

Introduction to Pressure Measurement

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Pressure-measuring devices come in a wide variety of designs and sizes to suit almost any application. This article describes the basics of pressure measurement and provides guidance on instrument selection.

Fluid pressure is a critical operating parameter in chemical process industries (CPI) plants; in fact, it is the second most common parameter measured after temperature. Pressure measurement applications range from simple setpoint monitoring to ensure sufficiently high or low pressure levels, to continuous monitoring as part of a complex automation system. The breadth of applications that require pressure measurement explains the diversity of sensing products on the market. With new instruments being introduced every year, it's no wonder that selecting the correct measuring device often seems like a daunting task. The key to matching the correct instrumentation to an application is understanding how pressure is measured and calculated.

What is pressure?

Pressure is defined as force divided by the area over which that force is distributed, *i.e.*, $P = F/A$. As this equation suggests, larger force equals larger pressure when area remains constant.

What is more difficult to understand from this definition, though, is that the existence of pressure requires a medium. When we speak of pressure in industrial settings, we are talking about the force that a liquid or gas (*i.e.*, a fluid) exerts onto a fixed area. Since pressure is a force, it cannot be measured directly; instead, the effect that force has on an area is what is actually measured.

How pressure sensors work

Almost all pressure sensors work the same way — they measure the deflection or displacement of a diaphragm or membrane that is acted on by a force and convert the amount of deflection/displacement into an electronic signal. Sen-

sors differ in the materials used to construct the diaphragm and how the deflection is measured. Virtually all industrial sensors are based on one of two principles of deflection measurement:

- *resistive pressure measurement.* In this type of sensor, the diaphragm is in direct contact with the fluid, separating the fluid from the instrument's electronics. The diaphragm's size, thickness, and material of construction determine the sensor's pressure range and media compatibility. Diaphragm deflection causes a type of resistor called a strain gage to either compress or elongate (Figure 1a). When four strain gages are connected, they form a Wheatstone bridge (*i.e.*, an electrical circuit that measures change in electrical resistance), which converts the deflection of the gages into an electrical signal. This design is shared by metal thin-film, ceramic thick-film, and micro-electrical-mechanical system (MEMS) sensors, as well as classic bonded strain gages.

- *capacitive pressure measurement.* In a capacitive pressure sensor, two membranes are mounted in parallel, one of which is in contact with the fluid under pressure (Figure 1b). They are compressed against each other in response to a change in pressure, which causes the capacitance to change. The capacitance change is picked up by an electronic circuit and converted into a pressure equivalent signal.

A variant of resistive pressure measurement is the piezo-resistive sensor (Figure 1c). Piezo-resistive microstructures are integrated onto a semiconductor chip and encapsulated in an oil-filled chamber, and this oil transmits pressure to the sensor via an external diaphragm. Due to their high complexity, these sensors are restricted to a narrow range of applications and are mainly used in specialty sensors.

Both resistive and capacitive sensing technologies have

been in use for decades and are well established, and it can be said with certainty that they work effectively.

The sensor material that forms the diaphragm in direct contact with the fluid dictates media compatibility and can impose limitations on applicability. For example, ceramic sensors require some kind of additional sealing — unlike metallic sensors, which can be welded to achieve a hermetic seal without any additional (soft) sealing material. Sometimes the process conditions (*e.g.*, temperature) or the fluid in contact with the sensor diaphragm is so aggressive or harsh that typical sensor materials would fail. In those cases, diaphragm seals must be used. Seals separate the sensor from the harsh medium with an additional membrane (which may be constructed of a highly resistant material such as titanium, or coated with polytetrafluoroethylene [PTFE] or

gold) and transmit the pressure to the sensor membrane via an additional internal fill fluid.

Furthermore, pressure sensors do not have perfectly linear behavior and they can be affected by external factors such as temperature. Therefore, the manufacturer needs to accurately describe tolerances and variations in each product's datasheet.

