Measuring temperature with Resistance Temperature Detectors (RTD) (e.g., Pt100) and thermocouples

White Paper

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In the area of physical measurement technology, temperature is the most frequently measured variable. Especially in the field of process technology, the temperature measurements are the "metrological backbone". In imc measurement devices, in the area of so-called "Mixed Signal Applications", there is hardly a measuring device available that comes without temperature-measuring capability. In this white paper, temperature measurement techniques will be illustrated of the two most common temperature sensors: the Resistance Temperature Detector (RTD) (Pt100) and the thermocouple.

Resistance Temperature Detector (RTD)

Concerning RTDs, the utilized physical effect is that electrical resistance varies with temperature. The relationship between the temperature and the resistance can be described by an equation. R_O is the nominal resistance for a given temperature T_O. T_M is the temperature of the resistor and a, b, c … are material-dependant constants. For example, R_O of a Pt100 conducts precisely 100 Ω at 0°C and supports a measurement range between -200 to 850°C. To determine the resistance value, a constant predetermined current, I_K, (typically ≤ 1 mA) is used and the voltage drop across the resistor is calculated. Figure 1 demonstrates the circuits that are commonly used:

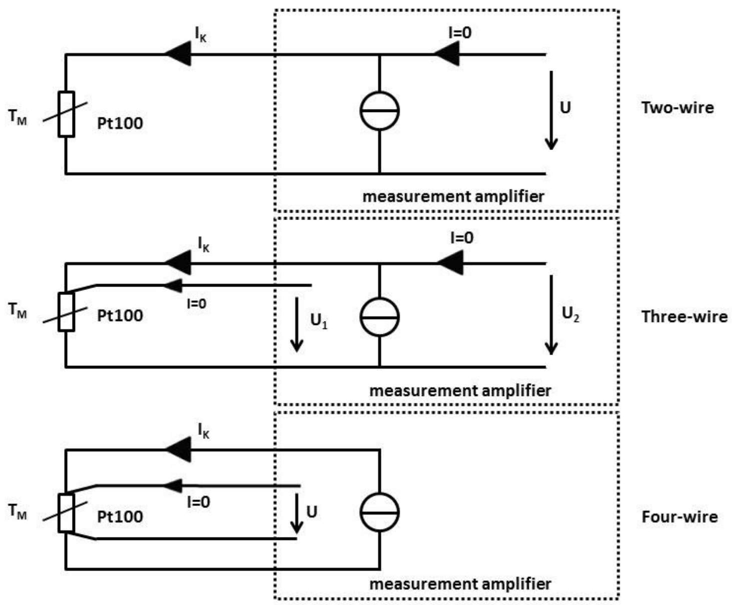

Figure 1: Connection of resistance temperature detectors (RTD)

In a **two-wire system**, the power source supplies the temperature-dependant resistance, and the measured voltage U consists of both the voltage drop across the resistor, and the voltage drop on the lead resistances of the supply cables. This means that a systematic error is generated due to the voltage drop on the leads. In other words, this means that while the current of the current source I_K is precisely known, the voltage U, however, due to the voltage drops from the top and bottom leads are measured to be too large.

A better method is the **three-wire system**. By taking measurements from both U_1 and U_2, the influences of the lead resistances are eliminated. This requires, however, that both the supply and return lines are of the same length, made from the same materials and exposed to the same temperatures. In this scenerio, the voltage I_K is once again known, however the voltage drop on the lower supply line is measured too high. From knowledge of U_1 and U_2, the resistance of the Pt100 can be determined for identical leads.

The most optimal method is the **four-wire system**. Under the condition that the voltage U can be measured without current, both the voltage at the measuring resistor and the current I_k through the measurement resistor is known, and thus, the resistance of the Pt100 is determined.

An important practical application parameter is the change in resistance with the change in temperature – also known as sensitivity. With a Pt100, at around 0.4 Ω/Kelvin at a constant current of 1 mA, a voltage change of about 400 µV/Kelvin occurs.

