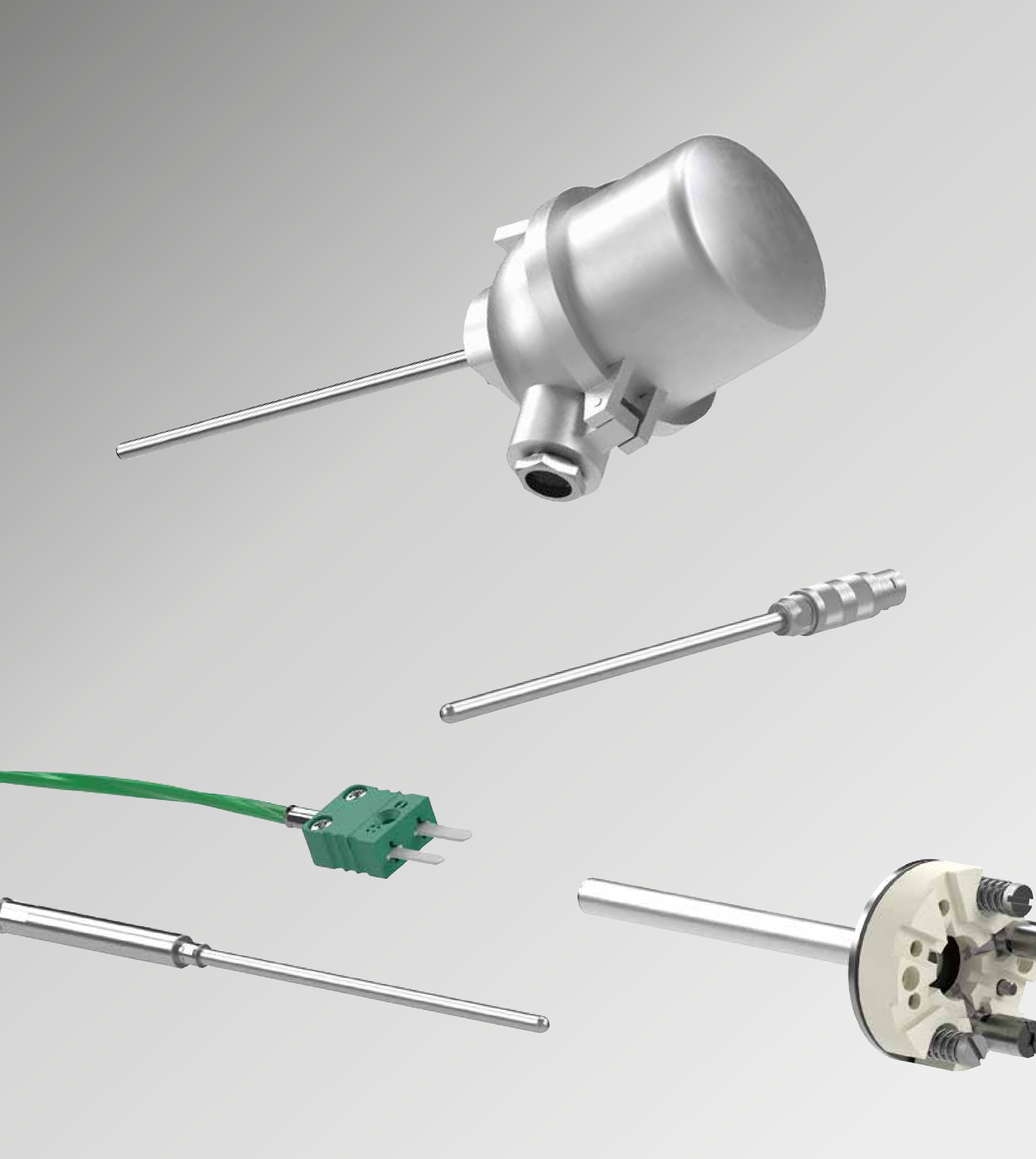

RÖSSEL MESSTECHNIK

RESISTANCE THERMOMETERS

IN INDUSTRIAL APPLICATIONS

Consultation. Solution. Innovation.

DIPL.-ING. REINHARD KLEMM
RÖSSEL-MESSTECHNIK GMBH

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RESISTANCE THERMOMETERS IN INDUSTRIAL APPLICATIONS

1. RESISTANCE THERMOMETERS

Resistance thermometers are passive electrical components that use the temperature dependence of the electrical resistance of metallic conductors to measure temperature.

Generally speaking, pure metals have a higher resistivity than alloys and have a relatively constant temperature coefficient of electrical resistance over a broad temperature range. High-purity precious metals, usually platinum, are used for precise measurements. These metals are largely resistant to aging and the thermometers can be made from them with low error limits. The resistor can also be made of ceramic (sintered metal oxides) or semiconductors. This makes it possible to achieve much higher temperature coefficients than with metals and hence also much higher sensitivities, though with less precision and considerable temperature dependence of the temperature coefficient itself. These resistors are referred to as thermistors, with high-temperature conductors (resistors with a negative temperature coefficient NTC) being less commonly used in measurement technology than cold-temperature conductors (resistors with a positive temperature coefficient PTC).

Conventional thermometers measure temperature based on the change in length or volume of a substance and are only suitable as display measuring devices. Resistance thermometers offer the advantage of delivering an electrical signal and are suitable for use in industrial measurement technology, where they are widely used as platinum resistance thermometers in particular.

The nominal value of such a resistance thermometer in industrial applications is usually 100 Ohm at 0°C.

1.1 Platinum resistance thermometers

Pt100 sensors are temperature sensors based on the change in the resistance of platinum under the influence of temperature. They are resistance thermometers, specifically PTC thermistors (PTC - positive temperature coefficient). For temperature measurements in the range from -200°C to 850°C, the electrical resistance change of a platinum wire or a platinum layer is often used. The platinum temperature sensors are characterized by their nominal resistance R0 at a temperature of 0°C.

The common types are:

- Pt100 (R_0= 100 Ohm)
- Pt200 (R_0= 200 Ohm)
- Pt500 (R_0= 500 Ohm)
- Pt1000 (R_0= 1 kOhm)
- The new Pt generation consists of the Pt 3000, Pt 6000 and Pt 9000.

The resistance change relative to temperature is defined in DIN EN 60 751:2009. The great advantage of standardizing the nominal resistance and the change in resistance is that the temperature sensors can be easily replaced without having to recalibrate the measuring chain. As a resistance thermometer, the Pt100 is more accurate in the lower temperature ranges than thermocouples, for example.

1.2 Structure

Platinum temperature sensors can be divided into two subgroups:

Platinum wire sensors

The temperature-sensitive element is formed from a platinum wire. The very thin and long wire is wound helically several times to save space. The nominal resistance is calibrated by shortening the platinum wire. Depending on the quality of the sensor, the coiled wire is either self-supporting, wound on a glass rod (glass measuring resistor) or embedded in a ceramic mass in a ceramic capillary (ceramic measuring resistor) as a housing. The platinum wire must be kept as free as possible from mechanical stresses, as these would falsify the measurement result. The ends of the platinum wire are welded to the connecting wires protruding from the housing. The ends of the tube are hermetically sealed by melting (for glass housings) or by casting with ceramic compound (for ceramic housings) in order to protect the platinum wire from chemical influences.

The advantage of platinum wire sensors is their high accuracy and long-term stability; the disadvantage is the relatively high cost of production and calibration.

Thin film sensors

The platinum is applied to a ceramic substrate in a meandering thin film process by means of sputtering. Once the connecting wires have been bonded and the nominal resistance calibrated by laser trimming, the platinum layer is coated with glass to protect it from chemical influences. The thin film sensor produced in this way can also be installed in a glass or ceramic tube and hermetically sealed to further increase its resistance to mechanical stresses and chemicals.

Thin film sensors offer the advantage of efficient manufacturing and calibration processes; the disadvantages are their lower temperature range and lower long-term stability than platinum wire sensors.

1.3 Designs

Pt100 resistance thermometers are available in various designs. The simplest case is the sensor without further encapsulation. For use with low chemical and mechanical stress, for temperature measurement inside devices for example, no further protection against environmental influences is required. The electrical connection can be made, for instance, by soldering into a circuit board or by surface mounting (SMD).

In industrial applications, on the other hand, the protection of the sensor and its ease of installation are crucial. Both are achieved by installing the sensor in standardized housings. Installing the Pt100 sensor in rigid or flexible tubes made of corrosion-resistant steel, for example, creates a so-called sheath sensor. This is often additionally separated from the medium to be measured by a thermowell. Other versions are sensors for measuring gas temperatures or for piercing into the object to be measured. The electrical connection of these sensors is made using permanently installed cables or plug connectors.

1.4 Connection

The electrical connection from the Pt100 sensor to the evaluating electronics can be made using the 2-wire, 3-wire or 4-wire method. The 3-wire and 4-wire method is devised to eliminate the error caused by the inherent resistance of the sensor connection wires. With the 3-wire method, one end is equipped with two connecting wires. With the 4-wire method, both ends are equipped with two connecting wires. Further information can be found in the Measuring circuits section.

Material for measuring resistors: Platinum

The platinum measuring resistors widely used in industrial measurement technology are governed by DIN EN 60 751, which specifies further summands for the function Rt = R(t) after the linear element.