Even seemingly comprehensive datasheets, though, can be confusing — or even misleading. For example, suppose the tolerance of a certain value is expressed as a percentage (*e.g.*, 0.25%). This can raise questions that are difficult to answer, such as: Is the value an individually adjusted parameter, or is it a maximum or typical value? Do most products center around this value, or only a small number (and if so, how many)? What is the worst-case value, and under what conditions?

Pay close attention to the format and structure of the datasheet, as these provide clues to how much data the manufacturer is willing to share in a transparent way, as well as how much knowledge and manufacturing-process know-how the company has. Any time you are in doubt, ask. If you don't get an answer, don't trust the data. Many sensors available today are marketed as "perfect" by manufacturers aiming to maximize market share. Therefore, it is very much a "buyer beware" environment.

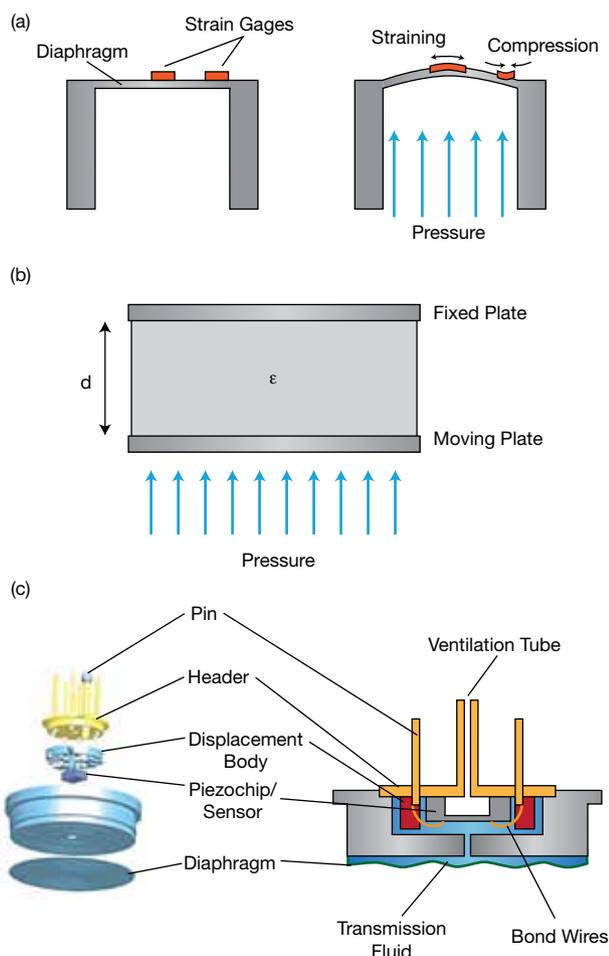
From bare sensor to working transmitter

In most modern applications, users require a complete instrument that measures pressure in a standardized way. Typical transmitters contain a process connection and an electrical output signal; both of these interfaces are standardized, but they are connected through various proprietary designs that are determined by the sensor technology and the particular application-specific function the instrument is intended for.

The term sensor is often used as a generic term for any type of sensing element, and could refer to a bare sensing element or a complex apparatus. Most manufacturers distinguish between sensors, transducers, and transmitters, each of which has its own distinct set of features:

- *sensor* — typically a bare sensing element or simple assembly. Sensors usually require a full design process to add or integrate them into a housing, and are generally not applied directly in industrial automation systems.

- *transducer* — an assembled sensor that has defined pressure ports and defined electrical outputs in addition to generic sensing functionality.



▲ **Figure 1.** Pressure sensors measure the deflection of a diaphragm or membrane that is acted on by a force and convert the amount of deflection into an electronic signal. In resistive pressure sensors (a), strain gages pick up changes in pressure by bending or compressing. In capacitive pressure measurement (b), the distance between two membranes changes with a change in fluid pressure. In piezo-resistive sensors (c), oil transmits pressure to the sensor chip via an external diaphragm.

