

Temperature Measurement

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INTRODUCTION

Temperature is a principle parameter that needs to be monitored and controlled in most food processing operations such as heating, cooling, drying and storage. Temperature sensors have been developed based on different temperature-dependent physical phenomena including thermal expansion, thermoelectricity, electrical resistance, and thermal radiation.^[1,2] Temperature sensors used in agricultural and food industries and research vary from simple liquid-in-glass thermometers to sophisticated and state-of-art thermal imaging. This article focuses only on temperature sensors that generate digital signals readily used for on-line monitoring and automatic temperature control purposes. The article focuses on the commonly used temperature sensors, principles, precision, response time, advantages, and limitations for agricultural and food engineering applications.

PRINCIPLES AND PROPERTIES

Resistance Thermometers

Resistance thermometers measure temperature of an object based on changes in electrical resistance of the sensing element. Two types of resistance thermometers are commonly used: thermistors and resistance temperature devices (RTD).

A thermistor uses a semiconductor as the sensing element. The electrical resistance of the semiconductor, made mostly from metallic oxides (e.g., NiO), decreases sharply as the temperature increases. Response follows the general relationship^[3]:

$$R = R_0 e^{\beta(1/T - 1/T_0)} \quad (1)$$

where R is the electrical resistance (Ω) at temperature T (K), R_0 is the electrical resistance at a reference temperature, T_0 . β is a constant for specific materials (K) and is in the order of 4000. The reference temperature, T_0 , is generally taken as 298K (25°C).

The sensing elements of commercially available thermistors are protected by noncorrosive materials

(e.g., epoxy, glass, stainless steel) and are in the form of beads, rods, probes, and disks. Sensors can be made as small as 0.1 mm in diameter to give short response time. Glass and stainless steel-sheathed probes between 2 mm and 3 mm are widely used. In measurement, a thermistor is connected to one leg of a Wheatstone bridge to yield a resolution as precise as 0.0005°C.^[3] Accuracy of a thermistor sensor is often limited by the readout device with a resolution of only $\pm 0.1^\circ\text{C}$. Nonlinearity in electrical resistance output limits application of a thermistor to relatively narrow temperature ranges (e.g., within 100°C). Long-term output stability is another common problem of thermistor probes.

The RTD uses metal materials (e.g., platinum) as the sensing element. Electrical resistance in a metal changes in a predictable manner with temperature. A general relationship is used to convert electrical resistance R to temperature T :

$$R_T = R_0(1 + aT + bT^2 + cT^3 + \dots) \quad (2)$$

where R_T is the electrical resistance at temperature T , R_0 is the electrical resistance at a reference temperature, usually 0°C, and a , b , and c are material constants. The number of terms used in Eq. 2 depends on the material used in the sensor, the temperature range to be measured, and the accuracy required. In many cases, only constant, a , is used to provide satisfactory accuracy over limited temperature ranges. Fig. 1 shows the temperature range and the output resistance ratio of the three commonly used metals: platinum, nickel, and copper. The RTD has a small positive temperature resistance coefficient of $0.0039 \Omega \Omega^{-1} \text{C}^{-1}$ for a platinum RTD at 25°C as compared with a high negative temperature resistance coefficient of about -0.045 for a thermistor with a β value of 4000.

The most widely used RTD is a platinum resistance sensor, which is measured to be 100 Ω and 139 Ω corresponding with 0 and 100°C, respectively. Lead wire resistance and changes in lead wire resistance with temperature may have significant effects on the resistance readings. In application, RTD resistance is transformed into voltage and measured in a bridge circuit connected by two, three, or four wires according to application objectives and the need to minimize the influence of lead



