Instrumentation & Measurement

Pressure Measurement

Winter 2024

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Today Topics

- ❖ Pressure Concepts
- ❖ Static/ Hydrostatic/ Dynamic Pressure
- ❖ Gauge/ Absolute/ Differential Pressure Measurement
- ❖ Pressure measurement Devices and Techniques
- ❖ Application Considerations

Pressure Definition

Pressure: The force exerted by a fluid per unit area is referred to as pressure.

Fluid: Liquid or gas

Example: The force applied to a gas container wall,

Force applied by a fluid on the inner surface of a pipe after the pump tuned on

The force applied by the water to the tank wall

Si unit

F = m . a

F: Force → Newton
M: Mass → Kg
a: Acceleration —> m per sec sq

Pressure Measurement Unit

SI unit

F = m . a

F: Force $\rightarrow$ Newton
M: Mass $\rightarrow$ Kg
a: Acceleration —> $\frac{m}{s^2}$

Weight= m . g

English unit

F = m . g

F: Force $\rightarrow$ Pound-force (lbf)
M: Mass $\rightarrow$ Pound-mass (lb)
g: gravity —> 9.8

1 lbf= 4.448 N

Pressure Units:

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

$$\text{SI unit } \Rightarrow \frac{N}{m^2} \text{ named as pascal } \Rightarrow 1 \text{ Pa} = \frac{N}{m^2}$$

$$English\, Ssytem \Rightarrow \frac{lb}{in^2} \text{ named as psi (pound per squar inch)}$$

$$\Rightarrow more\, accurately\, \frac{lbf}{in^2}$$

$$1\, psi = 6894.757 \text{ Pa}$$

$$\text{torr} \Rightarrow \text{ for very low pressure such as vacuum } 1 \text{ torr} \approx 133.3 \text{ Pa}$$

$$\text{bar} \Rightarrow 1\, bar = 100\, kP = 14.5\, psi$$

$$mmHg \text{ (millimeter of mercury)} \Rightarrow 1\, mmHg \approx 133.3 \text{ Pa}$$

$$Feet\, of\, water \Rightarrow 1\, feet\, of\, warter = 2989 \text{ Pa}$$

Pressure Measurement Unit

Pressure Equivalents								
	kg per sq cm	lb per sq in.	atm	bar	in. of Hg	kilopascals	in. of water	ft of water
kg per sq cm	1	14.22	0.9678	0.98067	28.96	98.067	394.05	32.84
lb per sq in.	0.07031	1	0.06804	0.06895	2.036	6.895	27.7	2.309
atm	1.0332	14.696	1	1.01325	29.92	101.325	407.14	33.93
bar	1.01972	14.5038	0.98692	1	29.53	100	402.156	33.513
in. of Hg	0.03453	0.4912	0.03342	0.033864	1	3.3864	13.61	11.134
kilopascals	0.0101972	0.145038	0.0098696	0.01	0.2953	1	4.02156	0.33513
in. of water	0.002538	0.0361	0.002456	0.00249	0.07349	0.249	1	0.0833
ft of water	0.03045	0.4332	0.02947	0.029839	0.8819	2.9839	12	1
1 oz/sq in. = 0.0625 lb/sq in.								

Note: use multiplier at convergence of row and column

Example: A blood pressure is 120 mmHg. How much would that pressure in psi?

$$mmHG \rightarrow inHG \rightarrow psi$$

$$120\ mm \leftrightarrow ?\ inch$$

$$\frac{120}{25.4} \leftrightarrow \frac{?}{1} \qquad ? = 4.724\ inch$$

$$25.4\ mm \leftrightarrow 1\ inch$$

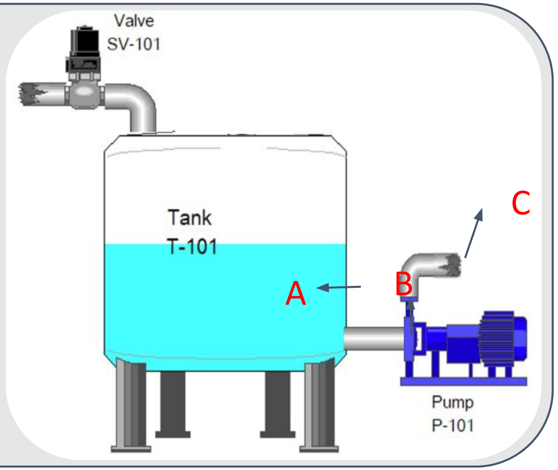
$$120\ mmHG \rightarrow 4.724\ inHG \rightarrow 4.72 \times \boxed{0.4912} = 2.32\ psi$$

$$2.32\ psi \times \boxed{0.07031} = 0.163\ Kg\ per\ sq\ cm$$

Pressure Source

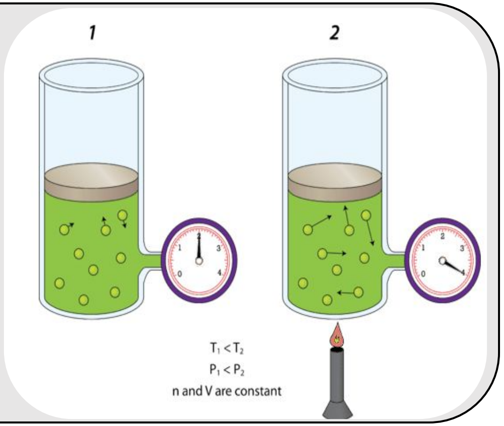
The pressure is defined as force exerted by fluid per unit area is referred to as pressure. Different sources can be identified for the exerted force.

For example the pressure resulted from weight of the fluid at point A or the pressure generated by pump at point C.

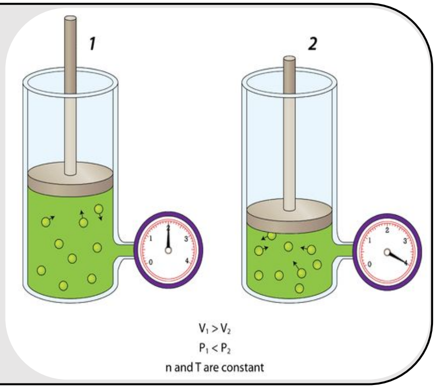


Heating up the fluid inside a closed container increases their pressure.

Decreasing temperature would have the reverse effect, pressure will decrease.



Compression of fluids such as gas increase their pressure.



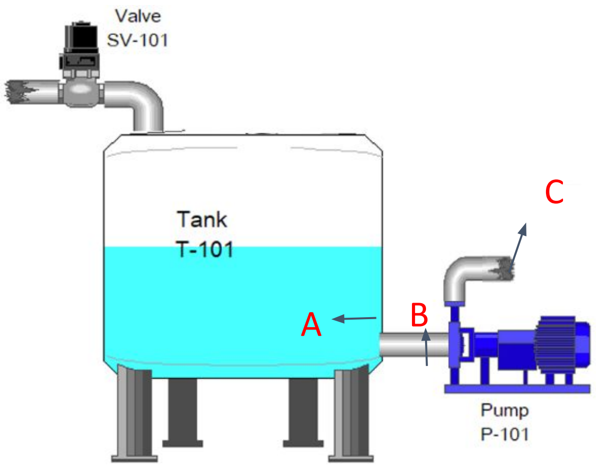
Photos Source

Pressure Types

The pressure is divided to two types: static and dynamic pressure

Total Pressure = Static Pressure + Dynamic Pressure

$$P_{Total} = P_{Static} + P_{Dynamic}$$



Since pressure is force in essence, an analogy can be drawn between pressure and energy as below:

$$P_{Static} \leftrightarrow Potential\ Energy$$

$$P_{Dynamic} \leftrightarrow Kinetic\ Energy$$

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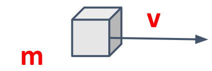
Dynamic Pressure

$$P_{Dynamic} = \frac{1}{2}\rho v^2 \quad \leftrightarrow \quad Kinetic\ Energy = \frac{1}{2} m v^2$$

$$\rho \leftrightarrow \ Fluid\ Density$$

$$v \leftrightarrow \ Fluid\ velocity$$



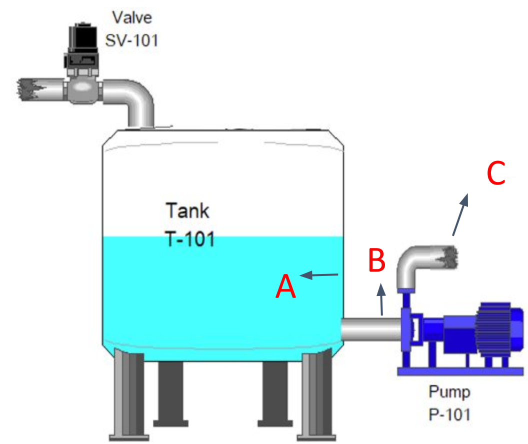
Dynamic Pressure is resulted from the force applied by a running fluid to an object in front of it.

For example when the water flows out of hose, by placing a finger in front of the water the force can be sensed.

Or in front figure after the pump turned on, if we put an object in front of running water at point C, a force will be applied to it. This is the dynamic pressure.

One example of a device which works based on the dynamic pressure is the rotameter, running water pushes the red float upward and gravity pulls it downward. At a point these forces balance each other.

The dynamic pressure is proportional to the square of the fluid speed and how heavy the fluid is. Faster fluid, higher dynamic pressure. Heavier fluid applies stronger force compared to lighter one at the same speed (Example oil vs water)



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Static Pressure

Static Pressure is the force applied by a non-moving fluid to the surrounding environment.

In static pressure the source of the force could be the weight of the fluid. This static pressure is referred to as **Hydrostatic(Head) Pressure**.