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- **transmitter** — a fully standardized instrument that includes standardized process connections, output signals, and electrical connectors. Because of their standardization, transmitters can be interfaced directly to other equipment without fundamental engineering.

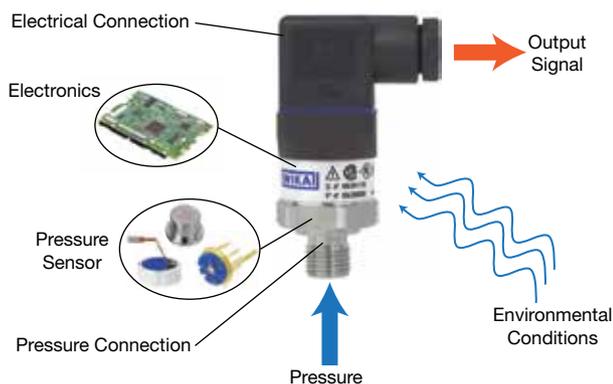
- **process (or “smart”) transmitter** — a high-end transmitter that features additional software with user-programmable functionality; human-machine interface (HMI) elements such as a display and keys; high accuracy; and a wide pressure range that is user-configurable. This type of transmitter offers many output and communication options, but typically has very few process connections and only a few pressure ranges. Standard industrial transmitters come with a fixed pressure range — users can generally choose from 20 to 50 (or even more) different, but pre-defined, ranges. Process transmitters, however, come with only five or six pressure ranges, but those can be fine-tuned by a function called turndown.

Every pressure transmitter contains a sensor; electronics that supply the sensor, amplify and condition the signal, and convert it to an output signal; a pressure connection; and an electrical connection (Figure 2).

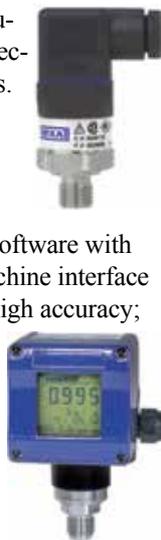
How to select the right instrument for the job

Although selecting the best pressure-sensing instrument can involve many variables, the following five basic questions can help you get started on making the most appropriate choice.

1. What is the process connection? The process connection, also referred to as the pressure connection, channels the pressurized medium to the sensor. Many different variants are available to suit a wide range of applications and industries, so it is important to select the correct



▲ **Figure 2.** A typical pressure transmitter is a fully standardized instrument that contains a pressure connection, a sensor, electronics, and an electrical connection, and outputs a standard electrical signal.



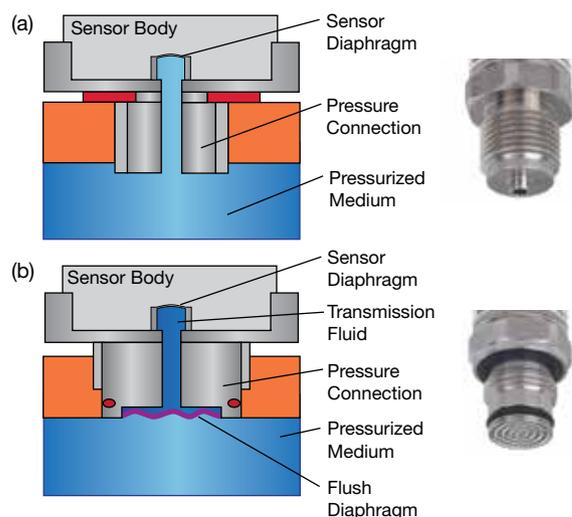
one. Some key differences to be aware of are:

- **internal vs. flush diaphragms.** The simplest connection has a passage that allows the pressurized medium to directly contact the sensor’s internal diaphragm (Figure 3a). A flush-diaphragm connection (Figure 3b) has an additional diaphragm (e.g., made of stainless steel) that is flush with the internal surface of the pipe or vessel and is in contact with the pressurized medium; an additional fluid transmits pressure to the sensor’s internal diaphragm. Internal-diaphragm connections are less expensive, easier to handle, and are commonly used with gaseous or liquid pressurized media. Flush-diaphragm connections are recommended for viscous, adhesive, abrasive, or crystalline media applications, and for applications that require residue-free pressure connection cleaning.