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

for the range t = 0 ... 850°C,

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

for the range t = -200 ... 0°C

Numerical value of the coefficients:

$A = 3.9083 \cdot 10^{-3} °C^{-1}$; $B = -5.775 \cdot 10^{-7} °C^{-2}$;
$C = -4.183 \cdot 10^{-12} °C^{-4}$.

The specified nominal value is R0 = R(0), i.e. the resistance at 0°C. The nominal values 100 Ω and 1000 Ω are preferred. These sensors are then called Pt100 or Pt1000. The range of possibilities extends from Pt10 to Pt10,000. The values for a Pt100/0 in the table in the appendix are calculated using these equations.

Normally, Rt is measured and the temperature t is sought. The resolution ("inversion") of these formulas together with the associated linearization is not easy. An iteration method is therefore usually used to calculate tables.

Parameters and error limits

Pt100 thermometers are classified according to their error limits. A distinction is drawn between wirewound resistors and film resistors:

- Class AA:
Error limit = 0.1°C + 0.0017 |t|
(-50 to 250°C - wirewound),
(0 to 150°C - film resistor)

- Class A:
Error limit = 0.15°C + 0.002 |t|
(-100 to 450°C - wirewound),
(-30 to 300°C - film resistor)

- Class B:
Error limit = 0.3°C + 0.005 |t|
(-196 to 600°C - wirewound),
(-50 to 500°C - film resistor)

Example:
Class B: At 500°C, deviations in the measured value of up to ± 2.8°C are permissible.
The temperature coefficient of the resistor is specified in the standard at reference temperature 0°C:

$$a0 = (DR / R0) * Dt\text{-}1$$

The characterizing value is calculated from the mean temperature coefficient over the range 0 ... 100°C at a0 = 3.851 - 10-3°C-1.

Nickel

Nickel has a greater degree of sensitivity than platinum and delivers a greater relative change in resistance for the same temperature change. However, this material has been removed from the standardization process. For Ni100, the following equation applied in the range from -60°C to +180°C:

$$Rt = R(t) = R0 + At + Bt2 + Ct4$$

where t = temperature in °C;
Ro = basic resistance value at 0°C;
A = 0.5485 Ω /°C; B = 0.665·10-3 Ω °C-2;
C = 2.805·10-9 Ω °C-4

Common values for Ro: 100 Ohm; 500 Ohm; 1000 Ohm

DIN 43 760 draws a distinction between two tolerance ranges (corresponding to the temperature range):

- -60°C to 0°C -> tdev= +/- (0.4 + 0.028 * t)
- 0°C to 250°C -> tdev= +/- (0.4 + 0.007 * t)

where (t) is the initial temperature and tdev is the deviation. A disadvantage of the platinum measuring resistor is the lower temperature range (-60°C ... +250°C) and the greater tolerance, especially in the range below 0°C.

1.5 High-temperature conductors

High-temperature conductors have a strongly non-linear relationship between resistance and temperature. A suitable mathematical description of the behavior is a function of the absolute temperature T in the form

$$RT = R(T) = A*eB/T = RT0 * eB(1/T - 1/T0)$$

T0 is any reference temperature, e.g. 293 K (20°C). Variable B is a material constant; guide value B = 2000 ... 6000 K.
The relative error limits of RTo are typically 20%, of B 5%.

The temperature coefficient is defined slightly differently for this purpose. In the borderline case of differentially small temperature changes, it results in

$$aT = 1/RT * DR/DT \text{ --> } -B/T2$$

This illustrates a measurement effect which decreases sharply as temperature increases, but which is high at room temperature. Example: B = 3600 K; T = 300 K; aT = -0.04 * 1/K. This is around ten times higher than the a0 (0.0003851 * 1/K) of platinum. Interconnection with ohmic resistors can minimize the problems of sample scattering and non-linearity, although this also reduces the sensitivity of the measuring arrangement.

2. FURTHER OBSERVATIONS

Although deceiving at first glance, the subject of temperature is extremely complex. Temperature measurement using resistance thermometers in particular is difficult to understand in physical terms without the theory of thermodynamics.

Not everyone who wants to measure temperatures with resistance thermometers needs to know the four laws of thermodynamics. However, some enthusiasts may be interested in a little background information. This is provided, hopefully in comprehensible form, starting on page 19 of this brochure.

3. DIN EN 60 751 (IEC 60 751)

IEC 60 751:2008, which came into force internationally in January 2009 with the German translation DIN EN 60 751:2009, draws a distinction for the first time between wirewound and film measuring resistors and between bare measuring resistors and thermometers that are ready-to-install or use. The background to the distinction between wirewound and film measuring resistors is that, due to the different manufacturing technologies, the film measuring resistors do not exactly follow the Callendar-vanDuesen equation, which describes the relationship between temperature and resistance of a wirewound platinum measuring resistor. The temperature range varies depending on the class accuracy (see table). In addition to resistance thermometers with 100 Ohm basic resistance at 0 C, others with 500, 1000, 5000 and 10000 Ohm are also available.

4. MEASURING CIRCUITS

Tolerances for resistors DIN EN 60 751:2009

Wirewound resistors		Flat film resistors		
Tolerance class	Valid temperature range in °C	Tolerance class	Valid temperature range in °C	Tolerance value in °C
W 0.1	-100 to 350	F 0.1	0 to 150	± (0.1+0.0017*I t I)
W 0.15	-100 to 450	F 0.15	-30 to 300	± (0.15+0.002*I t I)
W 0.3	-196 to 550	F 0.3	-50 to 500	± (0.3+0.005*I t I)
W 0.6	-196 to 660	F 0.6	-50 to 600	± (0.6+0.01*I t I)

I t I = Absolute value of the temperature in °C regardless of the sign

Table 1 Tolerances for measuring resistors

Tolerances for thermometers DIN EN 60 751:2009

	Valid temperature range in °C		
Tolerance class	Wirewound resistors	Flat film resistors	Tolerance value in °C
AA	-50 to 250	0 to 150	± (0.1+0.0017*I t I)
A	-100 to 450	-30 to 300	± (0.15+0.002*I t I)
B	-196 to 600	-50 to 500	± (0.3+0.005*I t I)
C	-196 to 600	-50 to 600	± (0.6+0.01*I t I)

I t I = Absolute value of the temperature in °C regardless of the sign

Table 2 Tolerances for thermometers

Graphical representation of tolerances

The tolerance is axially symmetrical to the horizontal zero line. Only the positive portion is shown.

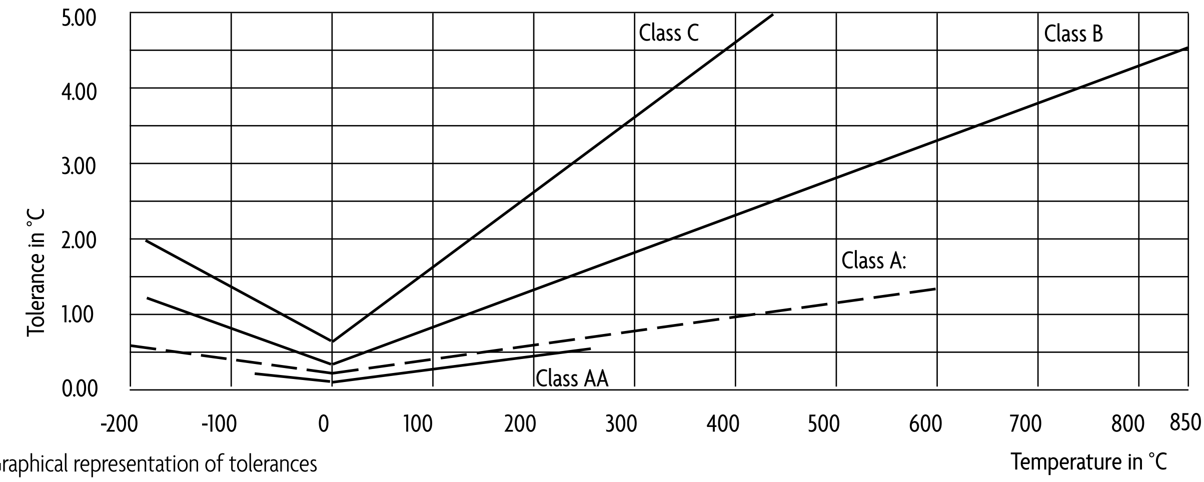


Fig. 1 Graphical representation of tolerances

A resistance measurement requires a constant current to flow through the resistor. The voltage applied is an easily measurable signal proportional to the resistance. However, this voltage itself often goes unmeasured. Only its change from an initial value by a differential circuit (e.g. Wheatstone bridge) is measured. To minimize the error caused by intrinsic heating, the measuring current must be as low as possible, typically 1 milliampere or less for the Pt100.

