Temperature Measurement Applications in Process Plants

By Ravi Jethra
Endress+Hauser Inc.
Greenwood, IN 46143

Abstract

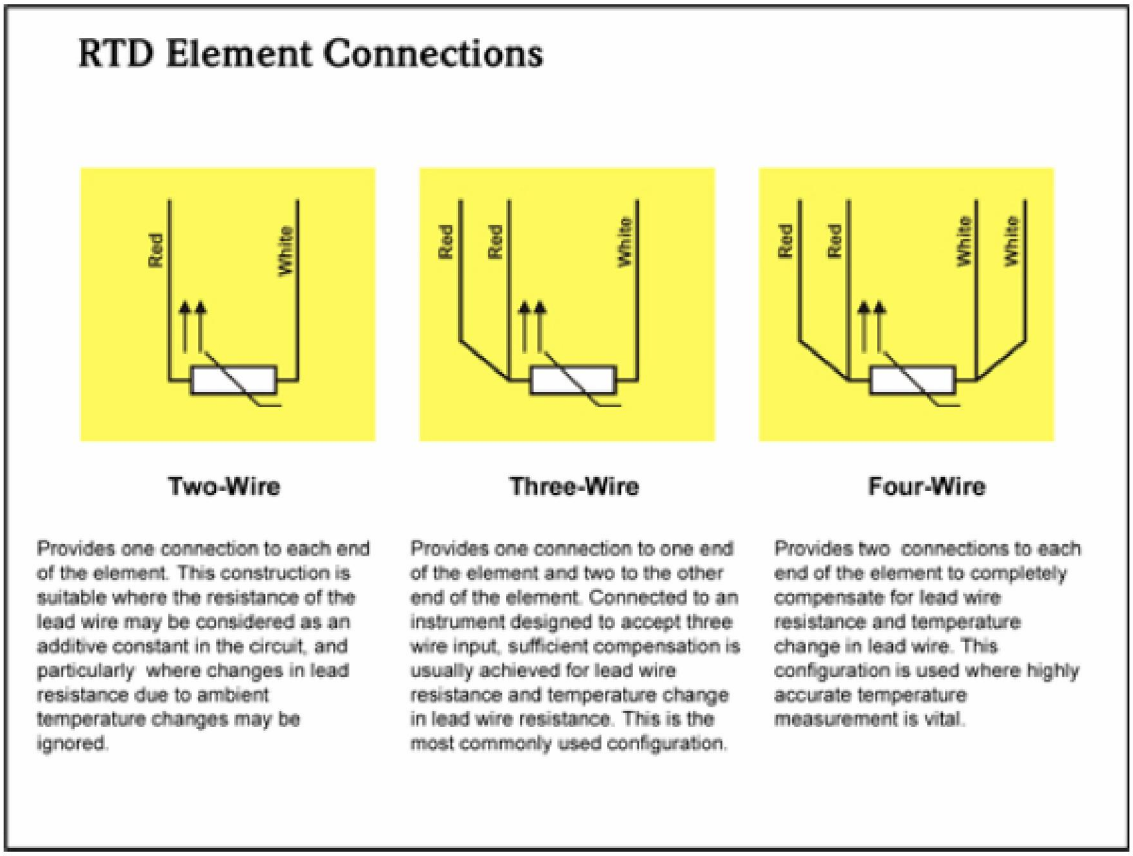
Temperature is one of the most common measurement parameter used for monitoring and control in process industries. This paper covers some of the basics of temperature measurement, and leads into some of the technical advances that impart higher a degree of safety and reliability to process plant operation. These advances are based on some of the latest and innovative technologies that are being implemented in process instrumentation.

Irrespective of the type of process plant, temperature measurement remains high on the list for operational excellence throughout the plant. Implementation of some of the new technologies results in improved safety and lower installation and maintenance costs. Incorrect measurement information due to temperature effects, non linearity or stability can result in major equipment getting damaged. Ensuring instruments that have minimal downtime from a maintenance standpoint, not just devices that have been evaluated to provide safety integrity level service in safety instrumented systems, is crucial for daily operations in a power plant.

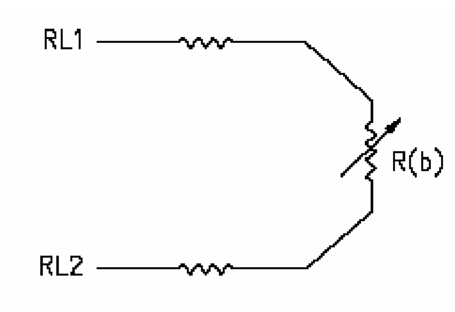
Introduction

An RTD is a device which contains an electrical resistance source (referred to as a "sensing element" or "bulb") which changes resistance value depending on its temperature. This change of resistance with temperature can be measured and used to determine the temperature of a process or of a material. RTD sensing elements come in two basic styles, wire wound and film. Besides the sensing element, which we have previously discussed, the measuring circuit also consists of a combination of lead wires, connectors, terminal boards and measuring or control instrumentation. The exact make-up of the measurement circuit is dependent on many factors including:

- Temperature in the sensing area as well as the environmental conditions expected to exist between the sensor and instrumentation.
- Distance between the sensor and instrumentation.
- Type of interconnections the customer prefers.
- What type of wiring system is currently in place (if not new).