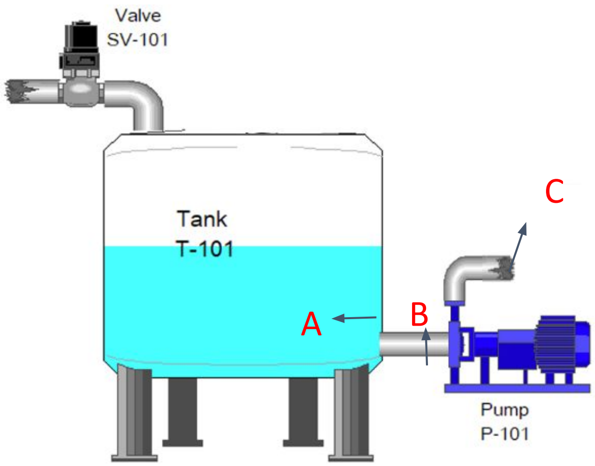
The static pressure could be resulted from other source such as pump for fluid inside the pipe, air compressor for the air inside the hose or heated gas inside a closed container. This static pressure is referred to as **Non-Hydrostatic Pressure**.

For more clarity the static pressure is categorized into two groups depending on the source of pressure.

Static Pressure = Non-Hydrostatic + Hydrostatic

Then

Total Pressure = Non-Hydrostatic + Hydrostatic + Dynamic Pressure



$$P_{Total} = P_{Static} + P_{Dynamic}$$

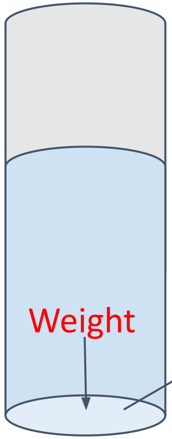
$$P_{Static} = P_{Non-Hydrostatic} + P_{Hydrostatic}$$

$$P_{Total} = P_S + P_D$$
$$= P_{NH} + P_H + P_D$$

Hydrostatic Pressure

Consider the front cylinder as a fluid container. The cross sectional area is A and the height of the fluid is h.

The objective is to calculate the pressure applied by the the fluid to the button of the tank.



$$Weight = m \times g$$

$$\rho(Density) = \frac{m}{V} \Rightarrow m = \rho \times V$$

$$m \leftrightarrow Mass,\ V \leftrightarrow Volume,\ g \leftrightarrow Gravity$$

$$\Rightarrow \quad Weight = \rho \times V \times g$$

$$Pressure = \frac{Weight}{A} = \frac{\rho \times V \times g}{A} = \rho \times h \times g$$

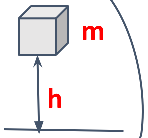
$$V = A \times h$$

$$P_{Hydrostatic} = \rho \cdot h \cdot g$$

$$\rho \leftrightarrow Fluid\ Density$$

$$h \leftrightarrow Fluid\ height$$

$$\leftrightarrow \quad Potential\ Energy = m\,g\,h$$



Hydrostatic Pressure

As the fron formula presents, the hydrostatic pressure depends on density and height.

For example 10 inch column of water apply more pressure than 5 inch.

Or 10 inch of the cooking oil or honey apply more pressure than 10 inch of water.

As the front formula shows hydrostatic pressure does not depends on the cross sectional area A. In general term , the hydrostatic pressure does not depends on the container shape, it just depends on the fluid elevation.

This Property of Hydrostatic pressure, Non dependency to shape of the container, made it a proper candidate for pressure unit.

some of pressure units are, mmHG (millimeter of mercury), inch of water , feet of water, inch of mercury

SI Unit

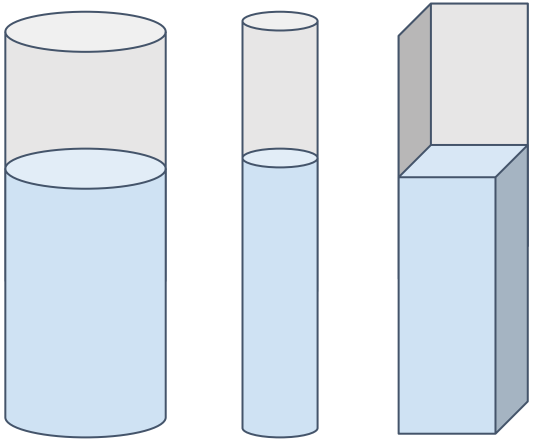
$$P_{Hydrostatic} = \rho \cdot h \cdot g$$

$$\rho \leftrightarrow Fluid\ Density\ in\ \frac{kg}{m^3}$$

$$h \leftrightarrow Fluid\ height\ in\ meter$$

$$g \simeq 10\ \frac{m}{s^2}$$

$$P_{Hydrostatic}\ will\ be\ in\ Pascal$$



Fluid height *h*

Pressure Measurement Unit

In the front figure the the density of water and mercury is given. The density shows that the mercury is 13.6 times heavier than water. 2 inch of mercury apply one pound of force per square inch (1 psi). Since the water is 13.6 times lighter, to make same pressure as 2 inch of mercury the height of water should be 13.6 times of mercury.

One common example for the height of mercury as the pressure unit is the human blood pressure expression. 120/100 mmHg.

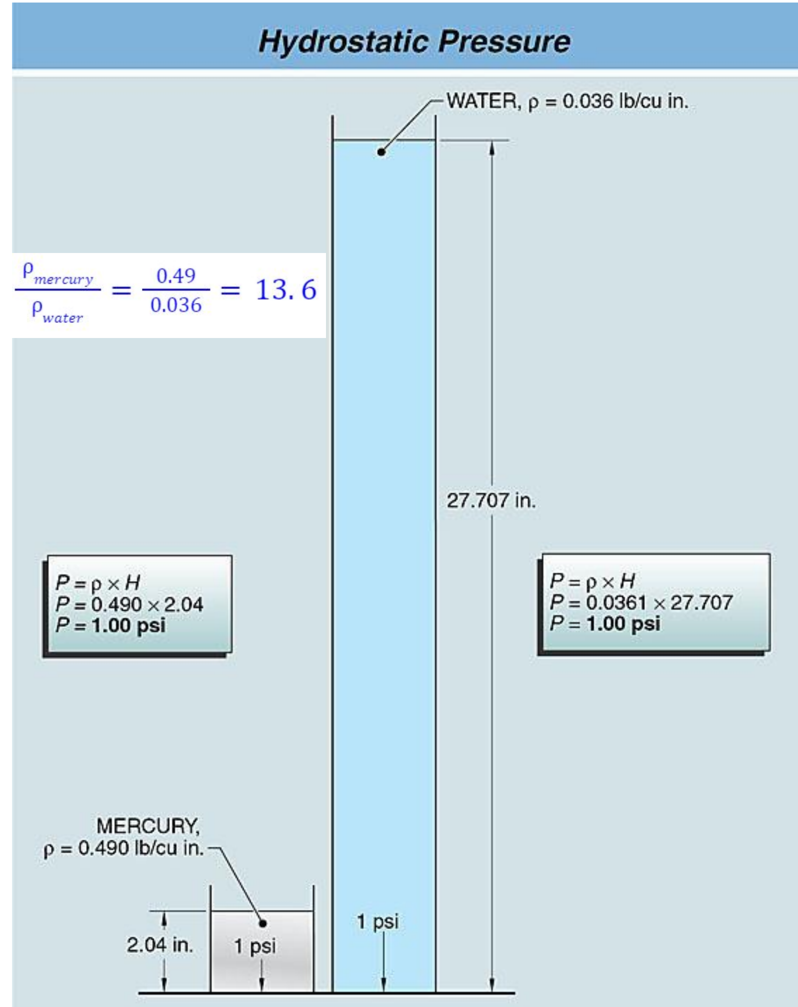
English Unit

$$P_{Hydrostatic} = \rho \cdot h$$

$$\rho \leftrightarrow \; Fluid\ Density\ in\ \frac{lb}{in^3}$$

$$h \leftrightarrow \; Fluid\ height\ in\ inches$$

$$P_{Hydrostatic} \leftrightarrow \; in\ psi\ (\frac{lb-force}{in^2})$$



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Atmosphere Pressure

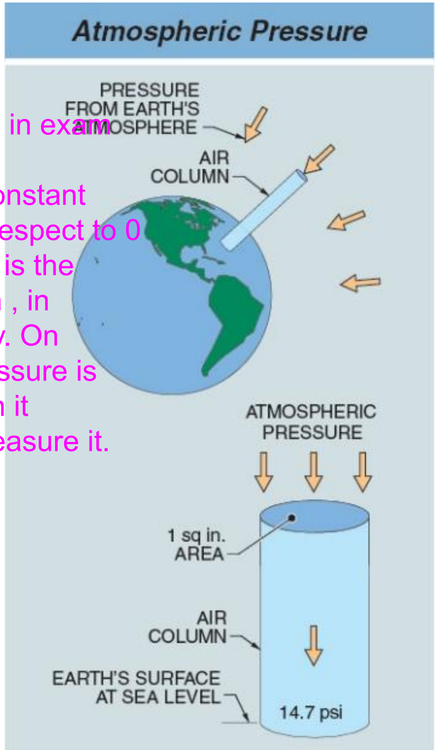
The air surrounding the Earth, known as the atmosphere, exerts force to the objects due to its weight. This force per unit of area is known as atmospheric pressure. The standard atmospheric pressure at sea level is approximately 100 kPa or 14.7 psi.

It's important to note that atmospheric pressure varies with elevation from the sea level. The higher elevation, the lower the atmospheric pressure. For instance, at the summit of Mount Everest, which is approximately 8844 meter above the sea level, the atmospheric pressure is around 5 psi. In comparison, at sea level, it is 14.7 psi.

The reason for this decrease in pressure with increasing altitude is that the column of air above Mount Everest's peak is shorter than column of air on the see level, leading to less weight and lower atmospheric pressure.

respect to tire pressure in exam

Absolute pressure is constant because is measured respect to 0 therefore we can say it is the same at each elevation , in cancon and mexico city. On contrary the gauge pressure is relative to ambient then it depends where you measure it.



Atmospheric Pressure

Pressure*	Location	Elevation†
5.0	Mt. Everest	29,002
11.1	Mexico City	7556
12.2	Denver, CO	5280
14.7	Sea level	0

* in psi
† in ft

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Absolute Pressure (Pressure measurement Types)

If a pressure is measured in reference to total vacuum, it is known as Absolute pressure.

