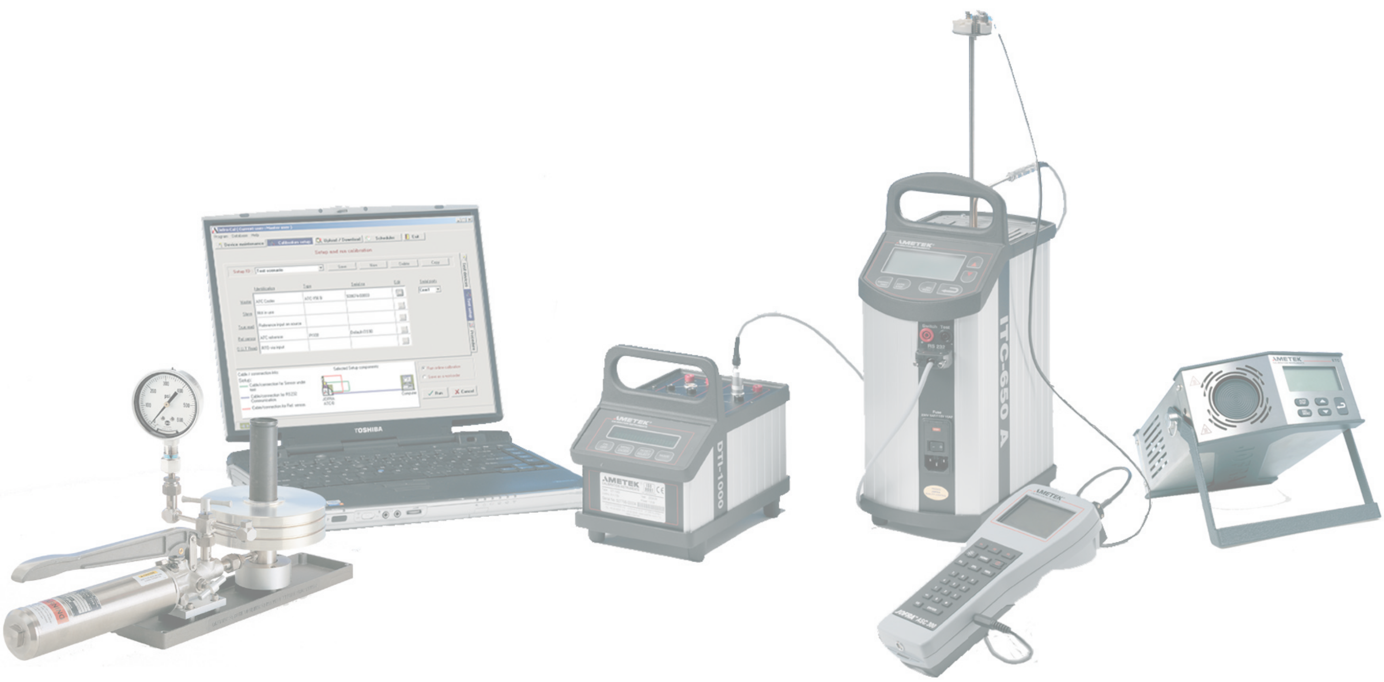
Calibration Theory

Industrial temperature measurement



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1. INTRODUCTION

Temperature is one of the most measured parameters within industry and science. A correct measurement is of great importance to the quality of the product, as well as to security and to energy consumption. Therefore, it is very important to choose the right sensor for the actual application. However, a 100% ideal solution for a measuring job is difficult to find if not to say impossible. The choice will often be a compromise between the requirements of the user and the limitations set by the sensor types that are suitable for the conditions at the measuring point.

The following paragraphs explain the theory behind electrical temperature sensors, choice of sensors and sources of error.

2. TEMPERATURE SCALES

2.1 Temperature scales

Four temperature scales are available:

Réaumur
Fahrenheit
Celsius
Kelvin

Kelvin is one of the basic units in the SI-system and is related to the thermodynamic temperature. The Kelvin scale is used in connection with scientific tasks. The Celsius scale and the Fahrenheit scale, on the contrary, are more commonly used and are as such the units that are used within the industry. The Celsius scale is used in Europe whereas the Fahrenheit scale is used in the USA.

Formulas for conversion between the most used units.

Celsius:	°C = 5/9 (°F - 32)	**Fahrenheit:**	°F = 9/5 °C + 32
	°C = K-273.15		°F = 9/5 K – 459.67

The international temperature scales from 1927 and on were all based on a number of temperature fix points. The numerical values of these had been determined based on the thermodynamic Kelvin scale. Temperatures in between were determined by using special standard thermometers and very thoroughly described interpolation methods.

Until 1990, the platinum thermometer was used as standard thermometer in the range up till 630°C, above this temperature and up till 1064°C, Pt10%Rh-Pt thermocouples were used, and from 1064°C and up the scale was defined in accordance with Planck's law of radiation.

In connection with a revision per January 1, 1990, the range for the platinum thermometer was extended up to the freezing point of silver, i.e. 961.78°C and the law of radiation was extended downwards to the same point. In the process, the use of the thermocouple as standard thermometer was obsolete. It should also be mentioned that today only triple points and freezing points / melting points are used to determine the temperature scale. The previously used boiling points are left out due to the big dependence on pressure. According to the ITS-90 scale water no longer boils at 100°C but at 99.974°C.

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3. TEMPERATURE MEASUREMENT

3.1 The definition of temperature

The temperature of a medium is an expression of its content of thermodynamic energy. The thermodynamic energy represents the average velocity of the unarranged molecular movement in the material. To measure a temperature is therefore different from measuring one of the other basic units. Metres for example can be measured with an inch rule without affecting or changing the length. To measure temperature is different. Actually, the content of thermodynamic energy in the medium should be measured, based on the definition. This is of course not possible in practice and therefore a measuring principle is used, where the medium affects a sensor / a sensor element. The measurement must take so long that molecules in sensor and medium assume the same mean velocity. When this has been reached, the two bodies will have the same temperature (measurement medium and temperature sensor).

To achieve this, the following 3 conditions must be fulfilled:

The bodies must not exchange heat with external or internal sources.
The bodies must be in mutual balance.
The bodies have had thermal contact through sufficiently long time.

4. PRINCIPLES OF TEMPERATURE MEASUREMENT

Electrical temperature measurement is based on electrically measurable changes that are taking place in materials when exposed to temperature changes.

These changes could for example be:

Changes in resistance in conducting materials
Changes in resistance in semiconductors
Thermal voltage
Drop in diode voltage
Drop in transistor voltage
Changes in frequency
Noise

The principles are used for the following thermometers:

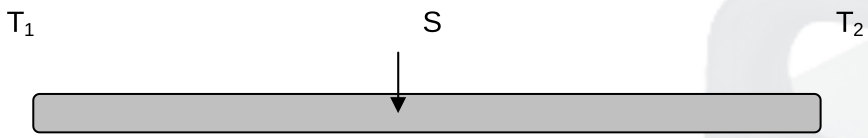
Resistance thermometers
Thermistors
Thermocouples
Frequency thermometers, etc.

In the following, only thermocouples and resistance thermometers will be dealt with.

5. THERMOCOUPLES

The thermocouple is an active temperature sensor that measures differences in temperature without auxiliary power.

In all metallic conductors a thermal voltage will appear, when a temperature difference between the conductors's free ends exists. This voltage is dependent on the temperature difference and on a material parameter called the thermal power *S*. Seebeck proved the phenomenon in 1821.

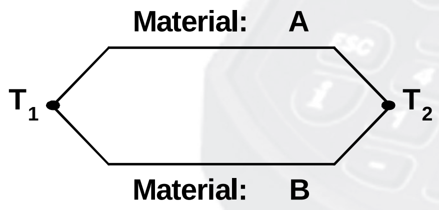


The relation between temperature difference and voltage is

$\Delta U = S \cdot (T_2 - T_1)$

The thermal power *S* of a material is called the absolute Seebeck coefficient [µV/°C]. It is not possible to measure this thermal power unless combined with another material. To achieve values with a common starting point, the precious metal of platinum is used as reference.

If two metals are connected to a closed circuit, the current running will be dependent on the difference between the thermal power of the metals and the temperature difference between the junctions.



The junctions are normally called soldering points, even though they are most often a welding.