In the DIN IEC 751, the limit deviations for RTDs are given. There are differences given between two tolerance classes, A and B, and the error in Kelvin are found by applying the numerical value of the RTD T_M:

Class A: }(0.15 + 0.002 T_M)

Class B: }(0.30 + 0.005 T_M)

Class A is in the temperature range -200 ... 650 °C when using the three- and four-wire systems. Class B applies throughout the range of -200 ... 850 °C.

Example:

With a Pt100 RTD from class A, a temperature of 80°C is measured. This means that the maximum measurement uncertainty (without instrument error) results to ± (0.15 + 0.002*80) K = ± 0.31 K. Thus, the measurement result due to sensor uncertainty is T_M = (80 ± 0.31)°C. The measurement uncertainty of a typical imc measurement amplifier for temperature measurements (e.g., C8 or OSC16/32) is ± 0.1K.

In imc measurement devices, the measurement amplifiers already exist within the module themselves. As for non-linearities of RTDs, operators also need not worry since these are automatically corrected by the measuring system using online calculating.

Thermocouples

When measuring temperature with thermocouples, a different physical arrangement is used. If you connect two different electrical conductors of materials A and B, the result is the material development of a thermoelectric voltage UAB. This electrical effect is called the Seebeck Effect.

The operation of a temperature measurement using a thermocouple is illustrated in figure 2:

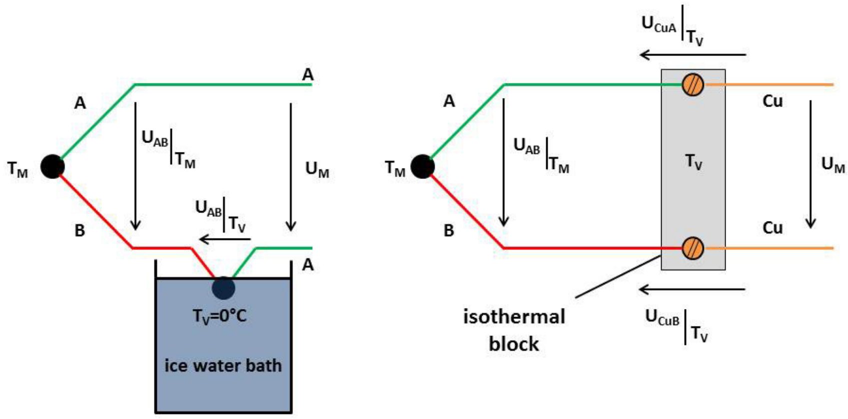

Figure 2: Temperature measurements using themocouples

Looking at the illustrastration on the left, if two thermocouples with the materials A and B are combined so there is a material transition from A to B at the measurement temperature T_M, and the second material transition of another thermocouple from A to B is submerged in an ice water bath with the reference temperature T_V = 0°C, then the measured voltage U_M yields to:

$$U_M = U_{AB}\Big|_{T_M} - U_{AB}\Big|_{T_V}$$

Thus, U_M is the thermoelectric voltage of the thermocouple with the materials AB at the measurement temperature T_M minus the thermal voltage of the same material submerged in an ice water bath. Because the thermal voltage of the thermocouple at 0°C is known, then from the measurement voltage U_M, the temperature at the measuring point T_M can be determined.

As pictured in the illustration on the right, when measuring the voltage U_M, a material transfer with copper wire from A (green) to the measurement device is (usually) done by connecting with copper wire again. However, this transition is not disruptive, as long as both cables have the same temperature. In this case, the resulting thermal voltages cancel each other out. As in the illustration on the left, using an ice water bath would be very cumbersome and is therefore not used in practice. Especially since the illustration on the right is a much more elegant method. In the right illustration, it can be seen that the two terminals of the thermocouple are connected with screws onto a so-called "isothermal block". An isothermal block is device that has properties to set the same temperature T_V at both screw terminals. An isothermal block should conduct heat very well, and on the other hand, be a good electrical insulator. In this case, the measured voltage U_M results to:

$$\begin{aligned} U_M &= U_{AB}\Big|_{T_M} - U_{AB}\Big|_{T_V} \\ &= U_{AB}\Big|_{T_M} + (U_{CuA} - U_{CuB})\Big|_{T_V} \\ &= U_{AB}\Big|_{T_M} + U_{AB}\Big|_{T_V} \end{aligned}$$