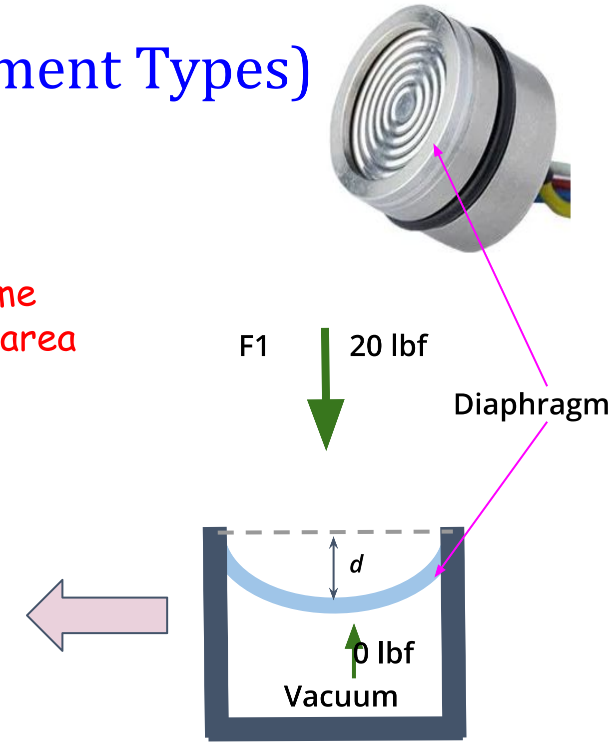
The absolute pressure value is constant everywhere because it is referenced to 0. example 5 psia, “a” in unit psia stands for absolute.

When it is being said the atmospheric pressure at sea level is 14.7 psi, in fact it is 14.7 psia because it is measure in reference to total vacuum.

Let's assume diaphragm area is 1 sq inch

d $\propto$ 20 lbf

20 psia



Gauge Pressure (Pressure measurement Types)

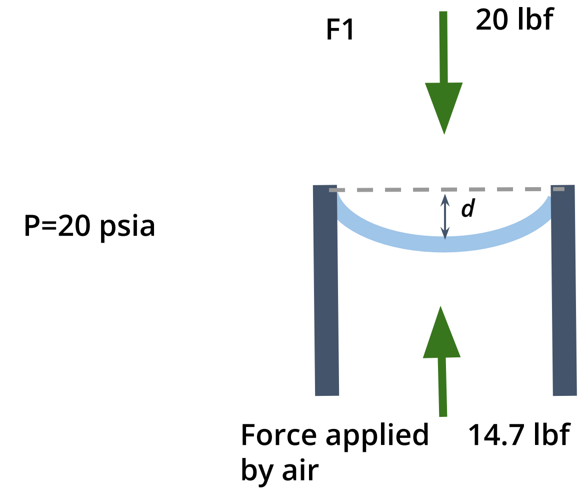
If a pressure is measured in reference to atmospheric pressure, it is known as Gauge pressure. example if pressure of a tank is 10 psig, it means it is 10 psi more than atmospheric pressure at the same place.

“g” in psig stands for gauge.

The gauge pressure value is relative and may change from a place to another since the atmospheric pressure depends on the elevation.

If the front measurement is done on the mountain everest, since the atmospheric pressure is 5 psi then the force differential will be 15 psi

On a seashore



$d \propto (20\text{-}14.7)=5.3$ lbf

P= 5.3 psig

measures the net force exceeding atmospheric force

Absolute = Gauge + Atmospheric pressure

On everest ⇒ 20 -5 =15 psig

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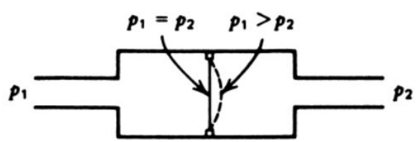
Differential Pressure (Pressure measurement Types)

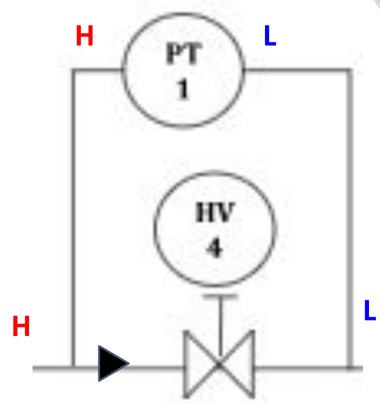
If a pressure is measured relative to another pressure except than atmospheric pressure, it is known as Differential pressure.

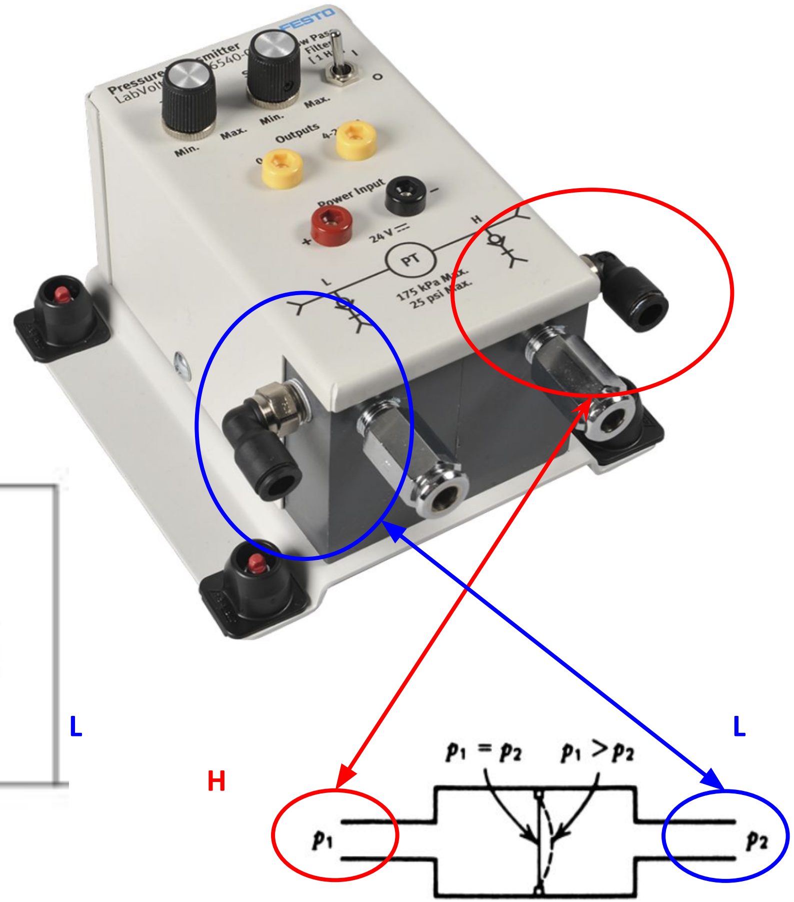


$$F = (p_1 - p_2)A$$

where A = diaphragm area in m^2

p_1, p_2 = pressure in N/m^2





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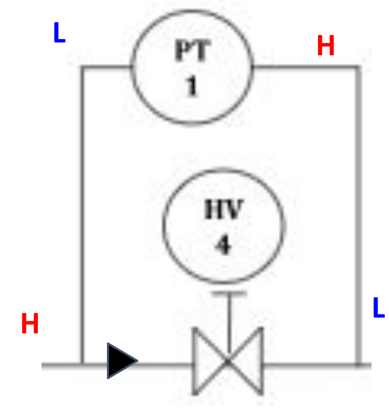
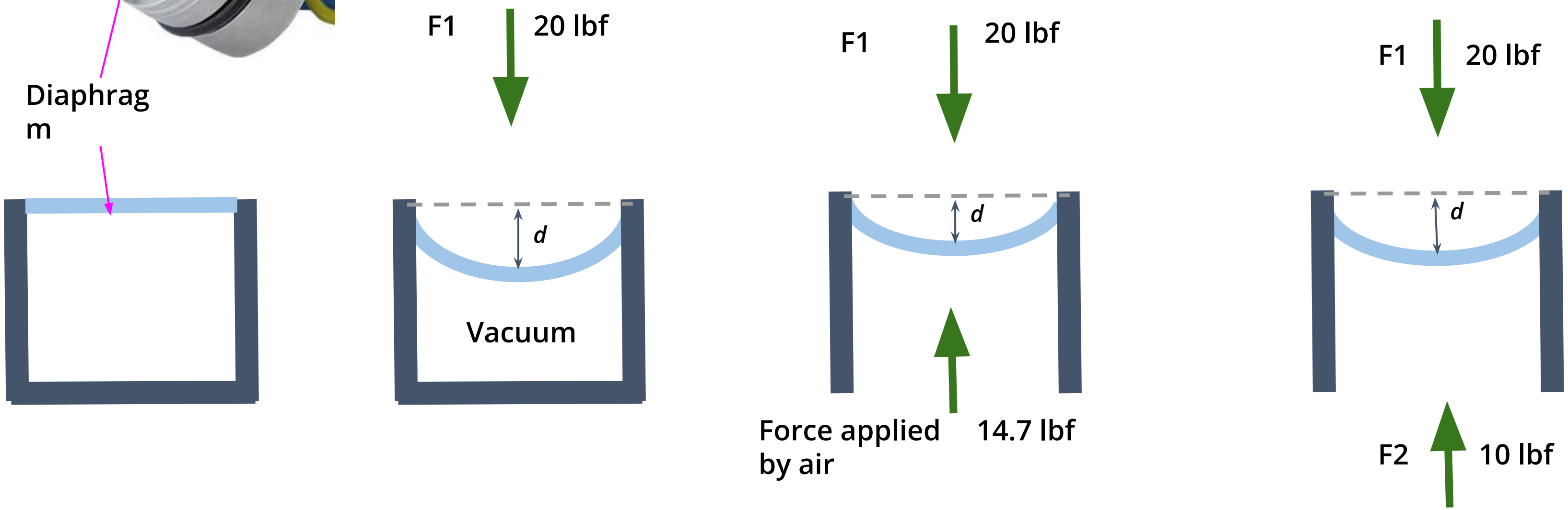
Question:

what will be the reading if the connection is made as front?