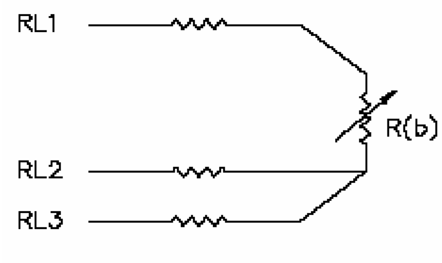


2-wire construction is the least accurate of the 3 types since there is no way of eliminating the lead wire resistance from the sensor measurement. 2-wire RTDs are mostly used with short lead wires or where close accuracy is not required.



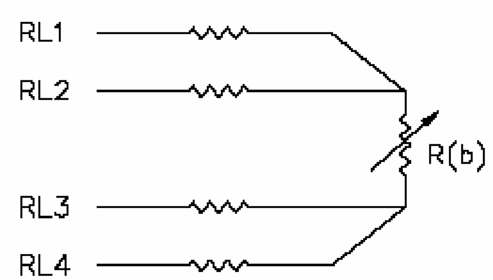
Measured resistance Rt = R1 + R2 + Rb

The 3-wire construction is most commonly used in industrial plant applications where the third wire provides a method for removing the average lead wire resistance from the sensor measurement. When long distances exist between the sensor and measurement/control instrument, significant savings can be made in using a three-wire cable instead of a four-wire cable.



(R 1+2+R b) - (R 2+3) = (R b)

The 3 wire circuit works by measuring the resistance between #1 & #2 (R 1+2) and subtracting the resistance between #2 & #3 (R 2+3) which leaves just the resistance of the RTD bulb (R b). This method assumes that wires 1, 2 & 3 are all the same resistance 4-wire construction is used primarily in the laboratory where close accuracy is required. In a 4 wire RTD the actual resistance of the lead wires can be determined and removed from the sensor measurement.



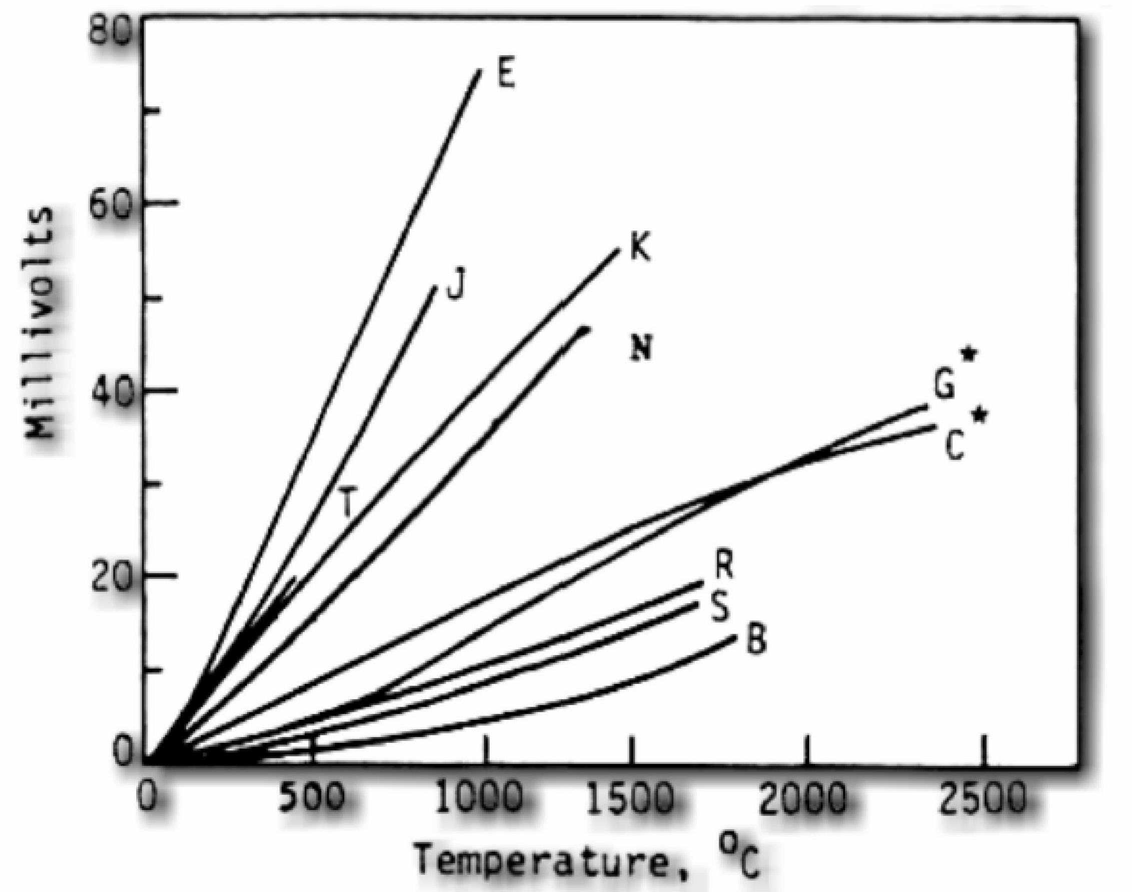
The 4-wire circuit is a true 4-wire bridge, which works by using wires 1 & 4 to power the circuit and wires 2 & 3 to read. This true bridge method will compensate for any differences in lead wire resistances.

