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Guide to Sensors for Monitoring and Process Control

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An industrial computer's ability to accurately 'control' any system relies on obtaining feedback about its current status. Process control industries are characterized by the need to monitor and control continuous (analog) properties, like temperature, pressure, and flow rate. The properties are critical to many of the industries that keep our world running, such as energy generation and delivery, wastewater management, and chemical processing.

It's important for engineers to understand the various types and applications of process control sensors in order to properly select, install, and maintain these systems. Not only can these sensors protect the delivery of critical assets, but they can also increase efficiency and give insights into process improvements.

Our team has compiled this sensor ebook in partnership with our friends at **Endress+Hauser**, a leader in process control sensing and monitoring. Endress+Hauser has generously provided devices for physical bench tests and product images for a wide range of sensor applications.

The content was written and edited by our engineering content team at Control.com, with special thanks to authors Antonio Armenta and Seth Price. We hope you find the content practical as you continue your journey of understanding electrical control systems.

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CONTENT

Guide to Sensors for Monitoring and Process Control

We rely on industrial sensors to measure and report every critical value of manufacturing and batch process automation systems. This might include conditions like the following:

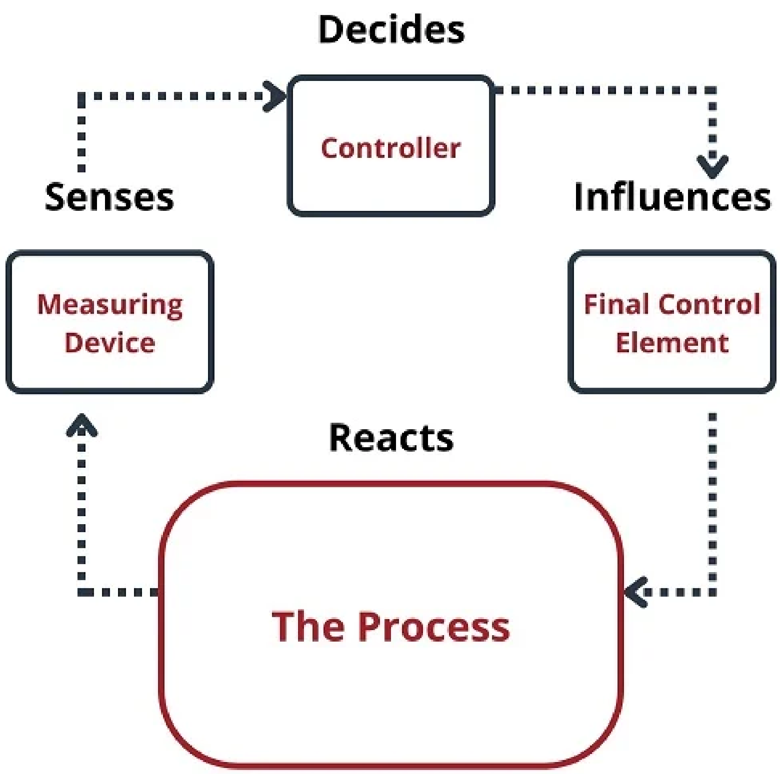
- Status of a conveyor
- Location of the object
- Temperature of a furnace
- Fill level of a tank

These properties impact production and must, therefore, be measured with sensors. Each sensor converts a physical property into an electrical signal.

Introduction to Process Control Sensors

Two distinct types of automation systems exist, each with distinct variables to measure. In product manufacturing and logistics facilities, sensors are devoted to detecting objects as they are created, modified, shipped, and delivered across the global manufacturing and supply chain network. This category of sensors is used for **manufacturing control**, also known as **machine control.**

In other industries, such as energy, oil and gas, and chemical processing, there are sensors that measure continuous values for ongoing processes that often work with fluids, gases, and varying conditions. These sensors are used for **monitoring control**, also known as **process control.** This ebook will focus on the various types of sensors used throughout these process control applications.



The traditional process control loop.

Sensors provide the first entry point of data into a closed-loop control system. With the gathered data, the controller can make a decision and send an output signal to control elements, like solenoid valves or motors. The system will react to these changes, and the new process values are measured by the sensors, completing the feedback loop.

- Pressure
- Flow rate
- Level
- Temperature
- Acidity and pH
- Gas, smoke, and air quality

The sensors use various creative methods to convert the physical data into an electrical value.

Pressure Sensors

The seventeenth century brought many of the greatest discoveries around the physical phenomenon of pressure. In 1647, French mathematician Blaise Pascal observed that the height of mercury in a vacuum changed depending on his elevation at the top or the bottom of a mountain. Shortly after, Robert Boyle declared his famous law, stating that the pressure and volume of a gas are inversely proportional.

Over the next century, Daniel Bernoulli advanced Boyle's work. He found that gas pressure can be increased by heating it while keeping a constant volume. Pressure sensors are designed using these fundamental principles.