Because the material transitions from material A to to copper and material B to copper are on the same temperature level T_V, they behave like a combination of materials A and B at the temperature T_V. The practical consequence of this equation is that the cold junction temperature,T_V, must be known. Typically, this temperature is measured with an RTD. Thus, by measuring the voltage U_M with knowledge of the type of thermocouple (not the temperature of the measuring pointT_M), you are determining the temperature difference between T_M and the reference junction channels. However, since T_V is known by the simultaneous measurement with the RTD (e.g., Pt100), the measured junction temperature T_M can be calculated. With the above equation, you can easily check with a jumper wire to connect between the terminals of the thermocouple. In this case, the result of the measurement will be the comparison of the temperature T_V of the isothermal blocks.

Using this method, thermocouples of various types can be measured. The operator needs only to specify in the imc DEVICES operating software which thermocouples are connested to which measurement inputs.

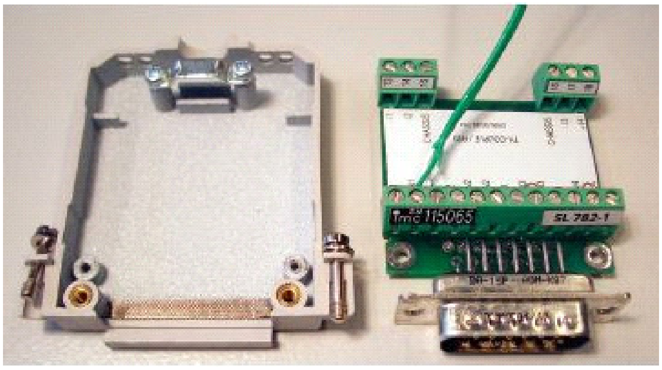

Figure 3: An open imc connector with thermocouple

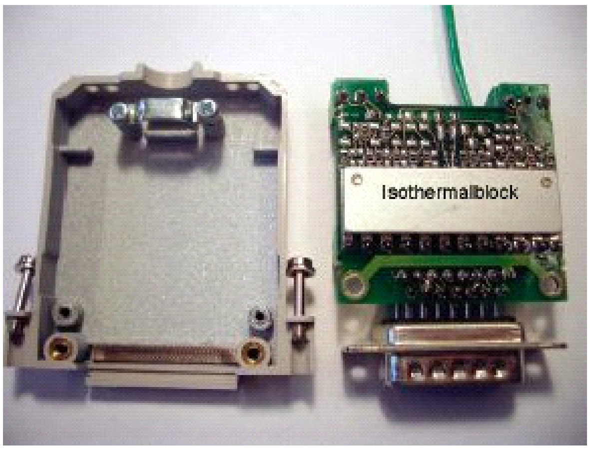

Figure 4: Backside of the connector with exposed isothermal block

Both RTDs and thermocouples have a non-linear relationship between the measured variable temperature and measurable voltage. This non-linearity is corrected within the imc measurement device before the computer support and then the target temperature is made.

Below is a table of some common thermocouples indicated with corresponding measurement ranges and error classes. There are those elements which are fixed with respect to thermal stress and tolerance.