- **thread.** Most pressure connections have a standard thread that allows them to be screwed in at measuring points without compatibility problems. However, different threads are standard in different regions of the world. Make sure that the instrumentation’s threads match those of the applications they are intended for.

- **seal.** An important component of a thread is its seal. Some threads are self-sealing, whereas others require an additional seal. There are many seal options. Parallel threads are either sealed between the thread and the instrument’s housing (behind the thread) or in front of it using a metallic spigot. Self-sealing, or conical, threads seal the process by applied torque and may require the use of additional sealing tape.

2. What is the pressure range? Pressure ranges, typi-



▲ **Figure 3.** In an internal-diaphragm connection (a), the process fluid comes in direct contact with the sensor diaphragm through a pressure port. In a flush-diaphragm connection (b), an additional stainless steel diaphragm is in contact with the process fluid, and a transmission fluid transmits the pressure to the internal diaphragm.

cally specified in an instrument's datasheet, define the limits within which pressure can be accurately measured or monitored (Figure 4). The most important specifications are the upper and lower limits, and whether the values are in units of absolute or gage pressure.

Overpressure limits lie outside (above and below) the pressure range. Pressure excursions into the overpressure range will not cause permanent sensor damage, but readings may be compromised (less accurate) and slightly out of specification. However, any pressure above the overpressure limit — in what is known as the destructive range — will cause irreversible damage, even if it is present for only a very short period of time (*e.g.*, pressure spikes).

The potential for pressure spikes must be considered in applications where pressure is dynamic. Dynamic pressure can be caused by switching a pump on and off, connecting or disconnecting a hydraulic system, or opening and closing a fast-acting fluid valve when fluids flow with high speed.

One well-known type of pressure spike is water hammer, which occurs in a hydraulic system when a valve is quickly turned on or off. This creates a pressure wave that propagates through the entire system, which can easily overload a sensor or even cause it to burst. Pressure spikes should be avoided by the total fluid dynamics design — the design of the system should be such that pressure spikes will not occur. The magnitude of pressure spikes can be reduced by installing either restrictors in the pressure port or a pressure port manufactured using electrical discharge machining (EDM) drillings. These drillings are used to produce extremely small holes (*e.g.*, 3-mm dia.) that provide only a small orifice for the fluid to reach the sensor, which greatly reduces the force of the pressure wave.

Both cavitation and the micro-diesel effect can also cause extremely high pressure spikes. Cavitation is generally described as the formation and implosive dissolution of hollow spaces (bubbles) in liquids due to pressure varia-

tions. The resulting short-term pressure and temperature peaks can cause erosion of metallic components.

Bubbles forming in a combustible air-hydrocarbon mixture due to cavitation can explode by local spontaneous self-ignition during a pressure increase. This is known as the micro-diesel effect. If no special measures are taken, the pressure wave resulting from a micro-explosion can cause serious pressure spikes that can destroy a hydraulic system's components.