In the international system of units (the metric system), pressure is measured in pascals (Pa), a unit of one Newton of force uniformly applied to a surface of one square meter. The atmosphere (atm) is another unit of measure, defined as the amount of pressure exerted by a one-meter-high column of water over a surface of one square centimeter. The most common unit of measurement in the United States is the pound per square inch (psi).

Diaphragm Pressure Gauge

Diaphragm gauges represent the most basic form of the pressure-sensing element. Pressure is calculated by determining the force applied onto a disc with a known surface area. There are rigid and flexible diaphragms, with the latter being the most common.

Pressure sensors often use the deformation of a diaphragm to directly measure changes in displacement or indirectly measure changes in capacitance.

In a flexible diaphragm, the sensing element suffers elastic deformation under pressure. By knowing the sensing material's mechanical properties, the deformation amount can be converted to a force value. Ultimately, the force value is mathematically converted to pressure.

One of the earliest and most common forms of a pressure sensor is the diaphragm pressure gauge. These sensors expose one side of their diaphragm to an external pressure while referencing the other to a known pressure. As a result, the diaphragm will bend according to the pressure differential, which can be measured using needles and displacement sensors.

Diaphragm pressure gauges have been around for decades. Their modern versions are reliable and offer a broad operating range.

Capacitance Manometer

Capacitance manometers are analogous to the basic diaphragm sensors but incorporate electrodes for interpreting pressure quantities. For example, a capacitance manometer has a diaphragm with an inlet and reference pressure. The electrode is mounted on the side of the reference pressure and sends an electrical signal directly proportional to the pressure differential.

Capacitance manometers are excellent calibration devices for other pressure diaphragms purely based on mechanical deflection. Also, these manometers can operate under a broad range of temperatures and work well under harsh conditions. They typically have low power requirements, which makes them suitable for many industrial control applications.

Piezoresistive Pressure Sensor

Piezoresistive sensors are also known as strain gauges. They are based on a concept known as resistive pressure measurement, in which a metallic strip is subjected to deflection, causing its electrical resistivity to change. This occurs because the metallic piece becomes shorter under pressure or longer when pressure is relieved. The resulting changes in resistivity are measured to obtain the corresponding pressure quantities.

Piezoresistive pressure sensor with metallic diaphragm.

Piezoresistive pressure sensors are generally considered robust and reliable over time. Their construction is also relatively simple, therefore having lower costs. They do, however, consume relatively high power compared to other pressure sensor variants.

Other Types of Pressure Sensors

The sections above describe the most common types of pressure sensors, but there are several others. One of these is the aneroid barometer. This sensor can measure environmental pressure, working solely on mechanical deformations. Another type of sensor is the bourdon tube, which is based on the aneroid barometer. These tubes have a helicoidal shape that also calculates pressure based on the deformation of the sensor.

Pressure sensors have many industrial applications. They are essential tools in systems that require high pressure and vacuum. In the manufacturing sector, they are required everywhere there is a hydraulic or a pneumatic system to keep pressure quantities under control.

Flow Rate Sensors

Flow rate sensors are essential in many industrial applications. These sensors measure the flow rate of liquids or gases in pipes, ducts, and other fluid systems by determining either the velocity or the mass flow rate in a process stream. They help to monitor and control processes, prevent system failures, and optimize performance.

The basic working principle behind flow rate sensors is based on the fundamentals of flow dynamics. First, it is established that mass is a conserved quantity that cannot be created nor destroyed. In other words, mass remains constant regardless of its containing boundaries. Then, in any situation where there is a mass flow, the mass that comes in equals the mass that goes out.

There are different techniques for measuring this mass flow in terms of velocity, which is proportional to the flow rate. In general, flow rate sensors measure the fluid's velocity at a specific point in the system with a known cross-sectional area. From this measurement, they can estimate the volumetric flow rate.

Various flow rate sensors are available today, each with particular working principles, advantages, and limitations. This article will review these flow rate sensors: differential pressure, electromagnetic, heat transfer, and ultrasonic.

Differential Pressure Flow Sensor

Differential pressure sensors are one of the most common flow sensors used in the industry. They function by measuring the pressure difference between two points of a fluid system. A pressure difference is created by forcing the fluid through a constriction, usually a smaller pipe diameter, increasing its velocity. Then, two pressure ports are positioned, one upstream and one downstream of the constriction. The resulting pressure differential is used to calculate the flow rate.

A differential pressure flow sensor.