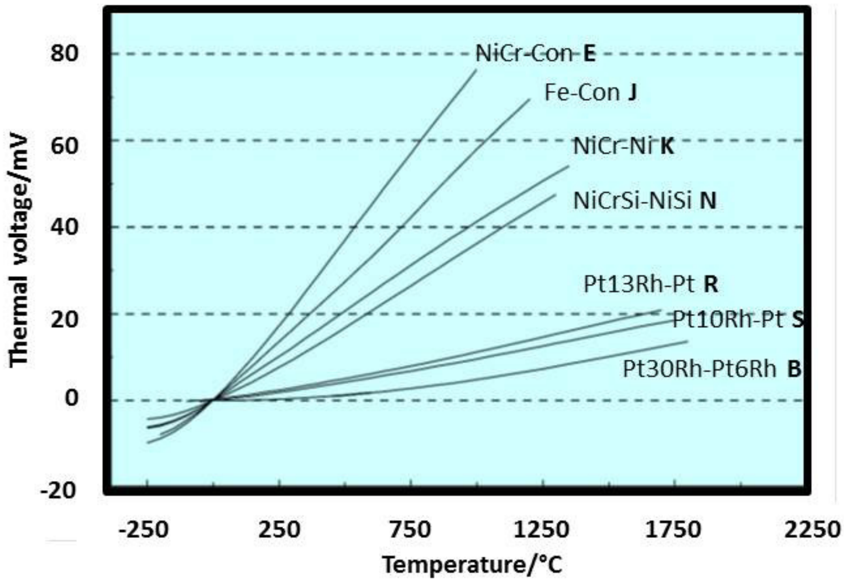

Figure 5: Characteristic curves of thermocouples according to DIN EN 60 584

Finally, in the following tables, some important technical data for the various types of thermocouples are compiled.

Thermocouple	Maximum Temperature	Defined up to	Positive Limb	Negative Limb
Fe-Con F	750℃	1200℃	Black	White
Cu-Con T	350℃	400℃	Brown	White
NiCr-Ni K	1200℃	1370℃	Green	White
NiCr-Con E	900℃	1000℃	Violet	White
NiCrSi-NiSi N	1200℃	1300℃	Mauve	White
Pt10Rh-Pt S	1600℃	1540℃	Orange	White
Pt13Rh-Pt R	1600℃	1760℃	Orange	White
Pt30Rh-pt6Rh B	1700℃	1820℃	No data	White

Figure 6: Definition of color-coded connection leads

Limit deviations of various thermocouples

Thermocouple	Type	Maximum Temp. °C	Defined up to °C	Limiting Deviations
Fe-CuNi	J	750	1200	Class 1 -40...750°C: ±0.004 T or ±1.5°C Class 2 -40...750°C: ±0.0075 T or ±2.5°C Class 3 - - -
Cu-CuNi	T	350	400	Class 1 -40...350°C: ±0.004 T or ±0.5°C Class 2 -40...350°C: ±0.0075 T or ±1.0°C Class 3 -200...40°C: ±0.015 T or ±1.0°C
Ni-CrNi	K	1200	1370	Class 1 -40...1000°C: ±0.004 T or ±1.5°C Class 2 -40...1200°C: ±0.0075 T or ±2.5°C Class 3 -200...40°C: ±0.015 T or ±2.5°C
NiCrSi-NiSi	N	1200	1300	Same as Type K
NiCr-CuNi	E	900	1000	Class 1 -40...800°C: ±0.004 T or ±1.5°C Class 2 -40...900°C: ±0.0075 T or ±2.5°C Class 3 -200...40°C: ±0.015 T or ±2.5°C
Pt10Rh-Pt	S	1600	1540	Class 1 0...1600°C: ±[1+(T-1100)0.003] or ±1.0°C Class 2 -40...1600°C: ±0.0025 T or ±1.5°C Class 3 - - -
Pt13Rh-Pt	R	1600	1760	Same as Type S
Pt30Rh-Pt6Rh	B	1700	1820	Class 1 - - - Class 2 600...1700°C: ±0.0025 T or ±1.5°C Class 3 600...1700°C: ±0.005 T or ±4.0°C
Fe-CuNi	L	600	900	100...400°C: ±3.0°C 400...900°C ±0.75°C
Cu- CuNi	U	900	600	100...400°C: ±3.0°C 400...600°C ±0.75°C

Figure 7: Thermocouple temperature range and limiting deviations

In DIN 43710, the thermocouple parameters are set for types "L" and "U" and in DIN IEC 584-1 for the other types. The maximum temperature is the temperature to which a deviation limit is set. With "defined up to" it is to mean the temperature to which a thermoelectric voltage is specified.

The sensitivity of thermocouples is usually lower than that of RTDs. For example, the sensitivity of a Type K thermocouple is about 40 µV/Kelvin and is therefore only 10% of the sensitivity of the Pt100 value. When thermocouples are suitable for high temperatures (e.g., as type S or B), the sensitivity is still substantially lower.

In summary, it can be stated that thermocouples can be used for much higher temperatures compared with RTDs. In addition, thermocouples are much less expensive than RTDs. A disadvantage of thermocouples is their low sensitivity and relatively large deviation limits.

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