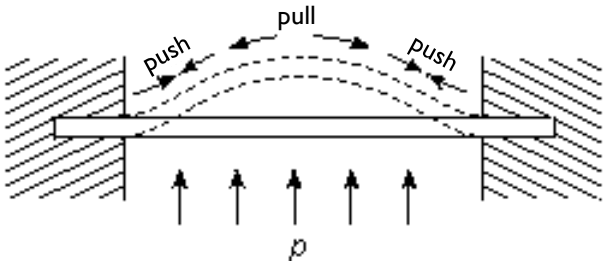


Wire Metal Foil

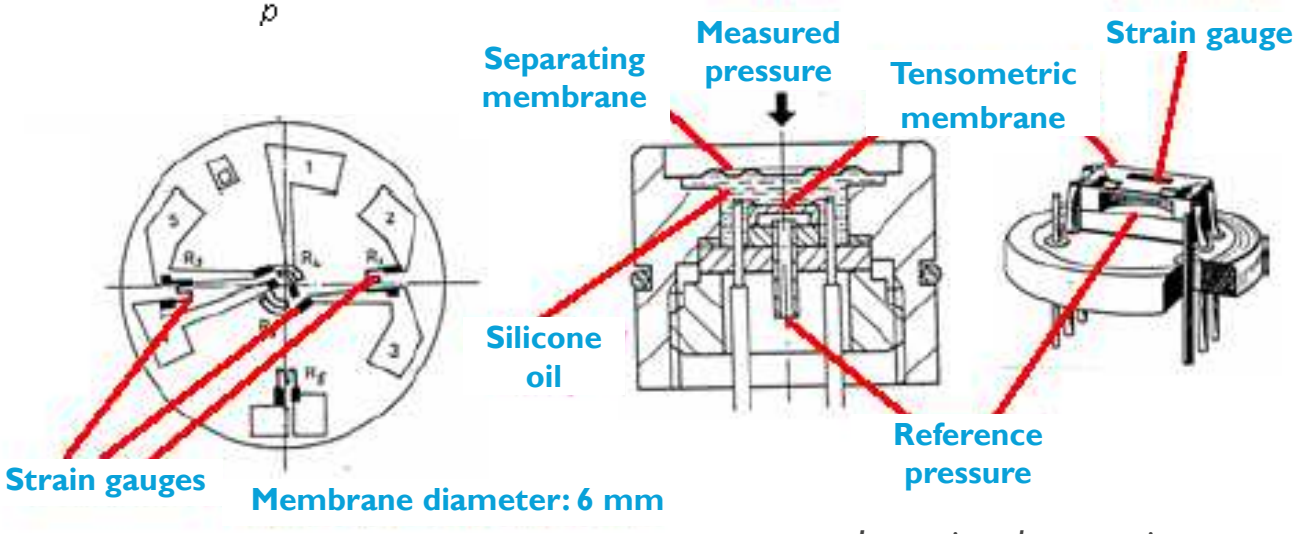
http://uprt.vscht.cz/ucebnice/mrt/F4/F4k42-tlak.htm

Semiconductor strain gauge

- by cutting or etching from a single crystal of silicon
- more sensitive than metal
- temperature dependence



