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1.2 Pressure

In the following, we will consider the different physical characteristics necessary to understand pressure sensors: Pressure as a Physical Quantity, Various Sensor Models with Absolute, Relative or Differential Pressure Sensors. We will take a detailed look at the physical properties of fluids.

1.2.1 Pressure as a Physical Quantity

A liquid or gas body locked within a container, which it entirely fills, exerts on all its walls a force known as PRESSURE which depends on:

- ➔ the nature of the fluid,
- ➔ the nature of the volume it occupies before and after filling, i.e. the conditions of transfer,
- ➔ finally, the temperature.

1.2.1.1 Definitions

Pressure due to external forces: Static Pressure

From the phenomenological point of view pressure, p, as a macroscopic parameter, is defined starting with force $d\vec{F}$, exerted perpendicularly on an element of surface $d\vec{A}$ of the wall, by the fluid contained in the container. p, $d\vec{F}$ and $d\vec{A}$ are bound by the relationship (1.1) from [1]:

$$d\vec{F} = p.d\vec{A} \tag{1.1}$$

then $$p = dF / dA \tag{1.2}$$

with p : pressure

$d\vec{F}$: force exerted perpendicularlyto $d\vec{A}$

$d\vec{A}$: an element of surface of the wall

The element of force $d\vec{F}$ caused by pressure p is perpendicular to the element of surface $d\vec{A}$. This quotient is independent of the orientation of the elementary surface $d\vec{A}$ and depends only on its position in the fluid.

On earth, fluids are subjected to the force of gravity which is why, in the case of a liquid column for example, contained in an open tube, placed vertically, the pressure at point M, at a distance h from the free surface, is equal to atmospheric pressure p_0 increased by the weight of the column pressing on the unit of area, i.e. (equation (1.3) from [1]):

$$p = p_0 + \rho g h \tag{1.3}$$

p : pressure at a point M

p_0 : atmospheric pressure

ρ : density

g : acceleration of gravity at the place of measurement

h : distance from free surface.

Dynamic Pressure

In the same way, for a fluid subjected to an unspecified acceleration, it is necessary to take into account the influence of the force of inertia on the pressure (see chapter 1.2.3.3 Measured Fluid).

1.2.1.2 Units

	pascal (Pa)	bar (bar)	atmosphere (Atm)	Comments
1 pascal	1	10^{-5}	$9,869\ 10^{-6}$	Standard International Unit
1 bar	10^{5}	1	$9,869\ 10^{-1}$	Bar is used for very small values of Pa , often used in aeronautics and meteorology.
1 kgf/cm^2	$9,8039\ 10^{4}$	$9,803\ 10^{-1}$	$9,86\ 10^{-1}$	Old Unit
1 atmosphere	$1,013\ 25\ 10^{5}$	1,0133	1	Normal Atmospheric Pressure
1 cm of water	98,04	$9,80\ 10^{-4}$	$9,68\ 10^{-4}$	
1 mm of Hg	$1,33\ 10^{2}$	$1,333\ 10^{-3}$	$1,316\ 10^{-3}$	For a Hg density of 13,59593 kg/ dm^3. In the field of vacuums one indicates 1 mmHg with a specific unit Torr
1 inch Hg	$3,386\ 10^{3}$	$3,386\ 10^{-2}$	$3,342\ 10^{-2}$	
1 psi	$6,890\ 10^{3}$	$6,89\ 10^{-2}$	$6,89\ 10^{-2}$	Pound per Square Inch, Used in Anglo-Saxon countries

Table 1.1: Units of pressure

1.2.2 Various Sensors Types

1.2.2.1 Absolute Pressure Sensors

An absolute pressure sensor measures static, dynamic or total pressure with reference to a vacuum (see Figure 1.1).

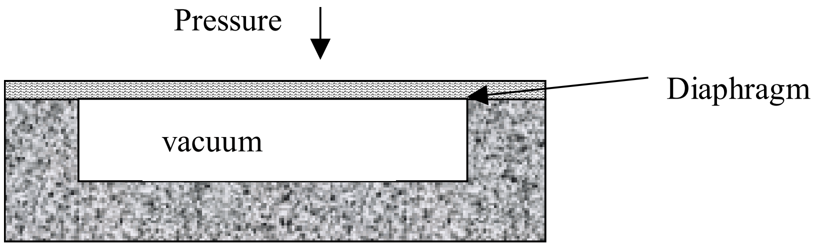

Figure 1.1: Absolute Pressure Sensor

1.2.2.2 Relative Pressure Sensors

A relative pressure sensor measures static, dynamic or total pressure with reference to ambient atmospheric pressure (see Figure 1.2).