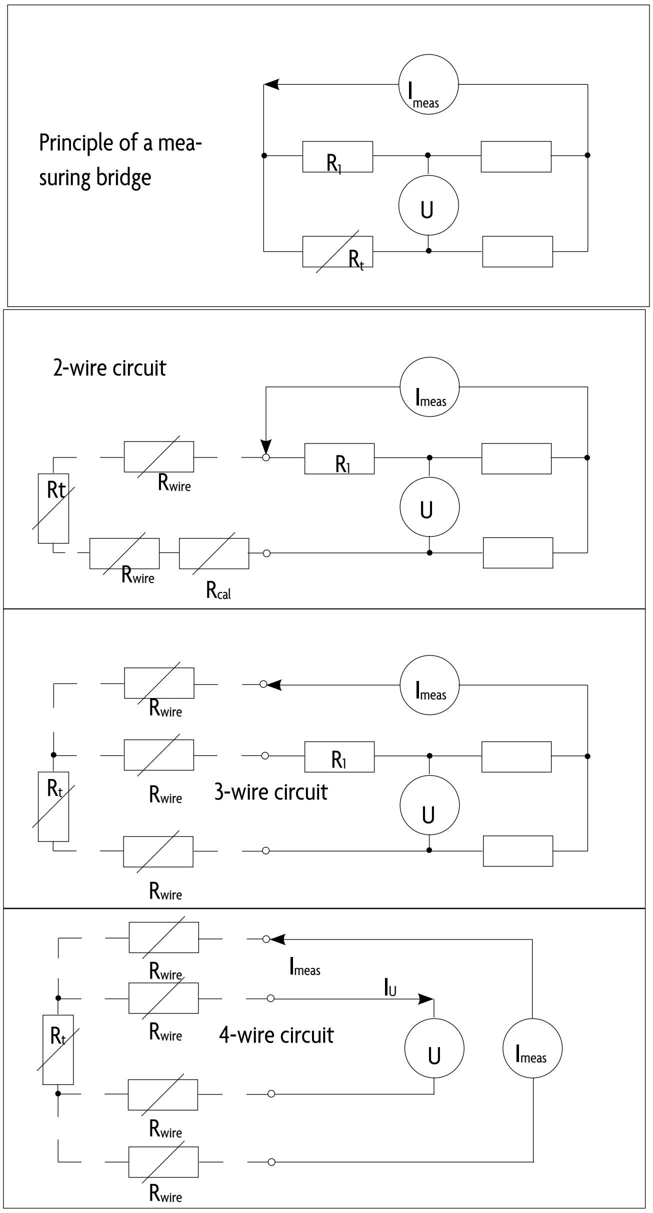


Fig. 2 Measuring circuits

In industrial systems, larger distances between the sensor and the transmitter often have to be bridged with correspondingly long supply lines. Platinum resistance sensors are also manufactured in 3-wire or 4-wire circuits to prevent the lead resistances from influencing the measured value. This allows the measuring current to be supplied separately and any supply line error to be offset. In outdoor areas, installation with 3 or 4 wires is strongly recommended. Bridge circuit: In principle, the following applies to the almost balanced Wheatstone bridge (with slight detuning):

$$U \sim DR = Rt - Rl$$

2-wire circuit:

$$U \sim Rt + 2*Rwire + Rcal - R1 \;($$

$$U \sim Rt + 2*Rwire - const$$

A ΔRwire cannot be distinguished from a ΔR.

The applicable standard therefore permits the 2-wire circuit only for Class B and C resistance thermometers. For Classes AA and A, a 3-wire or 4-wire circuit is specified.

Given that copper conductors have approximately the same temperature coefficient as a Pt100, any temperature change in the conductor with a loop resistance of 10 ohms, for example, is roughly equivalent to a temperature change at the measuring point of up to 10%; fluctuations of 50 ... 70°C are realistic in overhead lines.

3-wire circuit:

$$U \sim (Rt + Rwire3) - (R1 + Rwire2)$$
$$U \sim (Rt - R1)$$

Rwire is omitted if the wires are identical. (A trimming resistor is then unnecessary.) Rwire1 acts like a source resistor of the supply voltage and is practically unnoticeable.

4-wire circuit:

Where the constant current source is electronically stabilized, I is independent of Rt and of Rwire in the supply lines. If an electronic voltmeter with a high input resistance is used, IU<<I (no noticeable current branching) and IU*Rwire<<I*Rt (no noticeable voltage loss in the measuring leads), so that U=I*Rt, i.e. U ~ Rt.

5. MEASURING RESISTORS

All metals have a high conductivity which decreases as temperature increases. Conductivity is based on the mobility of the conduction electrons. The oscillation amplitude of the lattice atoms increases as temperature increases (see thermodynamic definition of temperature). The collision of the conduction electrons with the atomic shells and thus the deflection increases on a statistical average, which leads to a temperature-dependent increase in electrical resistance.

The specific temperature-dependent increase in electrical resistance is called the temperature coefficient. This is a material parameter. The relationship between temperature and resistance value is not linear. It is described mathematically by a higher-order polynomial.

A distinction is drawn between two groups of resistance temperature sensors with regard to the gradient of their characteristic curves: NTC and PTC sensors.

NTC sensors are materials with a negative temperature coefficient, also known as hot-temperature conductors. Ceramic materials are used in preference here.

PTC sensorsare materials with a positive temperature coefficient, also known as cold-temperature conductors. The vast majority of all metallic conductors fall into this category.

The materials used to manufacture temperature sensors have to meet various requirements in order to ensure reliable and reproducible results:

- High temperature coefficient
- Simplest possible transfer function
- Low dependence on environmental influences
- Large measuring range or temperature range
- Interchangeability, specifically a low level of specimen scatter within standards
- High long-term stability
- Good workability
- Attractive price

This is the reason why platinum has become widely accepted as a material for resistance thermometers in industrial temperature measurement technology. Other pure metals such as nickel and copper are only of minor importance as materials for industrial measuring resistors.

5.1 Wirewound measuring resistors

Each and every operating condition places different demands on the assembly of the measuring resistors. The suitability of wirewound or metal film measuring resistors depends on the application concerned. Although the boundaries are fluid, there are some distinctly overlapping areas.

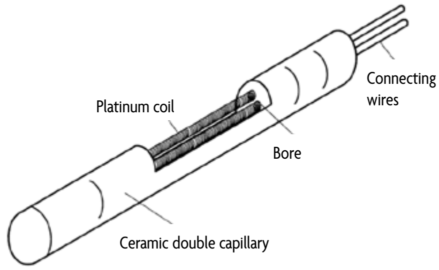


Fig. 3: Representation of a wirewound measuring resistor

With metal wirewound resistors, a platinum wire with a diameter of 10 ... 50 µm in diameter is drawn into the longitudinal holes of a ceramic capillary in the form of a wire helix. A glaze frit fills the capillary and seals the ends. Once the frit has been sintered, the wire is fixed. Nevertheless, the sensor is sensitive to vibrations. According to DIN EN 60 751, however, it only has to withstand an acceleration of 20 to 30 m/s2 in the 5 to 500 Hz range over the long term. Wirewound resistors have only limited resistance to temperature shocks.

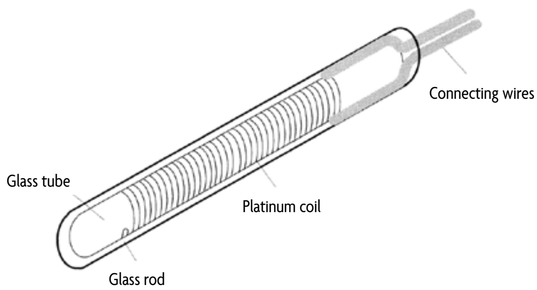


Fig. 4: Representation of a glass measuring resistor

Glass measuring resistors are generally wirewound resistors. They are highly immune to vibrations and resistant to temperature shocks, especially in the low temperature range. A disadvantage is the hysteresis, not insignificant, and the limited operating temperature range.

5.2 Metal film resistors

Metal film resistors have a thin layer of platinum applied to a ceramic carrier as a temperature-sensitive element instead of the wires.

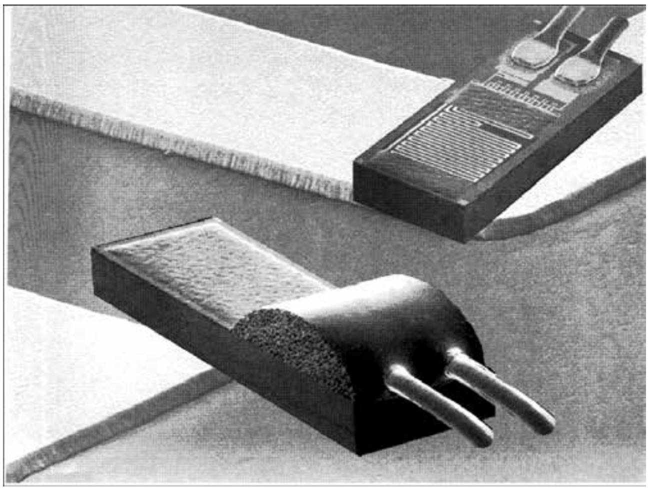


Fig. 5 Flat film resistors

A distinction is drawn between thick film and thin film resistors depending on the manufacturing process. The difference is the film thickness: 10 ... 15 µm (thick film) or 1 ... 2 µm (thin film). The conductor path width is between 7 and 30 µm.

The metal film resistors produced by cutting edge technology almost reach the temperature range of the metal wire resistors. However, the drift behavior at temperatures above 500°C and the hysteresis are much worse.

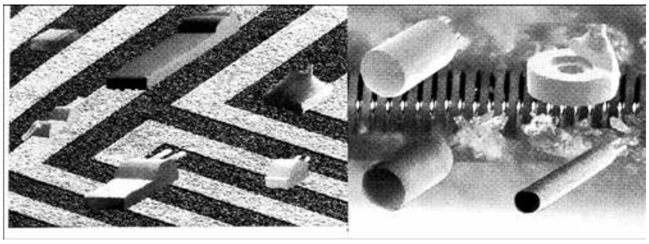


Fig. 6 Different designs of flat film resistors

Apart from price, the main strengths of metal film resistors are:

- Short response time
- High resistance to vibration
- Resistance to temperature shocks
- Smaller temperature-sensitive length

As an alternative to metal wirewound resistors, metal film resistors are increasingly being cemented (potted) into round ceramic tubes.