$d \propto 20$ lbf

$d \propto F1$

measuring net force

Absolute Pressure

$d \propto (20-14.7)=5.3$ lbf

$d \propto (F1-14.7)$

measures the net force exceeding atmospheric force

Gauge Pressure

$d \propto (20-10)=10$ lbf

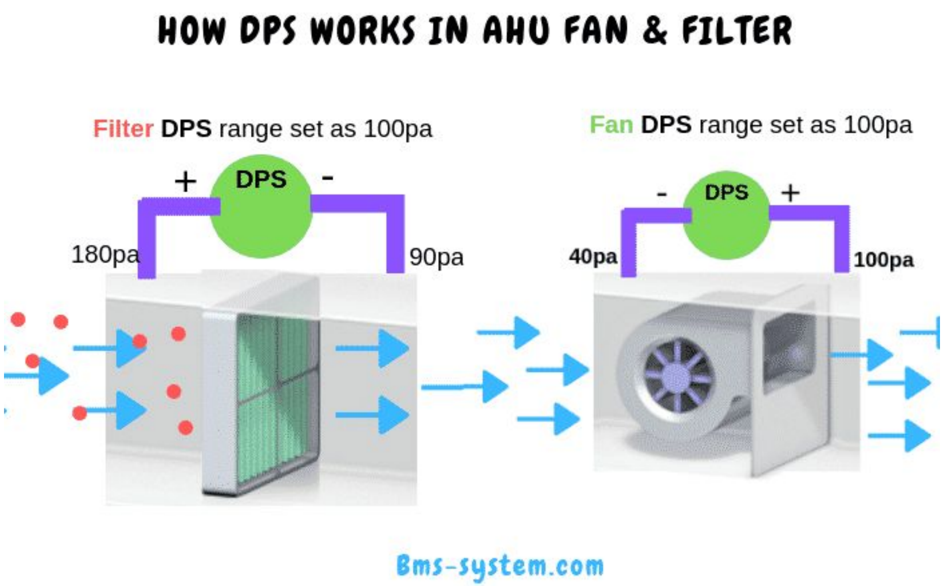
$d \propto (F1-F2)$

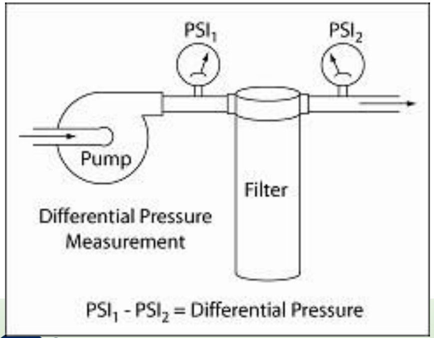
Measures difference between two forces

Differential Pressure

Application

Hydraulic or air filter for differential application





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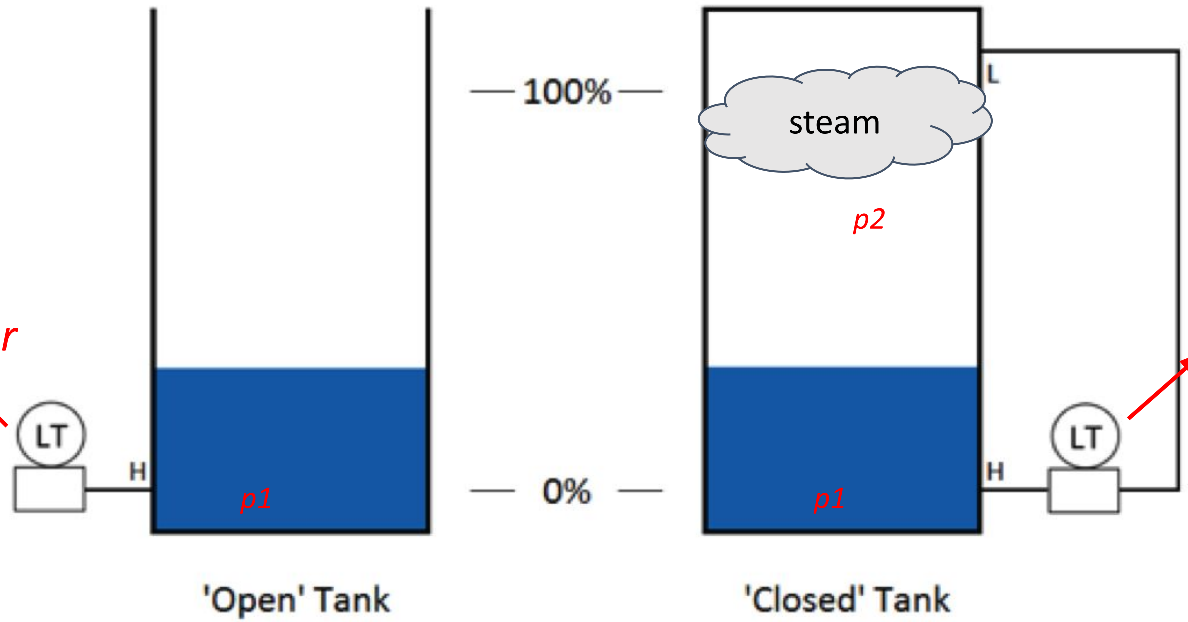
Application - Level measurement

Gauge Pressure Transmitter



Differential Pressure Transmitter

$p1=\rho gh$

$p1-p2=\rho gh$

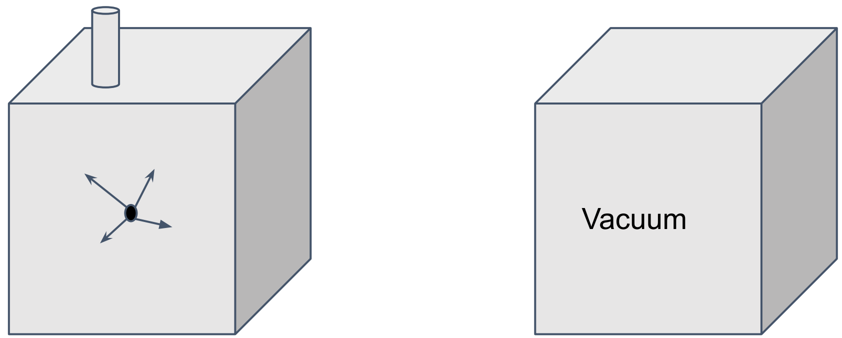
Vacuum

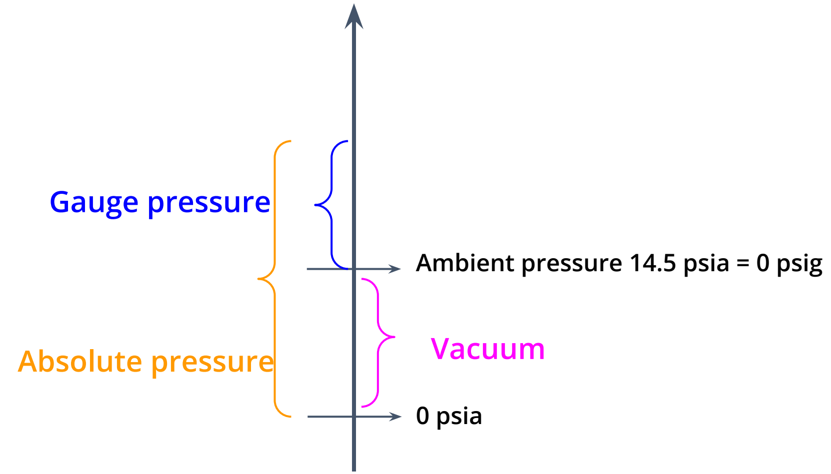
If a closed area is emptied from matters (gas, liquid, solid) it is known as void and the space known as vacuum.

For example the inner space of the front cube is emptied from the air and inside the cube there is no air molecule or anything else, this space is known as Vacuum space.

Since there is no air molecule inside then no force will be applied to the inner surface of cube it means no pressure exists.

Total vacuum is not common and usually the pressure less than atmospheric pressure is known as vacuum pressure.





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Question:

pressure of a tank is 2 psi less than atmospheric pressure , if we measure the pressure of the tank with absolute pressure meter how much will we read?

how about if we use gauge pressure meter ?

Atmospheric pressure is 15 psi

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Pressure Measurement Types

➔ Point Measurement

- Pressure switch
- In P&ID starts with PS example PSH-101 Pressure Switch High
- The mechanical or electrical types
- They have either mechanical contact output or Transistor output with NO or NC.
- They can be adjusted to open and close a contact at specific pressure

➔ Continuous measurement

- In P&ID referred to as PT stand for pressure transmitter
- They could be transducer with analog output 4-20 mA , 0-10 V or transmitter with digital network output.

Pressure Measurement Techniques

- Manometer
- Bourdon Tube
- Diaphragm
- Bellows
- Membrane and Strain Gauge
- Capacitive
- Inductive
- Piezoelectric
- Piezoresistive

Manometer

Manometer shows the pressure as a column of a liquid.

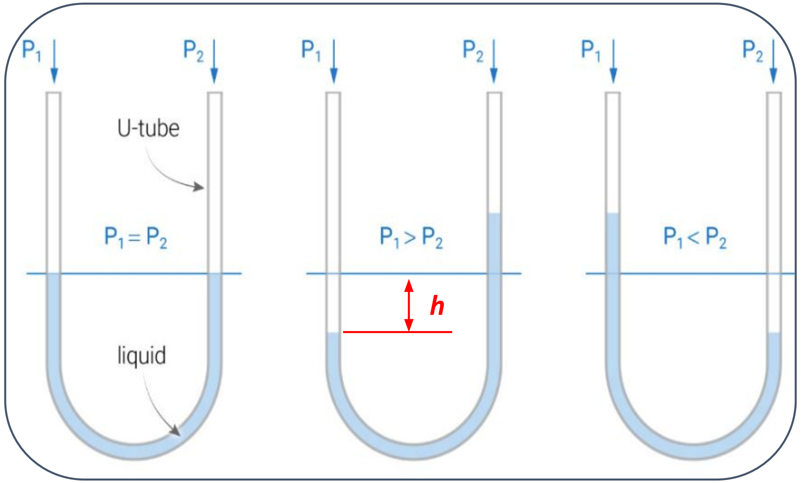
In the front figure you see a U-Tube manometer. when the p1 is more than p2, h represent p1-p2.