Although RTDs are typically ordered as 100 Ohm Platinum sensors, other resistance's (200 Ohm, 500 Ohm, 1000 Ohm, etc.) and materials (Nickel, Copper, and Nickel Iron) can be specified. Since RTDs are a resistor, they will produce heat when a current is passed through them. The normal current limit for industrial RTDs is 1mA. Thin film RTDs are more susceptible to self-heating so 1mA should not be exceeded. Wire wound RTDs can dissipate more heat so they can withstand more than 1mA. The larger the sheath or the more insulation there is the better chance there will be an error caused by self heating.

Temperature coefficient for RTDs is the ratio of the resistance change per 1 deg. change in temperature over a range of 0-100 deg. C. This ratio is dependent on the type and purity of the material used to manufacture the element. Most RTDs have a positive temperature coefficient which means the resistance increases with an increase in temperature. The temperature coefficient for pure platinum is .003926ohm/ohm/deg.C. The normal coefficient for industrial RTDs is .00385ohm/ohm/deg.C per the DIN std. 43760-1980 & IEC 751 - 1983.

Ni120 RTDs are more commonly used in the process industry. It is important to ensure that transmitters that are being used have the curves/linearization data built-in to the memory for the specific RTD without the need for any custom programming.

Thermocouples:
Base metal thermocouples are known as Types E, J, K, T and N and comprise the most commonly used category of thermocouple. The conductor materials in base metal thermocouples are made of common and inexpensive metals such as Nickel, Copper and Iron.



Type E: The Type E thermocouple has a Chromel (Nickel-10% Chromium) positive leg and a Constantan (Nickel- 45% Copper) negative leg. Type E has a temperature range of -330 to 1600°F, has the highest EMF Vs temperature values of all the commonly used thermocouples, and can be used at sub-zero temperatures. Type E thermocouples can be used in oxidizing or inert atmospheres, and should not be used in sulfurous atmospheres, in a vacuum or in low oxygen environments where selective oxidation will occur.

Type J: The Type J thermocouple has an Iron positive leg and a Constantan negative leg. Type J thermocouples can be used in vacuum, oxidizing, reducing and inert atmospheres. Due to the oxidation (rusting) problems associated with the iron leg, care must be used when using this thermocouple type in oxidizing environments above 1000°F. The temperature range for Type J is 32 to 1400°F.

Type K: The Type K thermocouple has a Chromel positive leg and an Alumel (Nickel-5% Aluminum and Silicon) negative leg. Type K is recommended for use in oxidizing and completely inert environments.

Type N: The Type N thermocouple has a Nicrosil (Nickel-14% Chromium- 1.5% Silicon) positive leg and a Nisil (Nickel- 4.5% Silicon- .1% Magnesium) negative leg. Type N is very similar to TYPE K but is less susceptible to selective oxidation effects. Type N should not be used in a vacuum or in reducing atmospheres in an unsheathed condition. The temperature range is 32-2300 deg F.

Type T: The Type T thermocouple has a Copper positive leg and a Constantan negative leg. Type T thermocouples can be used in oxidizing, reducing or inert atmospheres, except the copper leg restricts their use in air or oxidizing environments to 700°F or below. The temperature range for Type T is -330 to 700°F.