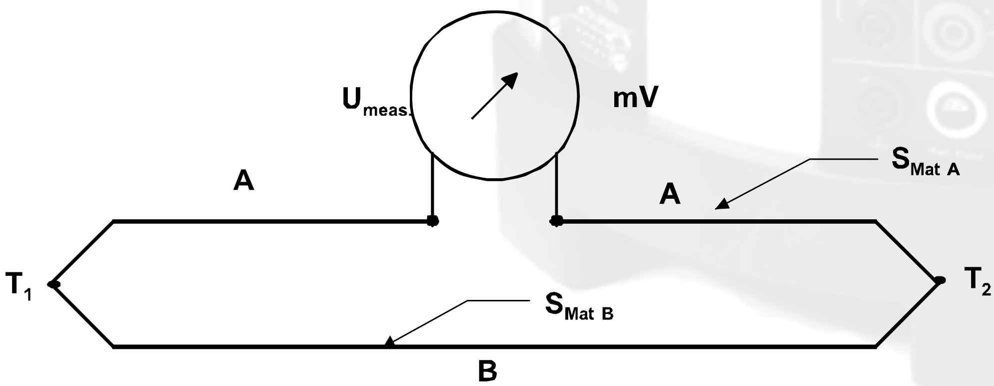
For practical temperature measurement, the absolute Seebeck coefficient cannot be used. The concept “relative Seebeck-coefficient” is used, which is simply the total thermal power for two random materials

I.e.:$S_{AB} = S_A - S_B$

Example: Iron (Fe) put together with constantan (FeCuNi)

$S_{Fe, FeCuNi} = +15\mu V/°C - (-38\mu V/°C) = 53\mu V/°C$

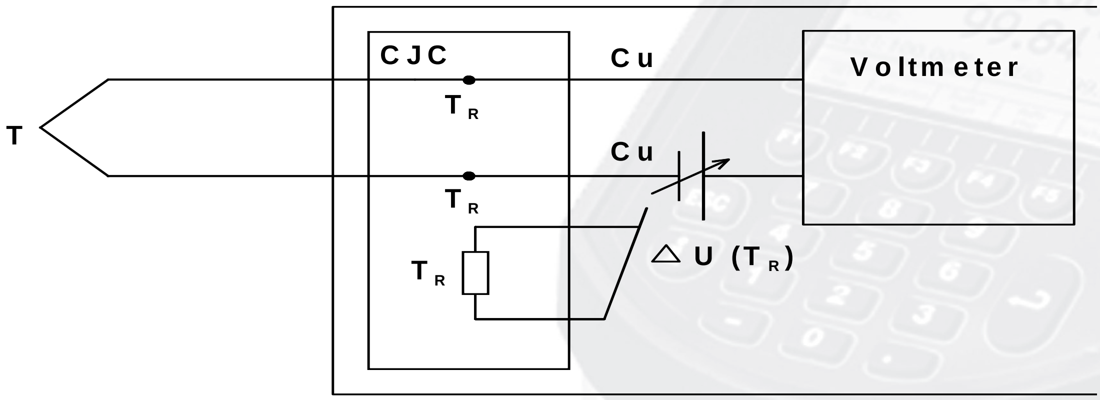
If the circuit is cut up, the thermal voltage may be measured with a sensitive millivoltmeter.



The thermocouple voltage is: $U_{meas} = (S_{mat\,A} - S_{mat\,B}) \cdot (T_2 - T_1)$
If you want to measure absolute temperature, one soldering point must be kept at a constant temperature. This soldering point is now called the cold junction point, and the other soldering point may be used as temperature sensor. As the ice point of water is fairly easy to realise, 0°C is often used as reference temperature. In tables on thermal voltages, 0°C is always used as reference.

For industrial use, this method is not practical. In modern electronic instruments for temperature measuring, you let the cold soldering point assume the temperature inside the instrument. A special electronic circuit then measures this temperature and adds the necessary correction voltage to the thermal voltage. Such an arrangement is called "automatic cold junction compensation".

AUTOMATIC COLD JUNCTION COMPENSATION (CJC)



If you have no such instrument available for control of a thermocouple, you may use the following procedure provided that the ambient temperature is known and constant with good approximation:

Example:
Thermocouple: NiCr-Ni type K

$U_{measured}$ = 44.221 mV
T_{ref} = 25°C

The procedure is now that T_{ref} = 25°C is converted into voltage - look into the table for type K. You will find the following

T_{ref} = 25°C ~ 1.277mV. i.e.
$U_{(NiCr\text{-}Ni)} + U_{Tref}$ = 44.221+1.277 = 45.498 mV

Looking into the table you will find that 45.498 mV ~ 800°C

If instead, you first converted the measured voltage into °C and then added T_{ref}, you would due to the non-linear characteristic get a wrong result, because

$U_{measured}$ = 44.221 mV ~ 780.2°C + T_{ref} = 25°C = 805.2°C,

i.e. an error of 5.2° C. The errors are dependent on type of thermocouple and level of temperature.

5.1 Types of thermocouples

Two metals or alloys welded/joint together form a thermocouple, so the number of possibilities is infinite.

It is a serious job to select the proper materials for a thermocouple. The types that for one reason or another are selected are defined very precisely as far as the composition of the alloy is concerned. This, together with the requirements to the accuracy tolerance makes it possible for different manufacturers to produce even complicated alloys completely uniform themselves.

The following thermocouples are international and described:

Name of type/alloy

*	T	Cu-CuNi	*	N	NiCroSil –NiSil
*	J	Fe-CuNi	*	S	Pt10%Rh-Pt
*	E	NiCr-CuNi	*	R	Pt13%Rh-Pt
*	K	NiCr-Ni	*	B	Pt30%Rh-Pt6%Rh

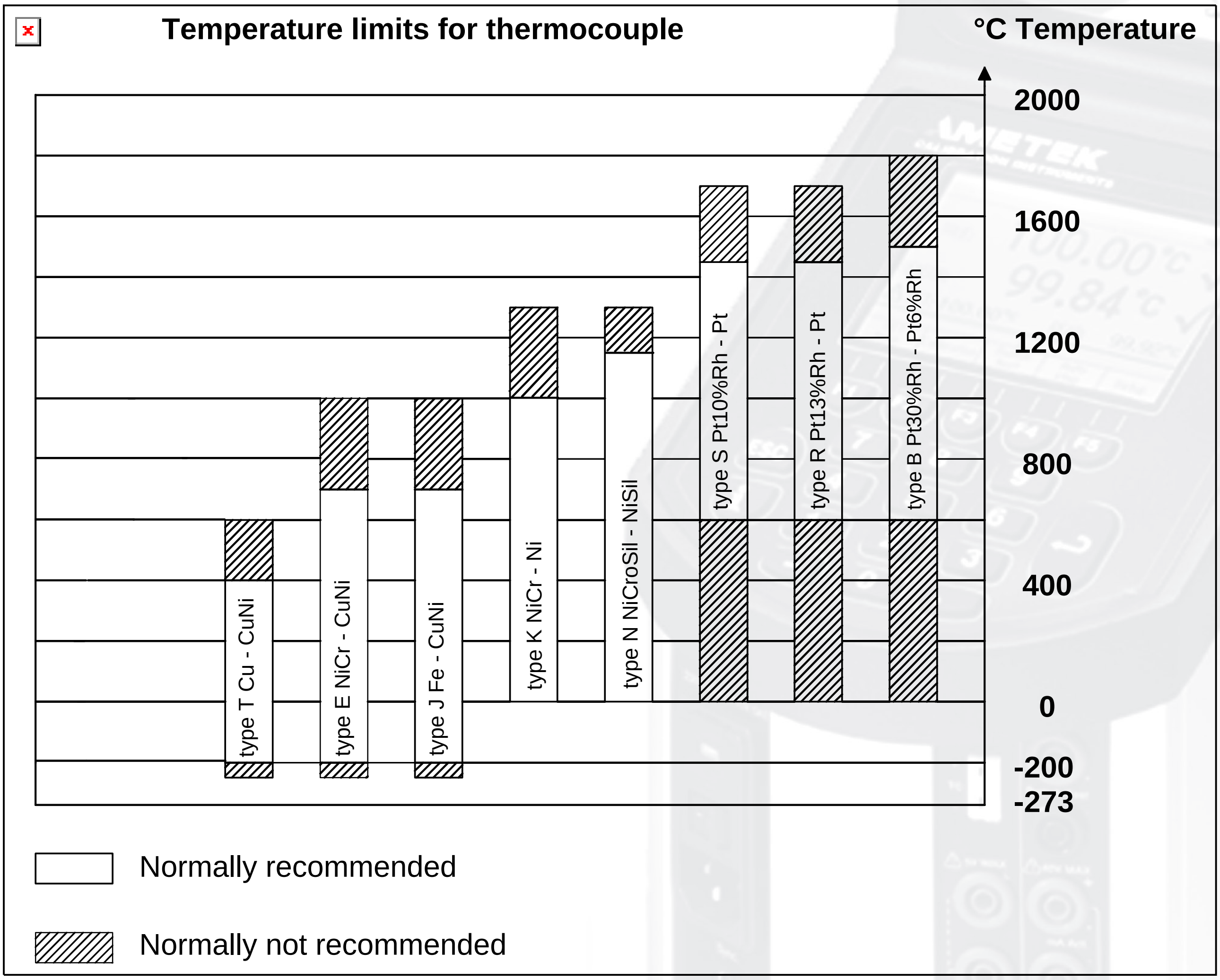
This international standard is called IEC 584 and is based on an American standard. At the time when this took place, the Germans had their own standard in the field, the DIN 43710, which also had the types of Cu-CuNi and Fe-CuNi. Even though the alloys were basically the same, they nevertheless deviated so much that they did not give the same thermo voltage. Therefore, it was decided to keep these types, which are today used under the names of:

Type designation/alloy
U Cu-CuNi (DIN)
L Fe-CuNi (DIN)

When naming a thermocouple, the positive conductor is always mentioned first.

5.2 Measuring range of a thermocouple

If you look at the number of thermocouples, they cover a large temperature range from –200 to 1800°C. The table below will give an overview of the temperature ranges, in which the thermocouples can be used. However, the recommended maximum operating temperature for the individual thermocouples is dependent on the diameter of the wire and the ambient atmosphere.


Temperature limits for thermocouple
°C Temperature
2000
1600
1200
800
400
0
-200
-273
type T Cu - CuNi
type E NiCr - CuNi
type J Fe - CuNi
type K NiCr - Ni
type N NiCroSil - NiSil
type S Pt10%Rh - Pt
type R Pt13%Rh - Pt
type B Pt30%Rh - Pt6%Rh
Normally recommended
Normally not recommended

5.3 Tolerances

We distinguish between three tolerance classes. Class 1 is the most accurate. Class 2 is standard, i.e. this is the quality that is delivered if nothing else is mentioned. Below you will find an overview.

