Chapter 1

# Pressure Sensors

## 1.1. Introduction

Together with temperature, pressure is one of the most important physical quantities in our environment. Pressure is a significant parameter in such varied disciplines as thermodynamics, aerodynamics, acoustics, fluid mechanics, soil mechanics and biophysics. As an example of important industrial applications of pressure measurement we may consider power engineering. Hydroelectric, thermal, nuclear, wind and other plants generating mechanical, thermal or electrical energy require the constant monitoring and control of pressures: overpressure could cause the deterioration of enclosures or drains and cause very significant damage.

As a significant parameter, pressure enters into the control and operation of manufacturing units that are automated or operated by human operators. Pressure measurement is also used in robotics, either directly in controls or indirectly as a substitute for touch (artificial skin for example), for pattern recognition or for determining strength of grip. All these activities require instrument chains in which the first element is the pressure sensor, delivering data relating to the pressure of compressed air, gas, vapor, oil or other fluids, determining the correct operation of machines or systems.

The variety of mentioned applications demands a great diversity of sensors. This diversity also derives from the fact that pressure covers a very wide range from ultra-high vacuums to ultra-high pressures. It can be expressed as an absolute value (compared to vacuum) or as a relative value (compared to atmospheric pressure); it

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can also represent a difference between two pressures or relate to various media and fluids whose physical characteristics (e.g. temperature) or chemical characteristics (e.g. risk of corrosion) are very varied. Pressure units are summarized in Table 1.1.

## 1.2. Pressure

In what follows, we will consider the different physical characteristics necessary to understand pressure sensors: pressure as a physical quantity, and various sensor models with absolute, relative or differential pressure sensors. We will take a brief look at the physical properties of fluids.

### 1.2.1. *Pressure as a physical quantity*

#### 1.2.1.1. *Static pressure*

From a phenomenological point of view, pressure, p, as a macroscopic parameter is defined starting with element of force $d\vec{F}$, exerted perpendicularly on an element of surface $d\vec{A}$ of the wall, by the fluid contained in the container:

$$p = dF / dA \tag{1.1}$$

The element of force $d\vec{F}$ caused by pressure p is perpendicular to the element of surface $d\vec{A}$.

For pressure p inside the fluid with free surface we may write:

$$p = p_0 + \rho gh \tag{1.2}$$

$p_0$: atmospheric pressure

$\rho gh$: hydrostatic pressure

$\rho$: density

g: acceleration of gravity at the place of measurement

h: distance from the free surface

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 | $9.869\ 10^{-1}$ | 1 Bar is standard atmospheric pressure |
| 1 $kg/cm^2$ | $9.8039\ 10^{4}$ | $9.803\ 10^{-1}$ | $9.86\ 10^{-1}$ | 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 an Hg density of 13.59593 kg/ $dm^3$. 1 mmHg is also called 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 |

**Table 1.1.** *Units of pressure*

### 1.2.2. *Absolute, relative and differential sensors*

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

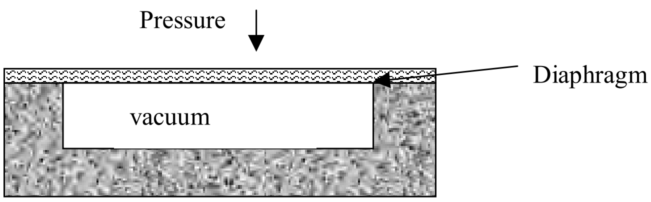


**Figure 1.1.** *Absolute pressure sensor*

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

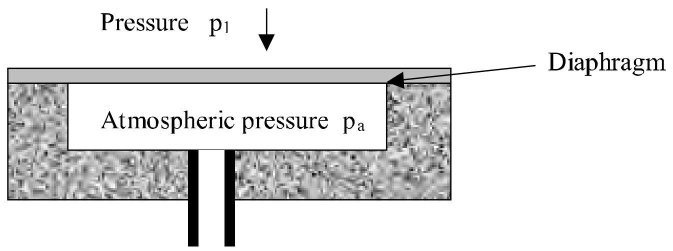


**Figure 1.2.** *Relative pressure sensor*

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

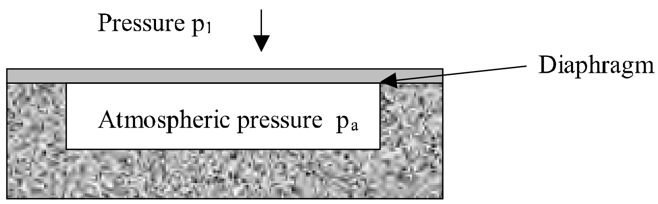


**Figure 1.3.** *Sealed Relative pressure sensor*

A differential pressure sensor measures a static, dynamic or total pressure with reference to an unspecified variable pressure $p_2$ (Figure 1.4).

