

Temperature measurement, control key to plant performance

By Gregory K. McMillan

Temperature is one of the four most common types of loops. While the other common loops (flow, level, pressure) occur more often, temperature loops are generally more difficult and important. It is the single most frequently stated type of loop of interest to users, and the concern for better control extends to the widest variety of industries.

Temperature is a critical condition for reaction, fermentation, combustion, drying, calcination, crystallization, extrusion, or degradation rate and is an inference of a column tray concentration in the process industries.

Tight temperature control translates to lower defects and greater yields during seeding, crystal pulling, and rapid thermal processing of silicon wafers for the semiconductor industry.

For boilers, temperature is important for water and air preheat, fuel oil viscosity, and steam superheat control. For incinerators, an optimum temperature often exists in terms of ensured destruction of hazardous compounds and minimum energy cost. For heat transfer fluids, such as cooling tower, chilled water, brine, or Therminol, good temperature control minimizes upsets to the users.

Good temperature control is important during the research, reaction, separation, processing, and storage of products and feeds and is thus a key to product quality. It is also of importance for environmental control and energy conservation.

Curiously, the slowness of the response of the temperature process is the biggest source of problems and opportunities for tight temperature control. The slowness makes it difficult to tune the controller because the persistence and patience required to obtain a good open- or closed-loop test exceeds the capability of most humans. At the same time, this slowness, in terms of a large major process time constant, enables gain settings larger

than those permissible in other types of loop except for level.

Once a properly implemented temperature loop is correctly tuned, the control error is often less than the tolerance (error limits) of the sensor. If one considers the accumulated error of an installed thermocouple or RTD system is about five times larger than the error limits of the sensor, one realizes system measurement error seriously limits temperature loop performance.

Thermocouples and resistance temperature detectors

In the process industry, 99% or more of the temperature loops use thermocouples or resistance temperature detectors (RTD). The RTD provides sensitivity (minimum detectable change in temperature), repeatability, and drift that are an order of magnitude better than the thermocouple, as shown in the table, "Accuracy, Range, and Size of Temperature Sensing Elements." Sensitivity and repeatability are two of the three most important components of accuracy. The other most important component, resolution, is set by the transmitter. Drift is important for extending the time between calibrations. The data in this table dates back to the 1970s and consequently does not include the improvements made in thermocouple sensing element technology and premium versus standard grades. However, the differences are so dramatic that the message is still the same.

The table, "Accuracy, range, and size of temperature sensing elements," includes data on thermistors, which have seen limited use in the process industry despite their extreme sensitivity and fast (millisecond) response, primarily because of their lack of chemical and electrical stability. Thermistors are also highly non-linear, but this can be addressed by smart instrumentation.

For bare sensing elements, thermistors have a much faster response than thermocouples, which are slightly faster than RTDs. This point rarely comes into play because for most industrial processes a 1- or 2-second additional lag time in a temperature loop is well within the uncertainty of the loop's dynamics. The secondary process time lags can easily change by 10 to 20 seconds for slight changes in operating conditions. Also, once these sensing elements are put inside a thermowell or protection tube (a closed-end metal tube that encapsulates and protects a temperature sensor from process flow, pressure, vibration, and corrosion), the fit, fill, material, and construction of the thermowell have the biggest impact on temperature measurement time lags, as noted in the tables, "Dynamics of Bare Sensing Elements" and "Dynamics of Thermowells." Protection tubes like thermowells provide isolation of the element from the process, but unlike thermowells, protection tubes do not necessarily provide a pressure-tight attachment to a vessel, a tapered or stepped

Accuracy, range, and size of temperature sensing elements

Criteria	Thermocouple	Platinum RTD	Thermistor
Repeatability (°C)	1 – 8	0.02 – 0.5	0.1 – 1
Drift (°C)	1 – 20	0.01 – 0.1	0.01 – 0.1
Sensitivity (°C)	0.05	0.001	0.0001
Temperature range (°C)	-200 – 2000	-200 – 850	-100 – 300
Signal output (volts)	0 – 0.06	1 – 6	1 – 3
Power (watts at 100 ohm)	1.6×10^{-7}	4×10^{-2}	8×10^{-1}
Minimum diameter (mm)	0.4	2	0.4