Tolerances for thermocouples acc. to IEC 584 - 2		
Thermocouple	**Temperature range**	**Tolerance** [1)]
Class 1		
Type T, Cu-CuNi	-40 to 350°C	±0.5°C or ±0.004·t_{actual}°C
Type E, NiCr-CuNi	-40 to 800°C	±1.5°C or ±0.004·t_{actual}°C
Type J, Fe-CuNi	-40 to 750°C	±1.5°C or ±0.004·t_{actual}°C
Type K, NiCr-Ni	-40 to 1000°C	±1.5°C or ±0.004·t_{actual}°C
Type N, Nicrosil-Nisil	-40 to 1000°C	±1.5°C or ±0.004·t_{actual}°C
Type S, Pt10%Rh-Pt	0 to 1100°C 1100 to 1600°C	±1.0°C ±(1.0°C +0,003(t_{actual} – 1100))°C
Type R, Pt13%Rh-Pt	0 to 1100°C 1100 to 1600°C	±1.0°C ±(1.0°C +0,003(t_{actual} – 1100))°C
Class 2		
Type T, Cu-CuNi	-40 to 350°C	±1.0°C or ±0.0075·t_{actual}°C
Type E, NiCr-CuNi	-40 to 900°C	±2.5°C or ±0.0075·t_{actual}°C
Type J, Fe-CuNi	-40 til 750°C	±2.5°C or ±0.0075·t_{actual}°C
Type K, NiCr-Ni	-40 to 1200°C	±2.5°C or ±0,0075·t_{actual}°C
Type N, Nicrosil-Nisil	-40 to 1200°C	±2,5°C or ±0,0075·t_{actual}°C
Type S, Pt10%Rh-Pt	0 to 1100°C 1100 til 1600°C	±1,5°C or ±0,0025·t_{actual}°C
Type R, Pt13%Rh-Pt	0 to 1600°C	±1,5°C or ±0,0025·t_{actual}°C
Type B Pt30%Rh-Pt6%Rh	600 to 1700°C	±1,5°C or ±0,0025·t_{actual}°C
Class 3		
Type T, Cu-CuNi	-200 to 40°C	±1,0°C or ±0,0015·t_{actual}°C
Type K, NiCr-Ni	-200 to 40°C	±2,5°C or ±0,0015·t_{actual}°C
Type N, Nicrosil-Nisil	-200 to 40°C	±2,5°C or ±0,0015·t_{actual}°C
Pt30%Rh-Pt6%Rh Type B	600 to 1700°C	±4°C or ±0,005·t_{actual}°C

Note [1)] : The highest value is valid. I.e. for example for type K class 2 the tolerance in the range –40 to +333°C is ±2.5°C and above it is ±0.0075·t_{actual}°C

5.4 Temperature-voltage-relation

The temperature-voltage-relation is not based on a simple relation. The size of the thermal power or the thermal voltage has a most complicated relation to the temperature. This appears from the fact that it takes a high power polynomial to describe this relation.

Additionally tables calculated from these with polynomial are available with thermal voltages per °C.

5.5 Compensation cable

The thermocouple goes from the hot junction in the sensor to the cold junction, which is normally found in the instrument, i.e. in principle a thermo wire should be used all the way. This is however unpractical as well as too expensive in many cases. Instead a special cable is used. The requirements to this cable are that it does not add additional thermal voltage to the measuring chain resulting in measurement errors.

There are three cable types, which can solve this task:

5.5.1 Compensation cable

The compensation cable is a cable made from metals or from alloys, which have the same thermoelectric characteristics as the thermocouple, but only in a limited temperature interval, typically up to 100°C. It is therefore important to ensure that the ambient temperature at the junction remains within the interval recommended by the supplier. If not, it will be the same as to add an extra thermal point in the measuring circle.

5.5.2 Extension cable

The designation extension cable covers a cable which holds the same alloy as the thermocouple or an alloy with the same thermoelectric characteristics as the thermocouple, but with a larger temperature interval than is valid for compensation cables, typically up to 200°C.

5.5.3 Thermocouple wire

Thermocouple wire is the material that is used for the production of thermocouples. By using this as extension cable you have eliminated minor errors coming from thermo junction.

There are however two reasons for not using thermo wire as extension. First of all the price is high, especially in the case of thermocouples made of precious metals, secondly it is most often only produced as solid wire which is rather difficult to use for installation purposes.

5.5.4 Colour codes

As there are many types of thermocouples and as you cannot see the alloy of a cable immediately, a colour code has been introduced. The standard valid today is IEC584-4. According to this standard all negative conductors are white, while the positive conductors and common isolation have the same colour. Before this standard was introduced, the DIN 43710 was used in Europe. In this standard all positive conductors were red, so one has to pay attention to what is connected together.

The below table indicates the colour codes according the IEC norm and other national standards.

Colour Codes for compensation cables				
Standard	**Thermocouples**	**Common Isolation**	**Isolation Positive**	**Isolation Negative**
IEC 584 - 4	Cu-CuNi Type T	Brown	Brown	White
	NiCr-CuNi Type E	Violet	Violet	White
	Fe-CuNi Type J	Black	Black	White
	NiCr-Ni Type K	Green	Green	White
	Nicrosil-Nisil Type N	Pink	Pink	White
	Pt10%Rh-Pt Type S	Orange	Orange	White
	Pt13%Rh-Pt Type R	Orange	Orange	White
	Pt30%Rh-Pt6%Rh Type B	Grey	White	White
DIN	Cu-CuNi Type U	Brown	Red	Brown
	Fe-CuNi Type L	Blue	Red	Blue
	NiCr-Ni Type K	Green	Red	Green
	Pt10%Rh-Pt Type S	White	Red	White
	Pt13%Rh-Pt Type R	White	Red	White
ANSI	Cu-CuNi Type T	Blue	Blue	Red
	NiCr-CuNi Type E	Purple	Purple	Red
	Fe-CuNi Type J	Black	White	Red
	NiCr-Ni Type K	Yellow	Yellow	Red
	Pt10%Rh-Pt Type S	Green	Black	Red
	Pt13%Rh-Pt Type R	Green	Black	Red
	Pt30%Rh-Pt6%Rh Type B	Grey	Grey	Red

5.6 Applications and limitations

A good knowledge of the conditions under which the measurement shall take place gives the best possibility for choosing the right type of thermocouple. For the thermocouples most often used the following should be observed as to applications and limitations:

5.6.1 Type J. Fe-CuNi thermocouple

* Cannot be used below 0°C, because condensation on the Fe-conductor will cause rusting.
* Most suitable for reducing atmospheres
* May be used up to 500°C as a max. Above this temperature the oxidation will be very heavy. Besides, both thermocouple wires will be attacked and destroyed by sulphur.
* Shows too high temperature after ageing.

5.6.2 Type T. Cu-CuNi thermocouple

* May be used below 0°C even with very high accuracy.
* May be used both in slightly oxidizing and slightly reducing atmospheres. Should, however, not be used for temperatures above 400°C.
* Not sensible to humidity.
* Both threads may be annealed to remove non-homogeneous stuff. In this way faulty voltages are omitted.

5.6.3 Type K. NiCr-Ni thermocouple

* Type K is widely used in numerous applications from –100°C to max. +1000°C ((recommended), depending on the wire diameter).
* For a short time up to 1200°C.

* In the range from 200 to 500°C a so-called hysteresis effect may occur, i.e. you do not reach the same value in heating and cooling. There may be a difference of up to 5°C.
* To be used in neutral or oxidizing atmospheres.
* Shows too low temperature after ageing.
* Is not recommended to be used in reducing atmospheres. In this case chromium will come out of the NiCr-conductor, the so-called migration. The thermocouple will change thermal voltage and show too low temperature. This error effect is called Green-rot.
* Sulphurous atmospheres are poisonous, because sulphur will attack both threads.

5.6.4 Type N. Nicrosil-NiSil thermocouple

The type N thermocouple is of a relatively new date and is constructed based on a type K thermocouple. The type K thermocouple is easily polluted at high temperatures by foreign bodies. By alloying both conductors with among others silicon, you have "polluted" the thermocouple in advance and in this way it is less exposed to pollution from other materials.

* The recommended max. working temperature is 1200°C (depending on the wire diameter).
* For a short time up to 1250°C.
* High stability in the range from 200 to 500°C (no hysteresis effect like for type K).

5.6.5 Type S. Platinum 10% Rhodium-Platinum thermocouple

* The recommended max. working temperature is 1350°C (depending on the wire diameter).
* For a short time up to 1750°C.
* Will be polluted at temperatures above 900°C by hydrogen, carbon and metallic gasses from copper and iron. Already at absorption of 0.1% iron in the platinum wire, the thermal voltage will change by more than 1 mV at 1200°C and 1.5 mV at 1600°C. The consequence is an indication error of more than 100°C and 160°C, respectively. The same pattern takes place in connection with absorption of copper. Therefore, you should never use a platinum thermocouple with a steel tube, unless the steel tube has a gas proof ceramic tube inside.
* May be used in oxidizing atmospheres.
* At temperatures above 1000°C, the thermocouple is also polluted by silicon. This silicon exists in some types of ceramic protection tubes used for the thermocouple. Therefore, it is important to use thermocouples with protection tubes of extremely pure aluminium oxide.
* Applications below 400°C cannot be recommended, as the thermal voltage here is very low and non-linear.