design of sensors with silicon membrane

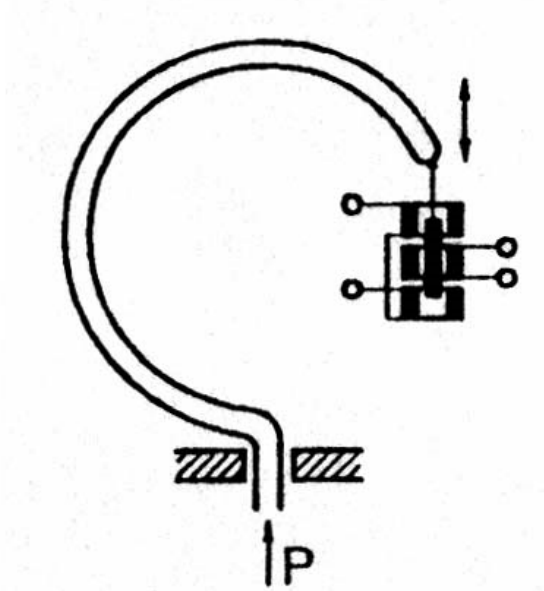


Měření tlaku. [online] Available from: http://uprt.vscht.cz/ucebnice/mrt/F4/F4k42-tlak.htm

In semiconductor resistance strain gauges, the piezoresistive phenomenon is more pronounced, i.e. the dependence of the resistivity ρ on the mechanical deformation.

TUBE PRESSURE DEFORMATION SENSORS

- the resilient element is designed to make it easy to measure its maximum deformation by position sensors



Bourdon tube pressure sensor

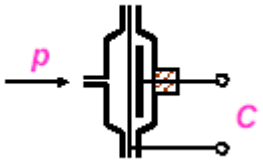
Měření tlaku. [online] Available from: http://uprt.vscht.cz/ucebnice/mrt/F4/F4k42-tlak.htm

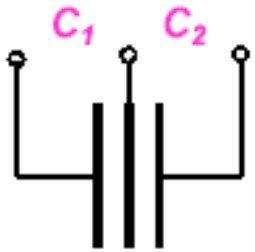
CAPACITIVE PRESSURE GAUGE

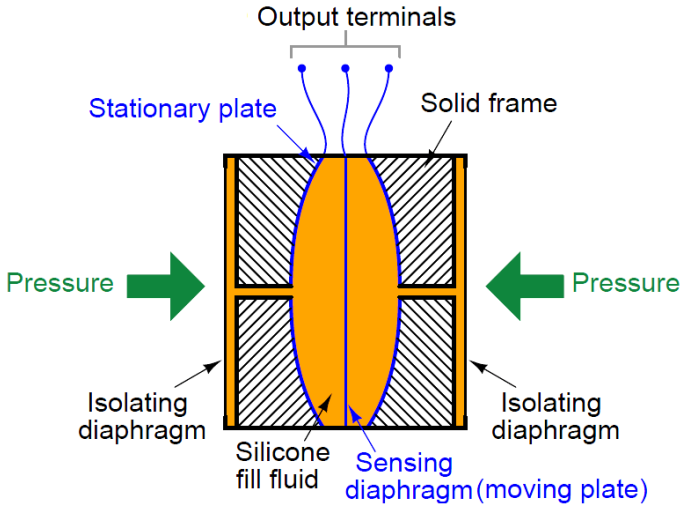
- The electronic components convert the applied force of the sample upon the pressure sensor into an electrical signal.
- Uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure, capacitance decreasing as pressure deforms the diaphragm.

$$C[F] = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}$$

ε_0 - vacuum permittivity
ε_r - relative permittivity
A - electrode area
d - electrode distance







- Differential capacitive sensor with separating fluid for measuring the pressure difference
- The membrane forms a central moving electrode
- Measuring range: 100 Pa ÷ 40 MPa

What is Capacitive Pressure Transmitter? [online]. ©2021. Available form: https://www.ouldsensors.com/what-is-capacitive-pressure-transmitter/