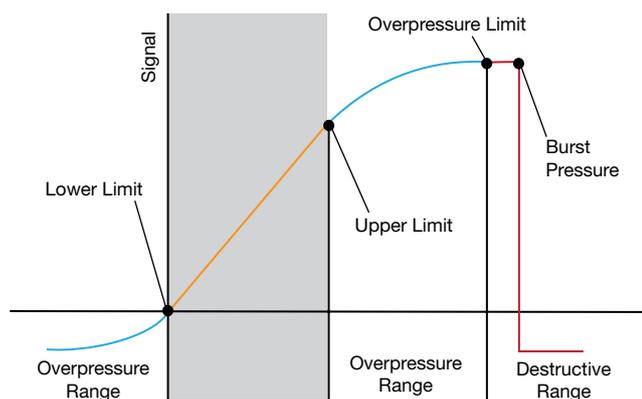
It is necessary to either prevent cavitation and micro-explosions, or ensure that the sensors are suitably protected from the impacts should any occur. Electronic pressure-measuring instruments designed specifically for critical applications have protective mechanisms built in, such as EDM drillings, restrictor elements, or specialized baffle and deflector plates within the pressure port.

3. What is the electrical output signal? Most electronic measuring instruments transmit an analog voltage or current signal to a downstream control unit. Instruments that output digital signals are also available. There are four main signal standards to select from:

- *standard analog.* The most common output signal, standard analog, can be a current or voltage signal. Current signals have lower sensitivity to electromagnetic interference than voltage signals and automatically compensate for loss of signal strength along the cable. The elevated zero point of the 4–20-mA current signal and 1–5-V voltage signal enables cable breaks and instrument faults to be detected. The 4–20-mA output signal is commonly transmitted using 2-wire technology, which enables the sensor to draw its power directly from the current loop. Voltage signals require a 3-wire connection that uses the third lead for the power supply.

- *ratiometric.* The most basic analog output signals are those that are proportional to the supply voltage, where the zero point and final value represent a constant percentage of the sensor supply voltage. For example, a 10–90 signal has a zero point that is 10% of the supply voltage and a final value that is 90%; if the supply voltage decreases by 5%, then the current analog signal also decreases by 5%. Thus, the ratio of the output signal to the supply voltage remains the same. Ratiometric sensors are often operated with a supply voltage of 5 V. The 10–90 signal is then specified in the datasheets as 0.5–4.5 V ratiometric.

- *digital output signal.* Pressure-measuring instruments that transmit digital output signals can communicate with other devices (*e.g.*, through a fieldbus system) to exchange operational data and parameters in addition to pressure readings. However, as industrial pressure transmitters do not require additional process data in order to function, these output signals have very few applications. Therefore, transmitters with a connection to CANbus or PROFIBUS-DP



▲ **Figure 4.** A sensor's pressure range (gray region) defines the lower and upper limits of pressure measurement, as well as the overpressure range.

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play a relatively minor role in industrial applications at the moment.

- *digital communication modulated on an analog output signal (i.e., HART)*. This signal is employed by virtually all high-end process (smart) transmitters. Because process transmitters typically offer only a few pressure ranges (most commonly five or six), they nearly always require a change in the pressure range (referred to as turndown). The small number of ranges and styles offered by manufacturers require the user to configure each instrument for its specific application. The standardized HART signal allows the instrument to communicate via the standard 2- or 3-wire signal connection and avoids the need for proprietary terminals, software, etc.

4. What is the electrical connector? Electronic pressure sensors have a choice of either standard plug-in connectors or output cables. The type of connector and cable have a considerable influence on the instrument's ingress protection (IP) rating (a measure of how well the device is protected against dust and moisture ingress) and its resistance to aggressive media or environmental influences like ultraviolet (UV) radiation, as well as its allowable ambient temperature range. It is necessary to consider the exact installation conditions and the operating environment to determine the best electrical connection. The most important point to keep in mind when considering a plug-type connector is that the mating plug and the entire associated cable entry form an integral part of the instrument housing's sealing system; if the connector is unplugged, the seal is broken and the instrument may be susceptible to the ingress of humidity and dirt — a very common cause of premature failure of transmitters in the field. Some studies suggest that up to 50% of all sensor failures in the field are directly related to the electrical connection.