Noble Metal Thermocouples are another category of thermocouples and are made of the expensive precious metals Platinum and Rhodium. There are three types of noble metal thermocouples:

- Type B (Platinum/Platinum-30% Rhodium)
- Type R (Platinum/Platinum-13% Rhodium)
- Type S (Platinum/Platinum-10% Rhodium)

Types R and S have temperature ranges of 1000 to 2700°F and Type B thermocouples have a temperature range of 32 to 3100°F. Types E, J, and T they find widest use at temperatures above 1000°F. Type K, like Type E should not be used in sulfurous atmospheres, in a vacuum or in low oxygen environments where selective oxidation will occur. The temperature range for Type K is -330 to 2300°F.

RTDs vs. T/Cs Characteristics

RTD Strengths: RTDs are commonly used in applications where accuracy and repeatability are important. Common instrumentation wire is used to couple the RTD to the measurement and control equipment making them more economical to install as compared to thermocouples which must use special extension wire, much like the composition of the thermocouple itself, to extend the wiring to the control equipment.

RTD Weaknesses: An RTD in the same physical configuration as a thermocouple will typically be 3 to 7 times the cost. RTDs are more sensitive to vibration and shock than a thermocouple and are limited to temperatures of approximately 800°F.

Thermocouple Strengths: A thermocouple can be used to temperatures as high as 3100° F. They generally cost less than RTDs and can be made smaller. TCs will respond faster to temperature changes and are more durable allowing use in high vibration and shock applications.

Thermocouple Weaknesses: Thermocouples are less stable than RTDs when exposed to moderate or high temperature conditions. Thermocouple extension wire must be used in hooking up thermocouple sensors to measurement instruments.

Summary:

RTDs and thermocouples are widely used in process plant temperature measurement. Each has its advantages and disadvantages. The application will determine which sensing element is best suited for the job. An RTD will provide higher accuracy and more stability than thermocouples. They also use standard instrumentation wire to couple the sensor to the measurement device. Thermocouples are less expensive than RTDs, are more durable in high vibration and mechanical shock applications and tolerate higher temperatures than RTDs. They can be made smaller than RTDs, generally, and can be formed to fit specific applications.

Over half of the temperature applications in the United States, and most often in process plants, involve direct wiring a temperature sensor to the controls system. Despite the large installed base of direct wired sensors, the trend is towards using transmitters in conjunction with temperature sensors.

TRANSMITTERS VS DIRECT WIRING

For temperature measurement, engineers must decide whether they wire the sensors directly to the control system (PLC, DCS, recording system…) or if they use transmitters. Nowadays, many engineers still wire direct because they mistakenly believe this is a cheaper and easier solution. The reality however, is that different: transmitters allow an engineer to save time and money, improve the measurement reliability and facilitate maintenance.

Why use transmitters?

Reduce wiring costs

If you do not use a transmitter, you need sensor extension wires to the control system for a precise temperature measurement. These wires are expensive and sometimes fragile. By using a transmitter, you only need inexpensive copper wires. The greater the distance between the sensor and the control system, the more money that can be saved! For applications involving, using a Pt100 4-wire, only a pair of wire is needed to run from the transmitter to the control system.

Basic information about thermocouple wiring: (Refer graphic below- Fig 1) There are 4 typical wiring setups:

- using extension wires to the transmitter
- using compensation wires to the transmitter
- using the thermocouple wires to the head mounted transmitter
- wiring direct to the control system

Extension wires:

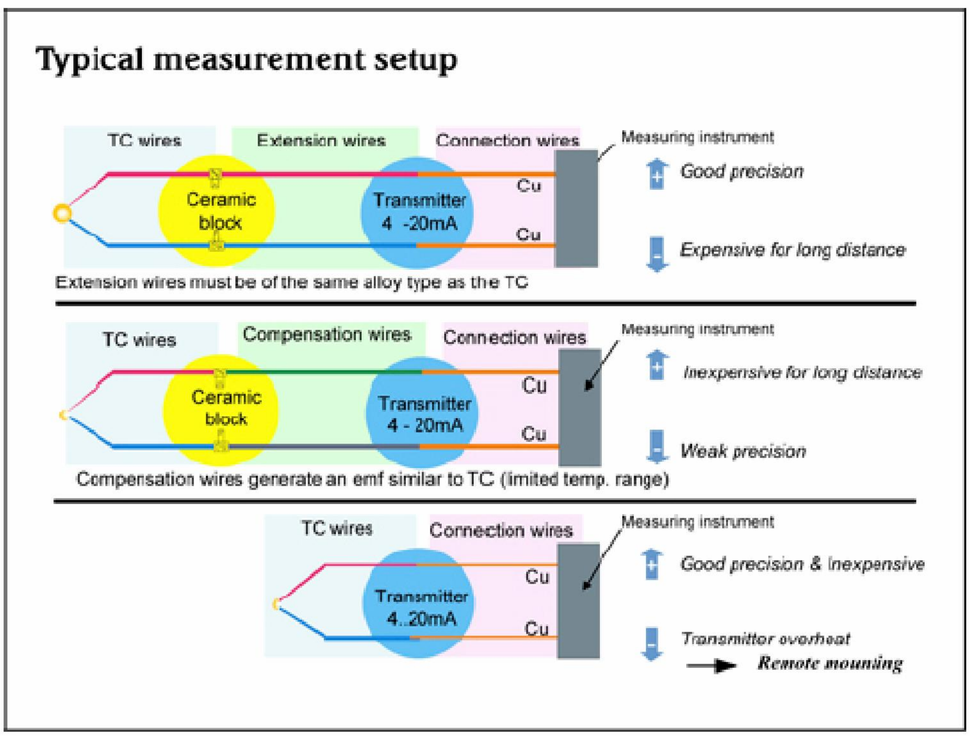
They are manufactured as stranded or solid conductors with various insulating materials and armoring. The conductors (the flexible strands or solid wires) consist of substitute materials. When a relatively flexible cable is required, flexible conductors are used. These conductor materials and the corresponding thermocouples have the same nominal structure and chemical composition.