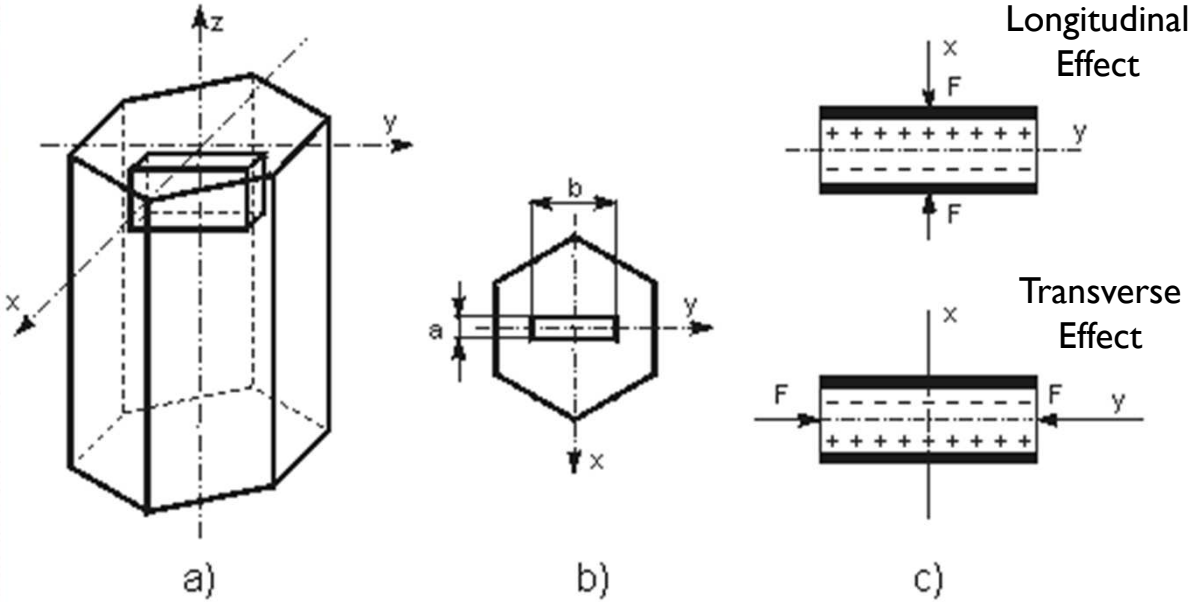
PIEZOELECTRIC PRESSURE GAUGE

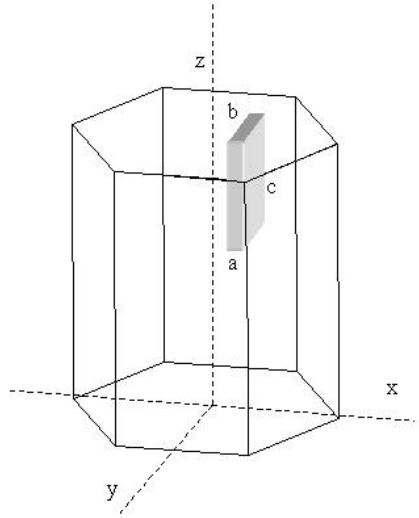
- Uses the piezoelectric effect
- Piezoelectric Effect is the ability of certain materials (e.g. quartz, $BaTiO_3$) to generate an electric charge in response to applied mechanical stress.

PIEZOELECTRIC SENSOR

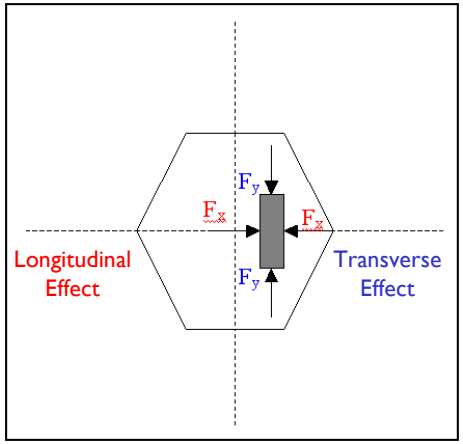
- A cut from a crystal that has piezoelectric properties
- x - electrical axis, y - mechanical axis
- Electrodes are applied on surfaces perpendicular to the electric axis
- The charge *Q* is proportional to the applied force F

