Temperature Basics

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Temperature Defined
Temperature Scales
Types of Temperature Sensors
Thermocouple
- Types
- Temperature ranges
- Lead wire colors
- Standards
RTD
- Temperature coefficient
- Construction
- Calibration
- Interchangeability
- Standards
Identification of Sensor Types
Sensor Selection - The Four Ps
Calibration
Preventive Maintenance

What is temperature?
- Measure of the average kinetic energy of particles in a substance.
- Temperature is the result of the motion of particles. Temperature increases as the energy of this motion increases.
- Physical quantity that is a measure of hotness and coldness on a numerical scale.
Temperature Basics

Temperature of some things:

- Ice 32°F
- Dry ice ~78.5°C (~109.3°F) at atmospheric pressure
- Liquid nitrogen -196°C
- “Fahrenheit 451” (Ray Bradbury) approximate auto-ignition point of some paper
- Sun 5700K (5430°C)
- Earth’s core 5700K (5430°C) (cooling at 100°C per billion years).
  The core may contain enough gold, platinum, and other siderophile elements that if extracted and poured onto the Earth’s surface, would cover the entire Earth with a coating 0.45 m (1.5 feet) deep.
- Lightning bolt 50,000K
- Earth’s average surface temperature — good luck trying to figure out that one!
- In photography K (Kelvin) is used to denote color temperature. Match flame is about 1700K, sunshine is about 5400K.

Temperature Scales

Celsius

- Swedish astronomer Anders Celsius (1701–1744)
- By international agreement the unit “degree Celsius” and the Celsius scale are currently defined by two different temperatures: absolute zero, and the triple point of VSMOW (Vienna Standard Mean Ocean Water).
- Triple point of water is defined as 273.16K or 0.01°C, the point at which water exists as a vapor, solid, and liquid.
- A degree Celsius (or a Kelvin) is what you get when divide the thermodynamic range between absolute zero and the triple point of water into 273.16 equal parts.
- In 1948, it was renamed Celsius because centigrade had other meanings in Spanish and French.

Kelvin

- One of the seven base units in the SI system of units named after the Belfast-born, Glasgow University engineer and physicist William Thomson, 1st Baron Kelvin (1824–1907)
- Based on absolute zero which is 0K, or ~273.15°C or ~459.67°F. Theoretical point at which all thermal motion stops.

Fahrenheit

- Temperature scale based on one proposed in 1724 by the physicist Daniel Gabriel Fahrenheit (1686–1736) freezing of water into ice is defined at 32 degrees, while the boiling point of water is defined to be 212 degrees — on Fahrenheit’s original scale the freezing point of brine was zero degrees.

The Celsius scale is widely used in industry with the Fahrenheit scale a close second. Kelvin is almost exclusively used for scientific and laboratory measurements.

A Kelvin or K does not have a degree symbol. It is used by itself such as 273K. On calibration reports you will see the calibration uncertainty expressed in millikelvin or mK so 1mK is 0.001K.
There are other types of sensors that have little practical use or are still in development such as the Johnson Noise Thermometer, and a device that uses a laser as a measure.

Mercury-in-glass is probably the most well known liquid displacement type of thermometer. Other types of fluid are used with some used to deflect a needle that indicates temperature.

As temperature increases the resistance increases and can be correlated to a temperature.
As temperature increases, the measured voltage increases and does so in a predictable manner. The thermocouple standards define the voltage vs. temperature relationship for several types of thermocouple junctions.

**Thermocouples**

Made by connecting two different metals to form a closed circuit.

- High durability
- Low initial cost
- Voltage change with temperature

Thermocouples

<table>
<thead>
<tr>
<th>Temp °F</th>
<th>Type J</th>
<th>Type K</th>
<th>Type T</th>
<th>Type E</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>32</td>
<td>1400</td>
<td>700</td>
<td>1600</td>
</tr>
<tr>
<td>-450</td>
<td>32</td>
<td>2156</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>128</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thermocouples

**Types**

- **Most common**
  - Type T: Copper-Constantan   Red/Blue
  - Type J: Iron-Constantan     Red/White
  - Type E: Chromel-Constantan  Red/Purple
  - Type K: Chromel-Alumel      Red/Yellow

- **High temperature types**
  - R, S, B Platinum/Platinum-Rhodium  2640°F
  - W3, W5 Tungsten/Tungsten-Rhenium  4200°F

Each type has a different temperature range and Voltage vs. Temperature relationship.