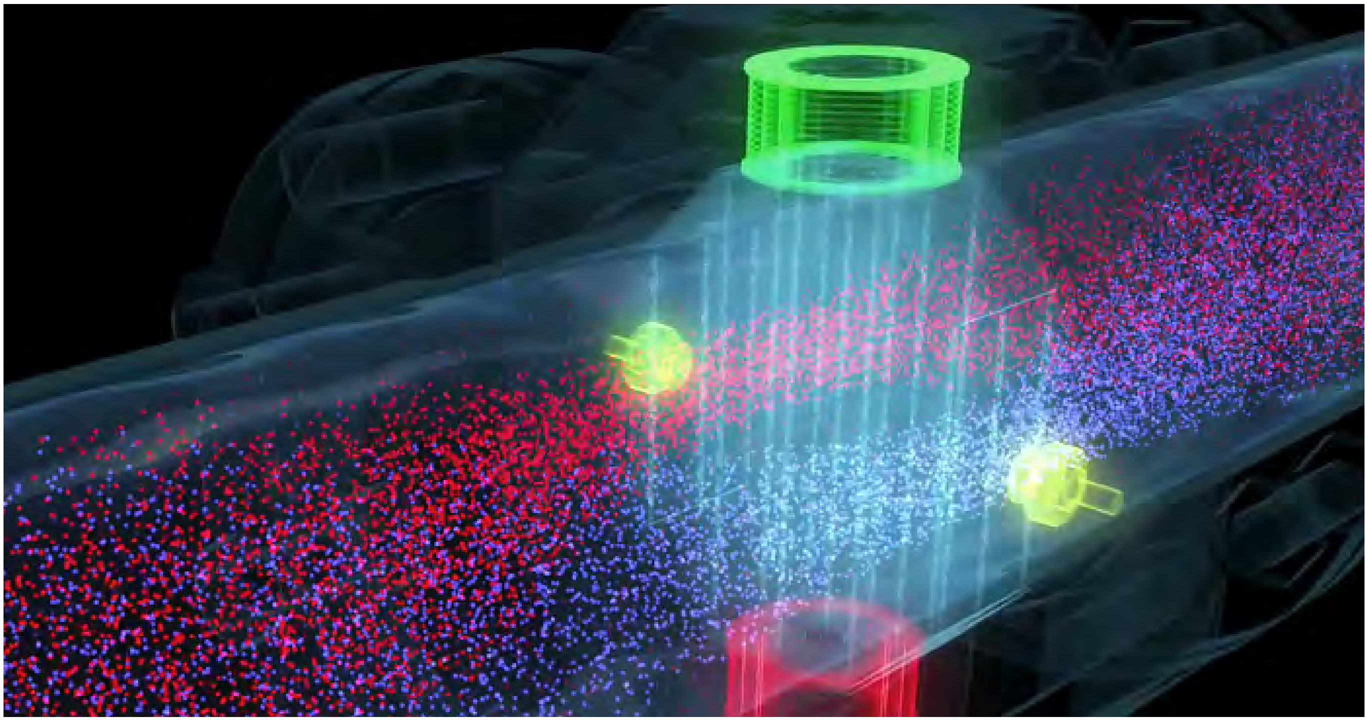
One common form of the differential pressure sensor is the Venturi meter. These sensors employ Bernoulli's equation, which states that the flow of a fluid has constant energy at every point, establishing a proportional relationship between the two pressure points.

Differential pressure sensors are relatively simple to build compared to other flow meters. They are widely regarded as reliable and cost-effective and are versatile because they can be used in a wide range of fluids and flow rates. Differential pressure sensors can, however, be prone to errors if improperly calibrated. They are also sensitive to rapid changes in fluid properties such as temperature and viscosity. Additionally, sensor design is crucial to avoiding unwanted pressure drops in the fluid system.

Electromagnetic Flow Rate Sensor

Electromagnetic flow rate sensors (often simply called flow sensors or flow meters) are designed based on Faraday's law of electromagnetic induction. Faraday's law establishes a relationship between a magnetic field and the current induced in an electrical conductor.

In flow rate measurement, electromagnetic coils (shown below in red and green) generate a magnetic field across the fluid, while sensors (shown in yellow) measure the induced voltage of the fluid as it flows through the magnetic field. The induced voltage is proportional to the fluid velocity and, thus, the flow rate.



System configuration of an electromagnetic flow sensor.

Electromagnetic flow rate sensors can be used in conductive and non-conductive fluids. Two advantages they have over differential pressure sensors are:

1. They do not create pressure drops in the system.
2. They are not affected by temperature or other changes in the fluid.

However, they are generally more expensive and require regular calibration to maintain accuracy.

Heat Transfer Flow Rate Sensor

Heat transfer is essential in flow rate sensors because heat transfer between fluid and sensor depends on the fluid velocity. The higher the fluid velocity, the higher the heat transfer rate. This rate can be measured using different methods, such as thermal conduction, convection, or radiation.

