Improving Temperature Measurement Accuracy in Biopharmaceutical Processes

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What we’ll discuss today

Designing a sensor and installation method specifically for an application yields the best temperature measurement.

Today we’ll discuss sensor selection, installation, and actions you can take to move beyond ± 0.5°C temperature measurement accuracy.

The goal is to improve accuracy and achieve lowest life cycle cost for the measurement point:

- Sensor selection
- Installation
- Calibration
- Transmitter
- Preventive maintenance

Lowest life cycle cost includes all the costs of making and maintaining the temperature measurement and minimizing energy costs associated with the process.

Accurate temperature measurement results in efficient use of energy and consistent product quality.

Selection

Many times the largest errors are due to the installation. Proper selection of the sensor and piping design can go a long way toward minimizing the error.

RTDs are not all created equal. In addition to interchangeability, review specifications for vibration resistance, temperature cycling, and long term drift.

First item to consider is the sensor interchangeability.
Interchangeability refers to the "closeness of agreement" between an actual sensor R vs. T relationship and a predefined R vs. T relationship.

ASTM E1137 and IEC 60751 are the two most commonly used standards that define a nominal R vs. T relationship. All sensors are manufactured with 0°C as the starting point. Variations in sensors result in the tolerance increasing as the temperature diverges from 0°C.

These equations can be used to calculate the interchangeability at any temperature. Note that the temperature t is an absolute value in °C. The resultant is the interchangeability in ± °C.

Note that the ASTM standard has slightly tighter tolerances for the two grades of sensors. All RTDs are built with the tightest tolerance at 0°C and as the temperature diverges from 0°C the tolerance increases. The vertical line on the graph represents 0°C and the tolerance on the y axis is expressed in ± °C from nominal.
Stability or long term drift is an important consideration in selecting an RTD for best accuracy. As you can see from the graph as temperature goes up the drift becomes much more significant.

“How far can I run the lead wires from RTD to signal conditioner?” is a commonly asked question and one with more than one answer.

Three wire RTD circuits have an inherent error associated with them because of differences in resistance of each lead wire. There are methods to minimize these errors.
Lead wires used to connect the sensor to a process control instrument can cause a measurement error.

Two and three wire circuits have the largest errors and the 4 wire will eliminate the error.

The table shows some maximum recommended cable lengths in feet to contain the lead wire error for the Grade A and Grade B sensors. As the wire size decreases so does the recommended cable length.

The best method is to use a 4 wire circuit which fully compensates for lead wire resistance in the circuit. Three wire circuits can be trimmed so that each leg is of equal resistance.

Two wire circuits are typically used for 1000 ohm RTDs in HVAC applications where low cost control equipment is used. The lead resistance becomes a very small percentage of the circuit and has minimal affect on accuracy when used with a 1000 ohm or greater sensor.
A 3 wire circuit provides an accurate measurement if the resistance in L1 = L3.

Using the current potential method in a 4 wire circuit eliminates all lead resistance and any terminal block or connector resistance. A known current is applied to L1 and L4 and a voltage measurement is made between L2 and L3. Then just do the math to find the resistance.

For 3-wire sensors, error is directly related to variation in lead resistance:
- Every .04 ohm variation results in ~ 0.1°C error
- Examples – assume 10% mismatch in resistance worst case
  - 22 AWG copper, nominal resistance .016Ω/foot
    - .004°C/foot error, typical 10’ cable = .04°C error
  - 30 AWG copper, nominal resistance .104 Ω/foot
    - .026°C/foot error, typical 10’ cable = .26°C error

Some examples of measurement errors due to lead wires in a 3 wire circuit. As you can see, the error grows quite fast with decreasing cable size and length.
One of the most common error sources is insufficient immersion. Sensor design can help minimize the error and is especially true for measurements in small lines. We’ll look at several that address the error.

Minimize thermal conduction path between sensor and process
- Small diameter sensor
- Direct immersion
- Tip sensitive sensor in thermowell

Sufficient immersion
- \(10 \times \text{the diameter (sensor or T-well OD)} + \text{sensitive length}\)
- Insulation added to external portions of the sensor
- Heat transfer compound in the thermowell

Choosing the proper sensor and installation configuration are two important considerations for achieving measurement accuracies less than 0.5°C.

First the sensor design selection needs to be compatible with the process. Line size, fluid properties, and flow rate affect the choice of sensor and installation technique.

Of all the error sources stem conduction seems to cause the most problems especially in tight locations. A thermowell and RTD assembly requires at least 4.5” of immersion to minimize the error. A direct immersion RTD requires at least 10x the probe diameter plus the sensitive length. Most RTDs have a sensitive length of 1”. So for a \(\frac{1}{4}\)” diameter RTD the minimum immersion is 3.5”.

Insufficient immersion will allow the ambient conditions to have either a heating or cooling effect on the sensing element. Error magnitude increases as the difference in the ambient temperature and the process temperature increases.

For a pipe there are two options, surface mounted or immersion. The two parts on the left are just two of a wide variety of surface mount sensors available and the two on the right are examples of the two most common styles of immersion sensors.

