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Tech Talk: (4) Pressure Measurement Basics

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I. Introduction

Accurate and reliable pressure measurement is a requirement for the safe operation of most industrial processes. It is probably the measurement parameter most applied by the Instrument Engineer. The object of pressure measurement is to produce a dial indication, control operation or a signal, typically the standard 4–20 mA, that represents the pressure in a process.

Pressure measurement is obtained from the effects of pressure which cause position movement, change in resistance or other physical effects which are then measured. The most common pressure sensors or primary pressure elements employ a Bourdon tube, diaphragm, bellows, force balance or variable capacitance arrangement. Some other methods are also outlined later in this article.

II. Pressure Units and Terminology

Process pressure is defined as the force applied to a surface area, for example, kg/m^2. The SI unit for pressure is Pascal (Pa), but bar is more commonly used for process measurement. *Table 1* shows the relationships for the more common pressure units.

Pressure is a relative measurement defined as either gauge or absolute. Gauge pressure varies with atmospheric pressure, which in turn varies with the altitude above sea level and the weather conditions. The relationship between these definitions is shown in *Figure 1*.

Absolute pressure $\mathbf{p_a}$ is the pressure above a total vacuum, and gauge pressure $\mathbf{p_g}$ is the pressure above or below atmospheric pressure $\mathbf{p_{atm}}$ giving

$$\mathbf{p_a} = \mathbf{p_g} + \mathbf{p_{atm}} \text{ for all } \mathbf{p_g} \text{ where } \mathbf{p_g} \text{ is negative if less than } \mathbf{p_{atm}}$$

To avoid sign confusion, pressures below atmospheric pressure are referred to as $\mathbf{p_{vac}}$ giving

$$\mathbf{p_a} = \mathbf{p_{atm}} - \mathbf{p_{vac}} \text{ for } \mathbf{p_g} < \mathbf{p_{atm}}$$

We can see from *Table 1* that 1 atm = 14.696 psi = 1.01325 bar which is equivalent to 0 psig and 0 barg. We can deduce that 30 psig = 44.696 psia = 3.082 bara and 10 psia = 4.696 psi vac = –4.696 psig. It is recommended that absolute pressures are stated as 'psia' or 'bara' and gauge pressures are stated as 'psig' or 'barg' to prevent confusion.

Gauge pressure is the unit most encountered, with a good example being vehicle tyre pressures which are in gauge pressure. A gauge pressure device will indicate zero pressure when vented to atmosphere.

Absolute pressure includes the effect of atmospheric pressure with the gauge pressure. An absolute pressure indicator would indicate atmospheric pressure (not scale zero) when vented to atmosphere.

A. Static and Dynamic Pressure

Static pressure is uniform in all directions, so pressure measurements are independent of direction in a stationary (static) fluid. Flow, however, applies additional pressure on surfaces perpendicular to the flow direction, while having little impact on surfaces parallel to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called dynamic pressure. An instrument facing the flow direction measures the sum of the static and dynamic pressures; this measurement is called the total pressure. Since dynamic pressure is referenced to static pressure, it is neither gauge nor absolute; it is a differential pressure.

While static gauge pressure is of primary importance in determining net loads on pipe or vessel walls, dynamic pressure is used to measure flow rates and airspeed. Dynamic pressure can be measured by taking the differential pressure between instruments parallel and perpendicular to the flow. Pitot–static tubes, for example, perform this measurement on aircraft to determine airspeed. The presence of the measuring instrument inevitably acts to divert flow and create turbulence, so its shape is critical to accuracy and the calibration curves are often non-linear.

Dynamic pressure can be expressed as

$$pd = 0.5\,\rho V^2$$

where pd is the dynamic pressure (Pa), ρ is the density of fluid (kg/m^3) and v is the velocity (m/s).

B. Differential Pressure Measurement

Differential pressure (dp), as the term implies, is the pressure difference between two points of measurement. Typical applications include pressure drops in ventilation systems, across

Table 1. Pressure units conversion

From	To				
	psi	kg/cm²	bar	mm Hg	atm
psi	1	0.07031	0.06895	51.715	0.06805
kg/cm²	14.223	1	0.9807	735.6	0.98692
bar	14.504	1.0197	1	750.06	1.01972
mm Hg	0.01934	0.00136	0.00133	1	0.00131
atm	14.696	1.0332	1.01325	760	1

Figure 1.