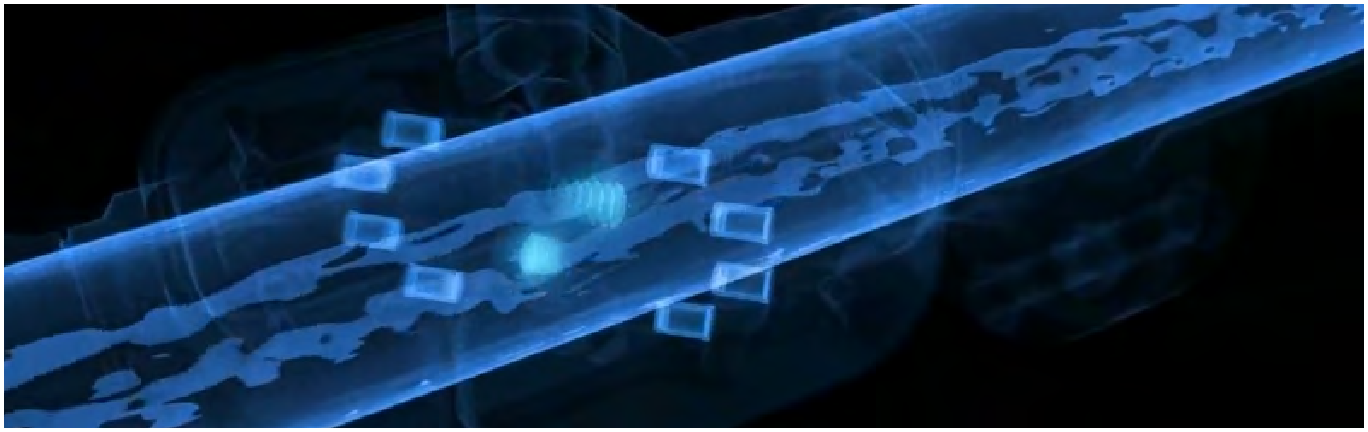
A heated element, known as a thermistor, is placed inside the fluid stream. Then, as the fluid flows past the sensor, heat is transferred to the fluid, changing the sensor's temperature. This temperature change is proportional to the fluid velocity and flow rate.

Like electromagnetic sensors, heat transfer sensors do not create pressure drops in the system and are unaffected by fluid viscosity changes.

Ultrasonic Flow Rate Sensors

These sensors are based on the Doppler effect and employ ultrasonic waves to measure flow. The Doppler effect explains a wave's frequency shift as it passes through a moving medium, like gas or liquid.

Ultrasonic flow rate sensors consist of a series of transducers on opposite sides of a duct carrying the fluid. They are placed diagonally to the flow. The frequency of the sound waves changes as they pass through the fluid. This frequency change is proportional to the velocity.



Transducer placement in an ultrasonic flow meter.

These sensors are minimally invasive because they are not required to be in direct contact with the fluid. This feature makes them well-suited for measuring corrosive or abrasive fluids. They are also regarded as reliable because of their high repeatability.

Liquid and Material Level Sensors

Level sensors measure the level of a substance in a container, typically liquids or granular materials. The output of these sensors is normally a distance quantity that estimates the level in relationship to the container dimensions. The resulting distance can then be converted to volumetric values based on the same tank dimensions.

There are different types of level sensors available, each with its own unique features and working principles. In this article, we will explore the working principles and applications of four types of level sensors: capacitive, ultrasonic, acoustic, and radar time domain reflectometers.

Capacitive Level Sensor

Capacitive level sensors work on the principle of electrical capacitance: the ability of a material to store an electric charge. These sensors measure the change in capacitance caused by the presence or absence of a substance in a container.

When a conductive probe is inserted into a container, it forms a capacitor with the container wall. When the container is empty, the capacitance is low. When the container is filled with the substance, the capacitance increases. This change in capacitance is used to determine the level of the substance in the container.

Capacitive level sensors can also act as 'switches' which energize the output when the level reaches a certain point.

Capacitive level sensors are suitable for use with liquids, powders, and granular materials. They are particularly useful in applications where the substance being measured is conductive or has a high dielectric constant.

Capacitive level sensors are largely unaffected by changes in temperature and pressure. However, they can be affected by buildup or scaling on the probe, which can cause errors in the readings. These errors are relatively minimal.

Ultrasonic Level Sensor

Sound waves are the working principle behind ultrasonic level sensors. In particular, these sensors use high-frequency sound waves to determine the distance between the sensor and the substance being measured.

A transducer sends out a sound wave, which bounces off the surface of the substance and returns to the sensor. The time it takes for the sound wave to travel to the substance and back is used to calculate the distance between the sensor and the substance.

Ultrasonic level sensors are well suited to applications where the substance being measured is not conductive or has a low dielectric constant (the opposite of capacitive level sensors).

Ultrasonic level sensors use sound waves to detect the presence of liquids and solids.