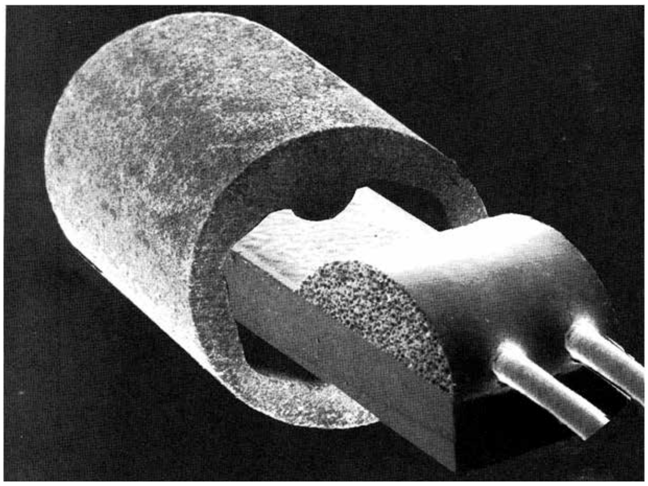


Fig. 7 "Potted" flat film resistor

This additional ceramic tube protects the sensitive surface of the metal film resistor. The drift behavior caused by contamination is significantly improved.

However, the previous strengths of metal film resistors, i.e. the price and above all the faster response time, are lost. The intrinsic heat-up due to the measuring current is also much more intense.

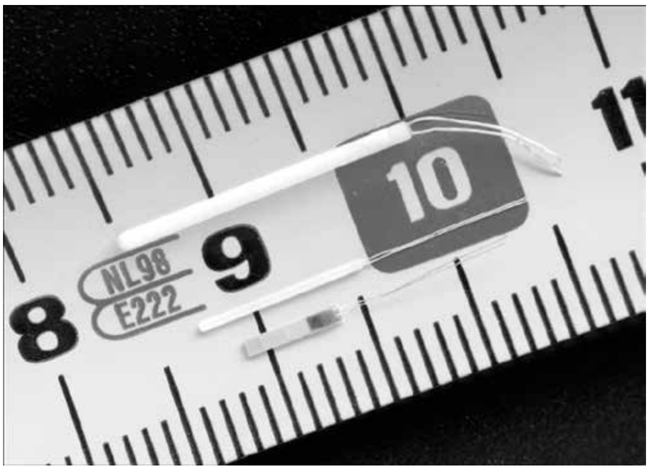


Fig. 8 Size comparison

6. RESISTANCE THERMOMETER DESIGNS

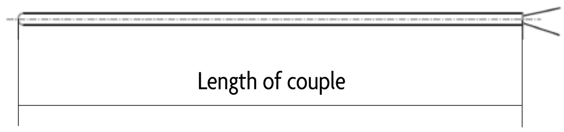
Sheathed resistance thermometers are closely related to the design of the widely used mineral-insulated thermocouples.

They are used in the range between -196°C and +600°C and combine the advantages of resistance thermometers with those of flexible thermocouples. Mineral-insulated sheathed cables are used as supply cables. The supply wires are embedded in a compact insulation made of MgO and surrounded by a metal sheath made of stainless steel (material no: 1.4541). The compact insulation completely fixes the wires so that neither vibration nor strong bending stress can cause damage.

Short circuits between the conductors or between the conductor and the sheath are also impossible. The minimum bending radius depends on the diameter of the sheathed cable. The guide value is 5 to 7 times the sheath diameter.

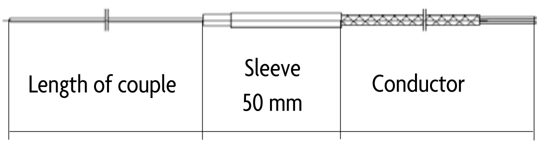
The temperature-sensitive length is 5 to 30 mm, depending on the measuring resistor used. It can be made longer or shorter as required. Flat film resistors are normally used as measuring resistors. Wirewound or glass measuring resistors can be used without a problem.

Sheathed resistance thermometers



Basic design of a sheathed resistance thermometer.
The length of the free connection ends can be determined within broad limits. The sheath is encapsulated and moisture-proof. Tmax for the encapsulation: 150°C. In the standard version, the sheath diameter is the same throughout. Stepped and reinforced versions are also possible.

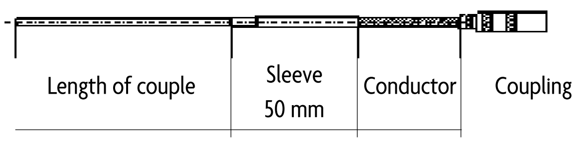
Permanently connected conductor



With this version, the stranded copper conductor is permanently attached. Depending on the cable type, the transition sleeve has a diameter of 6 or 8 mm. The standard length of the sleeve is 50 mm. Tmax at the sleeve: 150°C. The cable type (wire cross-section, insulation structure, shielding) is variable within broad limits.

A TEFLON-insulated cable with a cross-section of 0.38 mm2 is used individually and together as standard. The free wire ends are tinned.

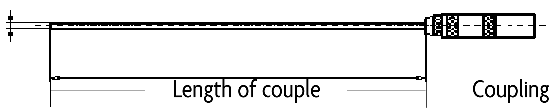
Permanently connected conductor and round coupling



The aforementioned design is extended by a plug system. The standard version is fitted with a round coupling. The precision brass contacts are gold-plated. The outer body brass body is matt chrome-plated.

Tmax at the coupling and sleeve: 150°C. Plug and coupling are automatically interlocked when they are joined, ensuring optimum contact reliability. Other plug systems are also possible.

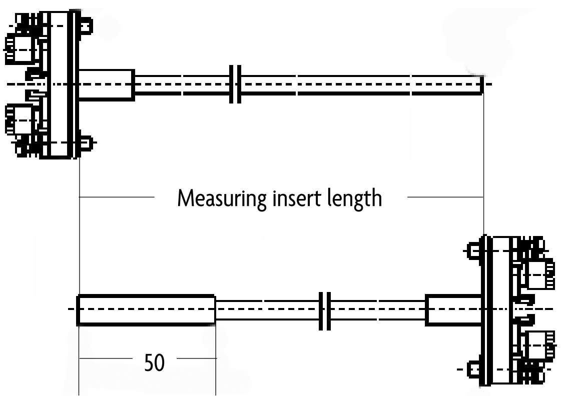
Permanently connected coupling



With this design, the round coupling is connected directly to the sheathed resistance thermometer. The standard version is fitted with a round coupling. The precision brass contacts are gold-plated. The outer body brass body is matt chrome-plated. Tmax at the coupling: 150°C.

Terminal assignment of the measuring inserts **Überschrift?**

Sheath measuring insert, continuous diameter or reinforced measuring tip

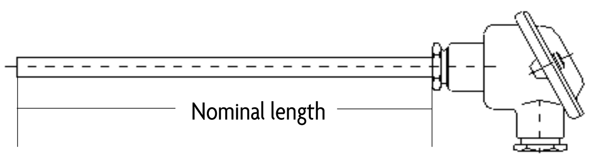


Measuring insert with connection base, sheathed terminals and pressing fixture. Suitable for installation in connection heads, type B according to DIN EN 50 446. An adapter plate is available for installation in terminal heads, type A.

Measuring inserts are not normally directly exposed to the measuring medium. They are preferably installed in protective fittings, also known as protective sleeves. The chapter that follows takes a closer look at these components.

Measuring inserts with sheath diameters of 3.0, 6.0 and 8.0 mm have become established in control technology. The length depends on the standardized fittings or the local or structural conditions.

Sheathed resistance thermometer with connection head, type B

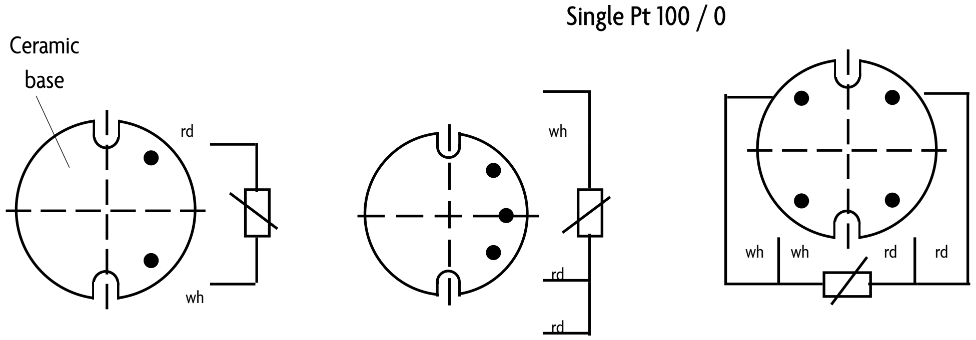


Terminal head
Type B

This design consists of a measuring insert with connection base and sheath terminals, installed in a terminal head, type B, according to DIN EN 50 446. A special stainless steel tube fitting holds the measuring insert in place. The nominal length is specified from the bottom edge of this screw connection.
Sheath diameters of 3.0 or 6.0 mm are frequently used. Other head shapes and sheath diameters are of course available.