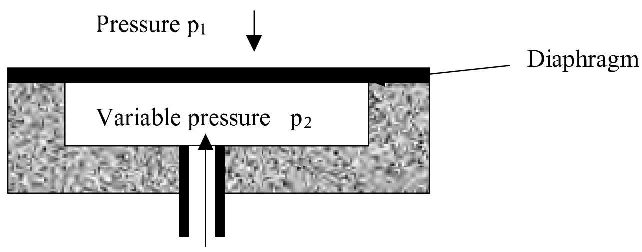


**Figure 1.4.** *Differential pressure sensor*

### 1.2.3. *Fluid physical properties*

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

We generally distinguish between two main fluid families: gases and liquids.

#### 1.2.3.1. *Liquids*

The total pressure is the sum of the static pressure, the pressure due to 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 Bernoulli's theorem:

$$p_t = p_s + p_d = p_s + \frac{1}{2}\rho v^2 \qquad (1.3)$$

with:

$p_t$: total pressure

$p_s$: static pressure

$p_d$: dynamic pressure

v: local velocity

ρ: density

#### 1.2.3.2. *Gases*

The pressure of a gas in a tank is the force exerted by gas on the walls of the tank per unit of area. When a tank contains a mixture of gases, we can define a partial pressure for each of them. The sum of the partial pressures is equal to the total pressure. The equation of an ideal gas is:

$$pV = nk_BT \qquad (1.4)$$

p: pressure

n: number of molecules

T: temperature

V: volume

$k_B$: Boltzmann constant

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 therefore a broken line, the average value l 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:*

$$K = \lambda / l \qquad (1.5)$$

K: Knudsen number

λ: mean free course

*l*: enclosure dimension

1.2.3.3. *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.

## 1.3. Pressure ranges

### 1.3.1. *Vacuum and ultra-vacuum*

The term vacuum gauges refers to sensors for the measurement of gas pressure much lower than normal atmospheric pressure. The interesting parameter is the average number of molecules contained pre unit of volume. Traditionally, four pressure ranges are used in setting up the scale of a vacuum (Table 1.2).

| | **Primary vacuum (or rough)** | **Intermediate vacuum (or medium)** | **High vacuum (or advanced)** | **Ultra-vacuum** |
|---|---|---|---|---|
| Approximate range of pressure | $10^5$ to $10^2$ Pa | $10^2$ to $10^{-1}$ Pa | $10^{-1}$ to $10^{-5}$ Pa | $< 10^{-5}$Pa |
| | $10^3$ to 1 mbar | 1 to $10^{-3}$ mbar | $10^{-3}$ to $10^{-7}$ mbar | $< 10^{-7}$ mbar |
| Number of molecules per $cm^3$ | $10^{19}$ to $10^{16}$ | $10^{16}$ to $10^{13}$ | $10^{13}$ to $10^9$ | $< 10^9$ |
| Free mean course | $10^{-6}$ to $10^{-3}$cm | $10^{-3}$ to 1 cm | 1 to $10^4$ cm | $> 10^4$ cm |
| Mode of flow | rolling (or viscous) | intermediate | molecular | – |

**Table 1.2.** *Various vacuum fields*

*Various vacuum gauges*

The main principle of primary vacuum measurement derives from a heating effect. For high vacuum cases, the principle uses the property of ionization. Vacuum gauges fit into three principal groups according to their physical effect (Table 1.3):

– mechanical effect gauges: the sensing element becomes deformed under the influence of pressure;

– heating effect gauges: the sensing element is a heated element whose temperature depends on the surrounding pressure;

– gauges using an electrical characteristic of a gas: measurement relates directly to the gas. The molecules are counted by counting the number of ions they provide for an electrical current.