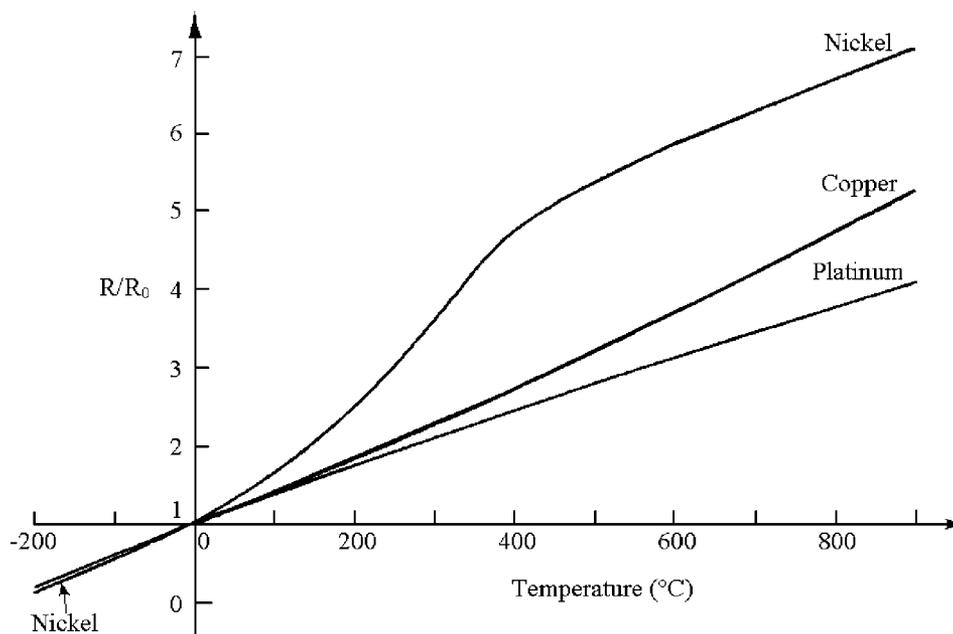


Fig. 1 Resistance–temperature relationship for platinum, nickel, and copper.

wire resistance. The RTD can be applied to measure solid, liquid, and gas substances at temperatures between -200 and 800°C . A major problem with RTD sensors is the relatively slow response time due to the protective sheath (ceramic, glass, or stainless steel). Sensor accuracy of the order of 0.2°C can be reached with careful calibration in specific temperature ranges.

Thermocouples

When two dissimilar metals are joined at two points (Fig. 2), a thermocouple circuit is formed. When these two junctions are at different temperatures, an electromotive force (emf) develops, causing an electric current to flow through the circuit. The magnitude of this emf is proportional to the temperature difference between the two junctions. This physical phenomenon, referred to as thermoelectricity, was discovered by T. J. Seebeck in 1821. The thermoelectricity is used for temperature measurement in thermocouple systems, in which one

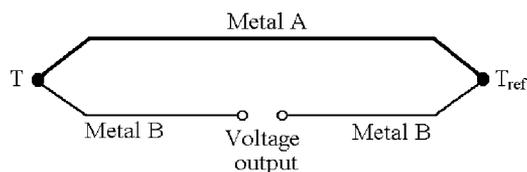


Fig. 2 Thermocouple circuit to measure temperature (T) with the cold junction (T_{ref}) from the output voltage (V).

junction is maintained at a known reference temperature (T_{ref}) while the other is positioned for temperature measurement. The temperature to be measured (T) is converted from thermoelectric voltage V according to:

$$T = T_{\text{ref}} + \frac{V}{\alpha} \quad (3)$$

where V is the measured voltage in the thermocouple circuit and α is the voltage/temperature proportionality constant ($\text{V}^\circ\text{C}^{-1}$). Voltage can be measured with a potentiometer or a high-impedance solid-state digital voltmeter. The value of constant α depends on the type of wires used to make the thermocouple. Theoretically, for precision work the reference junctions should be kept in a triple-point-of-water apparatus that maintains a fixed temperature of $0.01 \pm 0.0005^\circ\text{C}$. In reality, the reference temperature, T_{ref} , can be room temperature, measured with a thermistor in most computer-based data acquisition systems.

Different pairs of metals are used for thermocouple types commercially labeled as types S (platinum/platinum–10% rhodium), R (platinum/platinum–13% rhodium), B (platinum–30% rhodium/platinum–6% rhodium), J (iron/constantan), T (copper/constantan), K (chrome/aluminum), and E (chromel/constantan). Typical characteristics of these thermocouples are shown in Fig. 3.^[3] Thermocouples give relatively low voltage outputs (e.g., $0.04 \text{ mV}^\circ\text{C}^{-1}$ for type T). Type E thermocouples have the highest voltage output per degree among all commonly used thermocouple types, but type E