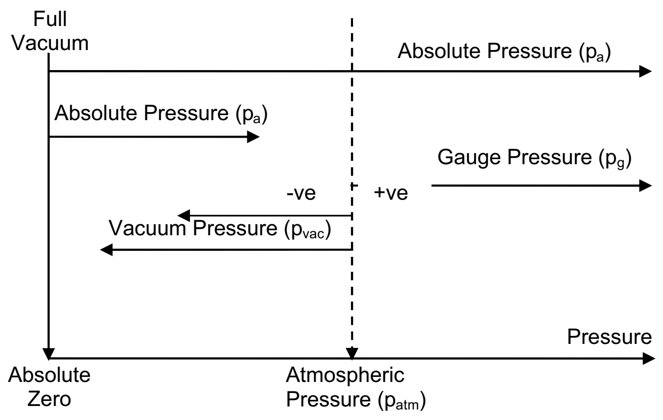


Figure 2.

primary flow elements such as an orifice plate, venturi or Pitot tube and across process equipment such as prime movers, filters and process columns.

Measurements of differential pressure are also used to find other quantities by making use of known formula, for example, liquid level and density on both vented or pressurised vessels and for gas pressure measurement on low-pressure vessels where a dp transmitter with the low-pressure side vented to atmosphere would give more accurate results than a pressure transmitter.

C. Pressure Gauges

Pressure gauges, of the dial type shown in *Figure 2*, can be used for test purposes, pneumatic signals or local process indication. The pressure-measuring element can be a Bourdon tube, diaphragm or bellows which are available in a wide variety of materials to satisfy process fluid compatibility.

Process measurement can be in the range full vacuum to 2000 barg. Pneumatic signal measurement use receiver gauges which have measuring ranges 3–15 psig or 0.2–1 barg.

Readability and location will determine the size of gauge specified. Generally, the larger the gauge diameter, the more accurate will be the reading as more graduations can be incorporated. Manufacturers' recommendations vary, but in general, the normal operating pressure of a gauge should be at around 75% of the scale presuming an adequate design/overpressure safety margin.

Pressure gauge selection criteria should include the measurement accuracy required. The following guidance is derived from B40.1 and B40.7 contained in Standard ASME B40.100. Standard BS EN 837-1:1998 also addresses this issue.

Grade 4A gauges offer the highest accuracy and are calibrated to ±0.1% of span over the entire range of the gauge. The gauges are called laboratory precision test gauges. These high-accuracy test gauges may be temperature compensated. They must be handled carefully in order to retain accuracy.

Grade 3A gauges are calibrated to an accuracy of ±0.25% of span over the entire range of the gauge. The gauges are called test gauges but are generally not temperature compensated.

Grade 2A gauges are calibrated to an accuracy of ±0.5% of span over the entire range of the gauge. These gauges are generally used for process pressure measurement. They are often referred to as process gauges and are not temperature compensated.

Grade 1A gauges are calibrated to an accuracy of ±1% of span over the entire range of the gauge. These gauges are high-quality general purpose industrial gauges.

Grade A gauges are calibrated to an accuracy of ±1% of span over the middle half of the scale and ±2% of span over the first and last quarters of the scale. These gauges are often referred to as industrial gauges.

Grade B gauges are calibrated to an accuracy of ±2% of span over the middle half of the scale and ±3% of span over the first and last quarters of the scale. These gauges are often referred to as commercial or utility gauges.

Note that wide ambient temperature excursions from that at which a non-temperature-compensated Bourdon gauge has been calibrated can lead to significant reading errors, typically ±0.4% of span for each 10°C change (rising or falling) from a reference temperature of 20°C.

If pulsation is present in the process, the maximum operating gauge pressure should not exceed 50% of the full-scale range. A safety blow out panel is normally specified for gas pressure gauges. Other considerations in gauge selection include the following:

- Gauge mounting: direct, rear or front flange;
- Orientation of pressure connection;
- Pressure connection thread type; gauges of 100 mm diameter and above would normally have 0.5″- or 15-mm thread connections for strength and stability;
- Liquid filling (typically glycerine or Fluorolube® for oxygen service) – used where vibration or severe pulsation is present and for wet environment including under water applications;
- Hermetic sealing – used where ambient conditions are corrosive, very dusty humid or wet. Ingress protection (IP) rating to be specified accordingly;
- Case material – typically, brass, stainless steel, phenolic or polycarbonate;
- Oxygen service cleaning;
- Maximum pressure red pointer;
- Maximum pressure follower pointer;
- Alarm electrical contacts;
- Pulsation dampener (snubber);
- ‘Pigtail’ – a coiled pipe used to introduce a condensate cooling barrier between the process and the instrument in steam applications;
- Flow restrictor in-line coupling – for high-pressure gas applications.