| Type of conversion | Physical principle | Applications |
|---|---|---|
| Mechanical | Bourdon tube gauge | Very low cost, low accuracy.<br><br>Recommended for static installations. |
| | Active diaphragm gauge | Low cost, low accuracy, fast, durable.<br><br>Recommended for rough vacuum. |
| | Piezoresistive diaphragm gauge | Industrial vacuum measurements especially for vacuum safety systems. |
| Electrical<br>(see section 1.4.3.1) | Ionization | Recommended for vacuum measurements up to $10^{-8}$ Pa in relatively protected environments like clean rooms or laboratories. Relatively bulky. |
| Thermal<br>(see section 1.4.3.2) | Pirani gauge | Particularly sensitive gauges recommended for very deep vacuum measurements in relatively protected environments. Fragile. |
| | Thermocouple gauge | Low precision, small size. |

**Table 1.3.** *Different conversion types used for vacuum measurement*

### 1.3.2. *Middle range pressure*

Average pressures usually lie in the range $10^2$ Pa to $10^8$ Pa. This pressure range occurs in the majority of industrial applications. All these principles first transfer pressure into mechanical deformation and/or stress that is then measured (see section 1.4). Table 1.4 shows the different types of conversion into electric signals used in mid-range pressures.

| Type of conversion | Physical principle | Applications |
|---|---|---|
| Resistance variation (see section 1.4.2.1) | Piezoresistive diffused (strain) gauge | Low cost, compact. Many general applications like altimetry, barometry, process monitoring, safety, etc. |
| | Gauge with taut wire | Laboratory instrumentation. |
| | Gauge with manganin wire | Extrusion presses. |
| | Potentiometer for low pressure | Limited lifespan and hysteresis. It is used especially for low pressure measurements (a few bars) in static barometry. |
| | Extensometric foil strain gauge | Many specific applications which require limited quantities of sensors. |
| | Gauges with deposited film | Rugged sensors used in harsh environments such as aerospace, transport, energy (liquid gases). |
| Capacitance variation (see section 1.4.2.2) | Standard capacitive pressure sensor | Very wide range sensors.<br><br>Pressure measurements in a harsh mechanical or thermal environment. |
| Inductance variation (see section 1.4.2.3) | Capacitive film sensors<br>Sensor with Electret effect | In-wall pressure measurements in a harsh mechanical or thermal environment.<br><br>Analysis of very fast pressure variations. |
| | Inductance and mutual inductance | Sensitive to vibrations. |
| Electromechanical oscillator (see section 1.4.2.5) | Oscillator with quartz | Excellent stability but requires numerical corrections; onboard anemobarometry on aircraft: digital avionics. |
| | Oscillator with vibrating tube or blade | Secondary or transfer standards, anemobarometry onboard aircraft. |
| Optical (see section 1.4.2.6) | Photo electricity | Laboratory measurements. |
| | Optical fiber | Remote measurement in harsh environments, e.g.: oil industry, energy industry, refineries, engines, etc. |
| Servo controlled sensors (see section 1.4.2.7) | Balance of force | Precision laboratory measurements.<br><br>Anemobarometric measurements.<br><br>Precision measurements of static pressures. |

**Table 1.4.** *Different types of conversion used for mid-range pressures*

### 1.3.3. *High pressure*

The field of high and very high pressures relates to the pressures beyond $10^8$ Pa. The measured fluids are almost exclusively liquids. When making these measurements, the physical principles of conversion into electric signals are the same as those used for measurements of average pressures, but the sensing element and the packaging of these sensors are very specific.

Table 1.5 explains the different types of conversion which are used for the measurement of high pressure.

| **Type of conversion** | **Physical principle** | **Applications** |
|---|---|---|
| Piezoelectric effect (see section 1.4.2.4) | Piezoelectricity | Measurements of high pressures in instrumentation on test benches or production machine tools.<br>For dynamic measurements (response time close to the millisecond).<br>Measured pressure in injection molds. |
| Electromechanical oscillator (see section 1.4.2.5) | Surface waves | High absolute precision and excellent stability but require numerical corrections, hence their use in systems including microprocessors. |

**Table 1.5.** *Types of conversion for high pressure measurement*

## 1.4. Main physical principles

Initially it must be noted that it is not easy to measure pressure directly from its action on the properties of a particular material. The sensitivity obtained in this case is extremely low and the performance poor. The only advantage is the very low cost. Therefore, the great majority of pressure sensors are “composite sensors” (Figure 1.5).