5. Are any special properties required? A list of special requirements needs to be established. This may steer the selection toward a specific model. Factors that may necessitate specialized devices include: hazardous area classifications that require specific approvals (e.g., Ex-i [intrinsically safe] or Ex-d [explosionproof], etc.); harsh environmental conditions, such as excessive heat or cold, heavy vibration, or chemical attack; and large temperature gradients between the pressurized medium and the surroundings, which can cause the formation of ice or condensation. Most manufacturers offer products in different accuracy classes as well as special models suited for these conditions.

Pressure measurement applications

The tasks assigned to pressure monitoring instruments in industrial environments are diverse and run the gamut from operations like extraction of water from wells, power generation within fuel cells, and the operation of cranes and

elevators. Regardless of the specific task at hand, electronic pressure measurement almost always falls into one of three categories:

- monitoring critical system pressure
- controlling pressure
- indirect measurement of process values.

Critical value monitoring

In critical-value monitoring applications, the pressure-measuring instrument reports whether a critical pressure level has been exceeded or not achieved. An example of this type of application is pressure monitoring on a supply pump. When simple monitoring of a fixed value is required, pressure switches (i.e., instruments that offer a binary/digital output directly related to a fixed pressure value) are also suitable. Pressure switches can be simple mechanical devices (often with a limited lifetime and low accuracy), or they can use electronic sensor technology, such as a pressure transmitter. The use of a pressure transmitter allows continuous pressure measurement, and can be helpful in other situations, such as leak detection. System leaks cause pressure to drop, and a pressure transmitter can help to detect such situations by tracking pressure levels over time. Critical-value monitoring can also be used to measure filter clogging by measuring pressures upstream or downstream of the filter to determine whether replacement is necessary.

Pressure control

Electronic pressure-measuring instruments can be employed in two types of pressure control: constant pressure control and control of a defined pressure profile.

Constant pressure control is advisable when the pressurized medium is supplied through pumps, or when the process itself causes unwanted pressure variations. To achieve constant pressure, the instrument sends continuous pressure measurements to an electronic controller, which checks whether and to what extent the current actual pressure deviates from the setpoint pressure. This information is then sent to a pump or valve controller, which adjusts the drive power or opening of the valve. This improves efficiencies in both control of the process and in energy consumption, since the pump uses only as much energy as is demanded.

Control of a defined pressure profile is used to ensure operation corresponding to a profile of values. Some chemical or physical processes require controlled increases and decreases in pressure that are dependent on time or other process parameters to ensure safe and efficient operation.

Typical applications include high-pressure pasteurization in the food industry, controlled polymerization in reactors, and pressure control in petrochemical refineries to optimize output. All of these processes require the intentional control of the pressure profile to ensure product quality.

Indirect measurement of process values

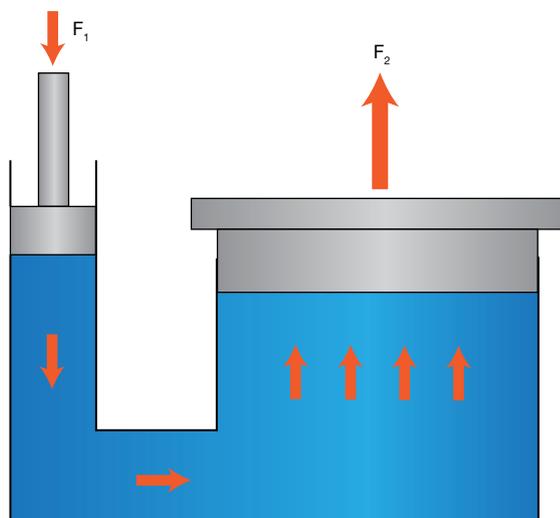
Pressure-sensing instruments are often used to indirectly determine three parameters: force, level, and temperature.

Indirect force measurement involves the use of pressure measurements to determine the amount of force generating the pressure. This is possible only when the system's geometry is known.

For example, in Figure 5, two movable pistons with different surface areas are in contact with hydraulic oil. If the smaller piston moves down, the pressure in the liquid remains constant and the larger piston is pushed up with a greater force.