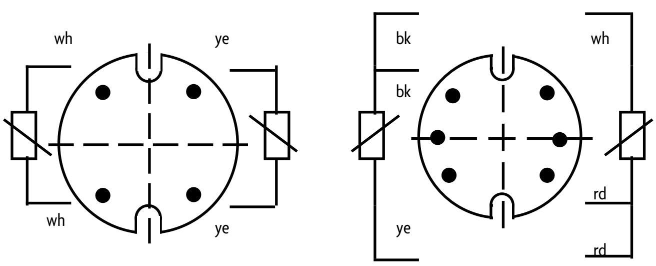
6.1 Terminal assignment and color coding of the sheath measuring inserts

Single Pt 100 / 0

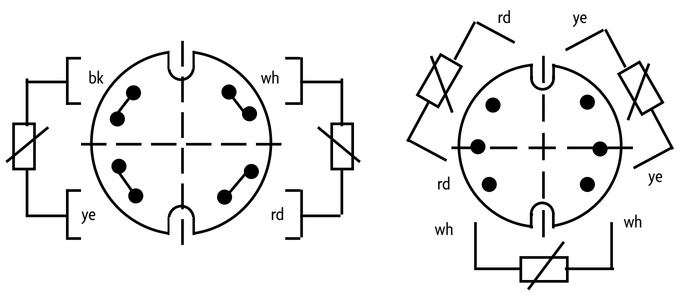


Red	= rd
White	= wh
Yellow	= ye
Black	= bk

Double Pt 100 / 0



Triple Pt 100 / 0



7. METAL THERMOMETER THERMOWELLS ACCORDING TO DIN 43 772

The table below shows a comparison of the different designs. The designs in italics correspond to the withdrawn DIN 43 763.

Type 1 / type A

Straight thermowell for insertion or welding

Type 2 / (type A)

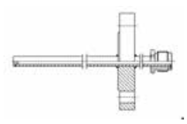
Straight thermowell for insertion or welding

Type 2G / type B & C

Straight thermowell for screwing

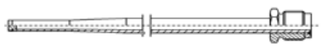
Type 2F / (type F)

Straight thermowell with flange



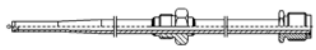
Type 3 / type E

Tapered thermowell for insertion or welding



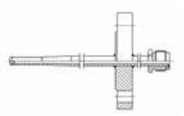
Type 3G / type G

Tapered thermowell for screwing



Type 3F / type F

Tapered thermowell with flange

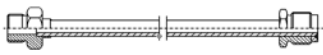


Type 4 / type D

Conical thermowell for welding for high-pressure applications

Neck tube

For thermowell, type 4



For applications involving the measurement of temperatures in gases, vapors or liquids inside pressurized pipes or containers, protective fittings according to DIN 43 772 are predominantly used. The advantage is that the measuring insert can be replaced without having to interrupt the process.

Type 1: Steel thermowells for pressures up to 1 bar and temperatures up to 550°C. Longitudinally welded and seamless tubes are commonly used, depending on the application. Outer diameters of 15, 22 and 32 mm and lengths of up to 2025 mm are standardized.

Type 2, 2G and 2F: Thermowells with outer diameters of 9, 11, 12 and 14 mm, wall thicknesses of 1, 2 and 2.5 mm and overall lengths of up to 545 mm. Type 2 is designed for installation in screw fittings, type 2G has a screw-in thread G½" A or G 1 "A.
Type 2F is provided with a flange according to EN 1094-1, and this must be specified separately.

Type 3, 3G and 3F: The outer and inner diameters of these thermowells are reduced in the front area of the measuring resistor in order to achieve a shorter response time. In all other respects, they correspond to the equivalent types 2, 2G and 2F.

Type 4: This type is designed primarily for applications in the pressure range above 120 bar. Depending on the material, pressures of up to 550 bar, temperatures of up to 730°C and flow velocities in air or superheated steam of over 80 m/s can be achieved. Type 4 thermowells are welded in. Outer diameters of 18 and 24 mm, bore diameters of 3.5 and 7 mm and various overall and cone lengths are standardized. Together with the neck tube, terminal head and measuring insert, they form the measuring point.

7.1 General information on thermowells

Type 1:
If thermowells are coated, e.g. with refractory enamel, at least 20 mm of the open end of the thermowell must remain uncoated. It should be noted that the outer diameter generally increases.

Types 2, 3, 3G & 3F:
The semi-finished products for the protective tubes are annealed and scale-free. Welds are made on the protective tube tip under inert gas. The retaining ring is welded on.

Types 2G, 2F, 3G, 3F and 4F:
The thermowells are inserted into the screw-in spigot or flange and are usually welded at the top and bottom edges of the screw-in spigot or flange. The process-side weld seam is executed first.

Form 4:
The thermowell is manufactured from solid material (one-piece) by deep-hole drilling.

Neck tubes:
The neck tubes are designed for use with weld-in thermowells, type 4.

All types:
Acceptance test certificates in accordance with EN 10 204 - 2.1, - 2.2, - 3.1 and - 3.2 as well as individual test certificates (e.g. PMI) are available, primarily for the wetted parts. Coatings or surface treatments, such as TEFLON, HALAR, PFA, QPQ hardening, stellite-tipping or similar, are also available. In all cases, the conditions and process parameters of the respective application must be taken into account when selecting a suitable coating.

7.2 Information on the selection of thermowell materials

All information is without obligation and does not constitute a warranted characteristic. Coatings on thermowells generally do not increase the operating temperature. They merely provide special protection against chemical attack, corrosion or abrasion. The table below makes no claim to completeness. All of these details must be checked very carefully in the context of the application concerned. We reserve the right to make changes in the interest of technical progress.

Materials for thermowells

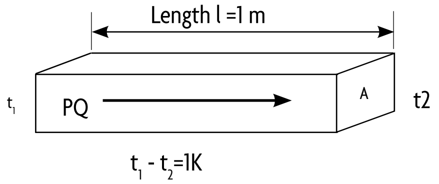
Letter(s) (optional)	Symbol	Material no. (AISI or ASTM)	Application temperature (guide values)
BF	St 35.8	1.0305 (A 106 A)	400°C
BL	C 22.8	1.0460 (A 105)	450°C
J	X 6 CrNiMoTi 17-12-2	1.4571 (316 TI)	600°C
DU	X 18 CrNi 28	1.4749 (446)	1100°C
R	X 10 CrAl 24	1.4762 (441)	1100°C
D	X 15 CrNiSi 2520	1.4841 (310 / 314)	1200°C
B	INCONEL 600	2.4816	1300°C
	X10CrMoVNb 12-1	1.4903 (P 91)	680°C
	X10CrMoWNb 9-1-1	1.4905 (---)	730°C
	X11CrMoWNb 9-3-1	1.4901 (P 92)	730°C
	Alloy 617 (NiCr23Co12Mo)		730°C
CH	16 Mo 3	1.5415 (A 204)	600°C
BB	13 Cr Mo 44	1.7335 (A182-F11)	600°C
BA	10 Cr Mo 910	1.7380 (A182-F22i)	600°C

Table 3 Materials for thermowells

8. THERMAL CONDUCTIVITY OF MATERIALS

Temperature measurement in a process requires thermal energy to be transported from the process medium to the resistance element via the thermowell and the measuring insert. The thermal conductivity of the materials used, or the thermal resistance of the insulating materials and unavoidable air gaps, is therefore of crucial importance.

All known substances, whether solid, liquid or gaseous, conduct temperature to a greater or lesser degree. The transfer of temperature – heat transport – is therefore a transport of energy. The parameter for the transport of thermal output is the specific thermal conductivity.



The specific thermal conductivity l corresponds to the thermal output PQ that is transported through a 1 m long rod at a temperature difference of 1 K between the start and end per cross-sectional area A.

$$PQ=l*A*l-1*DT \quad \text{where } DT = t1 - t2$$

And also where:

PQ	= transported thermal output
l	= specific thermal conductivity
l	= rod length
A	= cross-sectional area of the rod
t1	= temperature at the start of the rod
t2	= temperature at the end of the rod

An equivalent model applies to gases and liquids. The above formula for determining the specific thermal conductivity can also be applied to gases and liquids. However, it applies only under normal conditions.

The reciprocal value 1/l of the specific thermal conductivity is the specific thermal resistance.

The table in the right-hand column provides an overview of the specific thermal conductivity of solids, gases and liquids. The differences between the materials can be several orders of magnitude.

Material	Thermal conductivity λ in [W/m*K]
Acetylene	0.021
Alcohol	0.17
Aluminum	204
Asphalt	0.76
Benzine	0.13
Lead	35
Diamond	2300
Email	1.34
Glass	0.81
Graphite	120 ... 150
Rubber	0.16
Helium	0.11
Ceramic	1.7 ... 3.5
Carbon dioxide (CO_2)	0.015
Copper	380
Carbon	1.6 ... 4.7
Leather	0.15
Air	0.024
Nickel	85
Propane	0.018
Platinum	71.2
PVC film	0.16
Quartz	1.34
Mercury	10
Sand, dry	0.58
Oxygen	0.023
Silver	432
Steel, unalloyed	52
Steel, X12CrNi188	14
Nitrogen	0.025
Tantalum	54.5
Water	0.6
Hydrogen	0.18
Tungsten	167
Brick, dry	0.5 ... 1.4
Tin	67
Impurities	
Ice	1.75 ... 2.33
Scale, gypsum	0.6 ... 2.3
Scale, silicate	0.08 ... 0.18
Cooling water (gelatinous layer)	0.35
Coal dust, dry	0.11
Soot, dry	0.035 ... 0.07
Salt	0.6
Snow	0.16
Brine (gelatinous layer)	0.46

Table 4 Thermal conductivity

9. TIME BEHAVIOR OF CONTACT THERMOMETERS

The dependence of time behavior on numerous influencing factors makes it difficult to calculate the time constant exactly. It also precludes the specification of generally valid numerical values. On the other hand, it is practically impossible to determine the time behavior experimentally for every measurement problem. This is the reason why only "mean approximate values" can be given.