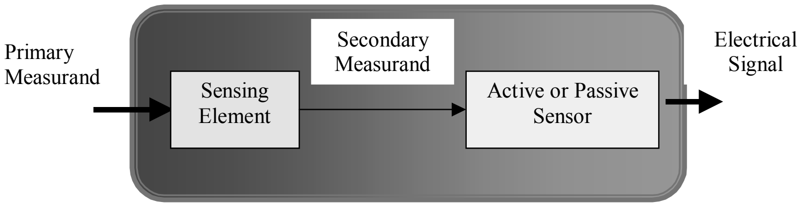


**Figure 1.5.** *Principle of a composite sensor*

The sensing element is the device which ensures initial translation of the pressure (primary measurand) into another non-electric physical quantity, the secondary measurand. The latter is translated by another sensor into an electric signal.

### 1.4.1. *The sensing device*

In the case of pressure p, the sensing element is designed to generally provide:

– a deformation and then a displacement;

– a force;

– a strain.

Typically, the most widely used sensing element is the welded diaphragm with effective section S which can be planar, corrugated, cylindrical or a more complex geometric form according to the pressure range or the fluid under consideration (see Table 1.6).

| | |
|---|---|
| o | Embedded diaphragm |
| o | Piston with spring |
| o | Corrugated diaphragm |
| o | Open manometric cell |
| o | Closed manometric cell |
| o | Biconical cell |
| o | Bellows |
| o | Bourdon tube |
| o | Helical twisted tube |
| o | One-eyed tube |

**Table 1.6.** *Examples of sensing elements*

The difficulty with pressure sensors lies primarily in choosing the best compromise between:

– Price.

– Performance.

– Production technology.

– Used materials.

Microelectronic technology adapted to micro systems allows bold, highly integrated and very economic designs. In addition, the progress made in the quality of materials, and the increasing power of data processing, allows the simplification of the geometry of the sensing element. Thus, most pressure sensors today use cylindrical or planar sensing elements (diaphragm).

The materials most often used for the production of sensing elements include the following:

| | |
|---|---|
| o | Stainless steel 17-4 pH |
| o | Stainless steel 316 |
| o | Hastelloy |
| o | Monel |
| o | Inconel |
| o | Titanium |
| o | Ni Span C |
| o | Quartz |
| o | Silicon |
| o | Sapphire |

**Table 1.7.** *Examples of constructional materials for sensing elements*

The different geometries of sensing elements are summarized in Figure 1.6.