Like capacitive sensors, ultrasonic level sensors continue to perform well with changes in temperature and pressure. On the downside, they can be negatively affected by the presence of foam or vapors, which can interfere with the sound wave and cause errors in the readings.

Time-Domain Reflectometer (TDR) Sensor

TDR sensors employ radar waves to determine the distance between the sensor and the substance measured. Radar waves are a form of high-frequency electromagnetic radiation generated by a transmitter device.

Radar waves can provide information about the distance, angle, and velocity of objects detected. In this particular application, radar waves simply measure the distance. These sensors are useful in applications where the substance measured has a low dielectric constant or is very opaque.

Other Level Sensor Types

In addition to the four sensor types discussed above, other level sensors available are optical, vibrating, and floating.

Optical level sensors emit infrared light and measure the reflected intensity. The amount of reflected light changes when the tip of the sensor is submerged, making them useful as level switches, which change output states from off to on when a liquid level is reached. These sensors only work in clear liquid.

A vibrating level sensor uses a vibrating probe submerged in the container. As the liquid level in the container changes, so does the frequency of the vibration. These changes in frequency are calibrated and converted to a level quantity.

The floating level sensor is perhaps the most simple and is also considered very reliable. A device floats over the substance in the container and provides an output based on magnetic, pneumatic, or optical devices. Floating level sensors are helpful in applications where the container is very large and where the previously discussed methods would not be practical.

Temperature Sensors

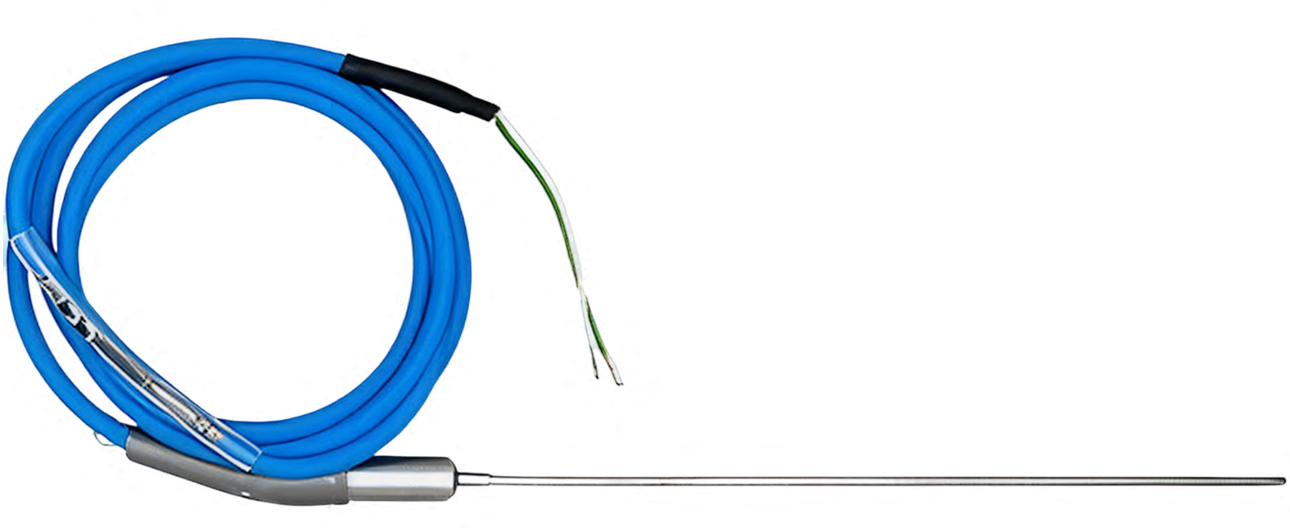
Measuring temperature is a centuries-old practice that is still fundamental to industrial automation today. An important breakthrough for temperature sensors was the discovery of the relationship between temperature and electricity. In 1821, German physicist Thomas Seebeck discovered the electric properties of bimetallic assemblies, also known as thermocouples. He realized that a voltage difference was produced when heating two metal parts with different properties. This became known as the Seebeck effect.

The discovery of thermal radiation in 1800 was another crucial moment. Scientists found ways to assess the infrared light produced by bodies emitting heat.

Temperature sensors convert thermal energy into electrical signals. For this to happen, thermal energy is first transferred from the sensed object to the sensor, which can occur through direct contact or radiation. In either case, heat transfer is required.

Thermocouples

Thermocouples utilize the relationship between temperature and resistance. In this configuration, two dissimilar metal wires are connected. The metal wires produce a temperature-dependent voltage that is measured by a device, such as a multimeter.



Thermocouples come in several types to support various temperature ranges.

Varying thermocouple material combinations produce different voltages at certain temperatures, leading to a variety of types that are acceptable for use at different temperature ranges. Each thermocouple type must be matched with a proper transducer to convert the small voltage generated to an equivalent temperature for that unique material combination.