ASTM Standard E230, ANSI MC 96.1, and IEC 584-3
Junctions can be grounded, ungrounded or exposed.

Thermocouples are typically used in an application where high temperature or high vibration is present. Their durability is probably their best asset.

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Thermocouples
Junctions can be grounded, ungrounded or exposed.

Advantages
- Very wide temperature range [1.2K to 2300°C]
- Fast response time
- Available in small sheath sizes
- Low initial cost
- Durable

Disadvantages
- Decreased accuracy vs. RTDs
- More susceptible to RFI/EMI
- Recalibration is difficult
- Requires expensive TC wire from sensor to recording device
- Difficult to verify
- Not as stable as RTDs

RTDs
3 common element styles
- Coil in the hole
- Wire wound
- Thin film

Resistor made from platinum, nickel, copper, or other metals

The platinum resistance thermometer (PRT) is the most widely used sensor type in applications where highly accurate, repeatable and stable measurements are required. Other metals are used but none have the wide temperature capability of platinum.
Basic Operation
- Resistance changes with temperature. As temperature increases, resistance increases in response.
- Small current is sent through the resistor element and electrical resistance is measured
- Performance defined by IEC 60751 and ASTM E1137

Temperature coefficient
- Also called the Temperature Coefficient of Resistance or alpha
- Units are ohms/ohm/°C
- The average change in resistance per unit change in temperature between 0 and 100°C
  - $\alpha = \frac{R_{100} - R_0}{100°C \cdot R_0}$
  - $R_0 = \text{resistance at 0°C}$
  - $R_{100} = \text{resistance at 100°C}$

For the current industry standard 100 ohm RTD the alpha is 0.00385, which means at 100°C the nominal sensor resistance is 138.5 ohms

Most common coefficients
- 0.00385 – ASTM E1137 or IEC 60751
- 0.003902 – American
- 0.003916 – JIS
- 0.003925 - SPRT, Secondary SPRT
- Must match your instrument to the proper temperature coefficient of your sensor

When specifying an RTD it is necessary to select the correct temperature coefficient to match the readout instrument or controller. Failure to do so will result in an inaccurate measurement.
Coefficient example
- A temperature is being measured with a sensor having a temperature coefficient of 0.003916 (JIS) but due to a sensor failure it was replaced with a sensor having a temperature coefficient of 0.00385.
- If the transmitter/controller is not recalibrated, at 100°C it will read 1.7°C low.

Interchangeability
- RTDs are manufactured to have 100 ohms at 0°C.
- Interchangeability refers to the “closeness of agreement” between an actual PRT R vs. T relationship and a predefined R vs. T relationship.
- Defined by ASTM E1137 and IEC 60751
- Nominal R vs. T of ASTM and IEC standards are equivalent but tolerances are different.

The two main standards in use today are the IEC 60751 and the ASTM E1137. Both have the same nominal R vs. T values but differ in defining some performance characteristics and the tolerances associated with the grades or classes of sensors. The interchangeability tolerances are the target that manufacturers shoot for when building the sensing elements.

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.
Standard Tolerance Defining Equation¹

- ASTM E1137 Grade A ± \[0.13 + 0.0017 | t |\]
- ASTM E1137 Grade B ± \[0.25 + 0.0042 | t |\]
- IEC 60751² Class AA² ± \[0.1 + 0.0017 | t |\]
- IEC 60751 Class A ± \[0.15 + 0.002 | t |\]
- IEC 60751 Class B ± \[0.3 + 0.005 | t |\]
- IEC 60751² Class C² ± \[0.6 + 0.01 | t |\]

Note 1: \(| t |\) = absolute value of temperature of interest in °C
Note 2: These tolerance classes are included in a pending change to the IEC 60751 standard.

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.

RTDs

Advantages
- Very stable output
- Linear and predictable
- Easy to verify and recalibrate
- High accuracy
- No special wires required for installation

Disadvantages
- More limited temperature range [-200°C to 500°C]
- High initial price
- Slower response time than a thermocouple
- Less durable than a thermocouple

Identification

RTD or Thermocouple?