5.6.6 Type R. Platinum 13% Rhodium-Platinum thermocouple

* Same as for Type S above.

5.6.7 Type B. Platinum 30% Rhodium-Platinum 6% Rhodium thermocouple

* Recommended max. working temperature 1500°C (depending on the wire diameter)
* For a short time up to 1750°C.
* Will be polluted at temperatures above 900°C by hydrogen, carbon and metallic gasses from copper and iron, however less than type S and type R.
* At temperatures above 1000°C, the thermocouple is also polluted by silicon. This silicon exists in some types of the ceramic protection tubes, which are used for the thermocouple Therefore, it is important to use thermocouples with protection tubes of extremely pure aluminium oxide.
* May be used in oxidizing atmospheres.

- ∗ Applications below 600°C cannot be recommended, as the thermal voltage here is very low and non-linear.

6. RESISTANCE THERMOMETER

The resistance thermometer is a passive temperature sensor, based on the physical phenomenon that an electric conductor changes its conductivity as a function of the temperature. Resistance thermometers can be split into two main groups:

Metal resistance thermometers
Semiconductor resistance thermometers

Within technical temperature measurement, the metals of platinum, nickel, copper and nickel-iron are used, but even high in price, especially platinum is the preferred metal. This is mostly due to the fact that being a precious metal, platinum has an eminent chemical stability towards most media and high stability at high temperatures. In addition, platinum has an excellent reproduction of its electrical characteristics due to its homogeneity. Therefore, the platinum resistance thermometer is used as interpolation instrument when determining the ITS, the International Temperature Scale.

The following will only deal with the platinum resistance thermometer.

6.1 Platinum resistance thermometer

6.1.1 Temperature – resistance relation
The relation between temperature and resistance has been laid down in the IEC 751 as table value and as an equation. For Pt100 the following equations apply:

For the temperature range from –200°C to 0°C the following will apply:

$$R_t = R_0 \cdot (1 + A \cdot t + B \cdot t^2 + C \cdot (t - 100) \cdot t^3)$$

For the temperature range from 0°C to 850°C the following will apply:

$$R_t = R_0 \cdot (1 + A \cdot t + B \cdot t^2)$$

The constants have been fixed as follows:

$$A = 3.90803 \cdot 10^{-3}$$
$$B = -5.775 \cdot 10^{-7}$$
$$C = -4.183 \cdot 10^{-12}$$

The temperature coefficient α is a value of the sensitivity of the resistance thermometer. It is also an expression of the mean value for the relative change in resistance per °C between 0 and 100°C.

$$\alpha = (R_{100} - R_0)/ R_0 \cdot 100 \ [°C^{-1}]$$

R_{100} = the resistance at 100°C
R0 = the resistance at *0°C*
For Platinum <u>α = 0.3850/°C</u>

6.2 Tolerances

A tolerance is an indication of the highest permittable deviation from true value under non-calibrated conditions. There are four different tolerances:

* Norm-related tolerances
* Commercial tolerances
* Company specific tolerances
* Relative tolerances

6.2.1 Norm-related tolerances

Norm-related tolerances are the tolerances that can be found in national or international norms on resistance elements. DIN43760, the German industrial norm, has been elevated into the international norm of IEC751 and indicates tolerances for platinum sensors as follows:

Class A: $\pm$ (0.15 + 0.002 t_{actual}) [°C]
Class B: $\pm$ (0.3 + 0.005 t_{actual}) [°C]

Where t_{actual} is the actual value of the temperature.

Based on these formulas it is seen that tolerances consist of two contributions, i.e. the zero point tolerance (0°C) and the temperature-dependant additional tolerance (inclination). Norm tolerances are in general valid, i.e. they are in force no matter whether it concerns Pt100 or Pt500, etc.

6.2.2 Commercial tolerances

Mercantile tolerances are a supplementary to the norm-related tolerances. Increasing demands to being able to measure more accurately and the fact that the norms only differentiate between two tolerance classes, have resulted in the concept called mercantile tolerances. These are described in 1/3 DIN, 1/6 DIN, and 1/10 DIN. The mercantile tolerances are so well integrated that they are accepted as an ordinary standard. Unfortunately, these norms may be abused to let the customer believe that he buys something, which is better than it actually is. It is an error that some suppliers wrongly inform that both the zero point tolerance and the temperature-dependant tolerance are a fraction of the norm tolerance.

The normal is that only the zero point tolerance is improved.

AMETEK Denmark A/S defines it in the following way:

1/3 Cl. B at 0°C: $\pm$(0.1+0.005$\cdot$ t_{actual}) [°C]
1/6 Cl. B at 0°C: $\pm$(0.05+0.005$\cdot$ t_{actual}) [°C]

6.2.3 Company specific tolerances

Company specific tolerances are yet another supplement to the norm tolerances. Some companies use tolerance classes, which are completely their own. This is most often the case, if a company can offer platinum elements that are better than what can be described with norm tolerances as well as mercantile tolerances.

For example: SDL band 5: $\pm$(0.045+0.001x t_{actual})[°C] in the range -50+400°C

Relative tolerances are another form of tolerance. Here, the tolerance or the permittable deviation is not measured in relation to the correct value, but in relation to another platinum resistance. In connection with measurement of energy amounts there is a need for measuring relatively between supply and return. It is for exactly such measurements that relative tolerances are used.

The tolerance may also be indicated as:

±0.1°C variance at 0°C and 100°C (group-paired)

6.3 Measuring resistance types and measuring range

The measuring element can be divided into the following groups:

Types

* Wire-wounded in ceramics
* Wire- wounded in glass
* Thin-film resistors

Measuring range

When evaluating the temperature ranges, it is necessary to differentiate between the basic values and whether the carrier material is ceramics or glass.

Generally, resistance thermometers are suited for the range from -50 to 400°C. For measurement of temperatures higher than 600°C, the use of thermocouples should be considered.

6.3.1 Wire-wounded measuring resistors in ceramics

For industrial use, the platinum wire has been completely or partly embedded to ensure optimum mechanical strength against impacts, chocks and vibrations.

In the reference resistor the platinum wire is loose to avoid differences in the expansion coefficients between platinum and ceramics and thereby influence the accuracy in negative direction. The consequence is naturally that these measuring resistors are not very robust and cannot stand impacts or vibrations.

6.3.2 Wire-wounded measuring resistors of glass

Glass resistors have the very big advantage of not being hydrostatic, i.e. they do not absorb water from the surroundings. So, if you have to make a temperature measurement in air with a quick reaction time it is quite obvious to use a glass-measuring resistor. The glass-measuring resistor is the most expensive one of the three types.

6.3.3 Thin-film resistors

The production process of thin-film resistors is as follows: a thin ceramic substrate is fused on to the platinum and a pattern is cut into the platinum until the desired basic value has been achieved. This type of measuring resistor shows very good characteristics towards vibrations. The thin-film resistors are cheaper than the wire-wounded resistors.

6.4 Coupling methods

Today the following different coupling methods may be chosen:

* 2-wire
* 3-wire
* 4-wire

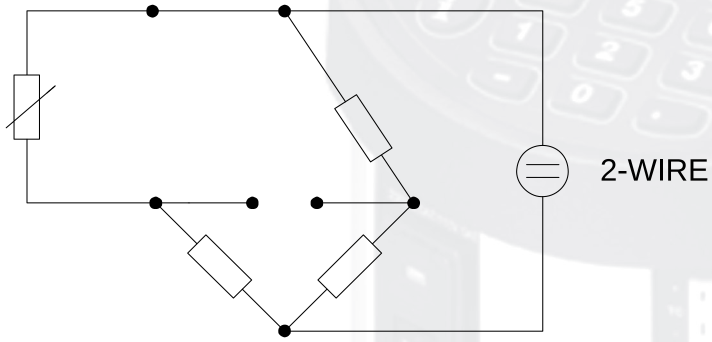
6.4.1 2–wire coupling

This coupling method will always result in measuring errors, because you cannot avoid also measuring the lead wires. If the measurement is done by means of a Wheatstone bridge, this measuring error can be adjusted away, but only at one temperature.

If only a narrow temperature range is measured, the measuring bridge is adjusted to be correct in the middle of the range. So, in this case it is possible to use the cheap 2-wire coupling. As an example this means that a lead wire resistance of 0.5Ω will give the following error depending on the basic value R_0

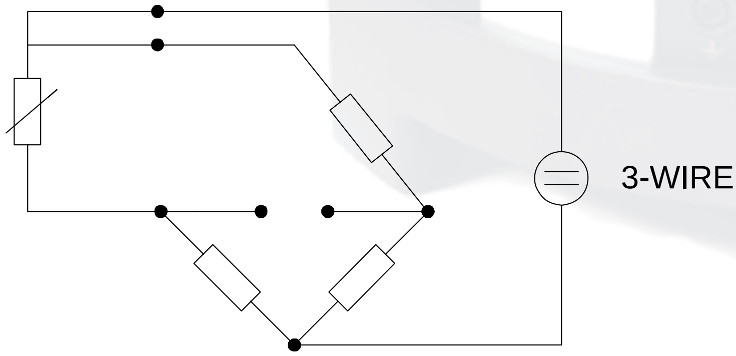
R_0	:	Pt100	Pt500	Pt1000
Measuring error	:	2,6°C	0,52°C	0.25°C

As expected the error declines as the value of R_0 increases.