A common pressure-measurement task in hydraulic systems is overload monitoring on a lifting gear. For example, when a crane lifts a load, the pressure required to generate the counteracting force in the hydraulic liquid increases. If the maximum permitted load is exceeded, the pressure will also exceed its upper limit. By measuring the pressure of the hydraulic fluid, it is possible to calculate the load torque limit.

Since many hydraulic applications are mobile (e.g., fork-lifts, construction machinery, and agricultural vehicles), the instruments used to measure this pressure must be capable of withstanding shock, vibration, and electromagnetic interference. Additionally, these instruments must be resistant to oil, dust, mud, and fuel, as well as extreme temperatures, and should be sealed well since they are often attached to machines that are washed with high-pressure cleaners.



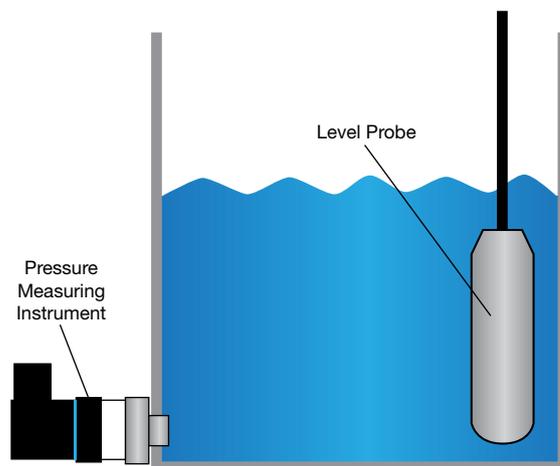
▲ **Figure 5.** In indirect force measurement, a system's known geometry can be used to calculate force based on pressure measurements. In this figure, two movable pistons are in contact with hydraulic oil. If the smaller piston moves down, the larger piston is pushed up with a greater force. Measuring the pressure exerted by the small piston allows the force to be calculated.

Indirect level measurement is possible because hydrostatic pressure under a static liquid column increases proportionately with the column's height. For example, pressure in a water tank increases 100 mbar for every meter of water depth; thus, water levels can be directly derived from pressure readings. The pressure-measuring instrument must be attached to the bottom of the tank's exterior (Figure 6) and exposed to interior pressure through an opening in the tank wall. Alternatively, submersible pressure transmitters (often referred to as level probes) can be dropped directly into the tank and provide the same functionality without drilling holes in the tank bottom.

If the tank is not vented or if it is under a pressure blanket, it is also necessary to measure the surface pressure above the liquid in the tank to determine hydrostatic pressure. This is done either by using two separate instruments and calculating the pressure differential in a downstream control unit, or by using a differential-pressure instrument that has two process connections and directly outputs the pressure difference between those as a signal.

A common application for indirect level measurement is automatic refilling of an empty (buffer) tank. An electronic pressure switch configured with both "tank is empty" and "tank is full" settings can automatically switch on and off a supply pump, and at the same time continuously indicate the current level.

Hydrostatic level-measurement devices must be resistant to the fluid and need to be sensitive to relatively small pressure changes. Submersible transmitters are submerged to depths of as much as several meters, and both the cable and the probe itself are in direct contact with the medium continuously. These instruments, particularly those installed in refineries and chemical plants, must often carry explosion-



▲ **Figure 6.** The water level in a tank can be measured indirectly by a pressure sensor. Because the pressure of water increases 100 mbar for every meter of water depth, the water level can be derived based on pressure differences. Alternatively, a level probe can be used.

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proof ratings and require high long-term stability. Devices designed for use in well, shaft, and bore-hole applications require slim designs and especially long, sturdy cables.

Indirect temperature measurement is typically used in refrigeration systems to monitor and control the evaporation and condensation of the refrigerant, but is also used in other chemical or physical processes.