As explained in the previous section, the range of specific thermal conductivity alone covers several powers of ten.

Therefore, contact thermometers are measured under defined heat transfer and standard conditions in suitable facilities.

Normal conditions are:

air pressure	1013 hPa
ambient temperature	23°C
laminar air flow	2 m/s
laminar water flow	0.2 m/s
temperature jump	max. 20 K
sensor geometry	round-cylindrical
flow direction	transverse to the longitudinal axis

This assumes that the rise in temperature over time is much faster than the time response of the test specimen. Especially in the case of fast response sensors with short transition times that generate an electrical output signal, the time response of the measurement technology is also important.

It is also necessary to consider that the time response of identical sensors is also significantly influenced by unavoidable manufacturing tolerances.

If the time response under normal conditions is to be transferred to a real industrial process, the following additional factors must be taken into account:

a) The relative thermal conductivity of the process medium in relation to water (for liquids) or air (for gases) must be known. Values of < 1 lead to longer transition times, values of > 1 to shorter times.

b) It is assumed that the heat capacity – i.e. the energy content – of the process medium is much greater than the heat capacity and the heat dissipation capacity of the temperature sensor.

c) As a first approximation, sensors (thermocouples and resistance thermometers) up to a diameter of 3 mm can be assumed to be homogeneous. They have an exponential transfer function and their time response corresponds to an electrical RC element.
Sensors with a larger diameter and sensor systems consisting of measuring insert and thermowell are not to be regarded as homogeneous and the real time response is significantly influenced by the design, construction type and manufacturing aspects.

d) In a real application, the flow to the sensor will generally deviate from the normal conditions. This applies not only to the angle of attack (deviation of 90° to the longitudinal axis of the sensor) but also to the flow conditions. Truly laminar flow can be regarded as a special case. Small pipe cross-sections and high flow velocities lead to considerable turbulence and, consequently, influence the time response. This influence is more pronounced in gases than in liquids.

e) The heat transfer coefficient describes the ability of a gas or liquid to dissipate energy from or to the surface of a substance. This depends, among other factors, on the specific heat capacity, the density and the thermal conductivity coefficient of the heat-dissipating medium and the heat-supplying medium. The coefficients for heat conduction are usually calculated using the temperature difference between the media involved. In contrast to thermal conductivity, the heat transfer coefficient is not a material constant. It is heavily dependent on the flow velocity v or the type of flow (laminar or turbulent) of the surrounding medium, on the geometric conditions and on the surface properties of the materials involved.

f) And last but not least, the ratio of the active sensor surface (media flowing around it) to the heat dissipation capacity and the mass of the sensor also play a key role in the time response.

Clearly, calculating the time response of contact thermometers is a highly complex area. VDE/VDI recommendation 3522 deals with this topic in detail.

RÖSSEL MESSTECHNIK

9.1 Correction factors for determining the heat transfer coefficients

for measurements in media other than air and water

Substance	-100°C[1]	-50°C[1]	0°C	20°C[4] 25°C[5]	50°C	100°C	200°C	300°C	500°C
Hydrogen	8.89	9.99	10.9	11.1	11.2	11.1	10.8	10.4	10.4
Carbon monoxide (CO)	0.82	0.89	0.99	0.98	0.96	0.96	0.95	0.95	(0.95)
Nitrogen	0.87	0.97	1.02	1.02	1.02	1.02	1.02	1.01	1.01
Nitrogen at 300 bar	(1.89)	(1.62)	1.47	1.38	1.34	1.24	1.15	(1.11)	(1.03)
Flue gas from natural gas	-	-	-	1.03	1.04	1.05	1.05	1.05	1.05
Methane	1.36	1.55	1.77	1.83	1.88	2.00	(2.29)	(2.52)	(3.00)
Ethylene	0.83	0.89	1.07	1.13	1.18	1.27	(1.41)	(1.58)	-
Carbon dioxide (CO_2)	-	0.63	0.71	0.73	0.77	0.80	0.85	0.88	1.01
Ammonia	-	1.36	1.41	1.44	1.48	1.55	1.67	1.75	1.85
Propane	(0.39)	(0.46)	0.99	1.07	1.12	1.26	(1.45)	(1.65)	-
Butane	(0.38)	0.41	0.44	1.08	1.17	(1.32)	(1.50)	(1.73)	-
Water vapor	-	-	-	-	-	1.28	1.26	1.33	1.48
Methanol	-	0.37	0.48	0.41	0.36	1.07	1.18	(1.28)	-
Ethanol	(0.14)	0.23	0.38	0.29	0.27	1.12	1.24	1.37	-
Tetrachloromethane	-	-	0.29	0.25	0.22	0.43	0.44	0.44	(0.45)
Benzene	-	-	-	0.29	0.26	0.93	1.17	1.26	-
n-heptane	-	0.32	0.37	0.31	0.27	1.16	1.40	(1.50)	--
Diphyl (Dowtherm)	-	-	-	0.16	0.17	0.18	0.21	-	-
HT oil C	-	-	-	0.10	0.11	0.12	0.15	0.19[2]	-
Ethyl glycol 25%	-	-	0.71	0.72	0.75	-	-	-	-
Hydrochloric acid 30%	-	-	0.71	0.64	0.60	-	-	-	-
Sulfuric acid 96%	-	-	-	0.26	0.29	-	-	-	
Caustic soda 50%	-	-	(0.28)	0.31	0.40	-	-	-	-
$MgCl_2$ brine 20%	-	0.50[3]	0.69	0.70	-	-	-	-	-

[1] Conversion factors for -100°C and -50°C are based on water or air at 0°C

[2] Based on water at 200°C

[3] At -20°C

[4] For liquids

[5] For gases

Table 5 Correction factors

The cells highlighted in gray show the correction factor for liquids, the cells not highlighted those for gases.

Numerical values of < 1 lead to longer transition times, values of > 1 to shorter times.

9.2 Guide values for the response time of contact thermometers

The response time of a contact thermometer is an indication of how quickly the thermometer follows a sudden change in temperature. The time response of a temperature sensor is described by an exponential function. The sensor (and the surrounding medium) should initially be at temperature T1. The temperature of the medium then changes abruptly to T2. The sensor accepts this value only after a delay. The measurement signal progression represents the transition function. Two values have been chosen to characterize this function: t0.5 and t0.9. This refers to the time after which the measurement signal reaches 50%, the so-called half-life, or 90% of its final value.

Response time of sheathed resistance thermometers Guide value in seconds (-5% / +15%)

Sheathed RT with film resistor

Measuring condition	Value time	Sheath diameter in mm					
		1.0	1.5	3.0	4.5	6.0	8.0
Water 0.2 m/s	50%	0.15	0.21	1.2	2.5	4.0	7
	90%	0.5	0.6	2.9	5.9	9.6	17
Air 2 m/s	50%	5	11	23	37	45	65
	90%	18	35	75	120	160	220

Guide values for thermowells DIN 43 772

Sheath measuring insert, 6 mm diameter

Measuring condition	Ø in mm	Type 2		Type 3		Type 4	
		11	14	9	11	18	24
Water 0.2 m/s	50%	32	38	25	29	31	38
	90%	88	90	70	81	96	110
Air 2 m/s	50%	133	152	110	127	270	315
	90%	415	460	370	395	840	1070

Table 6 Response times

10. INSTALLATION LENGTH AND HEAT CONDUCTION ERROR

Because of the system, temperature measurement with a contact thermometer is always prone to a heat conduction error. Although this error can be minimized, it cannot be eliminated completely.

The tables below list the recommended minimum installation lengths for temperature sensors with and without a thermowell.

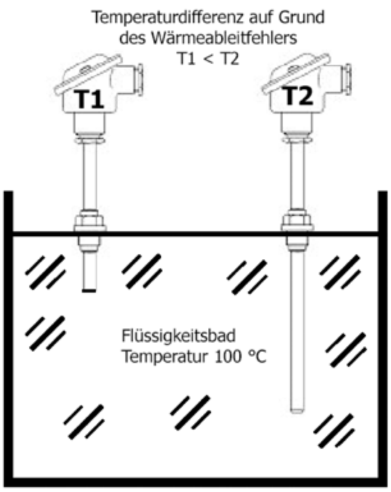


Fig. 9: Heat conduction error

Installation length = wetted length

It is clear that the measured temperature values for identical sensors must be lower on the left than on the right due to the different installation lengths.

However, these installation conditions cannot always be met in real technical systems. If the recommended installation lengths are not met, measurement errors due to heat conduction (heat conduction error) must be expected.

The quantitative magnitude of the error depends on the installation conditions concerned, the sensor design, the wall thickness of the thermowell, the medium and so on. It can therefore only ever be estimated.