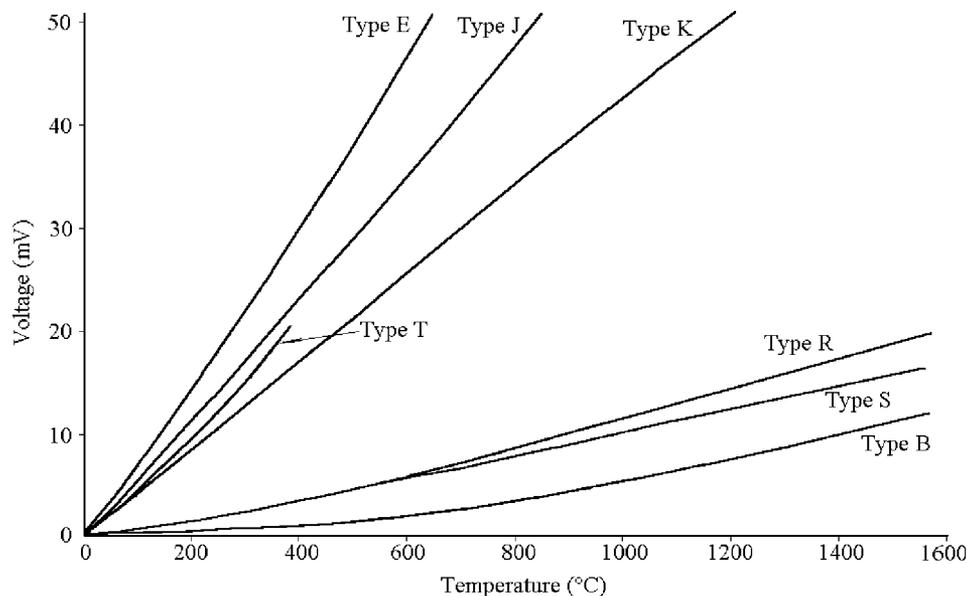


Fig. 3 Typical voltage-temperature relationship for common thermocouple materials when the reference temperature is 0°C.

thermocouples are not suited for reducing, sulfurous, vacuum, and low-oxygen environments. Types T and J are commonly used in industrial applications, because of their resistance to corrosion and harsh environments. For example, type J can be used between -150 and 760°C in both oxidizing and reducing environments, while type T can be used between -200 and 350°C . The upper temperature limit for type T is due to oxidation of copper at temperatures greater than 350°C .

The temperature-sensitive element in thermocouples can be made very small to provide a response time of only a few seconds.^[4] Thermocouples can be used to detect the transient temperature in a solid, liquid, and gas, with an accuracy of $\pm 0.25\%$ of reading for types R and S, and $\pm 0.5\%$ reading for type T over a measurement range of 100°C . Generally, thermocouples cannot be used in electromagnetic fields, because the metallic elements may interact with the electromagnetic field.

Sonic Thermometer

The basic principle of a sonic thermometer is the measurement of the time of an ultrasound pulse traveling between two transducers (Fig. 4). It is well known that the speed of sound increases when the air moves in the same direction as the sound. This pair of transducers (a, b) act alternately as transmitters and receivers, exchanging high-frequency ultrasound pulses. This speed of sound in air is used for rapid calculation of air temperature. The output of the sonic temperature (T_s , $^{\circ}\text{C}$) according to Kaimal and

Gaynor^[5] is:

$$T_s = \frac{L^2}{1612} \left(\frac{1}{t_1} + \frac{1}{t_2} \right)^2 - 273.15 \quad (4)$$

where L is the distance between the transducers (m), t_1 and t_2 are the travel times in each direction (sec). This sensor has a high sampling rate of up to 50 times per second. The measurement precision may reach 0.4% after careful calibration.

Radiation Thermometer

Radiation thermometers (often referred to radiometer, radiation pyrometer, or optic pyrometer) operate using electromagnetic radiation in the visible spectrum

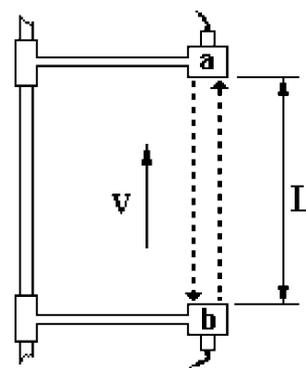


Fig. 4 Sonic anemometer (v , air speed; L , the distance between transducers a and b). (From Ref.^[11])



(0.3 μm –0.72 μm) and a portion of the infrared region (0.72 μm –40 μm). A radiation thermometer may use either a thermal detector or photon detectors as its sensing element. Thermal detectors are blackened elements designed to absorb incoming radiation at all wavelengths radiating from the measured object. Temperature rise of the detector caused by the absorbed radiation is measured by specially made RTDs, thermistors, or thermopiles (consisting of up to 30 thermocouples).