In a typical refrigeration circuit (Figure 7), the refrigerant enters the compressor as a low-pressure gas. It is compressed, which increases its temperature, then leaves the compressor as a high-pressure gas. The hot gas flows through the condenser, where it condenses to a liquid, giving off heat. The liquid flows under high pressure to the expansion valve, which restricts the flow, lowering the fluid's pressure. The low-pressure liquid then enters the evaporator, where heat is absorbed, and the refrigerant changes from a liquid to a gas. The low-pressure refrigerant gas then moves to the compressor, and the cycle is repeated.

In a refrigeration cycle, pressure is typically measured both before and after the refrigerant passes through the compressor, which allows control of the expansion valve and the compressor, as well as the fans that dissipate heat in the condenser. In the expansion valve, targeted depressurization of the refrigerant can be used to control the cooling effect. The measured pressure can convey the state of the refrigerant, which controls the evaporation process, and can also help to prevent damage to the compressor by ensuring that the refrigerant is completely gaseous before it enters. If ventilators are used in the condenser, the power of the ventilator can be adjusted based on pressure measurements, to either speed up or slow down condensation.

Pressure-measurement instruments used in this process must be resistant to all common refrigerants and temperature

extremes, as temperatures in refrigeration systems can vary between -40°C and 100°C . They must also be able to withstand condensation, the formation of ice, and vibration from the compressor.

Closing thoughts

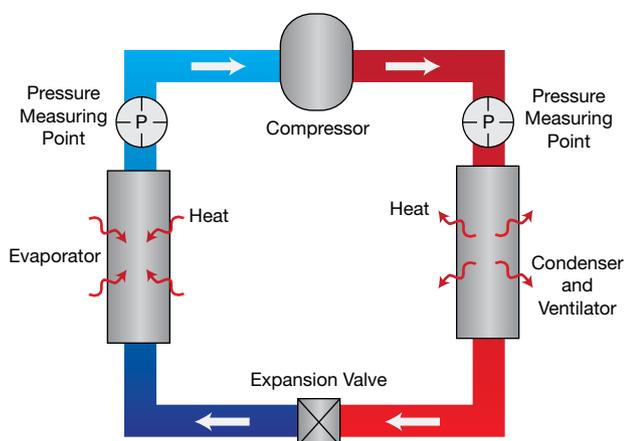
With hundreds — if not thousands — of different models of pressure sensors, transducers, and transmitters available, engineers are faced with a significant challenge in selecting the right instrument for the job. Picking the safe choice of a high-end, feature-rich, smart process transmitter may have been appropriate ten years ago when budgets were large and the number of measuring points small. Today's control systems are more advanced, and while the hunger for more data from more measuring points has increased, budgets have not.

Marketers may push the idea that only a certain measurement principle offers every advantage, but this tactic is often used to disguise the fact that the manufacturer has only mastered one principle and does not have products for the others. Purchasing departments sometimes try to commoditize sensors to leverage volumes and buying power, but this is far from ideal because no one instrument can be replaced by another without changes in certain specifications.

The choices are many, but the wise engineer understands the balance between price and value. You can spend \$100, \$1,000, or even more for basically the same function: to convert pressure into a standard output signal. The types of instruments discussed in this article, from bare sensors to smart process transmitters, span a large price range. Choosing the cheapest option may end up costing you much more in the future, but smart instruments are not always the smartest choice, either.

It pays to spend the extra time determining exactly what is required for the task at hand, discussing your options with manufacturers, and reading their literature carefully. If you are diligent in identifying the tasks and conditions for which you are selecting instruments, it will be much easier to make a financially sound choice — without overspending on something you don't need or underspending on an inferior or inappropriate device.

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▲ **Figure 7.** In a typical refrigeration cycle, liquid absorbs heat when it changes from liquid to gas, and gas gives off heat when it condenses from gas to liquid. Pressure is typically measured both before and after the refrigerant passes through the compressor.

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