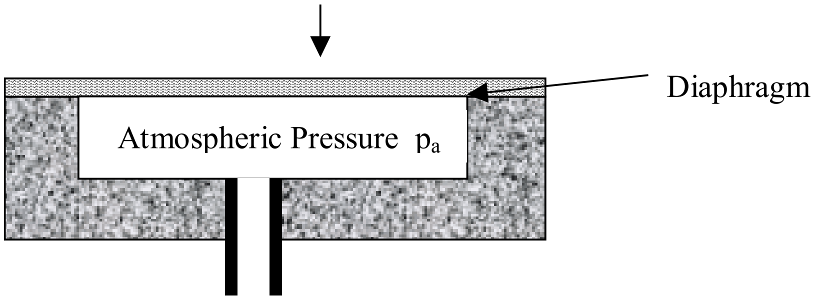

Figure 1.2: Relative Pressure Sensor

Note: Refers to Sealed Relative Pressure Sensors

A sealed relative pressure sensor measures static, dynamic or total pressure with reference to ambient atmospheric pressure, sealed at the time of sensor manufacture (see Figure 1.3).

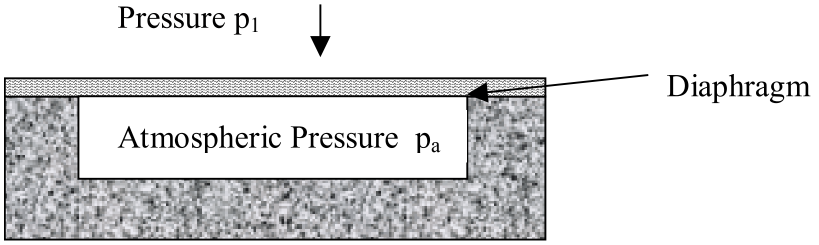

Figure 1.3: Sealed Relative Pressure Sensor

1.2.2.3 Differential Pressure Sensors

A differential pressure sensor measures a static, dynamic or total pressure with reference to an unspecified variable pressure (see Figure 1.4).

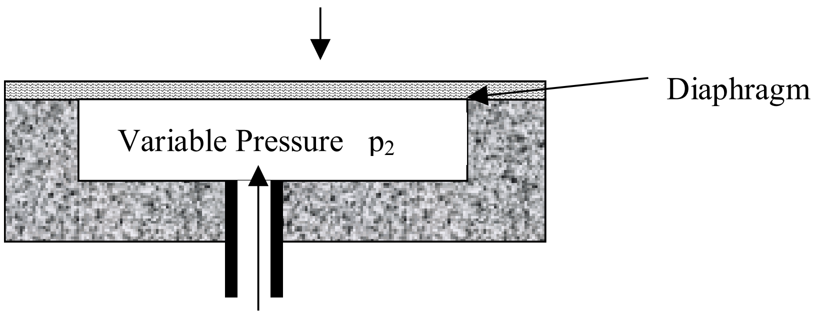

Figure 1.4: Differential Pressure Sensor

1.2.3 Fluid Physical Properties

There are two possible cases:

- ➔ a motionless fluid
- ➔ a moving fluid.

1.2.3.1 Pressure in Static Fluids

In static fluids, the pressure force F being exerted on the surface originates only from the random kinetic energy of molecules.

1.2.3.2 Pressure in Moving Fluids

In dynamic fluids force F originates from the random AND directed kinetic energy of the molecules.
Table 1.2 below explains the various pressures to consider in the case of a moving fluid.

Pressures in a moving fluid			
3 types of pressure are prevalent:			
Static pressure	of the fluid **at rest**.	$\mathbf{p_s}$	measurement identical to the preceding case,
Dynamic pressure	impact pressure, resulting from speed of moving fluid. This pressure must be detected in the direction of the fluid flow.	**pd**	For incompressible fluids: $p_d = \rho v^2/2$ ρ = density v = moving fluid velocity
Total pressure		**pt**	$\mathbf{p_t = p_s + p_d}$

Table 1.2: The various pressures exerted on a moving fluid.

We need to distinguish between two cases according to the nature of the measured fluid.

1.2.3.3 Measured Fluid

The measured fluid is the fluid which comes into contact with the sensing element. We generally distinguish between two main fluid families:

- ➔ gases
- ➔ liquids.

Case of liquids

A moving fluid creates another type of pressure, **Dynamic Pressure p_d**: see equation (1.4) from [1]

$$p_d = \frac{1}{2}\rho v^2 \tag{1.4}$$

p_d : dynamic pressure

ρ : density

v : moving fluid velocity

The total pressure is the sum of the static pressure, the pressure due to the external forces and the dynamic pressure.