Another type of thermal detector is the pyroelectric detector that is based on pyroelectric crystals (e.g., lithium tantalate crystals). Pyroelectric thermal detectors have shorter response times than the thermal detectors using a RTD, thermistor, or thermopiles and are responsive to a wide radiation range between x-ray (0.001 μm) and far-infrared (1000 μm).

The radiation thermometers can measure the targeted surface temperature from a distance, so there is no contact between the thermometer and the object. As the infrared sensors measure an object temperature at a distance, there is no limitation on the thermal tolerance of materials used to make the sensor. The time constant of radiation thermometers is short, often in the range between several microseconds to a few seconds. Radiation thermometers, however, only read the temperature information at the surface of a relatively opaque material. It cannot be used to measure the transparent materials because the sensor will detect surface temperatures behind the object. Radiation thermometers require information on emissivity of the measured body surface and an internal or external reference temperature to provide accurate temperature information.

Fiber-Optic Thermometers

In radio frequency and microwave heating and drying applications, temperature sensors with metal components cannot be used directly because of electromagnetic noise and interaction between the metal parts and electromagnetic fields. For these applications, fiber-optic thermometers are often used.^[6] Fiber-optic temperature sensors are developed from one of three methods: fluoroptic thermometry, Fabry-Perot interferometry, and absorption shift of semiconductor crystals.

The fundamental mechanisms behind fluoroptic thermometry rely on the use of phosphor (magnesium fluorogermanate activated with tetravalent manganese) as the sensing element. This material fluoresces in the deep red region when excited with ultraviolet or blueviolet radiation. The rate of decay of the afterglow of this material varies with temperature (e.g., 5 msec at -200°C , 0.5 msec at 450°C). Measuring the rate of afterglow decay allows an indirect determination of the temperature.

A Fabry-Perot interferometer (FPI) consists of two parallel reflective surfaces that form a cavity resonator. The space separating these two surfaces, also called the FPI cavity (1–2 wavelengths deep), varies with temperature. Changes in temperature result in the change of optical length (refractive index multiplied by cavity depth) of this resonator, even though the actual physical thickness of the film exhibits no measurable changes. Changes in the FPI cavity path, or in the optical path length of the resonators for light from a white-light source, are measured to determine the temperature of the sensing element.

A fiber-optic sensor based on absorption shift of semiconductor crystals relies on the temperature-dependent light absorption/transmission characteristics of gallium arsenide (GaAs). A unique feature of this crystal is that when temperature increases, the crystal transmission spectrum shifts to higher wavelengths (Fig. 5). The position of the absorption shift indicates the temperature measurement of the sensing element.^[7]

Probe size of fiber-optic sensors is generally small (as small as 0.8 mm in diameter, Fisco Technologies, Inc., Quebec, Canada). Fiber-optic temperature sensors provide accuracy comparable to thermocouples. They generally have short response times (from 0.05 sec to 2 sec in liquid foods) and are well suited to relatively fast microwave or radio frequency heating, or in applications with strong influence of electromagnetic fields.

SENSOR CALIBRATION AND RESPONSE TIME

Calibration of a given temperature probe is important to ensure reliable measurement. In general, two calibration methods are used. One method is to expose the sensor to an established fixed-point environment, such as the triple-point of pure water and the freezing and boiling points of water. Another method is to compare readings with those of calibrated and traceable temperature sensors when they

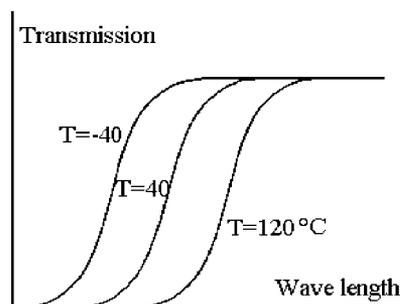


Fig. 5 Temperature-dependent light transmission of GaAs crystal as the sensing element of a fiber-optic thermometer.



are placed in the same thermal environment. Calibration procedures are standardized for specific applications.^[8]