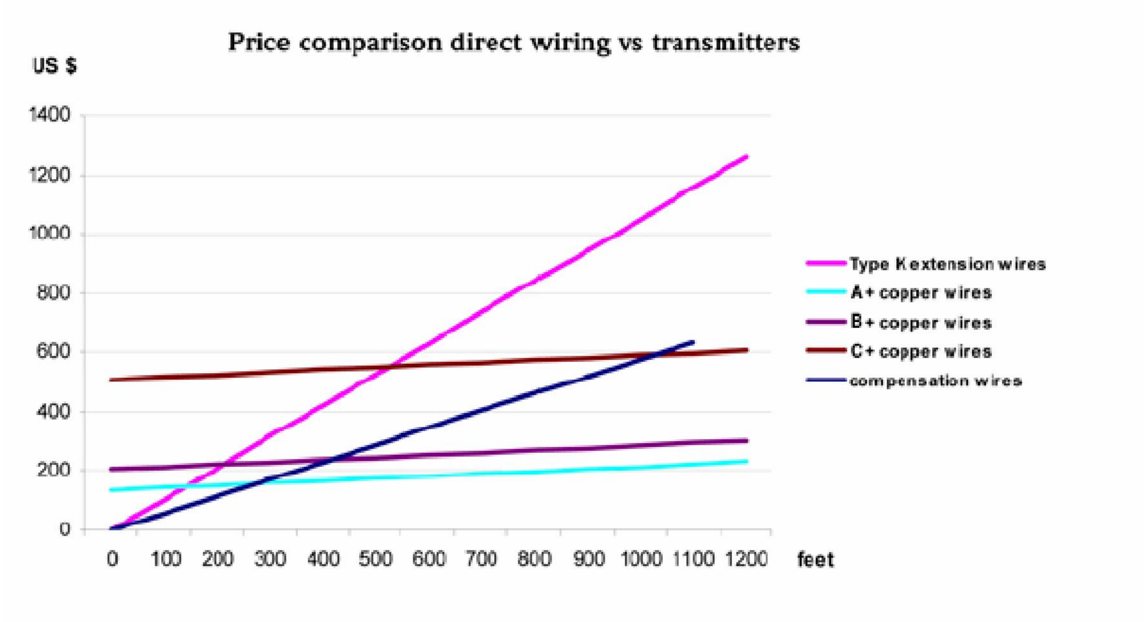
<u>Compensation cables:</u>
They are manufactured as solid conductors with various insulating materials and armoring. The conductors (the flexible strands or solid wires) are made of substitute materials and therefore their chemical composition differs from the corresponding thermocouple material. Different alloys may be used for the same thermocouple type. The substitute material and the corresponding thermocouple have the same thermoelectric characteristics within the allowed temperature range.

Let’s take a look at what distance it becomes economically sound to use transmitters: Example: Type K thermocouple.

<u>Assumptions:</u>

- Extension wires (twisted and shielded): $1.15 / foot
- Compensation wires (twisted and shielded): $0.78 / foot
- Copper connection wires : $0.10 / foot





Breakeven with extension wires:

PC Programmable DIN-rail transmitter (A): $175	Breakeven at 130 feet
HART head transmitter: $245 (B)	Breakeven at 200 feet
HART field transmitter: $670 (C)	Breakeven at 500 feet

(refer graphic above figure 2)

Breakeven with compensation wires:

PC Programmable DIN-rail transmitter: $135	Breakeven at 270 feet
HART head transmitter: $205	Breakeven at 410 feet
HART field transmitter: $510	Breakeven at 1020 feet

Eliminate plant noise

Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) are present in almost all types of plants. Their effects on the extension wires are important and obviously affect the measured value. By using transmitters, the temperature measurement can be made immune to EMI/RFI problems. EMC compliance to IEC61326 is necessary for use in noisy environments