6.4.2 3-wire coupling

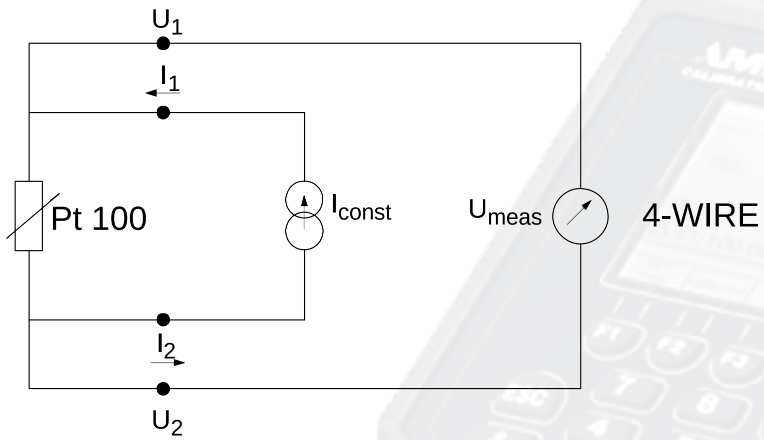
Here the measuring error will be 0°C, when the temperature 0°C is measured. This is of course due to the fact that the measuring bridge is in balance, when all resistors have the same size. Consequently, the lead wire resistance must be the same in the three wires. This means that a 3-wire coupling gives a fully compensated measurement at the temperature 0°C completely independent of the size of the lead wire resistance. The error only occurs, when the measured temperature is different from 0°C, and then the size of the error will grow along with increasing lead wire resistance. In this case it is a matter of changes in the sensibility of the measuring bridge. The size of the error will be less than 1/10 of the error in a 2-wire system, if the resistance in the individual lead wire is max. 10Ω.



6.4.3 4-wire coupling

With the 4-wire coupling you are not using the Wheatstone bridge as measuring circuit.

A constant measuring current is sent to the measuring resistor through two of the wires. The voltage that is created above the resistor is measured with a high impedance voltmeter over the two other wires. When the input impedance is within the mega-ohm range, the current and thereby the voltage drop in the measuring wires will be approximately zero. In this way you avoid including the lead wires in the measurement.



6.5 Self-heating

The current that is sent through a measuring resistor to measure the voltage has an electrical effect (Joule) that will heat the measuring resistor. The effect can be found from the relation.

$$t_{self\ heating} = P/_{EK} = R_T \cdot I^2/E_K$$

Manufacturers of measuring resistors indicate a self-heating coefficient E_K for the measuring resistor itself. This figure cannot be used for the entire sensor, because the size of the self-heating coefficient is dependent on the surface that is in contact with the medium, the coefficients of heat transfer and the temperature delay (sensor medium).

Examples

Medium: Water at 0.2 m/s

Ceramics measuring resistor	E_K = 300mW/°C
Measuring resistor in measuring insert	E_K = 80mW/°C
Measuring resistor in fittings	E_K = 10mW/°C

In air the values are typical in the range 25-100μW/°C. When the values are known, the spontaneous heating may be calculated based on the following:

You normally try to keep the measuring current so low (typically<1mA) that the self-heating max. becomes 0.1°C, or you use a pulsating current.

6.6 Application

Resistance thermometers are in general used where the following requirements and working conditions exist:

* Temperature range -50+400°C
* High absolute accuracy is a demand
* High relative accuracy is a demand
* High repeatability
* Not too heavy vibration conditions
* Mean response time
* Interchangeability

7. SELECTION OF TEMPERATURE SENSOR

An ideal solution to a temperature measurement task seldom exists. Selection of temperature sensor will invariably be a compromise between the requirements of the user and the limitations that are set by the possible types of sensor in connection with the conditions on the measuring point.

The following indicates the most important conditions for an appropriate selection of sensor.

Attention should be paid to the fact that a sensor measures its own temperature. Therefore it is quite decisive for the accuracy that the sensor assumes the temperature that is to be measured, that is without having any effect on this. A surface sensor with thermocouple could for example very well measure more accurately than a corresponding sensor made as a resistance thermometer.

7.1 The most important conditions for the choice of a sensor

Selection of sensors in practice should be based on a total evaluation, in which a.o. the following parameters are considered:

* Temperature range
* Corrosion conditions
* Breaking down due to wear and tear
* Static mechanical influence
* Dynamic influence
* Accuracy
* Pressure conditions
* Interchangeable (with pocket, interchange without stopping the process)
* Response time
* Conditions of pollution
* Variations in temperature – temperature shock
* Sensitivity

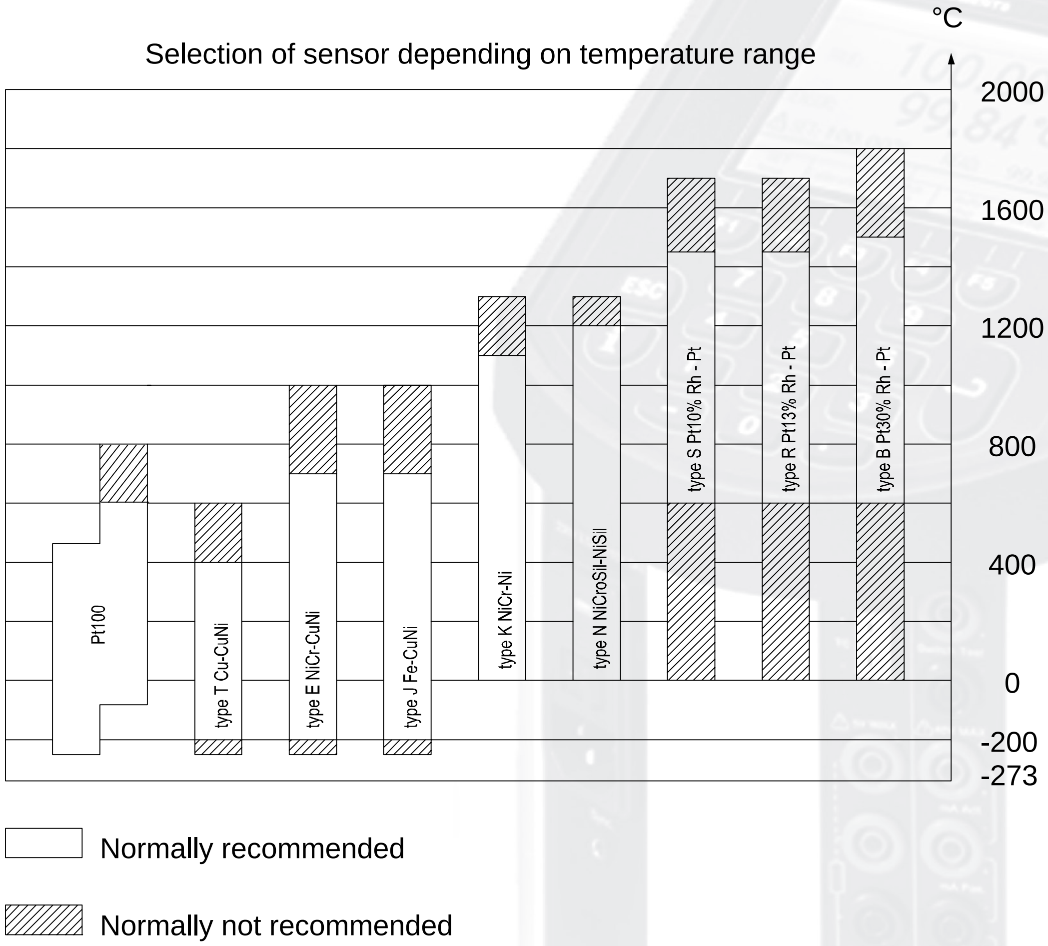
In the following some tools are given to simplify the necessary choice. It should be mentioned that these are not a “finial” solution but considerations to evaluate when selecting a sensor for a specific task.

7.2 Temperature range

This is normally one of the first things to evaluate, because the range of the individual thermo sensors easily determines the choice. At temperatures below 400°C resistance thermometers are often a natural choice. In the range 400 to 600°C thermocouples as well as resistance thermometers may be considered. If the measuring range is above 600°C, a thermocouple is often chosen.

Below table gives a general view of the temperature ranges that can be measured with a thermocouple and a resistance thermometer, respectively. Only remember to consider not only the normal temperature but also maximum and minimal temperatures that may occur. Furthermore, it may also be decisive how long the sensor is used.

Selection of sensor depending on temperature range



7.3 Corrosion conditions

Corrosion conditions are decisive for choice of fittings and thermo pockets, if any. If you suspect the medium you are going to measure to be aggressive, the following information must be available:

* Medium/media
* Concentration
* Temperature

This information will form the basis for finding the best-suited material for the job. Here the supplier will use public information about steel types and, above all, corrosion tables to find the best-suited material.

In some cases it is difficult to find a suitable alloy, which is why also other possibilities such as rubberizing, Teflon coating or plast coating are taken into consideration. Naturally, it is always helpful to have information about what other material sensors and the container are made of.

The solution to such a problem could also be to measure on the outside of the container using a surface sensor. A quite special problem may occur, if the electrical conditions make a galvanic corrosion occur. In such cases the least precious of the metals involved will be corroded. If the medium, in which the measurement should be done, is a gas type, you will only very seldom see corrosion at low temperatures, but at higher temperatures even air may be aggressive due to oxidation. The same goes for fuel gases with content of carbon monoxide, hydrocarbons or sulphur compounds. The material will be damaged or the protection tube become fragile due to decarburization, just as sulphides will be created.