For dirty, viscous process fluids such as heavy oil or slurries, the measuring element must be protected from the fluid using diaphragm seals (*Figure 3*). The diaphragm seal may be directly mounted to the gauge or remote mounted using a filled capillary connecting tube.

Figure 3.

Figure 4.

Figure 5.

Pressure gauges are high-maintenance items requiring frequent replacement to ensure correct service. It is worth considering the more robust and expensive pressure transmitter for critical applications.

Programmable digital pressure gauges (*Figure 4*) are available, capable of measuring gauge, absolute and compound ranges. (A compound pressure gauge is scaled from full vacuum through zero pressure up to the full-scale pressure.)

These instruments allow a selection of measurement units and are available with 4–20 mA output and alarm switches.

III. Pressure Transmitters

Pressure transmitters are available with pneumatic or electronic transmission and can be specified to measure gauge compound or absolute pressures (*Figure 5*). (A compound pressure transmitter provides a linear output signal from full vacuum through zero pressure up to the full-scale pressure.) Sensing element–measuring principles include capacitive, piezoelectric and force balance methods. Measured pressures up to 2000 barg, with accuracies as low as ±0.06%, and span turn-downs of up to 10:1 are available.

Remote seals are used when the process fluid is corrosive, viscous, subject to extreme temperature, toxic, in sanitary applications or tends to collect and solidify. The seals are available to suit all standard flange fitting types. A wide range of remote seal types are available which allow optimum design for flanged, wafer, flush mounting or hygienic applications for use in the food and pharmaceutical industries (*Figure 6*).

When a compact pressure transducer is required, such as on a compressor lubricating system, a range of miniature diaphragm sealed devices is available (*Figure 7*).

Two-, three- and five-valve manifolds (valves manufactured as a composite block) are available, providing safe pressure transmitter process isolation and on-line calibration facilities. Smart communications and signal transmission capability with 4–20 mA, 4–20 mA/HART, 4–20 mA/FoxCom, FOUNDATION Fieldbus, Profibus or Low Power 1–5 V output electronic modules are available.

Certifications can be obtained to meet hazardous area requirements, for example, Flameproof or Intrinsically Safe and also Safety Integrity Level (SIL) standards.

Figure 6.

Figure 7.

Table 2. General guidance on selection

Parameter	Bourdon tube	Diaphragm	Piston	Diaphragm/ piston	Solid state
Range	3–1200 barg	Full vacuum to 10 barg	1–850 barg	Full vacuum to 70 barg	Full vacuum to 70 barg
Accuracy	±0.5%	±0.5%	±2%	±2%	±0.25%
Cycle rate	≤25 cycles/min	≤25 cycles/ min	≤50 cycles/ min	≤50 cycles/min	>50 cycles/ min
Life cycles	10^6 cycles	10^6 cycles	10^6 cycles	2.5×10^6 cycles	100×10^6 cycles

IV. Pressure Switches

A pressure switch is a device capable of detecting a pressure change, and at a predetermined level, opening or closing an electrical or pneumatic contact. Pressure switches find application in many areas ranging from engine oil pressure monitoring and electrohydraulic control through to the monitoring of process fluid pressure for alarm and switching duties. Both pressure and differential pressure switches are available.

Much of the primary element technology to be found in pressure gauges and pressure transmitters can be found in the construction of pressure switches. This includes the Bourdon tube, bellows, diaphragm and solid-state designs. To these may be added piston and diaphragm–piston-type pressure switches.

Faced with a huge choice of instrument types, the engineer may either specify the duty and leave the selection to the manufacturer or stockist or apply engineering know-how to select the best instrument for the application. Most ground rules used for the specification of pressure gauges and transmitters apply for the specification of pressure switch wetted parts materials, process connections, housing materials, IP, hazardous area and functional safety certification.

In addition to the above, the engineer must understand and specify the requirements for the following:

- Operating pressure range;
- Design pressure limits;
- Accuracy and hysteresis limits;
- Dead-band limits;
- Cycle speed, number of operations and life expectancy;
- Number of switching points;
- Fixed or adjustable switching point/s;
- Electrical load rating and configuration of switch contacts;
- Ambient temperature limits.

General guidance in selecting the type of primary element to be used is shown in *Table 2*. The data are extracted from a manufacturer's published catalogue[1] and thus may vary between manufacturers. Current catalogue data should always be checked.