Dynamics of bare sensing elements

Bare sensing element type	Time constant (seconds)
Thermocouple 1/8-inch sheathed and grounded	0.3
Thermocouple 1/4-inch sheathed and grounded	1.7
Thermocouple 1/4-inch sheathed and insulated	4.5
Single Element RTD 1/8 inch	1.2
Single Element RTD 1/4 inch	5.5
Dual Element RTD 1/4 inch	8.0

Dynamics of thermowells

Process fluid type	Fluid velocity (feet per second)	Annular clearance (inches)	Annular fill type	Time constants (seconds)
Gas	5	0.04	Air	107 and 49
Gas	50	0.04	Air	93 and 14
Gas	150	0.04	Air	92 and 8
Gas	150	0.04	Oil	22 and 7
Gas	150	0.02	Air	52 and 9
Gas	150	0.005	Air	17 and 8
Liquid	0.01	0.01	Air	62 and 17
Liquid	0.1	0.01	Air	32 and 10
Liquid	1	0.01	Air	26 and 4
Liquid	10	0.01	Air	25 and 2
Liquid	10	0.01	Oil	7 and 2
Liquid	10	0.055	Air	228 and 1
Liquid	10	0.005	Air	4 and 1

wall, or a tight fit of the element. Protection tubes may be ceramic for high-temperature applications. The measurement lags from protection tubes are generally larger than for thermowells.

There are many stated advantages for thermocouples, but if you examine them more closely, you realize they are not as important as perceived for industrial processes. Thermocouples are more rugged than RTDs. However, the use of good thermowell or protection tube design and installation methods makes an RTD sturdy enough for even high-velocity stream and nuclear applications. Thermocouples appear to be less expensive until you start to include the cost of extension lead wire and the cost of additional process variability from less sensor sensitivity and repeatability.

The minimum size of a thermocouple is much smaller. While a tiny sensor size is important for biomedical applications, miniature sensors are rarely useful for in-

dustrial processes.

The main reason to go to a thermocouple is if the temperature range is beyond what is reasonable for an RTD or you do not need the accuracy of an RTD. Thus, for temperatures above 850°C (1500°F), the clear choice is a thermocouple for a contacting temperature measurement. For temperatures within the range of the RTD, the decision often comes down to whether the temperature is used for process control or just the monitoring of trends. If you have lots of temperatures for trending in which errors of several degrees are unimportant, you could save money by going to thermocouples with transmitters mounted on the thermowell (integral mount) or nearby. If you are using temperature for process control, data analytics, statistical or neural network predictions, process modeling, or in safety systems, a properly protected and installed RTD is frequently the best choice

for temperatures lower than 500°C (900°F). At temperatures above 500°C, changes in sensor sheath insulation resistance has caused errors of 10°C or more.

Tuning

The process time constant for continuous temperature loops on volumes and columns is so large that the temperature ramps in the time horizon of interest and the process can be approximated as “Near Integrating.” Temperature loops on batch processes have a “True Integrating” response. In both cases, the short cut tuning method can be used where the maximum percent change in ramp rate in four deadtime intervals divided by the change in percent controller output is the integrating process gain. The short cut method reduced the tuning test time from 10 hours to 10 minutes for a bioreactor. The controller gain for maximum disturbance rejection is approximately one half the inverse of the product of this integrating process gain and the observed total loop deadtime. The reset time is simply four times the deadtime, and the rate time is set equal to the thermowell lag time. For a fast setpoint response with minimal overshoot, either a smart bang-bang control or a combination of setpoint feedforward and a PID structure with proportional action on PV rather than error can be used.

Resistance temperature detectors (RTD)

RTDs operate on the principle that the electrical resistance of a metal increases as temperature increases, a phenomenon known as *thermo-resistivity*. A temperature measurement can be inferred by measuring the resistance of the RTD element. The thermoresistive characteristics of RTD sensing elements vary depending on the metal or alloy from which they are made.