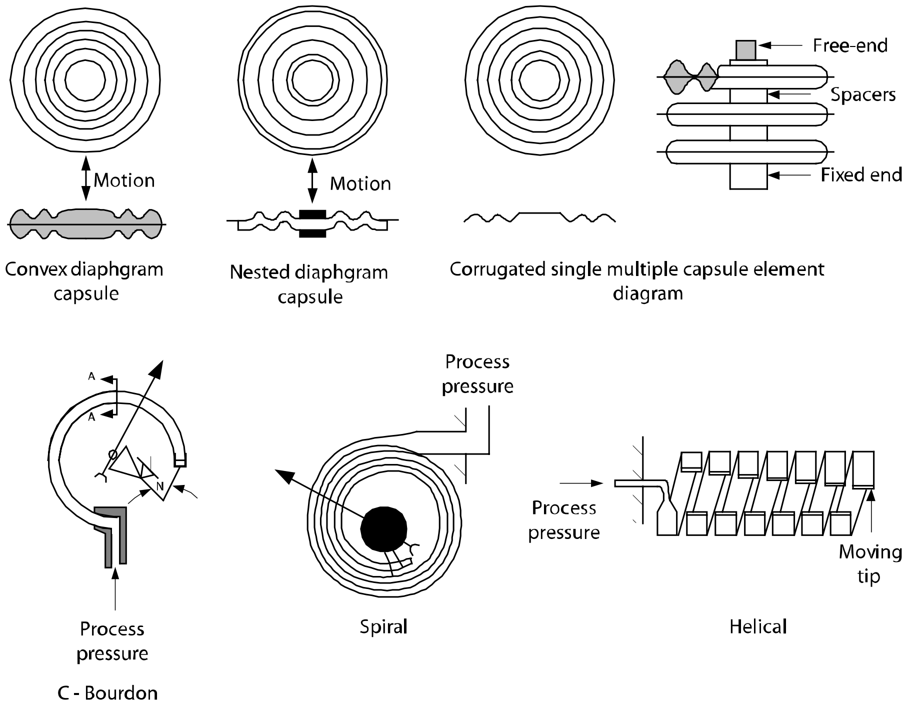


**Figure 1.6.** *Different sensing element geometry [1]*

### 1.4.2. *Sensors with elastic element*

1.4.2.1. *Conversion by resistance variation*

1.4.2.1.1. Potentiometer

The wiper of a potentiometer is connected to a diaphragm, a Bourdon tube or cell so that the deformation of this sensing element causes a displacement of the wiper (Figure 1.7).

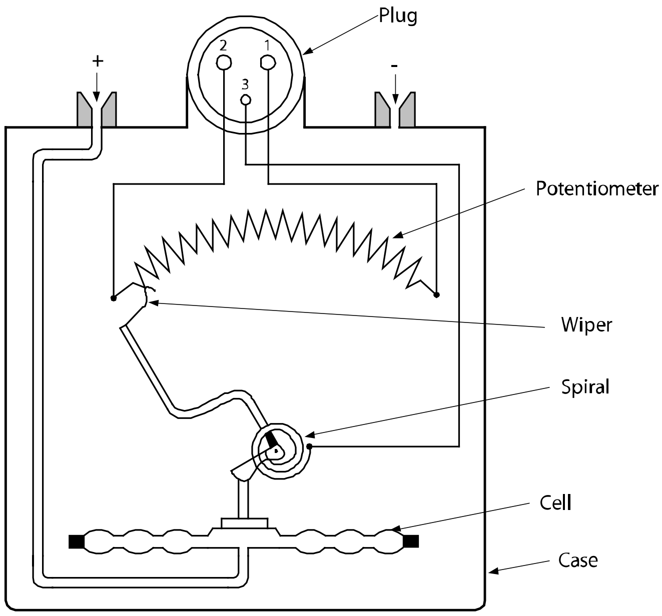


**Figure 1.7.** *Differential pressure sensor with a potentiometer [2] SFIM*

For an unloaded potentiometer with total resistance $R_n$, supplied with a source of voltage $V_s$, voltage $V_m$ between the wiper and one of its ends is:

$$V_m = V_s.R(x)/R_n \tag{1.6}$$

where

R(x): resistance between the wiper and the end of the potentiometer

$R_n$: total resistance

$V_s$: supply voltage

$V_m$: voltage between the wiper and one of its ends

If there is proportionality between:

– pressure p to be measured and deformation of the sensing element;

– deformation of the sensing element and displacement x of the wiper;

– displacement of the wiper and the resistance R(x);

then we may write:

$$V_m = k.\ V_s\ .p \tag{1.7}$$

where k is a characteristic constant of the device.

Table 1.8 indicates the advantages and disadvantages of such a principle:

| ADVANTAGES | DISADVANTAGES |
|---|---|
| – high output signal level (no need for amplifier)<br><br>– low cost<br><br>– technological robustness<br><br>– adaptable to many applications | – high hysteresis<br><br>– sensitive to vibrations<br><br>– moving contact: wear, contact resistance |

**Table 1.8.** *Advantages and disadvantages of potentiometers*

1.4.2.1.2. Metal strain gauges

Foil-type (piezoresistive) strain gauges are still very widely used. A resistive grid is created on foil glued to the sensing element. The measured pressure induces deformation, which causes change of resistance. If four such sensors are properly connected in a Wheatstone Bridge, temperature compensation and increase of sensitivity are achieved (Figure 1.8). The inner gauges measure tangential strain, while the outer gauges measure radial stress, which has opposite polarity.

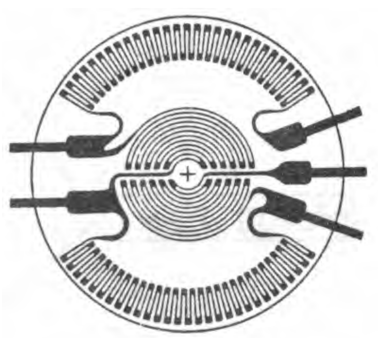

**Figure 1.8.** *Metal strain gauge for pressure sensors*