V. Pressure-Sensing Technology

A. Force Collector Types

These types of pressure sensors generally use a force collector (such as a diaphragm, piston, bourdon tube or bellows) to measure strain (or deflection) due to applied force (pressure) over an area.

Bourdon tubes. Bourdon tubes are circular-shaped tubes with oval cross sections (*Figure 8*). The process pressure acts on the inside of the tube. The outward pressure on the oval cross section forces it to become more rounded.

Because of the curvature of the tube ring, the bourdon tube then bends with the resulting movement being transmitted to the gauge pointer by gearing.

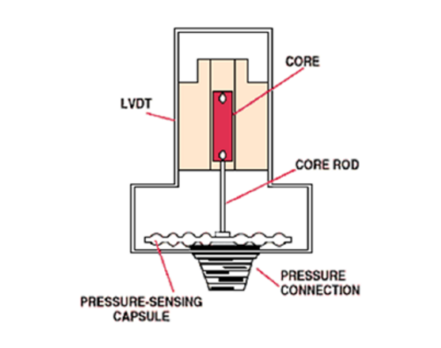
Bellows. Bellows or capsule-type elements are constructed of tubular membranes that are convoluted around the circumference (*Figure 9*). The membrane is attached at one end to the source and at the other end to an indicating device or instrument.

For differential pressure transmitters, the capsule is constructed with two diaphragms forming an outer case. The inter-space is usually filled with a process compatible fluid. Pressure is applied to both sides of the diaphragm, and it will deflect towards the lower pressure. To provide over-pressurised protection, a solid plate with matching convolutions is mounted in the centre of the capsule.

Diaphragms. A diaphragm is a circular-shaped convoluted membrane that is attached to the pressure fixture around the circumference (*Figure 10*). The pressure medium is on one side and the indication medium is on the other.

Figure 8.

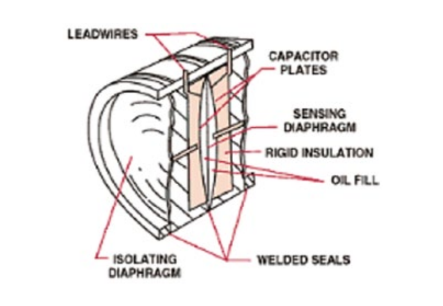
Figure 9.



Piezoresistive strain gauge transducer. The piezoresistive effect is based on bonded or formed strain gauges to detect strain due to applied pressure using various thin-film technologies. The strain gauges are connected to form a Wheatstone bridge circuit to maximise the output of the sensor and to reduce sensitivity to errors. This is the most commonly employed sensing technology for general purpose pressure measurement.

Capacitive transducer. A diaphragm and a pressure cavity are used to create a variable capacitor to detect strain due to applied pressure. Common technologies use metal, ceramic and silicon diaphragms. Generally, these

Figure 10.



technologies are mostly applied to low pressures.

Electromagnetic transducer. The displacement of a diaphragm is measured by means of changes in inductance (reluctance), linear voltage displacement transducer, Hall effect or by an eddy current principle.

Piezoelectric transducer. The piezoelectric effect in certain materials such as quartz is used to measure the strain upon the sensing mechanism due to pressure.

Potentiometric transducer. The motion of a wiper along a resistive mechanism is used to detect the strain caused by applied pressure.

B. Other Types

Resonant. The changes in resonant frequency in a sensing mechanism are used to measure the stress, or changes in gas density, caused by applied pressure. This technology may be used in conjunction with a force collector, such as those in the category above. Alternatively, resonant technology may be employed by exposing the resonating element itself to the media, whereby the resonant frequency is dependent upon the density of the media. Sensors have been made out of vibrating wire, vibrating cylinders, quartz and silicon micro-electromechanical systems (MEMS). Generally, this technology is considered to provide very stable readings over time.

Thermal. The changes in thermal conductivity of a gas due to density changes are used to measure pressure. A common example of this type is the Pirani gauge which is a robust gauge used for the measurement of the pressures in vacuum systems.

Ionisation. It measures the flow of charged gas particles (ions) which varies due to density changes to measure pressure. Common examples are the hot and cold cathode gauges.

VI. Conclusion

The instrument engineer is faced with a bewildering choice when specifying pressure-measuring instruments. It is recommended that the potential vendors are supplied with full data covering the physical properties of the process, including the normal measurement operating range and extremes, the operating environment, output signal form, hazardous area and functional safety requirements. The vendor's data sheet should always be cross-checked against the above requirements.

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