Wire-wound RTD

Wire-wound RTD sensing elements are constructed by coiling a platinum (or other resistance metal) wire inside (internally wound) or around (externally wound) a ceramic *mandrel* (spindle). Most RTD sensors for the process industry are internally wound and sheathed for protection. A dual-element, wire-wound RTD can be created by coiling a second set of wires

inside or outside the ceramic mandrel. If connected to a second transmitter, a transmitter with dual-sensor capabilities, or to another distributed control system card, a dual-element sensor increases the reliability of the temperature measurement. Wire-wound RTD elements are very sturdy and reliable. Compared to thin-film RTD elements, their accuracy tends to be higher, and their time response (how quickly the output reflects the temperature change) is several seconds faster than thin-film RTD elements. Wire-wound RTD elements work well for a variety of applications, although they may fail in high-vibration applications. Redundant, separate, single-element sensors are recommended for applications

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in which reliability and accuracy must be maximized. The single element has a lower gauge sensing element and smaller time constant than the dual element. The use of redundant sensors helps eliminate common mode failures and enables a better cross check of sensor drift than dual elements. Three sensors and middle-signal selection reduce noise and drift and provide inherent automatic protection against a single failure of any type.

Thin-film RTD

Thin-film RTD sensing elements are constructed by depositing a thin film of resistance metal onto a ceramic substrate (base piece) and trimming the metal to specifications. Sensing elements of thin-film construction are typically less expensive than those of wire-wound construction because less resistance metal is required for construction. However, thin-film RTDs tend to be less stable over time, typically have a more limited temperature range, and may be more susceptible to damage from rough handling.

Extension lead wires

To get an accurate temperature reading from an RTD, the resistance of the RTD sensing element must be measured.

Each copper lead wire that connects the RTD sensing element to the resistance measuring device adds a small amount of resistance to the measurement. If this added resistance is ignored, an error is introduced, and an inaccurate temperature measurement results. The error is referred to as the *lead wire effect*. The longer the wire run, the greater the error, or lead wire effect, reflected in the temperature measurement. To compensate for lead wire effect, three-wire and four-wire RTDs are used instead of two-wire RTDs. Three-wire RTDs are created by connecting one additional copper wire to one of the lead wires. Four-wire RTDs are created by connecting one additional copper lead wire to each of

the existing lead wires. These additional wires are used by the transmitter to compensate for lead wire resistances.

The third wire compensates for the resistance of the lead wires based on the assumption that each wire has exactly the same resistance. In fact, there is a tolerance of 10% in the resistance of standard wires. The fourth wire compensates for the uncertainty in the resistance of wires. For example, 500 feet of 20 gauge cable would add 10 ohms, which would cause a measurement error of 26°C (47°F) for a two-wire RTD. The 10% tolerance of the cable could create an error as large as 2.6°C (4.7°F) for a three-wire RTD. For high-accuracy applications or long-extension wire runs, a four-wire RTD or a transmitter mounted on the thermowell (integral mount) should be used. The increased accuracy, stability, and reliability of microprocessor-based transmitters and the advent of secure and reliable wireless networks make integral-mounted transmitters an attractive option. Accessibility is less of an issue because maintenance requirements are drastically reduced. The transmitters rarely need removal, wiring problems are gone, and calibration checks and integrity interrogation can be done remotely.

Thermocouples (TC)

A thermocouple (TC) consists of two wires of dissimilar metals (e.g., iron and constantan) that are joined at one end to form a *hot junction* (or sensing element). The temperature measurement is made at the hot junction, which is in contact with the process. The other end of the TC lead wires, when attached to a transmitter or volt meter, forms a *cold* or *reference junction*.

Thermocouple types

Several types of TCs are available, each differing by the metals used to construct the element. While accuracies are better for type T and E compared to J, the type selected in industry often comes down to the plant standards and the application temperature range. The following are several types of thermocouples:

- Type E—Chromel and constantan
- Type J—Iron and constantan
- Type K—Chromel and alumel
- Types R and S—Platinum and rhodium (differing in the % of platinum)
- Type T—Copper and constantan

Hot junction configurations

Junctions can be grounded or ungrounded to the sensor sheath. With dual-element TCs (two TCs in one sheath), the elements can be isolated or connected (“unisolated”). Each configuration offers benefits and limitations:

- **Grounded**—Grounding creates improved thermal conductivity, which in turn gives the quickest response time. However, grounding also makes TC circuits more susceptible to electrical noise (which can corrupt the TC voltage signal) and may cause more susceptibility to poisoning (contamination) over time.
- **Ungrounded**—Ungrounded junctions have a slightly slower response time than grounded junctions, but they are not susceptible to electrical noise.
- **Unisolated**—Unisolated junctions are at the same temperature, but both junctions will typically fail at the same time.
- **Isolated**—Isolated junctions may or may not be at the same temperature. The reliability of each junction is increased because failure of one junction does not necessarily cause a failure in the second junction.