Lead wires
- RTD has two, three, or four leads per sensing element
- TC has two leads per junction
- RTDs typically have red, white, green or black leads (not defined by the standards)
- TC colors match thermocouple type – red (common), yellow, purple, blue, white

Resistance check
- RTD will have about 109 ohms between leads
- TC typically less than 1 ohm

Continuity check
- TC grounded junction has path from leads to case

Magnet test
- RTD leads are not magnetic – usually copper
- TC type J has one iron lead which is highly magnetic
How do we decide which technology to use?

Thermocouple
- Exhaust gas
- Injection molding
- Bearings
- Refinery

RTD
- Pharmaceuticals
- Fuel custody transfer
- Chemical
- Tire/rubber

Accuracy and stability are almost always preferable characteristics to have in a temperature sensor and for that reason I recommend that an RTD be selected unless the environment or process characteristics dictate another technology. Those factors are discussed on the following slides.

Factors to consider
- Placement
- Protection
- Performance
- Price
- Service life

There are other factors to consider other than these but for most applications these will get you the measurement and service life from the sensor that you desire.

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.
Installation of a surface mount sensor can be accomplished with a hose clamp, tape, or an adhesive.

A few additional styles of surface mount sensors. Whether RTD or thermocouple they almost all look alike but are very different inside.

Installation is very easy to do and is low cost. Accuracy suffers though and measurement accuracy requirements may not be achieved.
An immersion sensor overcomes the negatives of the surface mount and in most cases dramatically improves the measurement accuracy.

Direct immersion of a small diameter sensor gives an accurate measurement at low cost. It is not always possible or desirable though because of maintenance or durability considerations.

These are just a few of the several styles available. Any piping connection either has been or could be adapted to a thermowell process connection.
A connection head is the best method and provides a convenient place to attach lead wires or to house a local transmitter.

Numerous styles and materials from plastic to aluminum are available. Some carry ratings for use in hazardous atmospheres.

Heads provide protection for transmitters and local indicators.
Hazardous atmospheres require an RTD and connection head assembly that carry an appropriate rating. A word of caution -- just the addition of a rated head to any sensor does not make the whole assembly rated. The entire assembly must be tagged and identified as having the desired rating.

Head is attached to the thermowell and sensor typically with a pipe nipple. The most versatile is the union connection. It allows easy removal of the sensor from a thermowell.

Here are some general performance specifications for RTDs and thermocouples. As you can see the RTD has quite a large accuracy advantage over the thermocouple.
High accuracy insures product quality and efficient use of your energy dollar.

A tapered thermowell will have a 3 to 4 times slower response than the ¼” diameter direct immersion sensor. This can be a big factor in accuracy for processes that are changing temperature rapidly. The sensor needs to be fast enough to keep up with the process.

Surface mount sensors will have a slower time response than an immersion style. They are affected more by the surface they are mounted to rather than by the sensor design.
Adding a transmitter can improve accuracy when a long run of lead wire is required. They also provide a more robust signal that is less susceptible to interference from electromagnetic or radio frequency interference.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Thermocouple</th>
<th>Wire Wound RTD</th>
<th>Thin Film RTD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy/Stability</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mod. Temp (-50 to 200°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Temp (-200 to 500°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higher Temp (over 500°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Response (&lt; 6 sec.)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long-term Stability</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Vibration (g level)</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extra High Vibration, Shock</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical Temp. Application</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What is Calibration?

- Calibration is performed to verify sensor/instrument performance.
- Calibration is the process used to ensure that a sensor/instrument maintains specification over time and changing ambient conditions.
- Calibration is the process used to maintain traceability of parameters with reference to national/international standards.
Calibration should be performed when starting up a new facility or if a new piece of equipment is added. This insures that the instruments have not been damaged during shipping or installation and provides a baseline for comparison to subsequent calibrations.

When? Is one of the most frequently asked questions about calibration. There is no generic answer for when; it all depends on the process and comfort level of the invested parties. Process conditions that affect the probe drift rate and the product value are the two main considerations. Consult with the manufacturer(s) of your system and they should be able to help you estimate the long term accuracy of their equipment based on your process conditions. After that it’s up to you to pick a frequency that meets your comfort level and that of any 3rd party watch-dogs that oversee your production facility. You may decide because of product value that a calibration is performed before and after each batch. Then if you desire, after 5 cycles are completed without a significant shift, the calibration cycle could be doubled.
Temperature Basics