This has the same value in all points for a fluid moving horizontally (incompressible, negligible viscosity, like liquids), following the theorem of Bernoulli. See equation (1.5) and (1.6) from [1]:

$$p_t = p_s + \frac{1}{2}\rho v^2 \tag{1.5}$$

$$p_t = p_s + p_d \tag{1.6}$$

with:

p_t : total pressure

p_s: : static pressure

p_d: : dynamic pressure

v: : local velocity

ρ : density.

Case of gas

The pressure of a gas in a tank is the force exerted by gas on the walls of the tank, by unit of area. When a tank contains a mixture of gas, we can define a partial pressure for each of them. The sum of the partial pressures is equal to the total pressure. The partial pressures are thus proportional to the concentrations of each gas in the mixture.

In the molecular mode each gas behaves as if it was alone. Pressure (p) of a gas is proportional to the number of molecules (n) contained in the unit of volume (V) at the absolute temperature (T). This leads to the **equation of a perfect gas** (1.7) from [1]:

$$pV = nk_B T \tag{1.7}$$

p : pressure
n : number of molecules
T : temperature
V : volume
k_B : Boltzmann constant.

The average translational energy of a gas molecule $\overline{E_C}$ is given by the equation (1.8) from [1]

$$\frac{3}{2}k_B T = \overline{E_C} \tag{1.8}$$

T : temperature
k_B : Boltzmann constant
$\overline{E_C}$: average translational energy of one gas molecule.

This leads to the equation (1.9):

$$pV = \frac{2}{3}n\overline{E_C} \tag{1.9}$$

p : pressure
n : number of molecules
V : volume
$\overline{E_C}$: translational energy of one gas molecule.

According to the kinetic theory, the molecules of a gas are driven in a continual and random manner and bump into each other.
The trajectory of a molecule between two shocks is a right-hand side segment traversed at constant speed and the direction of a segment after a shock has no correlation with the direction

of the segment before the shock. The trajectory of a molecule is thus a broken line, the average value λ of the length of its segments being the **free mean course.**
When the gas is contained in an enclosure, the molecules also have collisions with the walls and the pressure that they exert on them results from the average effect of these collisions.

A **vacuum** is often characterized by the **Knudsen number (1.10)** from [1]:

$$\mathbf{K} = \lambda / \boldsymbol{l} \qquad (1.10)$$

K : Knudsen number

λ : mean free course

l : enclosure dimension,

which compares the mean free course λ with the average dimension l of the enclosure.

For compressible fluids, in the subsonic domain, the relationship between the three different pressures

- static pressure (p_S),
- dynamic pressure (p_d), and
- total pressure (p_t)

is given by the equation (1.11) from [2]:

$$p_t = p_s\left[1 + \left(\frac{\gamma - 1}{2}\right) M_N^2\right]^{\frac{\gamma}{\gamma - 1}} \qquad (1.11)$$

p_t : total pressure

p_s : static pressure

γ : Cp / Cv, specific heat ratio of the considered fluid

M_N : Mach number

Giving the equation (1.12) from [2]:

$$\mathbf{M_N = v/c} \qquad (1.12)$$

v : fluid velocity

c : local velocity of noise at the time of measurement.

For compressible fluids, in the subsonic domain, the relationship between p_t and p_S is given by the following ***Rayleigh-Pitot*** equation (1.13) from [2]:

$$p_t = p_s \left\{ \frac{\left[M_N^2 \left(\frac{\gamma+1}{2} \right) \right]^2}{\left[\frac{2\gamma M_N^2}{\gamma+1} - \frac{\gamma-1}{\gamma+1} \right]} \right\}^{\frac{1}{\gamma-1}} \qquad (1.13)$$

p_t : total pressure

p_s : static pressure

γ : Cp / Cv, ratio of the specific heats of the considered fluid

M_N : Mach number

1.2.3.4 Sensor Pneumatic Connection influence

When measuring pressure with very slow changes in stationary fluids, there are no problems except that the connection must be leak-proof and free of contaminating material. When the fluid is moving (even when its pressure stays constant) and/or the pressure is changing relatively fast, the dynamic response of the tube connection in the sensor can significantly influence the pressure seen by the sensor in amplitude and phase.

For the measurement of a **liquid pressure**, [3] there is a **first order system** that brings in a delay with a time-constant τ depending on:

- ➔ the fluid viscosity,
- ➔ the connection tube length,
- ➔ the sensor volume variation per pressure change unit,
- ➔ the connection tube diameter.

For the measurement of a **gas pressure**, if the tube volume is comparable with the sensor volume, the tube behaves like a **second order system** with a natural frequency ω_N and an absorption constant ξ determined precisely as a function of:

- ➔ specific heat ratio,
- ➔ average pressure,
- ➔ fluid density,
- ➔ tube length,
- ➔ tube volume,
- ➔ sensor volume (pneumatic cavity),
- ➔ tube internal diameter,
- ➔ fluid viscosity.