Besides accuracy, precision, and resistance to corrosion, an important consideration in selecting temperature sensors is the sensor's response time. Response time is a measure of how quickly a sensor follows rapid temperature changes. The smaller the response time, the more closely the sensor follows the temperature change of the measured medium. For a step-change in the medium temperature, the temperature of the sensor $T(t)$ changes with time t following the relationship:

$$\frac{T_m - T(t)}{T_m - T_0} = \exp(-t/\tau) \quad (5)$$

where constant τ is the sensor response time (also referred to as the time constant). τ is defined as the time for a sensor to reach 63.2% of a step-change in temperature ($T_m - T_0$) [Fig. 6(a)]. The response time can be estimated from the overall surface heat transfer coefficient, h ($\text{W m}^{-2} \text{°C}^{-1}$), and other physical properties:

$$\tau = \frac{\rho C_p V}{hA} \quad (6)$$

where A is the surface area of the sensor (m^2), V is the volume of the sensor (m^3), ρ is the density of the sensor (kg m^{-3}), and C_p is the specific heat of the sensor ($\text{J m}^{-2} \text{°C}^{-1}$). It is clear from Eq. 6 that reducing the volume, V , of the sensing element (including the protecting sheath) and increasing heat transfer coefficient, h , can reduce sensor response time. That is why temperature probes are often made small. For a same sensor, however, the response time in water can be up to 100 times shorter than in air because of the difference in the overall surface heat transfer coefficient h . For many applications in which air temperature is to be measured, an aspirated temperature sensor is used to increase surface heat transfer coefficient and reduce sensor response time.

Sensor response time can be used to assess measurement error in various applications. Fig. 6(b) demonstrates the thermal lag of a temperature sensor when exposed to a medium with a temperature ramp of dT/dt . At steady-state, the temperature lag is calculated by multiplying the thermal constant, τ , with the ramp rate, dT/dt . For example, when the medium temperature changes at 10°C min^{-1} and the time constant of the sensor is 0.5 min, the maximum thermal lag will be 5°C . Knowledge of the time constant of sensors is essential in designing effective dynamic temperature monitoring and control systems.

APPLICATION OF TEMPERATURE SENSORS

Temperature sensors are selected according to required accuracy, response time, initial investment, maintenance

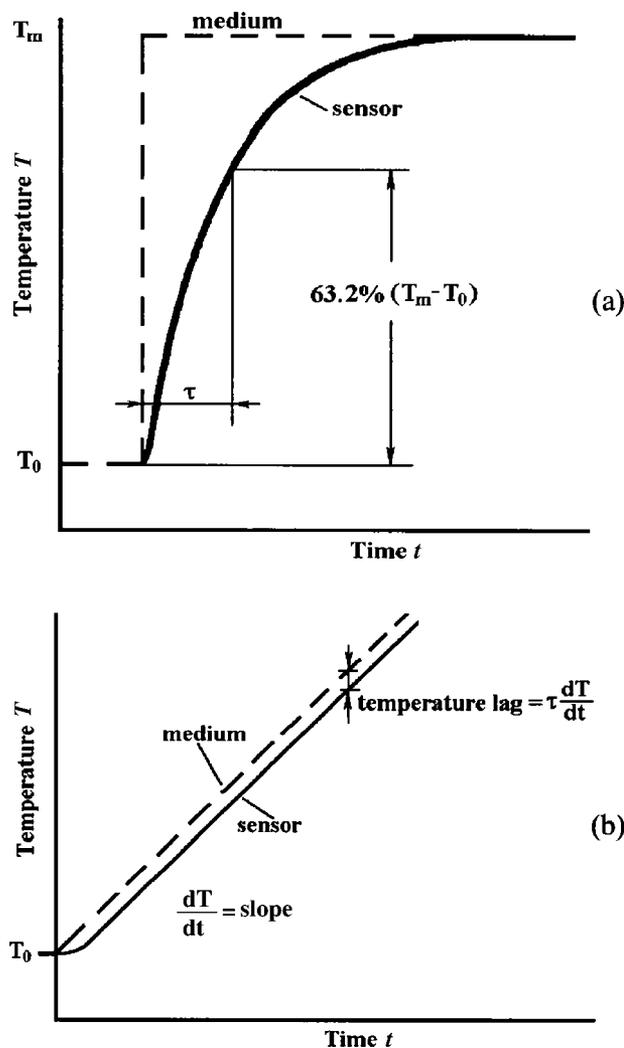


Fig. 6 (a) Response time, τ , defined under a step-change in medium temperature and (b) temperature lag of a sensor following a medium temperature ramp.