Luckily, a number of heat-resistant or inoxidizable materials on iron-chromium-nickel basis is available, all even with a very low content of silicium or manganese. In oxygenic gases a thick, sticky oxidation deposit is created acting as a protective layer, as long as it is not damaged by settlement of dust, oil ash or flux. When metallic protection tubes are unable to give sufficient protection, ceramic tube of porcelain or Al_20_3 must be used. As to chemicals these tubes are superior to metallic tubes in every way, but unfortunately they have only poorer mechanical strength and they are more sensitive towards quick deviations in temperature.

7.4 Mechanical load pressure, static and dynamic influence

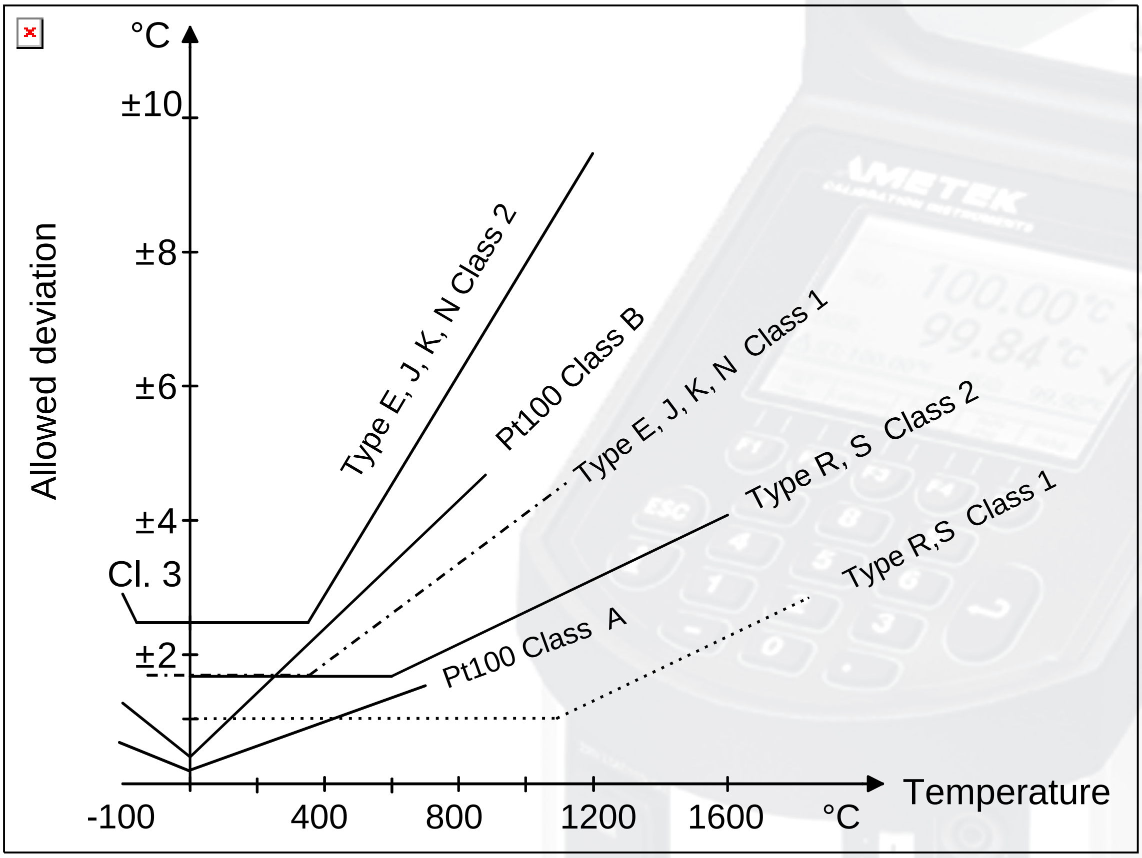
Temperature sensors are normally exposed to mechanical influence, which can reach from pure static load (for example the self-weight of long thermocouples) over mixed static and dynamic load to high frequency vibrations from fast moving floating media or swinging machine parts. To this should be added pressure influence from containers or pipelines. If the pressure conditions, under which a temperature sensor must be placed, are known, these are compared with data informed in the individual data sheets, and a pocket/protective tube that fulfils the desired requirements is chosen. Load diagrammes are based on DIN 43763.

Sensors placed in a tube with floating media are very often exposed to heavy mechanical vibrations. In this respect please note that load curves for thermo wells/pockets as function of pressure, material, temperature, velocity of medium in DIN 43763 only consider influence caused by force from the medium, and not the load that comes from vibrations. The size of this influence is especially dependent of the flow velocity (laminar or turbulent flow) and the built-in length.

AMETEK Denmark A/S can offer consulting around dynamic influence on sensors a.o. by means of special developed software programs.

7.5 Accuracy

To achieve the desired accuracy, a choice is made based on the norms. Please see page 12 for tolerance on resistance thermometers and page 7 for tolerance for thermocouples. Below graph will give a total picture.



If you are in the situation that the accuracy is not good enough, you will have to choose calibrated sensors or calibrated systems.

7.6 Response time

It is not a guarantee for the final achieved accuracy to choose resistance sensors with the absolutely best tolerance.

As described earlier, a thermometer cannot show the temperature without having assumed the level of energy corresponding to the actual temperature. The sensing element – be it thermocouple or resistance element - is the last part that is influenced by the temperature. So, if you have a dynamic process, the temperature sensor may chronically halt after the temperature.

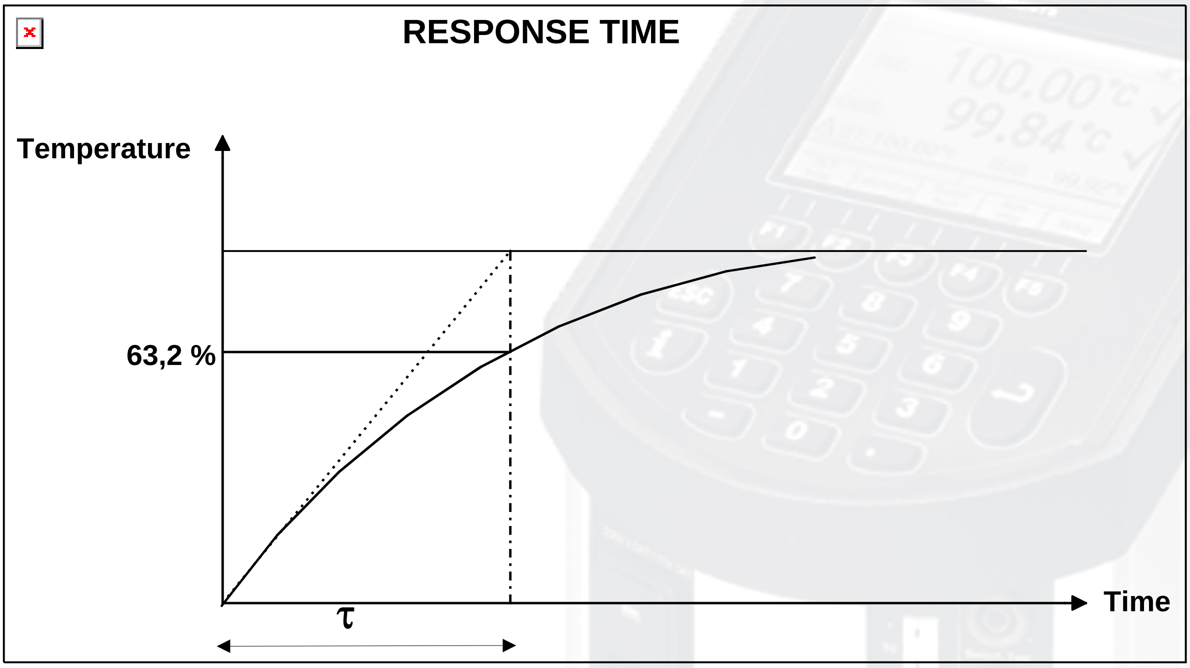
A temperature sensor's response time is a.o. influenced by the following conditions:

* Dimension of sensor
* Heat transfer number between medium and sensor
* Static or dynamic medium
* Type of medium. Liquid or gas
* Production method

For a quantitive description of the response time of a temperature sensor you make the assumption that the sensor is a first order system. I.e. you define that there is only a delay of the heat transfer between the medium and the sensor itself. This is rarely the case in practice, as a sensor most often consists of various heat delaying layers, such as pocket, protective tube, ceramic powder, and cavities. When simplifying nevertheless, it is partly because it gives relatively good agreement with the actual conditions and partly because it is easy to create formulas that can be used for calculations.

7.6.1 Response time

If a temperature sensor is exposed to a temperature response, its response or reaction can be described with the below graph.



If the time constant τ is known for a temperature sensor, it is also possible to state how many percent of the final value it has reached.

If you determine that the acceptable error percentage must not exceed the tolerance for the sensor, the following relation will give how many time constants that have to be passed, before the accuracy has been achieved:

Z = ln (100/X)

Where *X* is the error percentage that can be accepted, Z is the number of time constants to be passed to achieve the desired accuracy.