If an adequate laboratory setup is available, the magnitude of the heat conduction error can also be determined quantitatively. Sometimes, it proves to be unexpectedly difficult to convert the results found in industrial applications.

The recommended immersion depth of contact thermometers can be estimated using the following table:

	Sensor diameter in mm		
	1.5/1.6	3.0/3.2	5.0/6.0
Medium	Minimum installation length in mm 1)		
Gaseous 2)	22 ... 30	45 ... 60	75 ... 120
Liquid 2)	8 ... 15	15 ... 30	25 ... 50
Solid 3)	8 ... 12	15 ... 20	20 ... 30
	Sensor diameter in mm		
	11/12	14/15	22/24
Medium	Minimum installation length in mm 1)		
Gaseous 2)	150	300	450/480
Liquid 2)	120	150	250/300

Table 7: Immersion depth

1) For resistance thermometers, the length of the measuring resistor (depending on type 5 ... 30 mm) must be added to the table values.

2) Larger value --> stagnant medium,
smaller value --> flowing medium

3) Larger value --> narrow bore tolerance,
smaller value --> soldered into the mounting hole

The following rules of thumb can be used as a general guide:

For use in gases:
Minimum installation length 15 ... 20 x outer Ø

For use in liquids:
Minimum installation length 5 ... 10 x outer Ø

The graph below can be used to estimate the relative measurement error in percent in relation to n times the thermometer diameter for use in liquids. It should be noted that, equivalent to the time response, the heat conduction error also depends on the heat transfer properties of the medium.

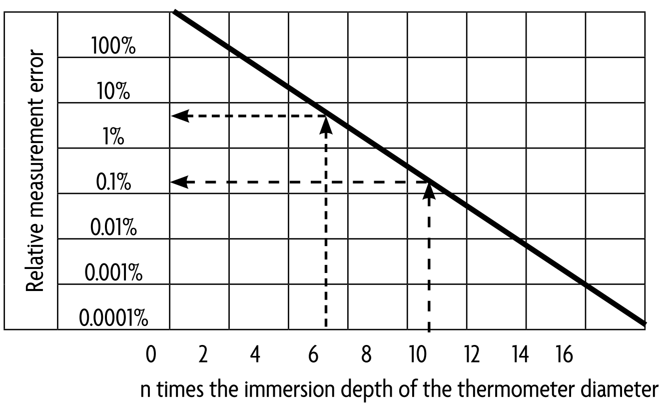


Fig. 10 Heat conduction error

11. Temperature

11.1 Temperature – What is this phenomenon?

Temperature is both a physical and a thermodynamic state variable.

The "absolute temperature" in Kelvin (K) means the average kinetic energy per degree of freedom of a particle or particle system.

Degrees of freedom characterize possible "types of movement" such as movements along the three spatial axes (translation), rotational movements (rotation) or oscillations of particles against each other (vibration). Temperature is a macroscopic, intensive and therefore phenomenological variable. However, it loses its meaning when considered at particle level.

The values of the relative temperature scale are given in degrees (°), although various empirical temperature scales are commonly used – Celsius (°C) or Fahrenheit (°F) in Anglo-American.

The transition temperature of chemically pure substances from one aggregate state to another, e.g. the triple point of water or the solidification point of metals with extremely high purity, is used as the starting point for their classification and the zero point.

High temperatures are commonly referred to as hot, low temperatures as cold. This corresponds to the intuitive approach of a relative scale, what is "hot" in bath water is only "lukewarm" in soup, "high temperature" is not a correct physical term in context.

The human sensation of heat is not based on temperature, but on the flow of heat. It is fitting that the sensation of heat is often referred to as perceived temperature and is thus perceived as warmth or cold. The perceived temperature sometimes differs considerably from the actual temperature.

11.2 Temperature sensation and thermal transfer

If two bodies of different temperatures are in thermal contact, the "zeroth law of thermodynamics" states that energy is transferred from the warmer to the colder body until both are in thermal equilibrium and have reached the same temperature. There are three possibilities for heat transfer:

1) thermal conduction
2) convection
3) thermal radiation

Humans can only feel temperatures in the range of +30 / -60°C relative to body temperature. Strictly speaking, we do not perceive temperatures, but instead the amount of heat flow through the skin surface, which is why we also talk about perceived temperature. This has a number of consequences for temperature sensation:

- Temperatures above the surface temperature of the skin feel warm, we perceive those below as cold
- Materials with high thermal conductivity, such as metals, lead to higher heat flows and therefore feel colder or warmer than materials with lower thermal conductivity, such as wood or polystyrene
- The perceived temperature is lower in windy conditions than in calm conditions. The effect is described at temperatures < 0 °C by the "wind chill" and at higher temperatures by the "heat index"
- Humans cannot distinguish between air temperature and superimposed heat radiation, which also applies in general and means, among other things, that air temperatures are always measured in the shade
- The same temperature is perceived differently by the two hands if they were previously exposed to different temperatures

Strictly speaking, this does not only apply to human perception. In many technical applications, it is not the temperature that is important but rather the heat flow.

For example, the Earth's atmosphere above 1,000 km is at temperatures in excess of 1,000°C, yet no satellites burn up as a result. Due to the low particle density, the energy transfer is extremely low. All solids, liquids and gases consist of atoms and molecules. These are in constant motion and forces act between them. Although the velocities of the individual particles of a substance are different, on average they are equal to 0 or equal to the velocity of the body.

The situation with the deviations from the mean value is different, especially the mean value of the square of the velocities. The value of the mean velocity squared of all particles of a substance depends on the type of substance, the state of aggregation and, above all, the temperature. The following applies to solids, liquids and gases: The higher the temperature of a body, the greater the mean velocity squared of all particles of the substance of which the body consists.

The temperature is therefore a measure of the average undirected, i.e. random, kinetic energy of a collection of particles. The particles here are the air molecules or the molecules or atoms of a gas, a liquid or a solid. In statistical mechanics, the temperature is related to the energy per degree of freedom. In an ideal gas consisting of monoatomic molecules, this is three translational degrees of freedom per molecule and, in the case of multi-atomic gases, further rotational degrees of freedom can be added.

For gases, this relationship between temperature and particle velocity can even be quantified according to the above relationship. For ideal gases, doubling the temperature on the Kelvin scale leads to an increase in the root-mean-square particle velocity by a factor of $2^{1/2}$ = 1.414. Two different gases have the same temperature if the product of the molar mass of the respective gas and the square of the root mean square particle velocity is the same.

In thermal equilibrium, each degree of freedom of matter (motion, potential energy, vibrations, electronic excitations, etc.) absorbs an amount of energy corresponding to the temperature. The exact amount has to be calculated from the regular distribution (Boltzmann constant) and is determined by the ratio of energy to temperature times the Boltzmann constant kB. In the case of continuous (classical) kinetic energy, this is exactly kBT/2. The Boltzmann constant gives a correlation between energy and temperature of 11,606.7 Kelvin per electron volt. At room temperature (~300 Kelvin) this results in 0.0258472 eV.

The average kinetic energy of the particles depends on the molecular mass or molar mass. However, the heavy particles are also slower. In ideal gases, the increase in mass and decrease in speed balance each other out, which leads to Avogadro's law.

However, the thermal energy, like the temperature itself, is merely a mean value within a multi-particle system and its relationship with the particle velocity can also be derived from the Maxwell-Boltzmann distribution:

Ekin = 0.5 * m v2

where Ekin and v2 are mean values.

Thermal equilibrium has an important property that leads to the formulation of the Zeroth Law of Thermodynamics.

12. THERMODYNAMICS

Thermodynamics is a branch of classical physics. It is the study of energy, its manifestations and the ability to perform work. It has a wide range of applications in chemistry, biology and technology. For example, it can be used to explain why certain chemical reactions occur spontaneously while others do not. Thermodynamics is a purely macroscopic theory which assumes that the physical properties of a system can be described sufficiently well with macroscopic state variables. The theory is an effective one because it ignores the movement of individual atoms and molecules and considers only mean values such as pressure and temperature.

The equations that provide concrete relationships between the state variables for special physical systems (e.g. ideal gas) are called equations of state.

Statistical mechanics according to James Clerk Maxwell and Ludwig Boltzmann can confirm many aspects of thermodynamics using microscopic theories. In its overall presentation, however, it still retains the excellent status of an independent physical theory. However, its applicability must be restricted to suitable systems, namely those that are composed of a sufficient number of individual systems, i.e. mostly particles

12.1 History

Thermodynamics emerged as an independent field of knowledge in the course of the 19th century based on the work of James Prescott Joule, Nicholas Leonard Sadi Carnot, Julius Robert von Mayer and Hermann von Helmholtz.

Historically, it was built on four main laws. In their original formulation, these are purely empirical laws based on empirical observations. Entropy is introduced as an abstract auxiliary quantity. This representation was provided with a mathematical structure by the work of Josiah Willard Gibbs, the first person to recognize the significance of the fundamental equation and formulate its properties.

12.2 Laws of thermodynamics

0. Law: If two systems are in thermodynamic equilibrium with a third, they are also in equilibrium with each other.

1. Law: Energy can neither be generated nor destroyed, merely converted into other types of energy.

2. Law: Thermal energy cannot be converted into other types of energy to any degree.

3. Law: The absolute zero point of temperature is unattainable.

"Zeroth" law (sometimes also referred to as the 4th law)

Assumption:

A is in thermal equilibrium with B.
Furthermore, B is in thermal equilibrium with C.