Resistance Temperature Detectors (RTDs)

Electrical resistance is a function of temperature. Most commonly known by the acronym RTD, these sensors monitor the changes in resistance to measure the temperature.

By far, the most common metal used for this application is platinum due to its durability and stability. Platinum RTDs can be fabricated in two ways: thin-film and wire-wound. The thin-film configuration uses a very thin platinum wire coated with silicon. Wire-wound RTDs consist of platinum winding inside a ceramic tube.

There are also different wiring configurations: 2-wire, 3-wire, and 4-wire. The 2-wire sensor is the simplest configuration, employing single wires connected at each end of the sensing element. Although simple, these sensors can produce errors, with readings higher than the actual temperature.

Many sensors, like this RTD temperature sensor, use a fieldbus protocol like IO-Link or HART.

The 3-wire connection is the most popular in the industry. It reduces errors by incorporating an additional wire to remove the resistance of the measurement cable. The 4-wire configuration provides maximum accuracy by employing two pairs of wires, one for carrying the current and the other for measuring resistivity.

Thermistor Sensors

The word 'thermistor' is a contraction of the words thermal and resistor. These sensors use semiconductor materials and behave similarly to RTDs, measuring electrical resistivity. Thermistor materials such as metallic oxides and ceramics provide greater operating ranges than RTDs.

There are two types of thermistors: negative temperature coefficient (NTC) and positive temperature coefficient (PTC). NTC thermistors are the most popular. In this configuration, the resistance value decreases with the increase in temperature. However, the relationship between the two quantities is non-linear. Therefore, NTC thermistors must be calibrated for the specific application to produce accurate results.

PTC thermistors are more commonly used for circuit protection. These sensors make the electrical resistance highly sensitive to temperature changes, producing accurate results and larger operating ranges.

Infrared Thermometer

Contactless temperature sensors can detect the infrared radiation emitted by sensed objects. Infrared sensors absorb some of the radiation and convert it into an electrical signal.

Acidity and pH Sensors

In the chemical processing industry, one important measurable quantity is pH. The pH of a solution will determine its reactivity with other chemicals and may indicate hazards associated with its handling and disposal.

The pH scale ranges from 0 to 14:

- Solutions with a pH below 7 are acidic.
- Solutions above 7 are basic.
- Neutral solutions, like water, have a pH of 7.

Environmental guidelines determine the disposal procedure based on its pH. For example, during neutralization, a base is added to an acid (or vice versa) to reduce the corrosive effects of the solution. This should be performed in a controlled environment.

The pH probe is designed for various temperature environments.

When a strong acid dissociates in water, H+ ions are released, along with negative ions. The H+ cation quickly combines with a water molecule, forming an H_3O^+ (hydronium ion). Specific probe materials can be used to either attract or allow these hydronium ions through, creating a charge difference that can be measured. The more hydronium ions, the more the voltage difference, the lower the pH, and the stronger the acidic property.

Components of pH Sensors

The standard pH meter has several components:

- Two probes: one for reference and one for measurement.
- Calibration knobs or screws.
- A display.
- Potentially, a computer interface.

The reference and measurement probes are often paired into one combination probe. The combination probe has an alkali metal embedded into a glass or plastic bulb, accessible to the solution through a membrane. The reactive alkali metal undergoes an ion exchange with the hydrogen ions in the solution. As this happens, a small electrical potential is created between the exposed layer of the probe and a reference layer inside the probe.

Calibration knobs or screws are typically recessed in the meter to make them difficult to accidentally move during measurements. It is worth investing in a small precision screwdriver set and keeping it with the meter.

The meter may be a stand-alone device or interface with a computer to aid in data logging and monitoring applications. The meter will display the value of the pH and may also display the voltage difference between the probes and the temperature.

The pH probe is designed for various temperature environments.

The rookie instrumentation engineer who tries to simply record the voltage by means of an analog-to-digital converter from the pH probe into their own software will be disappointed. As it turns out, the pH probe has an extremely high impedance (in the gigaohm range). To interface with this device, an impedance-matching circuit must be constructed.

Calibration of pH Sensors

Depending on the specific model of the pH meter, calibration is typically performed through a calculation of the slope and intercept. Three different pH value solutions are employed as reference values. These can be created by hand or purchased as pH buffer solutions.

There are several common methods once the solutions are on hand. Sometimes, the meter will specify pH buffer solutions within the pH range that will be used for the final measurements. For example, in a process that will measure basic solutions, the pH probe may require pH 7.0 and 10.0 solutions as its calibration standard. The meter will need to be recalibrated before being used to measure acids.