Surface mount is a poor choice for high accuracy measurements of a process fluid.

Following are several sensor designs that perform well with short immersion lengths.
Mini sanitary style with 1/8” diameter stem to minimize stem conduction error. Minimum recommended immersion is 1.1”.

RTD and thermowell for small diameter lines. Thermowell is 3/16” diameter with minimum immersion of 1.25”. RTD is removable for ease of maintenance. System remains closed.

This one is an RTD and thermowell assembly that is 3/16” diameter and a 1/8” diameter RTD. At least 1.25” of immersion is necessary for an accurate measurement.

A hybrid surface mount RTD that installs in-line. Useful for high flow rates, viscous or sticky fluids, or where flow restriction has to be avoided.
A hybrid form of surface mount sensor is the non-intrusive. A sensing element is bonded directly to the process tubing and insulated with a high efficiency material. A SS cover protects the sensor from ambient conditions. Performance is better than a standard surface mount but is not as good as an immersion style.

An elbow thermowell works well for line sizes down to \( \frac{3}{8} \)”. They can be welded in or installed with clamp type fittings.

A special elbow fitting with an integral thermowell allows for sufficient immersion length in tubes down to 0.5” diameter.
Application: used where fast response and/or extra strength is needed for high flow rates or viscous products. Time constant is 3.5 seconds max.

Application: used in vessels and larger line sizes. Thermowell is 3/8” OD and installs with any size Tri-clamp® connection. RTD is spring loaded and attaches thermowell with a Tri-clamp® connection.

A variation of the direct immersion type has the sensor welded directly into a tube spool piece. The sensor is .083” diameter and has a 1” immersion.

Designed to replace a section of tubing and provide a very fast time response. The .083” diameter sensor is immersed directly in the fluid.
The sensor designs we just reviewed are capable of accurate measurement only if they are installed correctly. Next we’ll look at some details of how the sensor is installed.

Installation

Sensor installation can be done in a tee mounting configuration to maximize immersion and minimize stem conduction.
- Can be done with direct or indirect immersion

To gain additional immersion depth a tee fitting makes an excellent choice. Flow should be directly at the tip of the sensor to minimize vibration and drag effects.

In small diameter lines there is typically not enough room to get the proper immersion length to avoid stem conduction. This illustrates three methods of modifying the piping to provide extra room. The one on the right is the best method because it provides for the flow coming directly at the tip of the sensor for less stress on the probe and it also washes out the dead leg portion of the tee.
Stem conduction or immersion error is shown on this graph for various installation methods and probe types. Surface mount and incorrectly installed RTDs have the largest errors. Direct immersion and properly designed RTD/thermowell assemblies have the least error.

Air flow past the external portions of the sensor can exacerbate stem conduction error. The poorer the installation the more likely that a fan blowing on the assembly can increase the error.

This graph shows that a ¼” diameter direct immersion sensor will handle about 30 or 40 fps flow velocity and above that it can vibrate and fail. The same immersion length with a ¾ NPT tapered thermowell increases the safe flow velocity to 250 fps.
A thermowell and RTD assembly was immersed in a bath to determine the stem conduction at various depths. At 4.5 inches most of the error has disappeared. As you can see the error is mostly independent of the bath temperature used. As an example a thermowell with 2.5” immersion gives us an error of about 0.45°C.

Accuracy can be improved by matching a transmitter to the RTD if present in the measurement loop. Some have capability of being programmed with the calibration coefficients (most accurate) and others may only have zero and span adjustments.

At a minimum, the RTD resistance is checked in a temperature bath at the zero and span temperatures. Those resistance values are used to adjust the transmitter output. For those transmitters that have curve fitting capability, a full calibration of the RTD is performed and the resulting coefficients are entered into the transmitter.
Heads provide protection for transmitters and local indicators.

Some of the equipment required for matching an RTD to a transmitter.
- Software and interface for PC programmable transmitters
- Decade box and ammeter for analog transmitters with adjustment potentiometers.

As you can see, matching is a very economical method to improve your system accuracy.
In addition to the initial calibration, periodic checks are necessary to track and maintain performance.

RTD

- Insulation resistance check
- Ice bath check

Insulation resistance (IR) is the first and most important electrical check to make on the RTD. Without acceptable IR an accurate calibration cannot be performed. Low IR is an indicator of moisture or contaminants inside the probe and the result is shunting between the element coils or other internal lead wires and causes low resistance and a corresponding low temperature reading.

This is a typical wire wound sensing element. They are about 1” long and 1/16” diameter and are potted inside a stainless steel sheath. If moisture gets into the sheath and sensing element the result can be a shorter path for the excitation current and the result is a low resistance measurement.
**Insulation Resistance**

**Test method**
- Lower resistance = lower measured temperature
- Test at 50 VDC
- IR should be >100 megohms at 25°C

IR decreases with an increase in temperature so at room temperature a value much higher than what is really needed for an accurate measurement is required. An industrial grade RTD accuracy is not significantly affected until the IR drops below a few megohms. The measurement is made by touching one lead of a megohmeter to the leads and the other to the probe sheath. Some industrial grade probes are tested to higher levels to insure maximum performance at high temperatures.