Let's assume the liquid in U-tube is water and p2 is connected to openair and *h* is 2 inch. Then we say the P1 gauge pressure is equal to 2 inch of WC (Water column).

If the liquid was mercury, we could say p1= 2 inch of mercury.

The liquid could be anything as long as its relative density to the water is known, then we could say how much the pressure is.

For example if the liquid inside was oil and its density was 0.9 times of water then it could be said the P1= 2 x 0.9 =1.8 inch WC



Picture source

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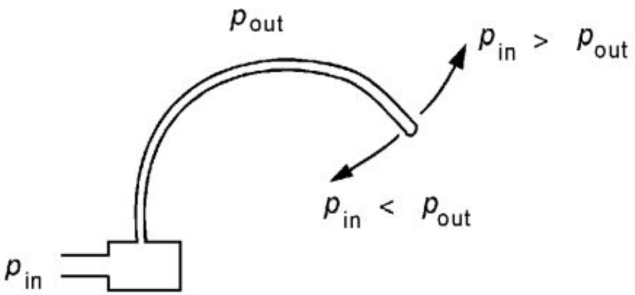
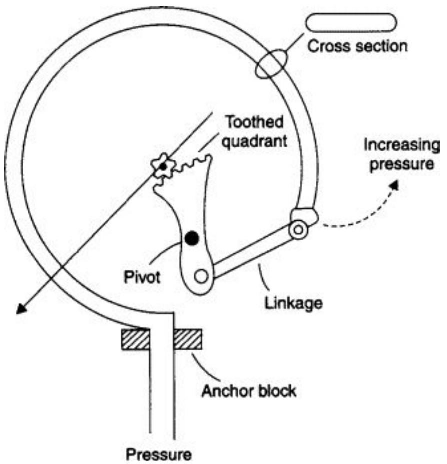
Bourdon Tube

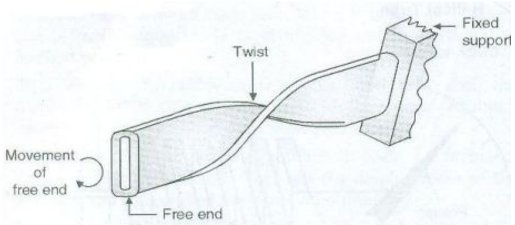
- The P_{out} is the chamber pressure. Usually atmospheric pressure
- P_{in} is unknown pressure. The pressure we want to measure.
- When the P_{in} is more than P_{out}, the tube will move to straighten out. This motion can used to rotate a dial or converted to electrical signal.
- Example Gauge pressure in lab



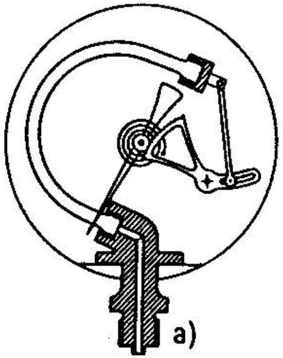


Bourdon Tube

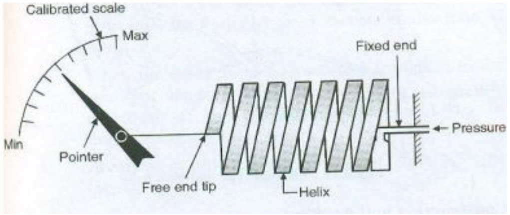
Twisted Bourdon



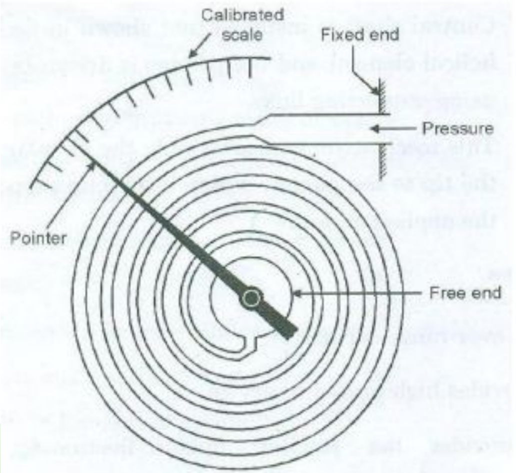
C-Shaped Bourdon



Helical Bourdon



Spiral Bourdon



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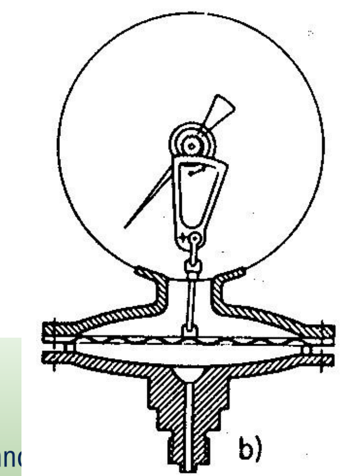
Diaphragm or Membrane

- The applied pressure will deform the diaphragm.
- The deformation can be measured by different techniques such as:
  - Converting to direct mechanical motion example below figure
  - Strain Gauge
  - Capacitive method
  -



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Metal Membrane with Strain Gauge

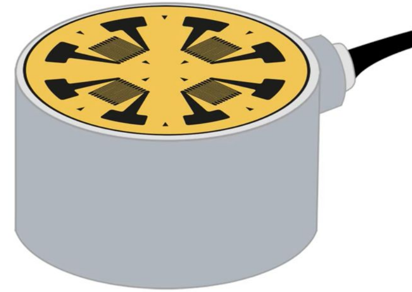
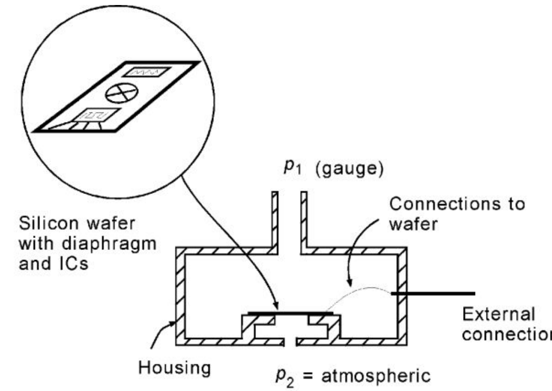
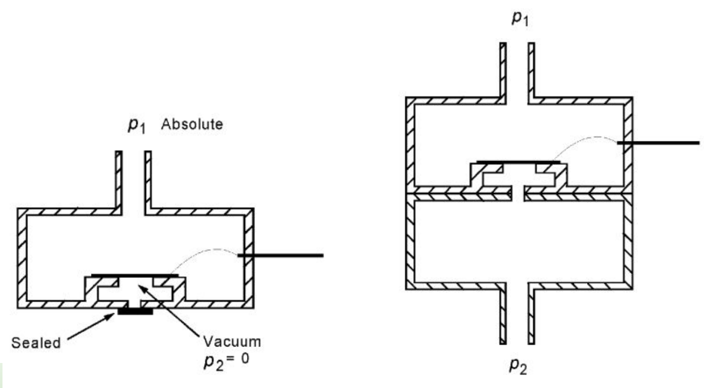


Photo Source

Strain gauges are planted on to diaphragm. deformation cause the change of resistance.



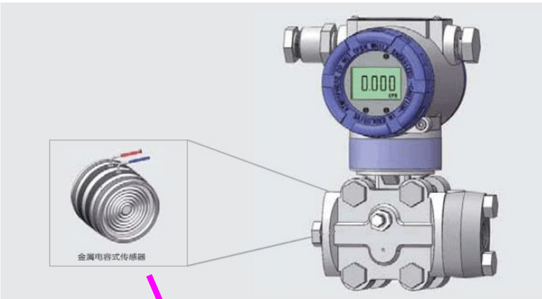
Video about Pressure measurement



a) Measurement of absolute pressure

b) Measurement of differential pressure, $p_1 - p_2$

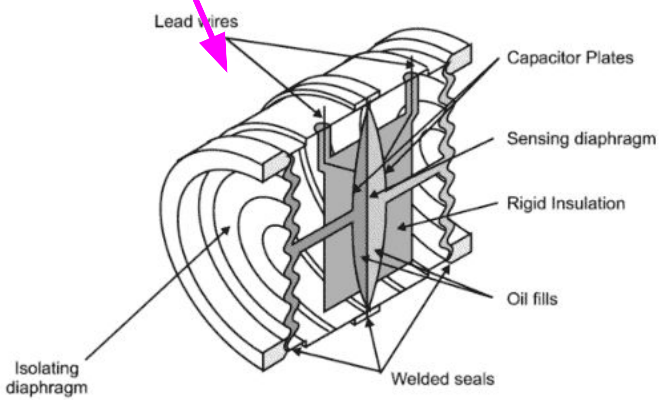
Capacitive Pressure Sensing Element



$$C = \varepsilon \frac{A}{d}$$

$$d \downarrow \quad \Rightarrow \quad C \uparrow$$

$$d \uparrow \quad \Rightarrow \quad C \downarrow$$



Q = C V

Photo source

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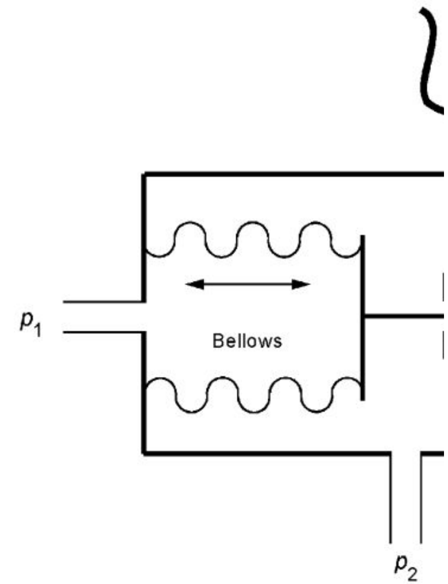
Bellows