Perhaps the most common calibration procedure is as follows. The probe is placed into one of the known solutions. If it does not match, there is often a set screw that controls a small potentiometer to adjust the value. Once the first value matches, the probe is removed from the first solution, rinsed with deionized water, and then placed in the second known solution. Often, there is a second set screw that must be adjusted until the pH on the meter matches the known solution's pH. The probe is then removed from the second solution and rinsed again. A good practice is to measure the third solution and track the error.

Variations in this procedure involve writing down a voltage at each pH and then fitting a line to the values. Certain meters will allow the user to program a "slope" and an "intercept" from this best-fit line. This is especially common with computer-based systems.

Effects of Temperature on pH Measurement

Temperature can appear to change the pH of a solution. As the temperature increases, so do the molecular vibrations, causing more molecules to dissociate, increasing the hydronium count. However, even though pH decreases, the solution is not actually becoming more acidic. Instead, the neutral point of the solution shifts with temperature, meaning a solution may be neutral at a pH of 6.5 at an elevated temperature. Rather than try to track how each solution will behave with temperature, the pH is adjusted for temperature to keep neutral at 7.0.

To account for this effect, some pH sensors have a built-in temperature sensor. This is typically either a Pt-100 RTD, a thermistor, or a K-type thermocouple located near the probe tip or in the meter itself. The latter assumes that the temperature difference between the meter and the probe is small.

If there is no built-in temperature sensor, the instrumentation engineer must account for the effect of temperature on the pH measurement. This can be performed mathematically, or perhaps more commonly, by calibrating the pH probe at temperature.

Gas Sensors

Gas sensors are designed to detect the presence of specific types of gases in the air, including toxic, combustible, and hazardous gases. Gas detection is based on the ability of gases to interact with certain materials, producing a measurable change in the electrical or optical properties of the material. There are various types of gas detectors, including electrochemical sensors, catalytic sensors, infrared sensors, and photoionization detectors.

Electrochemical Gas Sensor

Electrochemical gas sensors measure the concentration of a specific gas in the air through a chemical reaction that occurs at an electrode. The basic structure of these sensors consists of two electrodes submerged in an electrolyte solution. One electrode is coated with a catalyst to facilitate a chemical reaction between the gas to be detected and the electrolyte. When the electrochemical reaction occurs, an electrical current is produced proportional to the gas concentration in the environment.

An electrochemical oxygen sensor.

Electrochemical gas sensors are the most common type of gas detector, and they can be found in industries such as mining, oil, and gas. They are also used in both residential and commercial buildings. Carbon monoxide, hydrogen sulfide, and methane are common hazardous gases detected by these sensors.

Catalytic Sensor

Catalytic sensors detect the heat generated by the combustion of gas on a heated element. These sensors typically use platinum or palladium catalysts to promote the reaction. The heat produced changes the resistance of the material, which is then measured by electrodes and converted into a gas concentration reading.

These sensors are used in industrial settings to detect the presence of combustible gases such as propane and methane. They are also used in residential and commercial buildings to detect natural gas leaks from appliances like stoves and furnaces.

Photoionization Detector

Photoionization gas detectors use ultraviolet light to ionize gas molecules, creating a measurable electrical current. These sensors are highly sensitive and can detect gases at very low concentrations.

They are commonly used in applications such as workplace monitoring and leak detection. They are also used in the petrochemical industry to detect the presence of volatile organic compounds in refineries and chemical plants.

Smoke Sensors

Smoke is made up of gases and solid particles suspended in the air. It contains carbon monoxide, carbon dioxide, and many other chemicals. Smoke sensors (which we commonly refer to as 'smoke detectors') identify the presence of smoke in the air to provide an early warning of potential fires nearby. The two most common types of smoke sensors are ionization and photoelectric.

Ionization Smoke Detector

Ionization smoke detectors use the radioactive material Americium-241 to ionize the air inside a sensor chamber. Once smoke enters the chamber, it interferes with the ionization process, altering the flowing electrical current.

These sensors are the most common smoke detectors found in residential buildings. They are relatively inexpensive to build and are sensitive to the particles produced in fast-burning fires. They can, however, be prone to false alarms triggered by cooking smoke or steam from a shower.

Photoelectric Smoke Detector

Photoelectric smoke detectors work by using a small light source and a sensor within an empty chamber. Smoke that penetrates the chamber scatters the light from the emitter source, triggering an alarm.

Many smoke detectors use the scattering of light, and some, like this model, include a heater to remove fog that can create false positive readings.

These sensors are also common in residential and commercial buildings. They can be found in aircraft, boats, and other enclosed spaces, such as tunnels in mining operations where fires can be catastrophic.

Air Quality Sensors

In many applications, the quality of the air is important. High concentrations of carbon monoxide (CO), carbon dioxide (CO_2), or nitrogen oxides (NO_x), as well as lowered visibility can indicate poor air quality.