PIEZOELECTRIC PRESSURE GAUGE

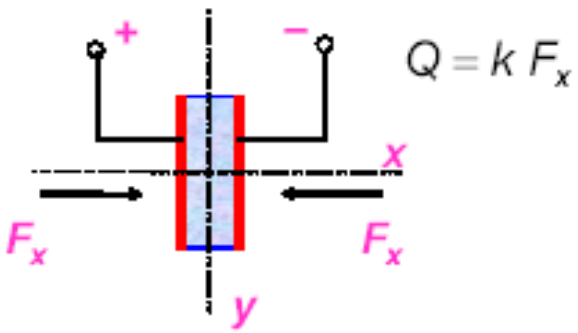




http://e-automatizace.vsb.cz/ebooks/mmv/tlak/tlak_tlakomery_elektricke.htm

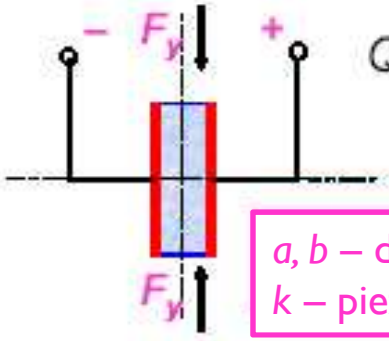


Longitudinal Effect



$$Q = k\,F_x$$

Transverse Effect



$$Q = -k\,F_y\,\frac{b}{a}$$

a, b – dimensions o the cut
k – piezoelectric coefficient

http://www.umel.feec.vutbr.cz/%7Eadamek/uceb/DATA/s_6_1.htm

PIEZOELECTRIC PRESSURE GAUGE

- when a force is applied to the piezoelectric element, a charge is created
- the piezoelectric sensor is a charge generator
- suitable for measuring fast processes
- suitable for measuring at high temperatures
- measuring range up to 100 MPa

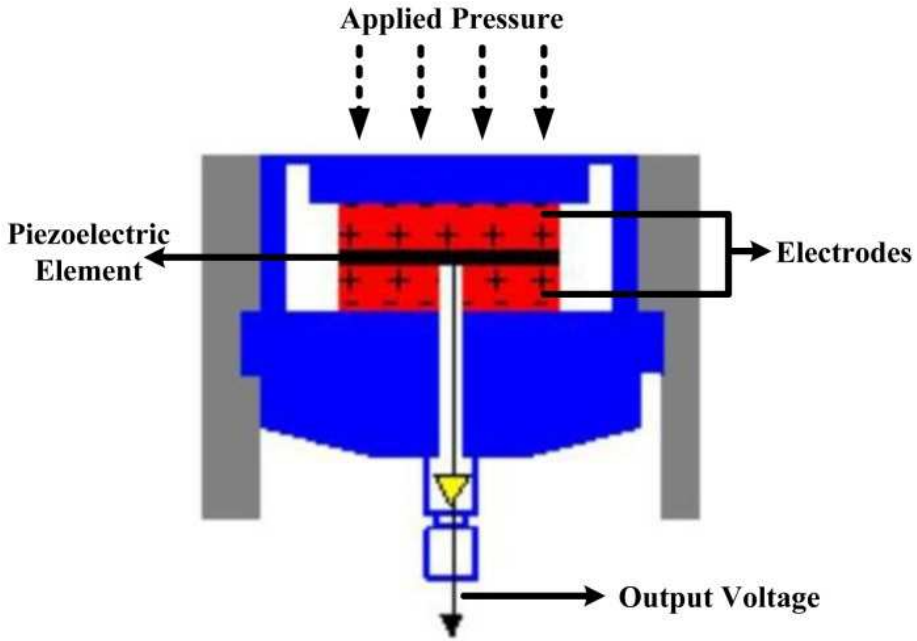
$$U = \frac{Q}{C} = \frac{k \cdot F_x}{C}$$

U – Output voltage

Q – Amount of charge

k – Piezoelectric coefficient (C/N)

F_x – *Applied force in x-direction*



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