The Seebeck effect

TCs use a phenomenon known as the Seebeck effect to determine process temperature. According to the Seebeck effect, a voltage measured at the cold junction of a TC is proportional to the difference in temperature between the hot junction and the cold junction. The voltage measured at the cold junction is commonly referred to as the Seebeck voltage, the thermoelectric voltage, or the thermoelectric EMF. As the temperature of the hot junction (or process fluid) increases, the observed voltage at the cold junction also increases by an amount nearly linear to the temperature increase.

Cold junction compensation

As with RTDs, each type of TC has a standard curve. The standard curve describes a TC's voltage versus temperature relationship when the cold junction temperature is 0°C (32°F). As mentioned, the cold junction is where the TC lead wires attach to a transmitter or volt meter. Because the voltage measured at the cold junction is proportional to the difference in temperature between the hot and cold junctions, the cold junction temperature must be known before the voltage signal can be translated into a temperature reading. The process of factoring in the actual cold junction temperature (rather than assuming it is at 0°C [32°F]) is referred to as cold junction compensation.

Installation

The best practice for making a temperature measurement is to keep the length of the sensor wiring as short as possible to minimize the effect of electromagnetic interference and other interference on the low-level sensor signal. The temperature transmitter should be mounted as close to the process connection as possible. To minimize conduction error (error from heat loss along the sensor sheath or thermowell wall from tip to flange or coupling), the immersion length should

be at least 10 times the diameter of the thermowell or sensor sheath for a bare element. Thus, for a thermowell with a

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1 inch outside diameter, the immersion length should be 10 inches. For a bare element with a ¼ inch outside diameter sensor sheath, the immersion length should be at least 2.5 inches. Computer programs can compute the error and do a fatigue analysis for various immersion lengths and process conditions. For high velocity stream and bare element installations, it is important to do a fatigue analysis because the potential for failure from vibration increases with immersion length.

The process temperature will vary with process fluid location in a vessel or pipe due to imperfect mixing and wall effects. For highly viscous fluids such as polymers and melts flowing in pipes and extruders, the fluid temperature near the wall can be significantly different than at the centerline (e.g., 10 to 30°C; 50 to 86°F). Often the pipelines for specialty polymers are less than 4 inches in diameter, presenting a problem for getting sufficient immersion length and a centerline temperature measurement.

The best way to get a representative centerline measurement is by inserting the thermowell in an elbow facing into the flow. If the thermowell is facing away from the flow, swirling and separation from the elbow as can create a noisier and less representative measurement. An angled insertion can increase the immersion length over a perpendicular insertion, but the insertion lengths are too short unless the tip extends past the centerline. A swaged or stepped thermowell can reduce the immersion length requirement by reducing the diameter near the tip.

The distance of the thermowell in a

pipeline from a heat exchanger, static mixer, or desuperheater outlet should be optimized to reduce the transporta-

tion delay but minimize noise from poor mixing or two-phase flow. Generally 25 pipe diameters is sufficient to ensure sufficient mixing after the recombination of divided flows from heat exchanger tubes or static mixer elements. For desuperheaters, the distance from the outlet to the thermowell depends upon the performance of the desuperheater, process conditions, and the steam velocity. To give a feel for the situation, there are some simple rules for the straight piping length (SPL) to the first elbow and the total sensor length (TSL). Actual SPL and TSL values depend on the quantity of water required with respect to the steam flow rate, the temperature differential between water and steam, the water temperature, pipe diameter, steam velocity, model, type, etc., and they are computed by software programs.

$$\text{SPL (feet)} = \text{Inlet steam velocity (ft/s)} * 0.1 \text{ (s)}$$

$$\text{TSL (feet)} = \text{Inlet steam velocity (ft/s)} * 0.2 \text{ (s)}$$

Typical values for the inlet steam velocity, upstream of the desuperheater range from 25–350 ft/s. Below 25 ft/s, there is not enough motive force to keep the water suspended in the steam flow.

ABOUT THE AUTHOR

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