Z is typically 4-6 τ

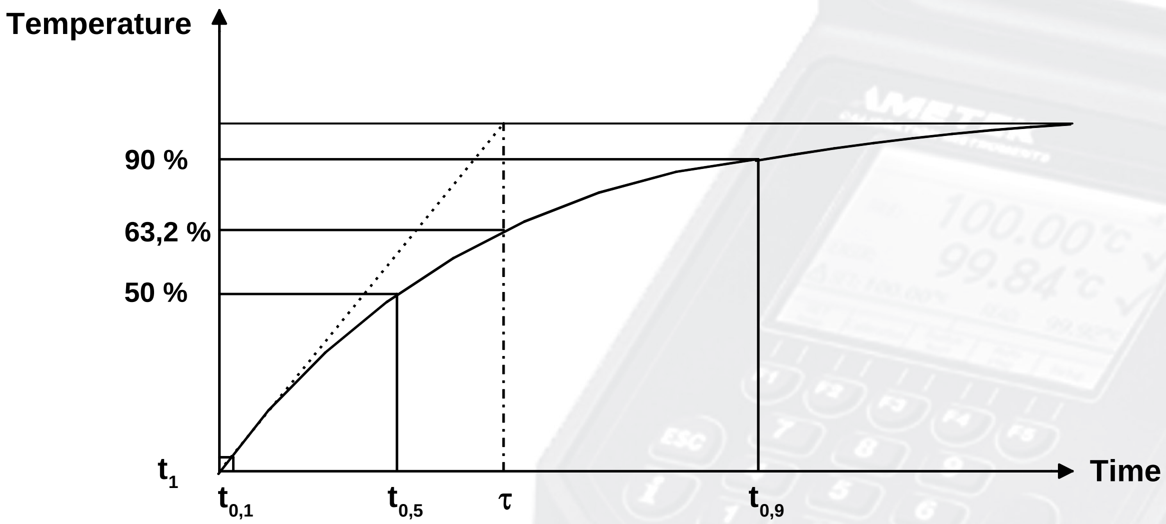
7.6.2 Other expressions of response time

As the response time is not a simple 1. order system, as mentioned, AMETEK Denmark A/S indicates a more differentiated value than just a time constant. In the indication of the response time, different conditions have been included such as medium involved, and movements of the medium compared to the sensor. Two times are indicated:

$T_{0,5}$ is the time it takes the sensor to reach 50% of a change in temperature.
$T_{0,9}$ is the time it takes the sensor to reach 90% of a change in temperature.

The indicated times have been found by testing the given type of sensor. There are therefore no approaches to a 1. order system.

RESPONSE TIME



Time constant τ in relation to other expressions of response time

It is possible to convert from this system to a time constant system with the purpose of being able to make calculations with the indicated formulas for the spring response, the ramp function or the sinus function.

This is done in the following way:

$$\tau = T_{0.9} / 2.3$$

or

$$\tau = T_{0.5} / 0.7$$

It should be emphasized that the above methods of calculation are approaches.

One of the factors that have major influence on the response time is the thermal mass of the sensor or in plain words its size. This fact makes it possible that values informed by a supplier with a good approach can be used on similar products from other manufacturers.

Another factor that has great impact on the size of the time of reaction, is the heat transfer ability between the sensor and the actual medium. In general, the heat transfer between sensor and liquid is much easier than between sensor and a gas.

8. MOUNTING AND INSTALLATION

Many things have to be considered in connection with mounting and installation of temperature sensors. The following is only mechanical, practical considerations.

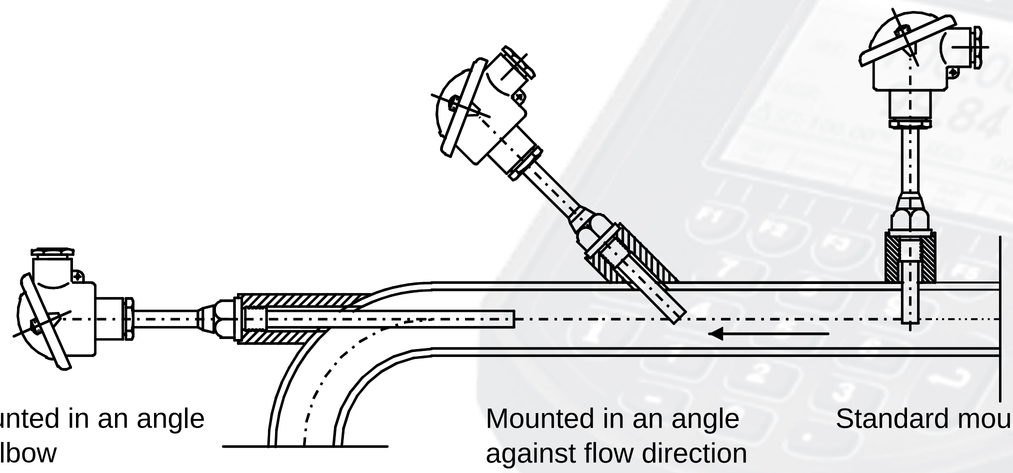
8.1 Mounting possibilities

There are three different ways:

* Mounted at right angles to the tube (standard)
* Mounted counter the flow direction, most often angled 45°
* Mounted counter the flow direction in an angle piece. Elbow placing

Mounting methods are illustrated below.

Installation of screw - in sensor



No unique prescriptions are given here as to which mounting should be used for specific measurements. Each individual installation must be evaluated separately. The length of the sensor can be decisive for the way of placing.

8.2 The length of the sensor

It is of decisive importance to choose the correct sensor length with a view to errors caused by heat dissipation from sensor tip to the surroundings. On this point you should choose length according to the following guidelines. The numbers in the table indicate the factor by which the sensor diameter has to be multiplied to calculate the length of the sensor.

Medium	Dynamic	Static
Liquid	5-10	10-20
Air	10-20	20-40

For example: A sensor with a diameter of 9 mm placed in a dynamic air stream should have an insertion depth of between 90 and 180 mm. To this insertion depth should further be added the physical length of the sensor element or the temperature sensitive length (TSL), which may vary from a few mm to 50-60 mm.

If the length after these calculations is bigger than the radius of the medium tube, you have the possibility of placing the sensor in an angle. Or if this is not sufficient, the sensor may be placed in an elbow.

The length of the sensor also has to be evaluated as regards vibrations, shocks and resonance frequency. Here it is important to ensure that the sensor does not get too long if mounted in a very turbulent liquid medium.

Finally, the mounting should be done in such a way that it leaves room around the sensor with a view to replacing the measuring insert.

8.3 Isolation

In cases where the measurement is carried out on media that have a temperature very different from the surroundings, the medium tube has to be isolated to minimize the effect from heat conduction. To ensure that heat transfer errors are eliminated, the sensor is some times isolated with a layer so thick that the connection head of the sensor is inside the isolation.

9. SOURCES OF ERROR

There are many possible errors in connection with temperature measurement. In the following is dealt with the types of error that are either caused by the physical conditions or general electrical conditions. If the error is connected to the measuring element (or the transducer) please refer to these sections.

Sources of error:

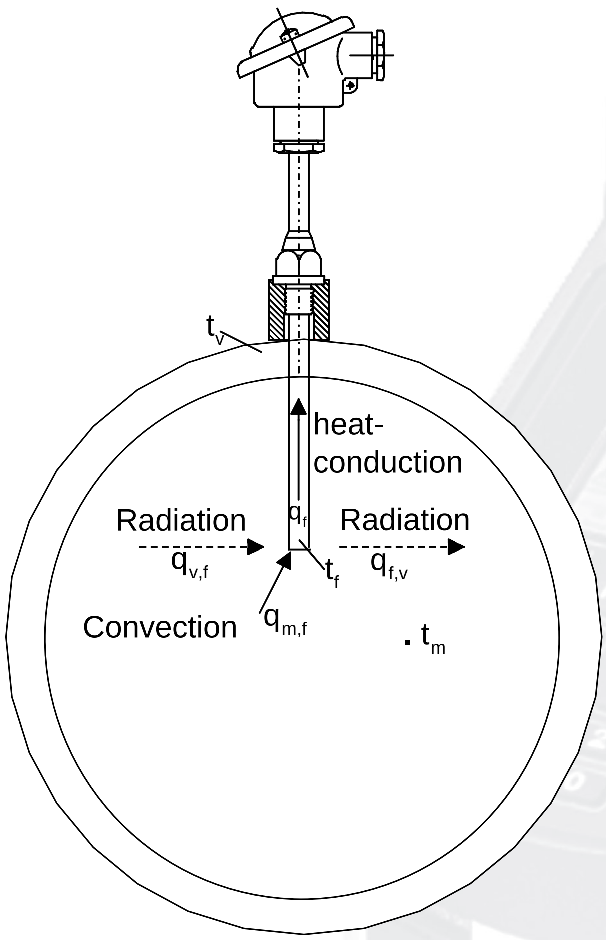
- Heat conduction in the temperature sensor
- Radiation to and from the surroundings
- Heat capacity of the temperature sensor
- Dynamic temperature
- Earth currents
- Electric noise
- Non-tempered measuring instrument

9.1 Heat balance

Heat energy is like electric current it follows the easiest way. That is the reason why measuring errors can occur in connection with heat conduction along a temperature sensor.

On the below figure are shown the different factors contributing to the heat balance of a temperature sensor.

Heat balance for a thermometer



Where:
t_m temperature of the medium
t_f temperature of the sensor
t_v temperature of the tube wall

These contributions will have the effect that the temperature t_f of the sensor will be different from the temperature $t_{m.}$ of the medium. It is very complicated to find a true correction for the entire system and we would therefore like to split up the problem in two cases.