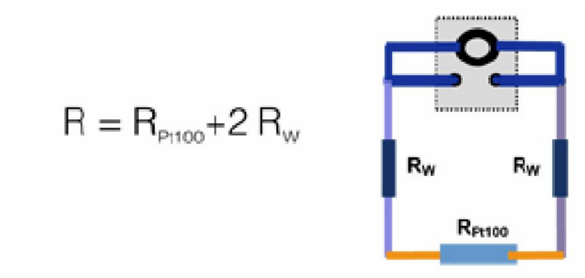
Make maintenance easier / Advanced diagnostics

You can save long and unnecessary trips to the field. The smart diagnostics capabilities of the sensor indicate (via HART® and upscale/downscale output signals) if the sensor is broken or if there is corrosion on the sensor input loop.

Increase accuracy

Temperature transmitters not only accept RTD inputs with 2, 3 or 4 wires. There are over two dozen different types of RTDs or thermocouples that can be connected to a transmitter without the need for special programming.

As can be seen from the calculations below (Fig 2), a 2-wire RTD would produce the largest error because the measured resistance is the combination of the sensor and the wires.



Example 1: Pt100 RTD 2-wire connection with direct wiring

l	→ Distance to control system	l	= 50m (164 feet)
ρ	→ Resistivity of copper (Cu)	ρ	= 0.0175 Ω x mm^2 / m (20°C)
A	→ Wire cross section	A	= 1.25 mm^2 (AWG16)
R_w	→ Lead wire Resistance	R_w	= ?

$$R_w = \frac{l \times \rho}{A} = \frac{50m \times 0.0175\Omega \times mm^2}{1.25mm^2 \times m} = 0.7\Omega$$

IEC751 at t = 20°C → R_{Pt100} = 107.79 Ω

Resistance seen by the transmitter due to lead wire resistance → R

$$R = R_{Pt100} + 2 \times R_w = 107.79\,\Omega + (2 \times 0.7\,\Omega) = 109.19\,\Omega$$

IEC751 R_{Pt100} = 109.19 Ω → t ~ 23.6 °C **Basic error:** **3.6 °C or 6.48 °F**

Wires add an inaccuracy of 3.6°C (6.48°F) whereas transmitters send an amplified 4-20 mA temperature proportional output signal to the control system.

Reduce control systems costs
If you wire directly to the control system, you need several different input cards for different sensor types.

Price for a 4-channel RTD input card: $399.00
Price for a 4-channel TC input card: $399.00
Price for a 4-channel 4-20mA Analog input card: $225.00

This also makes things simpler for process engineers since only one input type would be used (same 4-20mA card for flow, pressure, level… inputs).

What about routine maintenance? You can switch from a thermocouple to a Pt100, simply reconfigure the transmitter and send the output to the control system.

Allow sensor flexibility
You need a new sensor type? Just replace it and use the same transmitter since transmitters accept universal inputs (12 different thermocouple types, 6 different RTD,

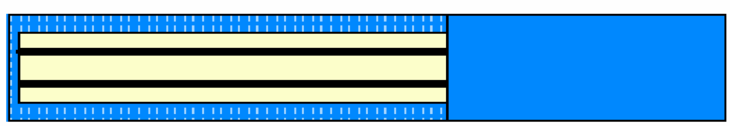
mV and Ohms). You can switch to another sensing element without worrying about the installation and wiring changes.

Avoid ground loops
In applications where fast response time is needed, customers use grounded thermocouples. This thermocouple type may cause a ground loop. This will be avoided by using transmitters with superior galvanic isolation (up to 2kV galvanic isolation).

Ground is an elusive and often misunderstood electrical concept. Its very name implies that the soil we walk on is the place to which all currents and voltages are somehow referred. In an electric power distribution system, a rod driven into the earth or a buried metal pipe is 'ground.' Unfortunately, that is not the entire the story. The local 'ground' where you are now located can be several volts above or below that at the nearest building or structure. If there is a nearby lightning strike, that difference can rise to several hundreds or thousands of volts. This arises not only from the resistance of wiring but its inductance. If the currents change very rapidly, the voltage drops in the ground system will approach several hundred volts for short periods of time. Some of the instrumentation installed in today's industrial plant is wired in close proximity to power wiring.

For example, studies conducted by industrial process companies have shown that the operation of an oil burner igniter can produce transient differences up to 2000 volts routinely. Imagine the potential for similar voltage spikes in other industrial environments. The voltages themselves can obviously provide a great source of interference for a measurement loop, but the currents which cause them can also induce significant currents and voltages in the signal wires located nearby. Circulating currents in ground loops may also be periodic in addition to being transient events.