cost, ambient condition, and stability of calibration. Examples of typical applications of temperature sensors discussed above are summarized in Table 1. Thermistors are generally used for measuring temperature in a narrow range, because of their high precision ($\pm 0.1 \text{°C}$) in small ranges.^[2] Thermocouples are widely used because of acceptable precision, rapid response time, and low cost. RTDs, however, provide better accuracy and stability. The sonic thermometer is commonly used to measure air temperature in the turbulent environment of storage houses and bins. Radiation thermometers are especially suitable for measurement of moving objects or objects inside vacuum or pressure vessels. Radiation sensors respond very quickly, but are more costly than thermocouples or RTDs.



Table 1 Property and examples of typical applications of temperature sensors

Sensor	Signal output	Measurement range (°C)	Accuracy	Example of typical applications
Thermistor	Resistance	– 50 ~ 200	± 0.1%	Reference for data loggers
RTD	Resistance	– 200 ~ 850	± 0.2°C	Precise and stable measurements
Thermocouple	Voltage	– 250 ~ 400	± 0.5°C	Most food and agricultural applications
Sonic anemometer	Voltage	– 10 ~ 80	± 0.4%	Airflow temperature in storage and bins
Far-infrared thermometer	Voltage	~ 4000	< 1%	Surface temperature of foods in drying and baking
Fibre-optic thermometer	Voltage	– 50 ~ 250	± 0.5%	Microwave and radio frequency heating and drying

The sighting path and optical elements of the radiation detectors must be kept clean. Fiber-optic thermometers can be used in very strong electromagnetic fields.

Even for the same type of temperature probe, a large variety of styles is available for use in food and agricultural engineering applications. Precautions are needed in selecting appropriate probe style to match mechanical, chemical, and sanitation requirements. Some styles directly expose the sensing element to the environment while others are protected with a sheath or thermal well for durability and maintaining a seal. Heat sink paste should be used with thermal wells to increase heat transfer to the thermometer and avoid offsets and thermal time lags. Thermal wells and sheaths should be selected to protect the thermometer, but not add excessive mass and create thermal lags.

For measuring the temperature of fluid in a pipe, a probe in a sheath may be swaged into a bore-through style compression fitting. Care must be taken when selecting and installing exposed thermocouples or those in grounded metal sheaths. When an exposed or grounded style thermocouple contacts highly conductive materials such as metal piping or the food itself, “ground loops” may produce signal noise and inaccurate readings in the measuring system. In such cases, it is advisable to use an ungrounded or electrically isolated probe construction.

Government regulations must also be considered in selection of temperature probe type and documentation of probe calibration. For example, USDA regulations require that each retort system (for canning) be equipped with at least one mercury-in-glass thermometer having readable 0.5°C divisions as the reference for the process, even when other electronic methods are used for recording and process control.^[9] Regulations may also require specific probe types for sanitation and clean-in-place (CIP) systems.

Special systems are available for heat penetration studies in cans and pouches. Generally, these special systems consist of the thermocouple probe and a receptacle, which provide means to penetrate the package, hold the probe in place, and maintain a seal (e.g., Ecklund Harrison Technologies of Fort Myers,

Florida). Probes are available as flexible thermocouple wire, rigid plastic bodies, and as metal “needle” types. A needle type is mechanically stronger, but it can conduct heat along its length and lead to inaccurate results. For viscous food with low thermal conductivity, a plastic probe is preferred. Placement of a probe in the can requires consideration of can geometry and food material properties to ensure that the critical point (cold spot) is measured. For more viscous products heated by conduction, the critical point is generally the geometric center of the container. But for those less viscous, and therefore heated by internal convection, the critical point may be closer to the bottom of the container.^[10]

Selection of temperature probes also includes selection of compatible signal conditioning equipment. Common bench-top display units or PC based equipment for the laboratory may be entirely unsuitable for use in processing. It is important to select probes styles that can be connected to suitable cables or enclosures for signal conditioners and transmitters that are protected from possible heat, moisture, chemical, and mechanical damages. Transmitters should be selected according to the type of temperature sensor, precision, range, and type of output required. Although standards such as 4 mA–20 mA d.c. analog signals are still commonly used, modern temperature sensors are now being interfaced to measurement and process control systems using highly sophisticated technologies such as Ethernet, Field Bus, and most recently, wireless networks.

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