9.1.1 Heat transfer for a thermo pocket/well

The size of the measurement error for a tube-formed pocket with thin wall is dependent of the convection contribution (medium – sensor) $q_{m,f}$ and the heat conduction contribution q_f.
It can be expressed as follows

$$\Delta t_{convection} = t_m - t_f = \frac{t_m - t_v}{\cosh(L \cdot x)}$$

Where:
L Built-in length in mm

$$x = \sqrt{\frac{h \cdot U}{k \cdot A}}$$

h Heat conduction coefficient (medium-pocket) in J/m^2 s °C
k Thermal heat conductivity for thermal pocket in J/m^2 s °C
A Heat conducting cross-sectional area in mm^2 (metal thickness of the pocket)
U Circumference in mm of the thermo pocket

From this expression can be seen that the size of the product $L \cdot x$ has big impact on the error, i.e. diameter, metal thickness, and insertion length.

Practical actions to minimize the error as follows:

- Ensure a good isolation around process tube or container
- Use sufficiently small metal thickness for the thermo pocket
- Use big insertion depth
- Use an earthed version of thermocouple
- Place the sensor where the medium is in motion to ensure that the mounting spot is not a cold spot that may conduct heat from the sensor
- Choose a sensor type with short time of reaction
- Keep the part of the sensor that is not placed inside the hose or the container isolated in order to minimise the temperature potential that pulls the heat flow out through the sensor

Also, some parts of steel may be replaced by parts of synthetic materials to increase the heat transfer resistance.

9.1.2 Radiation to and from thermo pocket/well

We know that energy may be transmitted by radiation through transparent material, if a temperature potential is present. In practice this means that the heat energy that a sensor absorbs from the medium by means of convection and conduction is radiated to the surroundings instead of being conducted to the sensor.

Provided that the surface area of the pocket is small compared with that of the wall, the correction for the contribution from radiation may be expressed as follows

$$\Delta t_{radiation} = t_m - t_f = \varepsilon \cdot \delta \cdot \frac{(T_f^{\,4} - T_v^{\,4})}{h}$$

Where:

h	Energy transfer coefficient (medium-pocket) in J/m^2 s °C
ε	The emissivity of the thermo pocket/well (a quantity to account for non-blackness of the sensor $0<\varepsilon<1$
δ	The radiation value for a "Black" body, Stefan – Boltzmann's constant
T_f , T_v	The absolute temperature of the sensor and the wall in K

From the expression one can see that the radiation correction is decreased, if you ensure a high energy exchange rate (medium – pocket), a low emissivity number for the pocket (brightness), and a good heat isolation of the walls.

Errors due to radiation exchange can be pretty big. In an incinerator with a temperature of approx. 850°C and a wall temperature of approx. 250°C, i.e. a temperature potential of 600°C, the measuring errors may be as high as 50°C. So, this error source contributes with errors so big that compensating actions must be taken. The following is an example:

- Distance as big as possible between heat radiation exchangers
- Reduction of sensor diameters
- Placing of sensors, where the surrounding walls seem to be most hot
- Mounting of one or more radiation shields on the temperature sensor

10. SIGNAL CONDITIONING AND TRANSMISSION

In a process the temperature often has to be measured in one place and the measurement data have to be sent to another place – often to a control room several hundred meters away – where the measurement data are used. In this respect, accuracy, stability, lifetime and costs have to be optimised. The most important factor in temperature control is good, reliable temperature data. To choose the right temperature sensor and the right method to transmit temperature data is the most important task.

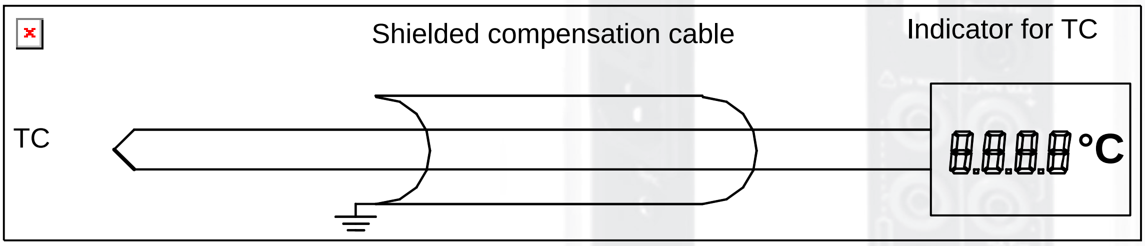
In this section we will concentrate on the signal transmission task.

Having chosen the optimal temperature sensor for a measuring task, next step in remote temperature measurement is to send information from the temperature sensor to the control room. Connecting the thermocouple or the resistance thermometer directly with a cable can do this, or you can have a transmitter placed close to the temperature sensor, from which an amplified signal is sent to the control room.

10.1 Direct cable connection

The direct cable connection has been used for many years and is easy to handle.

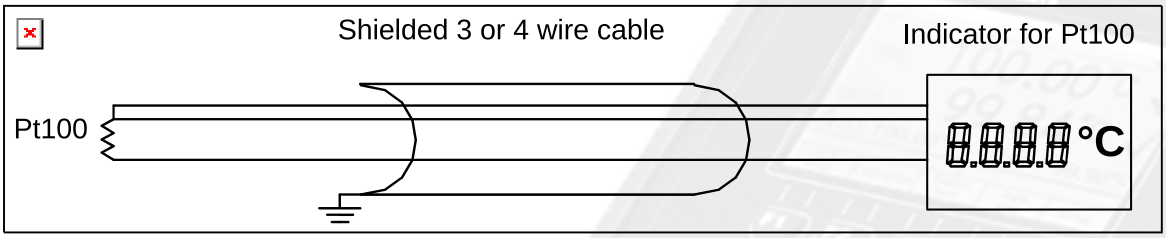
10.1.1 Direct cable connection to a thermometer
It takes great care to install compensation cables to thermocouples. Each type of thermocouple must have its own special compensation cable, which is described with a colour code in accordance with the standards.



10.1.2 Electrical noise
Electrical noise is often varying or is periodical and therefore it is difficult to locate and eliminate errors. The easiest way to avoid noise is by keeping as much distance between signal cables and noise sources as possible. Shielded cables reduce the problem but increase the costs.

10.1.3 Direct cabling to resistance thermometers
Contrary to thermocouples, resistance thermometers do not require a special cable. Copper cables are sufficient to send temperature information from resistance thermometers to a control room. If you only use a 2-wire connection between the temperature sensor and the control room, i.e. two wires in the cable, the resistance of these two wires will be added to the resistance in the resistance thermometer, which will of course result in a permanent measuring error of several degrees depending on the length of the cable. Add

to this that variations in temperature along the two wires in the cable will change resistance of the cable. This will cause variation in the temperature indication up to several degrees, depending on the length of the cable and the variation in temperature. Therefore, it is recommended to use at least three and preferably four wires in the cable, so-called 3- or 4-wire configuration between the resistance thermometer and the control room. 3- or 4-wire configurations can only be used, if the instrumentation in the control room is designed for this. Instrumentation in conventional 3-wire configuration compensates for the resistance itself and the variation contained in this, but the measuring principle with 3-wire configuration has built-in errors. Only instrumentation with 4-wire configuration or a special 3-wire configuration, which simulates 4-wire configuration gives the correct compensation for the cable resistance and thereby the best accuracy, when resistance thermometers are used for measurement of temperature.



10.2 Transmitters

Transmitters are electronic instruments that transform a measured value from one representation to another. This new representation is normally standardized and can be sent over several thousand metres without problems. Always consider using transmitters, when the temperature information has to be sent over distances that are bigger than 70 metres. In surroundings with electrical noise, where an accurate and reliable signal transmission is important, the use of transmitters should be considered even in connection with very short distances. This means of course that the transmitter you are using must not be affected by electrical noise and must be stable in the environment where it has to be used.

Transmitters can be split up based on different characteristics:

1. 2-wire or 4-wire transmitters
2. Transmitters with voltage, current or digital output signal
3. Isolated or non-isolated transmitters
4. Analogue or “smart” transmitters

10.2.1 2-wire transmitters

2-wire transmitters are using the same two wires for receiving energy to the transmitter as well as for sending the signal from the transmitter to the control room. The output signal is a standardised current signal, which alternates from 4-20 mA, determined by the measured temperature. The lowest temperature normally corresponds to 4 mA, and the highest temperature to 20 mA. The energy that powers the transmitter is lower than 4 mA so that the measuring signal is never affected. As the output signal always has to be at least 4 mA, breakage on the wires from the transmitter to the control room will be detected, if the output signal becomes 0 mA. 2-wire transmitters are naturally cheaper to install than the 4-wire transmitters. That is often the reason to choose 2-wire transmitters.

10.2.2 4-wire transmitters

4-wire transmitters are using two wires to receive power to the transmitter and two other wires to send the signal from the transmitter. 4-wire transmitters are necessary when the output signal must refer to zero, for example from 0-20 mA, or when 0-5 V is desired. The power consumption of the 4-wire transmitters is not limited to 4 mA, and therefore the quality of the 4-wire transmitter was previously of a higher quality than the 2-wire transmitter. In general, 2-wire transmitters are preferred, because cable costs are lower and because the price difference between 2-wire and 4-wire transmitters in the same quality is small.

10.2.3 Isolation

The isolation to earth of isolated temperature sensors is minimised dramatically with the increase in temperature. Due to the difference in the electrical potential in the earth, where the temperature sensor is mounted, and the potential where the instrument is mounted, an earth current will flow in the transmission cables.

The Power Regulation from 1994, which is based on European recommendations, means in practice that the receiving instrument is often connected to earth. Therefore it is recommended to use isolated transmitters, especially when operating with high temperatures in the temperature sensor. This will be valid for many resistance thermometer systems and most thermocouple systems.

11. TABLES

Enclosed tables for thermal voltages are based on the latest temperature scale ITS 90 and the resistance table for Pt100.

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