Grounded Thermocouples:



Ground loop potentials and currents are a major problem for this thermocouple type.

There is one completely satisfactory way to solve these problems — insert an isolation stage between the signal and the rest of the measurement system.

Ground loop problems are most likely to occur in industrial plant environments such as:
- Aluminum smelters (High operating voltages in smelters)
- Cement plants, power plants (High voltages relating to material handling equipment)

In applications where fast response time is needed, customers use grounded thermocouples.

This thermocouple type may cause a ground loop. This will be avoided by using a transmitter with good galvanic isolation (2kV). You might also have this problem with an ungrounded sensor in case of insulation breakage…

The Need for Galvanic Isolation

Isolation is a universal way to eliminate ground loop problems. Isolation simply means using one of a number of electronic techniques to interrupt the connections between two grounds while passing the desired signal with little or no loss of accuracy. Without a path for ground currents to flow, these currents cannot induce signal errors. Isolation also solves the other problem encountered with ground loops — voltage differences which cannot be rejected by the signal conditioner.

Galvanic isolation refers to a design technique which will separate signal currents from AC power distribution introduced stray noise currents. Basically this process will provide two separate paths for signal and noise currents which will not allow them to mix or to mix only over short distances, thereby minimizing the effects of noise currents on the signals.

An example of Galvanic Isolation method is a transformer. It provides galvanic isolation in that no electrical current can flow directly from one winding to the other as they are not in direct electrical contact. However, a signal can flow via electromagnetic coupling between the two windings.

Why use galvanic ally-isolated transmitters for non-grounded RTD applications?

This question is often being raised by users of RTD sensors. Since Pt-100 thermal elements are not usually grounded, it is often assumed that they do not require isolated transmitters for proper operation. If the measurement environments were ideal, indeed this assumption could be, at least, partially correct. Unfortunately, industrial environments are often ridden with various types of airborne contaminants in solid, liquid and gaseous forms. These may precipitate and settle inside, and around the instruments' and the sensors' terminals. Add just a little bit of humidity and you have created several potential parasitic leakage current paths, which could seriously affect the device measurement accuracy as well as the signal integrity.

Parasitic resistance paths may also be caused as a result of metal migration internal to the sensor structure, but these are not related to environmental conditions and are more common in sensors used at elevated temperatures. Isolated transmitters break the path of the parasitic resistance and prevent a leakage current from flowing through the transmitter's circuitry, hence avoiding the errors almost entirely.

Galvanic ally- Isolated transmitters in general also provide for a far superior noise rejection as well as far superior protection from electrical transients and surges in electrically noisy environment or during weather extremes such as lightning or thunderstorms.

The current generation of temperature transmitters has a galvanic isolation that is at least about 3-5 times better than any the previous generation units.

Corrosion detection
Corrosion of the sensor connections can lead to corruption of the measured value. Temperature transmitters now offer the option of detecting corrosion on thermocouples and resistance thermometers with a 4-wire connection before measured value corruption occurs. Sensor connection cable corrosion can lead to false measured value readings.

Sensor backup
Sensor backup offers you maximum safety. If sensor 1 fails, the device automatically switches to sensor 2.

Low Voltage Warning
Temperature transmitters now have the capability to provide a low voltage warning if the potential drops below a threshold value. The alternative is to continue reading with some of the older transmitters and get a faulty reading when the voltage levels drop. When voltage falls below 11V dc, the unit indicates warning for low voltage instead of continuing to send you a false and misleading reading! With older technology transmitters, when voltage drops, the unit continues to send a signal, although it could be off by as much as 25% or higher from the reading.

Gold-plated terminals (virtually eliminates corrosion of terminals). Customer saves big-time for not having to replace a transmitter if the terminal block goes bad, as with some of the low-end transmitters.

- 6 large-size terminals for sensor connection. No need to share terminals between sensors - minimize chances of mis-wiring. Transmitters are now available that can take AWG12 wire; no need to mess with tiny screw drivers.
- Wiring graphic is laser etched on terminal block - How many times has a technician gone to site without an Instruction Manual? Well, it's no longer a problem with the transmitters currently available.
- Ambient Temperature Monitoring – Transmitters now have built-in RTD at the electronics module that monitors for ambient temperature. When temperature exceeds the limits the unit is specified for, the unit gives a warning indication. With older transmitters, the unit would just get its electronics module cooked, by the time the customer comes to know about it.
- Large and brilliant blue back-lit display. Irrespective of whether you mount the transmitter in a pitch dark location or in path of direct sunlight - you can still get a clear reading from a distance of 8-10 feet. The digits on a new transmitter display are a least twice the size of any of the older devices. So you can see it from a farther distance. Transmitter displays now also have a bar graph to give you a visual indication from an even farther distance on reading.
- Split- ranging function for dual sensor units. Switch reading from sensor 1 to sensor 2 dependent on temperature