- The pressure difference between P1 and P2 is converted to displacement then displacement to electrical signal.
- If we let the p2 inlet to be connected to air , then p1 will be measured in reference to atmospheric pressure. The instrument will act as a gauge pressure.
- If we connect P1 to one point and P2 to other point of system, (like two sides of a valve, or two points of a pipe), then P1 will be measured relative to p2. In this case the pressure instrument is used as differential pressure instrument.
-



$$F = (P_2 - P_1) . A$$

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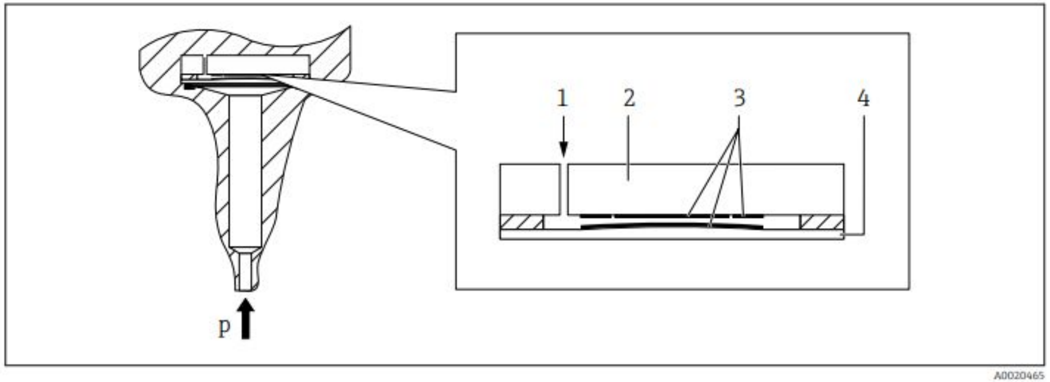
Ceramic Membrane

Property:

- Wide range of chemical compatibility
- Can be used for vacuum
- Membrane robustness
- The measuring range can be achieved by ceramic process isolating diaphragm



1 Air pressure (gauge pressure sensors)
2 Ceramic substrate
3 Electrodes
4 Ceramic process isolating diaphragm

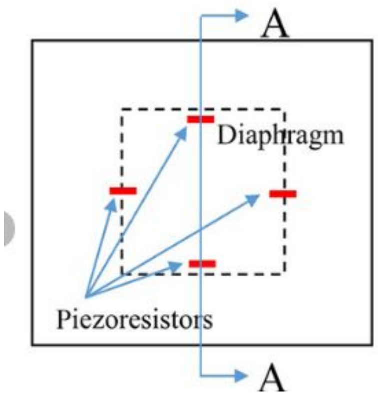
[Video about Pressure measurement]

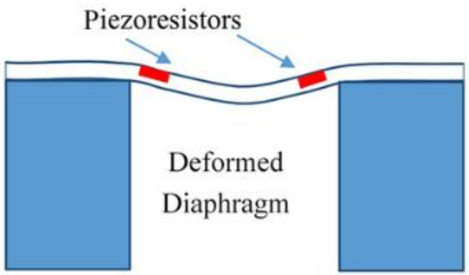
[Source: Druckmesstechnik (endress.com)]

Piezoresistive Gauge

Semiconductor material resistance change by deformation resulted from applied stress.

The can be made in tiny sizes

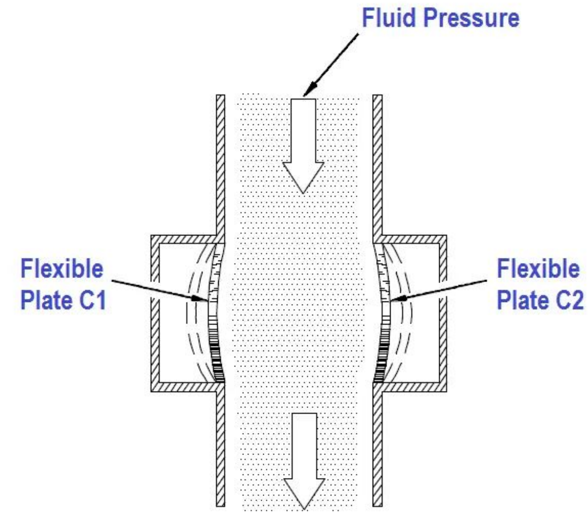


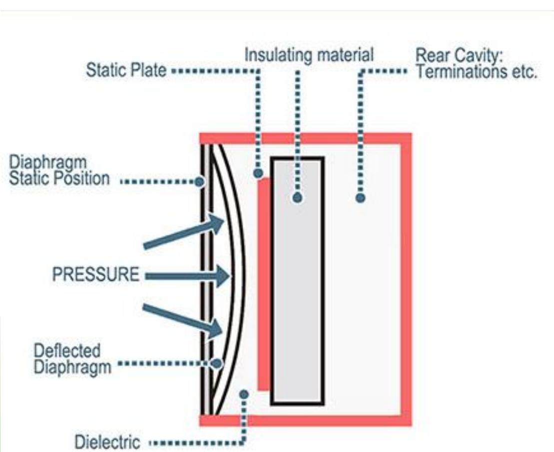


Capacitive Pressure Sensing Element

Property

- Nonlinear
- electronic is not straight forward , needs bridge circuit
- it can be designed for different sensitivity
- Can be made in small size





$$C = \varepsilon \frac{A}{d}$$

$$d \downarrow \Rightarrow C \uparrow$$

$$d \uparrow \Rightarrow C \downarrow$$

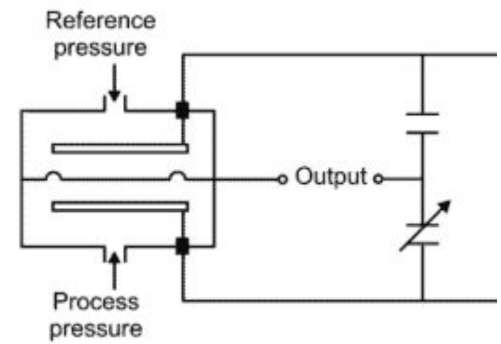
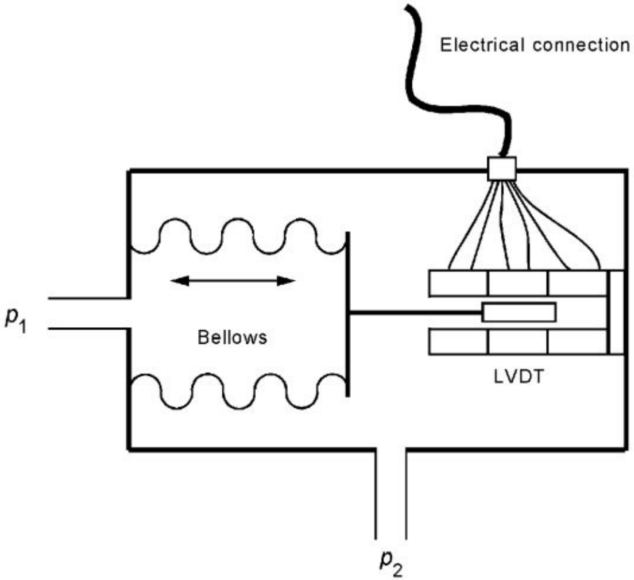


Photo source

Inductive



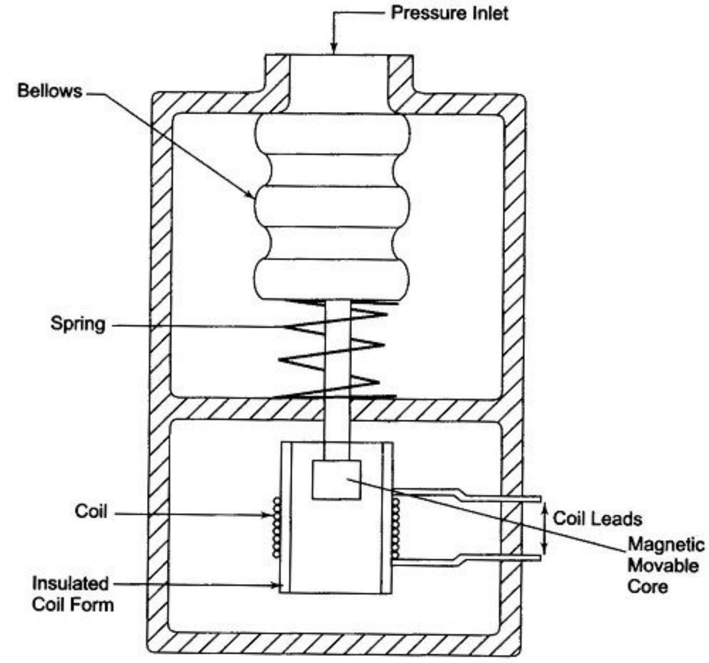
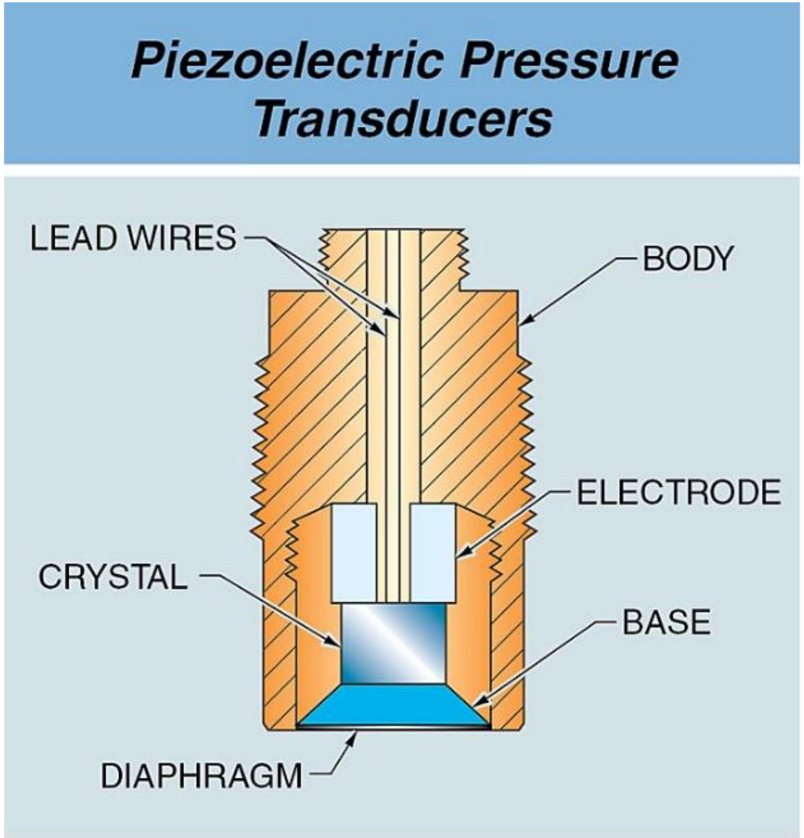


Fig. 13.22 Pressure Inductive Transducer

Piezoelectric

A piezoelectric pressure transducer is a diaphragm pressure sensor combined with a crystalline material that is sensitive to mechanical stress in the form of pressure.