**Ice Point Check**

Using an Ice Bath, check resistance at 0°C

Crushed ice made with purified water is packed into an insulated container. Purified water is added to fill in the gaps. If the ice floats, you have added too much water. Adding a stirring feature to keep the water flowing around the ice minimizes temperature gradients within the bath. Each probe should be immersed at least 4”. Do not use the probe to beat a hole in the ice. You may damage the sensing element. Use a scrap probe or similar rod to form the holes.

Using a high accuracy meter
- Reading should be 100 ± 0.12 ohms for Class B and 100 ± 0.06 ohms for Class A per the ASTM E 1137 or IEC 60751 standards
- Outside this range and the probe should be replaced

If the probe does not meet the resistance tolerance it should be replaced. There is not any reliable and cost effective method to repair it. Save the sensor for recycling! There is $$ worth of platinum in each probe. Save it up for a department lunch.
There are many sources of error that should be included in any error budget calculation. We’ll look at an example that shows the more common sources and how improving the sensor and installation method improves the measurement accuracy.

**Typical Application**

A 4” pipe with a water-like fluid moving at 100 ft/sec, 65°C (150°F)
2.5” immersion
100 ohm PRT per ASTM E1137 Grade B Transmitter with matching capability
Ambient 20°C
Control to better than ± 0.5°C

Our sample application is water flowing in a pipe and is a good demonstration of the many error sources present.

**Error Sources**

<table>
<thead>
<tr>
<th>Error</th>
<th>Value in °C</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interchangeability</td>
<td>0.523</td>
<td>ASTM E1137</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>0.0003</td>
<td>ASTM E1137 or mfr spec's</td>
</tr>
<tr>
<td>Stability</td>
<td>0.01</td>
<td>Mfr spec's</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.1</td>
<td>Mfr spec's</td>
</tr>
<tr>
<td>Thermal EMF</td>
<td>0.03</td>
<td>Test or mfr spec's</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0</td>
<td>Mfr spec's</td>
</tr>
<tr>
<td>Self Heating</td>
<td>0.007</td>
<td>Mfr spec's</td>
</tr>
<tr>
<td>Time Response</td>
<td>0</td>
<td>Mfr spec's-application</td>
</tr>
<tr>
<td>Stem Conduction</td>
<td>0.45</td>
<td>Test data-application</td>
</tr>
<tr>
<td>Lead Wire</td>
<td>0</td>
<td>ASTM B193 + B355</td>
</tr>
</tbody>
</table>

There are many sources of error with some being sensor related and others caused by the installation.
The RTD mfr’s lab has an uncertainty of 0.025°C for industrial grade sensors. We need to include this in our calculation if they have not already included it in their product specifications.

Next is RFI/EMI (radio frequency and electromagnetic interference). For our application the value is zero because we have a grounded metal housing around the PRT and transmitter. It’s usually a good idea to run shielded cable from the transmitter and ground the shield at the controller end, leaving the PRT end open.

Vibration will cause a PRT to drift faster than normal and we have to depend on the manufacturer to supply a value. Same for mechanical shock and thermal shock.

Thermal radiation is dependent on the installation. For our example we have no other heated equipment or radiation source located nearby so that value is also zero.

That completes our error table so the next step is to combine the errors.

Our PRT is connected to a transmitter so we need to include the accuracy in our calculation. From the table for RTD input it is ± 0.1°C
First we square all the errors and then add them together. Taking the square root of the sum results in 0.713°C. Then we apply our coverage factor which results in a measurement accuracy of ± 1.43°C. If you recall from our example specifications we were shooting for something better than 0.5°C. Now what?

Fortunately there are a few things we can do to improve accuracy. First is to choose a PRT with a tighter interchangeability. That will cut that error source in half. That’s still not enough though so we need to look at the next largest error source which was stem conduction. Adding insulation to the pipe will decrease it to near zero, or we can select a longer immersion length and install it into a tee to allow for more immersion. From our stem conduction graph we see that 4.5” will nearly eliminate the error. Those two changes may get us to 0.5°C however with another simple technique we can add a margin of certainty to our measurement. Matching the transmitter to the PRT will reduce the interchangeability error to about 0.08°C.

Entering the revised errors for interchangeability and stem conduction changes our measurement error to ± 0.195°C.
Combining Errors

- Combining our revised errors

- Accuracy = √(0.082² + 0.00032² + 0.012²)...
  = ± 0.195°C

- Apply the coverage factor of k=2 and our improved measurement accuracy is now ± 0.39°C with a 95% confidence level

- For more information on uncertainty and accuracy check out “A Beginner’s Guide to Uncertainty of Measurement” by Stephanie Bell of the National Physical Laboratory.

Conclusions

- Knowing PRT interchangeability is not enough

- Many sources contribute to the total error, some are PRT driven, some are installation driven with the larger errors related to the installation

- ASTM E1137 and IEC 60751 standards provide some performance information, but it is not comprehensive or particularly stringent

- Specific details must be known about the application for an accuracy estimate to be made and a suitable confidence level determined

- Consult with manufacturer to determine sensor error sources

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