Temperature Measurement Application Guidelines

a. Previously, we stated that a thermocouple signal is a very small voltage (millivolt) and because of this weak signal, thermocouples are very susceptible to electrical noise. These stray voltages can come from many sources such as electric motors, heaters or even 2 way radios. To avoid this problem, use an ungrounded thermocouple and shielded extension wire.

b. There should never be a third metal in the hot junction to create a thermocouple junction, all that is needed is to electrically short the ends together. Butting the wire ends against a metal surface will create a junction. Remember, that the thermocouple signal is generated over the entire length of wire.

c. Non-thermocouple materials cannot be used in the thermocouple circuit. It is permissible to use non-thermocouple materials as terminal blocks or splices as long as there is no temperature gradient across these devises.

d. The largest possible extension wire should be used to connect a thermocouple. This phrase used to be true 30 years ago before there was solid state electronics. The old instruments were Voltage based circuits and resistance was critical. The newer solid state electronics are current based so extension wire resistance is not important.

e. Transmitter Grounding: The transmitter will operate with the current signal loop either floating or grounded. However, the extra noise in floating systems affects many types of readout devices. If the signal appears noisy or erratic, grounding the current signal loop at a single point may solve the problem. The best place to ground the loop is at the negative terminal of the power supply. Do not ground the current signal loop at more than one point. The transmitter is galvanic ally isolated to 2 kV AC (from sensor input to output), so the input circuit may also be grounded at any single point. When using a grounded thermocouple, the grounded junction serves as this point. When installing a transmitter; the shield on the analog output must have the same potential as the shield at the sensor connections. In plants with strong electro-magnetic fields, shielding of all cables with a low ohm connection to ground is recommended. Shielded cable should be used in outdoor installations, due to the danger of lightning strikes.

f. RTDs are now specified according to IEC751 curve or calibration standards, with an alpha =0.00385. For lot of the process plants that were built several years ago with older field instruments, caution is advised while replacing older RTDs. The alpha coefficient value for the existing RTD should be checked before ordering a replacement.

g. Temperature Measurement points in a Power plant

- Coal Mill, Oil or natural gas supply
- Residue Disposal : Gypsum treatment
- Water supply and treatment
- Heat Generation : Main firing system, combustion air system, electrostatic precipitator, desulphurization, de-nitrification
- Steam/Water : feed water system, condensate system
- Turbines : Steam, Gas, Lubricant supply

The graphic above shows a field installation for controlling temperature and pressure of steam in the low-pressure system. These are process inputs for controlling the regulating valve. The head mount temperature transmitter is used in conjunction with an integrated temperature sensor assembly.

The graphic below shows three temperature instruments (sensor and transmitter) in the steam pipe to the middle-steam header. The temperature sensors are Thermocouples. It is designed with 2 out of 3-measurement choice for reliability and safety.

Compact Transmitters

Water, pressure, heat and chemicals from wash down procedures combine to create a highly moist and corrosive environment that can be damaging to traditional temperature sensors and transmitters. Short sensor life, repeated replacement, and even potential failures all can be a direct result from this environment. An integral temperature sensor and transmitter offers a unique solution for wash down environments and many others. The compact temperature transmitter consists of a 4-wire Pt 100 Class A sensor, available in several different lengths, built-in 4-20mA transmitter. Its integral design offers power plant personnel a low-cost device for temperature monitoring that is resistant to moisture and corrosion. Waterproof and impervious to water, steam, pressure and chemicals, the design of the compact device uses no external screw connections. Instead, they are available with M12 micro-connector that easily plugs in to a commercially available cable eliminating any potential for mechanical damage to the temperature device or other cable. The miniature RTD is hermetically sealed and both the sensor and transmitter are completely potted to withstand the rigors of the process and provide accurate and reliable measurement.

The compact temperature transmitter is ideal for monitoring temperature in the smallest places, for example within tanks and pipes that are not exposed to high pressures or temperature extremes.

Summary

Temperature sensors are commonly used with direct wiring to the control system. The benefits of using transmitters however, have led to an increasing trend of their use. The benefits relate not only to cost savings but also reduced downtime, maintenance and advanced diagnostics. Transmitters also offer the option of digital communication protocols such as HART, Foundation fieldbus and Profibus. Future technology advances would be on the lines of improved software that is intuitive and easier to program, availability of more diagnostics and service tools to facilitate commissioning and maintenance.

References

Recommended Books for additional reading:

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Author the Author

Ravi Jethra is currently employed by Endress+Hauser as Product Performance Manager – Temperature with a secondary role in Power industry. He is based in Greenwood, IN and can be contacted at (317) 535 2147.