Needs to have temperature compensation



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Application Considerations

Condensation

Condensation happens due to the humidity and change of ambient temperature.

Condensation in manometer will lead to inaccuracy.

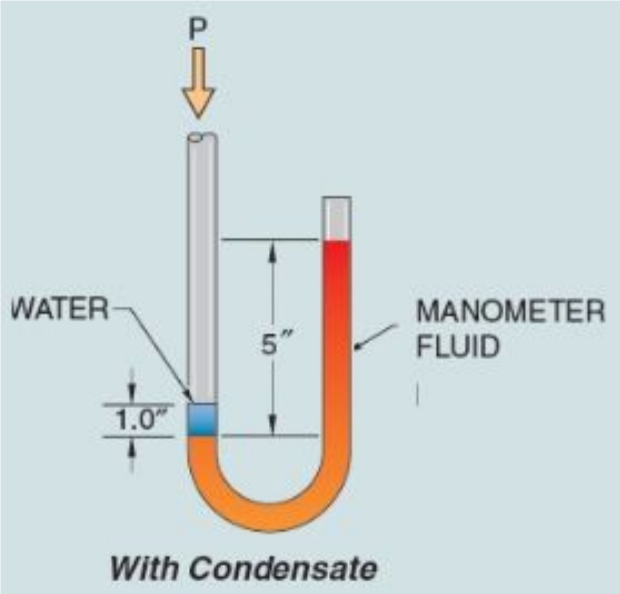
In the front figure, the orange color fluid inside the manometer is 2 times heavier than water.

When the pressure P is applied to the left leg, the fluid elevates upto 5 inches in the right leg.

Since there was a water inside the tube, the elevation is not only due to P but also the weight of 1 inch water column.

Then :

P= 5x2 -1 =9 water column

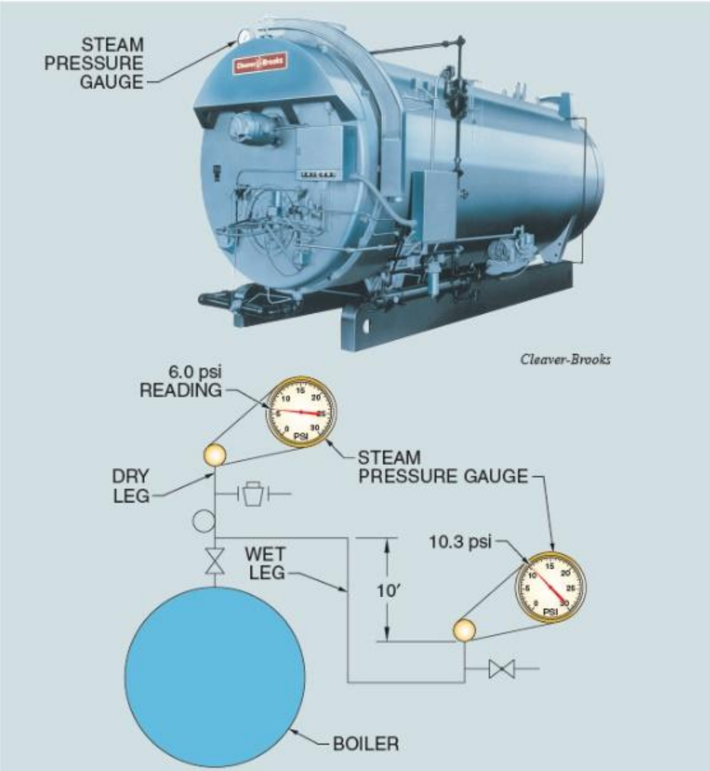


Hydrostatic Pressure Effect

If the objective is to measure pure non-hydrostatic pressure, then we should be aware of existence and effect of hydrostatic pressure.

As front figure shows the steam pressure in dry leg is 6 psi which represents the steam pressure. In wet leg the pressure is 10.3 psi. The extra pressure in wet legs comes from column of water inside the wet leg.

Steam Pressure Measurement



What is the hydrostatic pressure on a vertical distance of 10′ (120″)?

$$P = \rho \times h$$
$$P = 0.0361 \times 120$$
$$P = \mathbf{4.33\ psi}$$

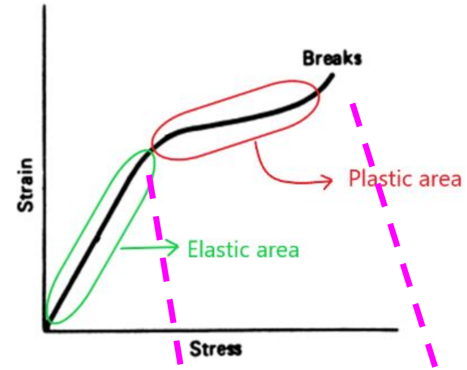
Determining Hydrostatic Pressure

Overpressure

All the sensors with the bourdon tubes or diaphragm work based on the elasticity of the materials. It means that once pressure is removed the deformation will be retracted and the sensing elements return to original form in order to be ready for a new measurement.

Then there is a limit to the pressure applied to measuring device, otherwise the sensing element enters to plastic area and deformation will become permanent and device will be damaged and has to be replaced. This pressure limit is known as overpressure or proof pressure.

This limit is not the maximum of measurement range.



PSIG ranges

Gauge pressure	Proof pressure	Burst pressure
0-25	100	500
0-50	150	750
0-100	300	1,000
0-250	500	2,000
1-500	1,000	3,000
0-1,000	2,000	5,000
0-3,000	4,500	7,500
0-5,000	7,500	10,000
0-10,000	12,500	20,000

Setra_Model_206_Data_Sheet.pdf

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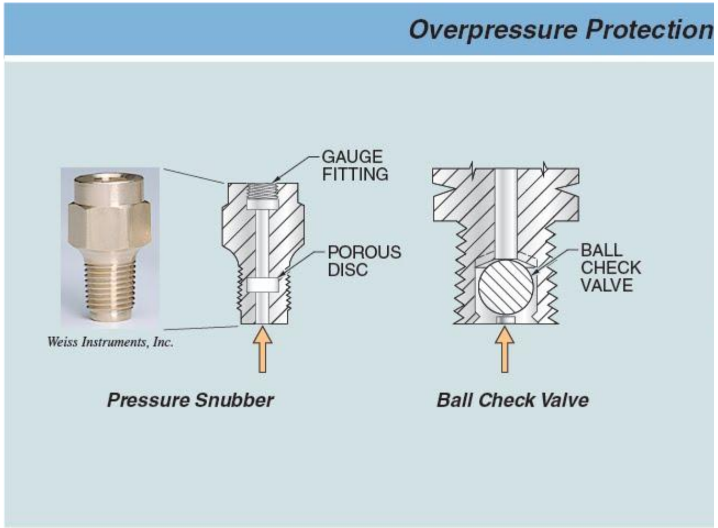
Overpressure Protection

➔ An **snubber** is shock absorber or pulsation dampers.

- Porous Filter (metal disk with tiny holes)
- Ball Check valve
- A variable orifice
- A piston type

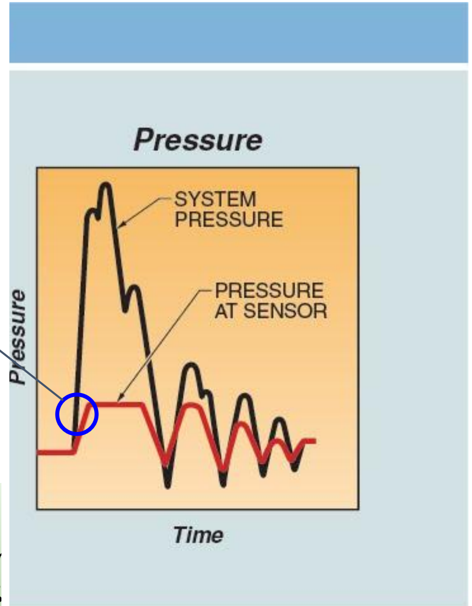


Drawback could increase the error in measurement. (Figure front)

Piston type can clean sediment.

➔ **Pressure Relief Valve**

Error



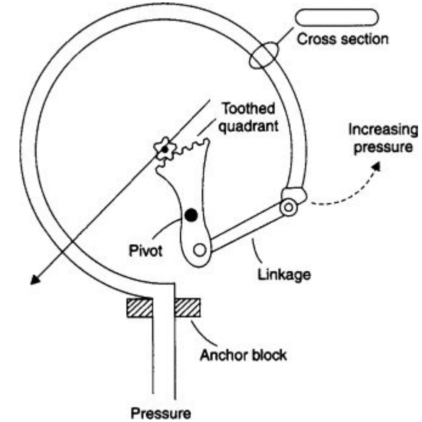
Porous disk

Liquid Filled vs Dry Gauge

The vibration is one of the gauge failure cause. The mechanical parts like mechanical linkage pinios, pivots could be damaged by vibration and lead to inconsistent performance.