Sometimes, the simple presence of gas or air particulates does not constitute an emergency, but we still need to monitor a certain threshold to preserve a safe and healthy environment. Consider vehicles in a tunnel with limited ventilation. Sensors can tune the flow rate of fresh air to create a healthy environment while conserving energy in times when extra ventilation is not required.

Optical air quality sensors for CO, CO2, and visibility.

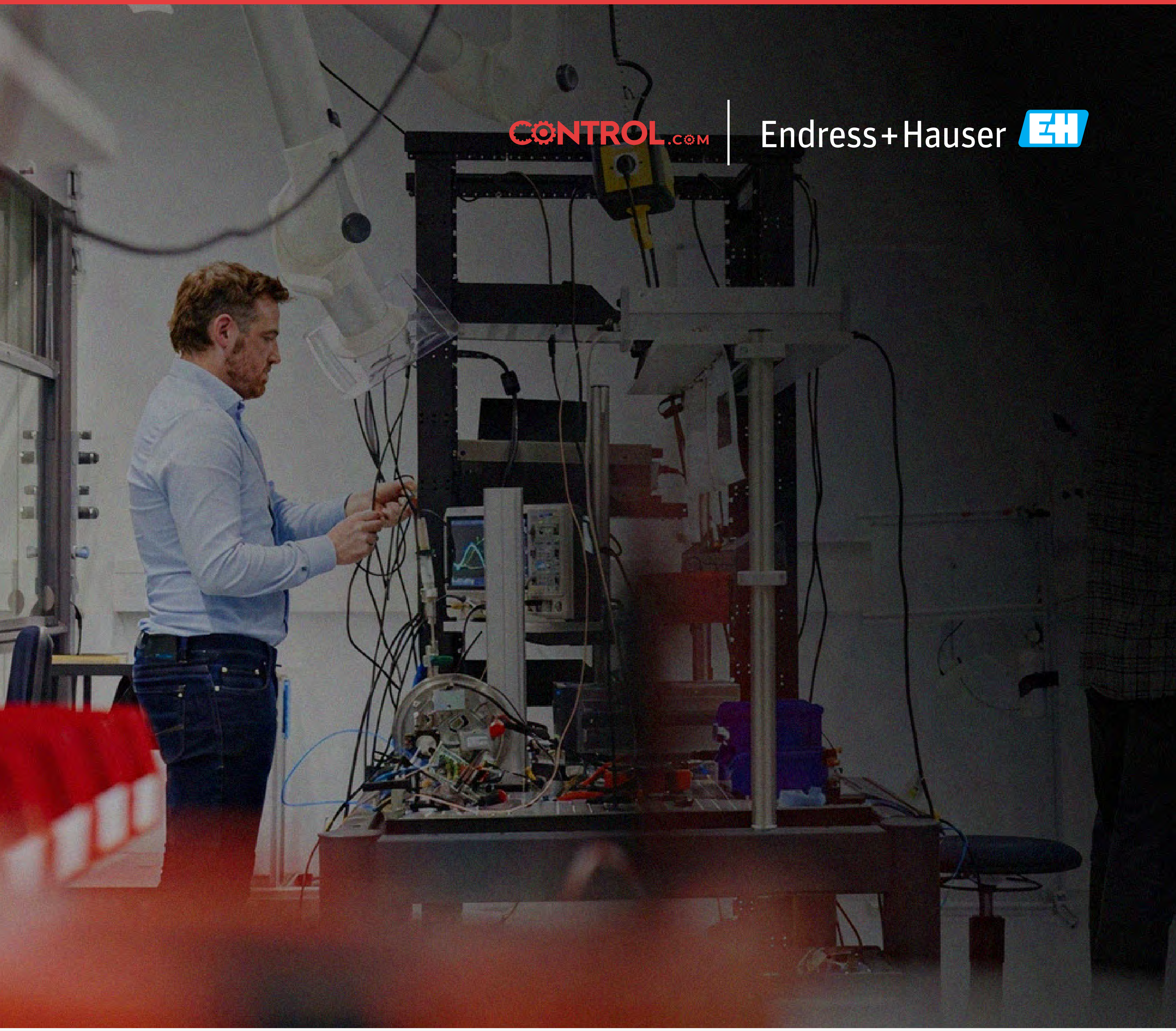
Most air quality sensors combine multiple functions into one unit that relies on optical (photoelectric) sensing, just like smoke detection.

Conclusion

Process sensors help keep critical operations online. In addition, the data must often be stored for long periods. It is analyzed to improve energy conservation and process effectiveness over time.

Building sensors into process control tasks can be more difficult than it is for discrete product sensing. Engineers in process control industries work hard to select the right sensors for each application.

Our team would again like to express our thanks to the writers and to the contributions of Endress+Hauser in illustrating and explaining the intricacies of sensor technology. We hope you are now better equipped to select, install, and troubleshoot sensors, helping drive the future of modern monitoring and process control.



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