Terminology

- ITS-90 = International Temperature Scale of 1990
- IPTS-68 = International Practical Temperature Scale
- TPW – triple point of water 0.01°C or 273.16 K
- \( R_0 \) = resistance at 0°C
- SPRT = standard platinum resistance thermometer
- Dewar = insulated container
- IR = insulation resistance
- K – Kelvin temperature scale (used for ITS-90)
- mK or milliK = .001 K
- NIST – National Institute of Standards and Technology
- NVLAP – National Voluntary Laboratory Accreditation Program
- A2LA – American Association for Laboratory Accreditation

Evolution of standard temperature scales

- IPTS-27
- IPTS-48
- IPTS-68
- ITS-90

ITS-90 (International Temperature Scale)
- Released in 1990
- The official international scale
- In better agreement with thermodynamic values than the IPTS-68

ITS-90 vs. IPTS-68
- ITS-90
  - Uses TPW
  - Most accurate
  - Complex equations
- IPTS-68
  - Simpler equations
  - Less accurate
  - Callendar-Van Dusen equation

Beginning in 1927 the International Bureau of Weights and Measures decided that a better standard was required for temperature and the International Practical Temperature Scale was born. Since then about every 20 years the scale has been refined to improve accuracy. In 1990 the name changed to International Temperature Scale and the equations defining the R vs. T relationship became more accurate.

Factory Calibration Options

- Matched Calibration
  - Matched with other probes
  - Matched to a transmitter
- Multiple Point Calibration
  - -196, -38, 0, 100, 200, 300, and 420 °C
  - Matched to a Temperature Readout (meters)

Calibrating an RTD and adjusting the readout or transmitter accordingly is a cost effective method to improve measurement system accuracy. This eliminates most of the RTD interchangeability tolerance and can also minimize other instrument errors inherent in the system.
The ice bath is the easiest and most accurate method of checking an RTD. Addition of a stirring motor insures even temperature throughout the insulated Dewar. Ice is made from pure water, crushed, and packed into the Dewar. Purified water is added to fill in the gaps. Too much water and the ice will float which is not desirable.

The triple point of water (TPW) cell may be the most commonly used type of fixed point and is used in ITS-90 calibrations. Water can exist as a solid, liquid, and vapor at 0.01°C and this device creates this temperature.
Comparison calibrations can be performed in a laboratory or in the field. High accuracy can be obtained with careful selection of equipment. Durability is as important as accuracy when used for field calibrations. Equipment that cannot stand up to field use will drift quickly and not give the expected measurement uncertainties.

This is NOT the type of device to use for field calibrations. It is extremely fragile and very expensive, about $10k with calibration.

Photo of an SPRT element inside its quartz sheath.
A little closer look.

Yes, the quartz sheath does break very easily and is one of the few things duct tape won’t fix!

Preventive Maintenance

Corroded terminals can cause high resistance in the leads

3-wire circuits are susceptible – accuracy depends on each conductor having exactly the same resistance
  - Terminals clean and tight
  - Terminal block clean and dry, secured to head
  - Wires are tinned, or terminated with spade lugs
  - Connector pins connect firmly and are clean
  - Use gold plated pins in a high quality connector

4-wire circuits also compensate for some poor maintenance
  - Compensate fully for all lead wire resistance in the circuit
The connection head shown in the lower right corner had a lot of dust in it that caused some electrical leakage between the terminals resulting in a bad temperature reading.

Something as innocuous as a fan blowing can cause a measurement error if it is directed on the external portions of the temperature assembly.
Temperature Basics

**RTD**
- Choose the correct temperature coefficient. Most common is a .00385 conforming to IEC 60751 or ASTM E1137
- Interchangeability – choose class A for better accuracy
- 3 or 4 wire – 4 wire provides better accuracy
- Choose correct length to match thermowell or provide significant immersion to avoid stem conduction – for a direct immersion probe minimum immersion = 10x probe diameter + sensitive length

**Thermowell selection**
- Corrosion
- Erosion
- Wake frequency and strength
- Time response
- Immersion length

**Thermowell selection**

**Summary**
- There are many types of temperature sensors. RTD and thermocouple are the most widely used in industry.
- RTD is the most accurate and TC is the most durable
- When selecting a sensor remember the 4 Ps
  - Performance
  - Placement
  - Protection
  - Price
- Periodic calibration is necessary to maintain measurement accuracy

**BE educated**

Watch for upcoming RTDology® events

- View presentation notes from previous sessions on our website at: www.burnsengineering.com/RTDology