Liquid-filled gauge:

- Dampens dial vibration and makes reading easier
- Dampens dial vibration and reduce mechanical failure
- Prevent of condensation and icing inside the gauge
- Glycerin is used for room temperature applications
- Silicon oil for high temperature applications
- Longer life than dry gauges



High Temperature

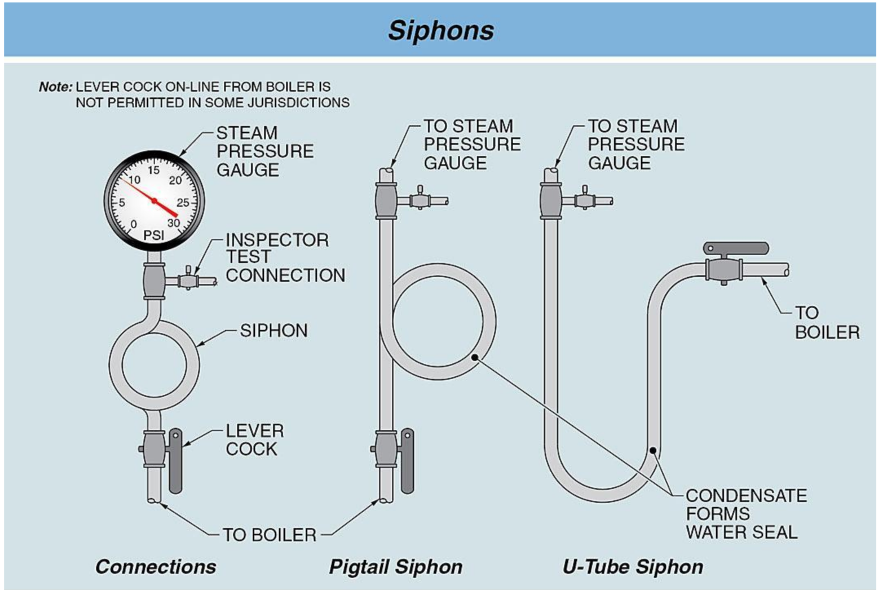
The temperature tolerance for sensing elements and electronic unit of the sensors are limited and they should not be exposed to a high temperature.

some process with high temperature example are boilers or hot steam pipes.

A siphon forms a water seal, or trap, preventing high-temperature steam from entering a pressure gauge.

A valve (Lever cock) in front figure helps to disconnect the sensor and siphon from the process for maintenance and services.

Test port with a valve is to help for live pressure inspection or extra measurement.



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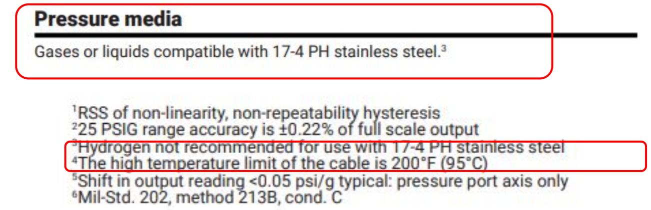
Corrosive Materials

Setra_Model_206_Data_Sheet.pdf


Pressure media

Gases or liquids compatible with 17-4 PH stainless steel.[3]

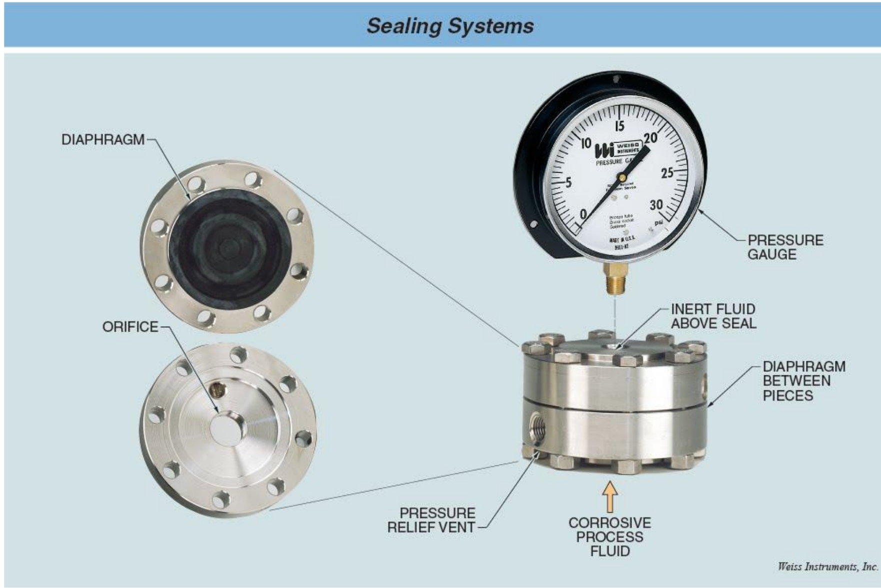
[1]RSS of non-linearity, non-repeatability hysteresis
[2]25 PSIG range accuracy is ±0.22% of full scale output
[3]Hydrogen not recommended for use with 17-4 PH stainless steel
[4]The high temperature limit of the cable is 200°F (95°C)
[5]Shift in output reading <0.05 psi/g typical: pressure port axis only
[6]Mil-Std. 202, method 213B, cond. C

Some chemical materials are corrosive and they will damage the sensor element overtime.

Either the material types which can be in contact with sensor elements are usually mentioned in sensor data sheets or the sensor material types are mentioned in data sheet and it is left to client to determine if the sensor is good for the the application or not.

The other method is to avoid the damage of the corrosive material is to prevent the direct connection between the corrosive material and the sensing element such as diaphragm. To do so, a sealing as front figure can be used.

Between *external diaphragm and sensing element is filled with a pressure transmitting liquid such silicon oil.*

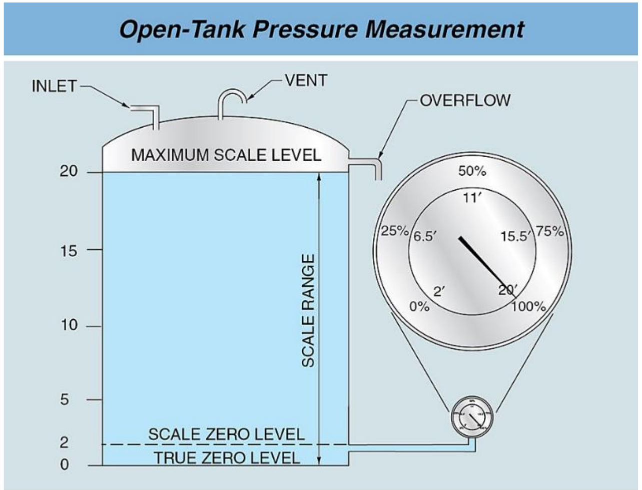


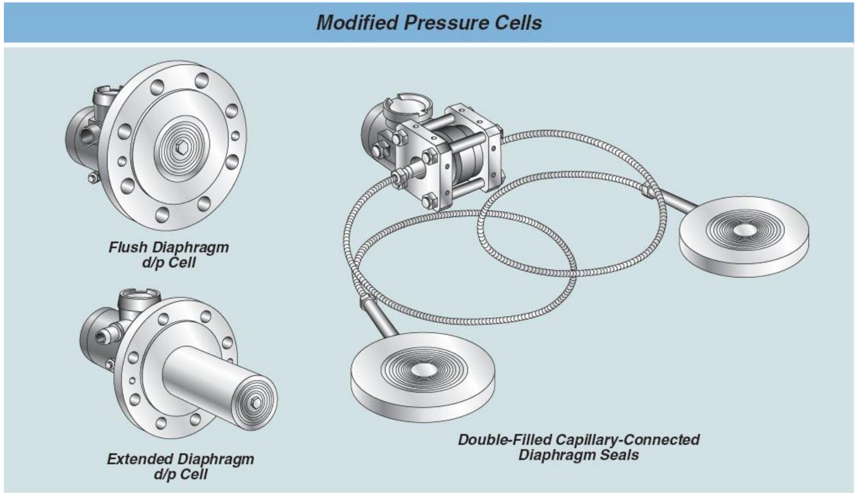
Blockage and Corrosive Material

Usually, the entry point of the pressure sensing element and the pressure inlet port are small. When dealing with fluids that contain solid particles, these particles have the potential to deposit and accumulate on the sensor's inlet port, obstructing the entry. Alternatively, they can deposit on the sensing membrane, which can interfere with the accuracy and sensitivity of the measurement.

To prevent the deposition of solid materials on the sensor's inlet and separate it from the fluid, a diaphragm seal can be employed. This seal acts as a protective barrier. Inside the seal, a pressure transmitting oil, such as silicon oil, is used to facilitate the transmission of pressure.

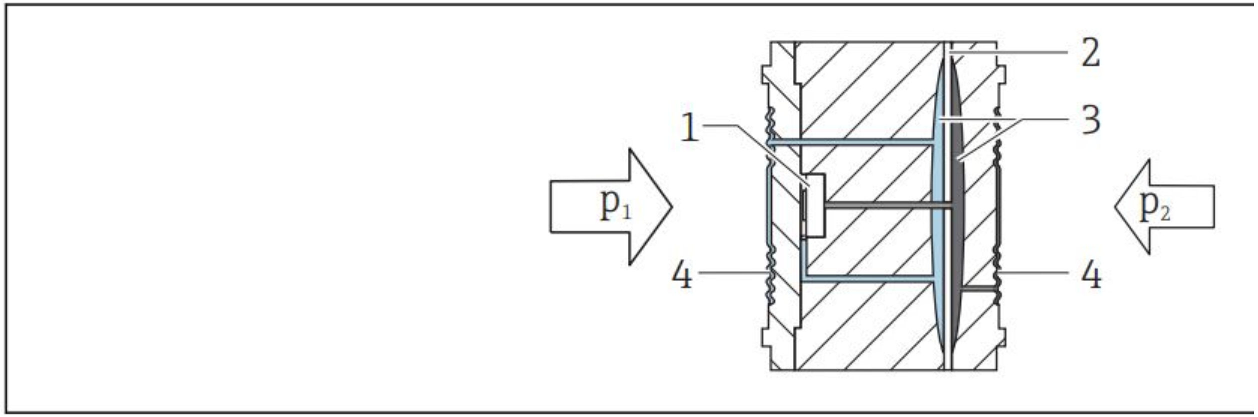
An example where this is commonly observed is in pressure sensors used to measure the level of tanks. By employing a diaphragm seal, the sensor remains isolated from the fluid, ensuring that solid particles do not hinder the sensor's performance.





Deltabar M PMD55 (ondemand.com)

Metallic process isolating diaphragm



1 *Sensing element*
2 *Overload diaphragm/Middle diaphragm*
3 *Filling oil*
4 *Process isolating diaphragm*

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End of Slides