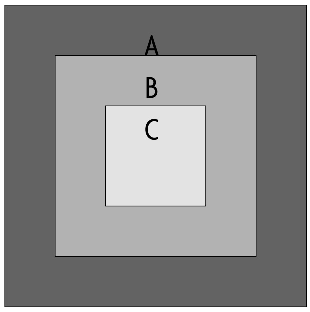


Fig. 11 Zeroth law of thermodynamics

Conclusion:

Zeroth law of thermodynamics:

If two systems are in thermodynamic equilibrium with a third, they are also in equilibrium with each other.

Hence this definition of temperature:

Two systems that are in thermal equilibrium with one another are at the same temperature. A is therefore at the same temperature as B and C.

In purely practical terms, the application of the zeroth fundamental theorem in temperature measurement is as follows:

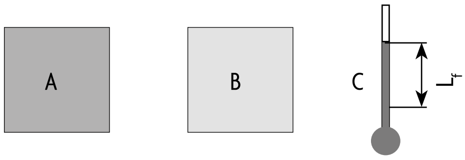


Fig. 12 Zeroth law of thermodynamics

If system C (e.g. liquid-glass thermometer) with the temperature-dependent variable Lf shows the same value for Lf in contact with system A as in contact with system B, then A and B are at the same temperature.

If system A is in thermal equilibrium with system B and B is in thermal equilibrium with a system C, then A is also in thermal equilibrium with C.

In other words, the equilibrium is transitive. This makes it possible to introduce a new state variable, the empirical temperature d, so that two systems are at exactly the same temperature when they are in thermal equilibrium.

This law was only formulated after the three other laws. Because it forms an important basis, however, it was later referred to as the "Zeroth Law". It is the basis for all measurements with contact thermometers and explains why a thermometer in contact with the object to be measured can measure its temperature.

13. TEMPERATURE SCALES AND THEIR UNITS

A temperature scale is an arbitrary definition of the order of magnitude of temperature and allows the temperature to be specified in relation to a reference value.

Two fixed points are defined. For practical purposes, these fixed points are values that occur in nature and can be reproduced by experiments. The distance between the fixed points is then divided equally – e.g. in the Celsius scale, the distance between the ice point and boiling point of water under normal conditions is divided into 100 scale parts.

Another method, which has not been able to establish itself despite certain advantages, is based on the change in volume of gases at constant pressure. Rudolf Planck proposed the temperature difference as the unit, which corresponds to a change in volume by a factor of (1 + 1/273.15).

Such a logarithmic temperature scale extends from minus infinity to plus infinity. It does not require an absolute zero point, which cannot be determined exactly.

The Kelvin scale, on the other hand, starts at absolute zero and uses the linear 100 division of the Celsius scale. However, absolute zero is practically a limit value approaching zero. It is defined by the cessation of all particle movement, meaning that in principle it cannot be measured. The best-known temperature scales with their various characteristics are shown in the table below. The temperature scale currently in use is the "International Temperature Scale of 1990" (ITS-90).

SI unit

The SI unit of thermodynamic temperature (formula symbol: T) is the kelvin with the unit symbol: K. One Kelvin is the 1/273.16th part of the thermodynamic temperature of the triple point of water at which its solid, liquid and gaseous phases coexist. The zero point of the Kelvin scale is at absolute zero.

It is permitted to specify temperature differences in both °C and K (same numerical value). However, it is advisable to state temperature differences in K to make the difference between temperature and temperature difference clearer.

Non-SI units

The empirical temperature (formula symbol: d; often also t), also known as the Celsius temperature, as it is given in degrees Celsius (unit symbol: °C), is thus derived from the thermodynamic temperature by:

$$d\,/\,°C = T/K - 273.15$$

In principle, temperature differences can also be expressed in degrees Celsius, which has the same scale interval as the Kelvin scale. However, its zero point refers to the freezing point of water at normal pressure (mean air pressure at sea level – 1013 hPa).

The freezing point defined in this way is 0.01 K below the temperature of the triple point of ultra-pure water.

In the USA, the Fahrenheit scale with the unit degrees Fahrenheit (unit symbol: °F) is still very common.

The absolute temperature on a Fahrenheit basis is referred to as degrees Rankine (unit symbol: °Ra). The Rankine scale has the same zero point as the Kelvin scale at absolute zero, but in contrast to the latter, it has the scale intervals of the Fahrenheit scale.

Overview of the various temperature scales

Scale	Kelvin	Celsius	Fahrenheit	Rankine	Delisle	Newton	Réaumur	Rømer
Unit	Kelvin	Degrees Celsius	Degrees Fahrenheit	Degrees Rankine	Degrees Delisle	Degrees Newton	Degrees Réaumur	Degrees Rømer
Unit symbol	K	°C	°F	°Ra, °R	°De, °D	°N	°Ré, °Re, °R	°Rø
Lower fixed point F_1 =	T_0 = 0 K	$T_{melting}(H_2O)$ (2 = 0 °C	Refrigerant mix = 0° F (3	T_0 = 0 °Ra	$T_{melting}(H_2O)$ = 150 °De	$T_{melting}(H_2O)$ = 0 °N	$T_{melting}(H_2O)$ = 0 °Ré	$T_{melting}$(Lake) (4 = 0 °Rø
Upper fixed point F_2 =	$T_{Tri}(H_2O)$ = 273.16 K	$T_{boiling}(H_2O)$ (2 100 °C	T_{human} (3 = 96 °F	–	$T_{boiling}(H_2O)$ = 0 °De	$T_{boiling}(H_2O)$ = 33 °N	$T_{boiling}(H_2O)$ = 80 °Ré	$T_{boiling}(H_2O)$ = 60 °Rø
Scale interval	$(F_2–F_1)$ / 273.16 (1	$(F_2–F_1)$ / 100	$(F_2–F_1)$ / 96	1 °Ra = 1 °F	$(F_1–F_2)$ / 150	$(F_2–F_1)$ / 33	$(F_2–F_1)$ / 80	$(F_2–F_1)$ / 60
Inventor	William Thomson, Lord Kelvin	Anders Celsius	Daniel Gabriel Fahrenheit	William Rankine	Joseph-Nicolas Delisle	Isaac Newton	René-Antoine Ferchault de Réaumur	Ole Rømer
Year of origin	1848	1742	1714	1859	1732	~ 1700	1730	1701
Area of circulation	Worldwide (SI unit)	Worldwide	USA	USA	Russia (19th Century)	–	Western Europe until end of 19th Century	–

1) Originally defined via Celsius scale (temperature difference 1 K = 1 C)
2) Traditional fixed points; original reversed (similar to Delisle scale); defined today via Kelvin scale. (Temperature difference 1°C = 1 K)
3) The temperature of a cold mixture of ice, water and ammonia or sea salt (–17.8 C) and the "body temperature of a healthy man" (35.6°C) were used
4) The melting temperature of a brine (–14.3°C) was used

Table 8 Temperature scales

14. MEASUREMENT BASED ON TEMPERATURE RADIATION

The temperature can be determined without contact by measuring the temperature radiation emitted by all bodies above absolute zero. The measurement is carried out using a pyrometer or a thermographic camera, for example.

Different wavelength ranges can be used (Stefan-Boltzmann law or Wien's displacement law), depending on the temperature. At low temperatures, bolometers, micro-bolometers or cooled semiconductor detectors are used, and at high temperatures, uncooled photodiodes or the visual comparison of the intensity and color of the glow are used (tungsten filament pyrometer, "disappearing filament pyrometer").

A thermographic camera generates a false color representation of the radiation emission in the mid-infrared (approx. 5...10 µm wavelength), which can be coupled to the temperature scale by calibration in the form of a color scale. As with pyrometers, measurement errors occur due to different emissivities of the objects being measured. Where emissivities are known, measurement accuracies or contrasts down to temperature differences of 0.01 K are possible.

15. TEMPERATURE MEASUREMENT USING CONTACT THERMOMETERS

The expression "contact thermometer" refers to all thermometers that come into direct contact with the medium whose temperature is to be measured. Contact thermometers include expansion thermometers (liquid and bimetal thermometers) and all electrical or electronic thermometers that work with temperature sensors.

Industrial contact temperature sensors consist of the temperature-sensitive element (e.g. thermocouple or Pt 100), which is installed in a thermowell or immersion tube for protection. In many cases, the tube has a clamping base at the upper end for connecting the electrical cables.

This overall structure is standardized and referred to as a measuring insert. Measuring inserts can be fitted with a thermowell and a terminal head. The thermowell and terminal head together form the protective fitting. The protective fitting protects the sensitive measuring insert from mechanical and chemical stress and the connection terminals against dirt and moisture.

15.1 Measurement by thermal contact

The temperature is measured using thermometers or temperature sensors. Establishing thermal contact requires sufficient heat conduction, convection or a radiation equilibrium between the measured object (solid, liquid, gas) and the sensor. The measuring accuracy can be impaired, for example, by unbalanced thermal radiation, air movement or heat dissipation along the sensor. The measuring accuracy is theoretically limited by the random Brownian motion.

Temperature detection by thermal contact can be divided into three different methods:

Fig. 13 Dial thermometer

a) Mechanical detection

The temperature is determined by utilizing the different thermal expansion coefficients of materials using gas or liquid thermometers (e.g. traditional mercury or alcohol thermometers) or bimetallic thermometers.

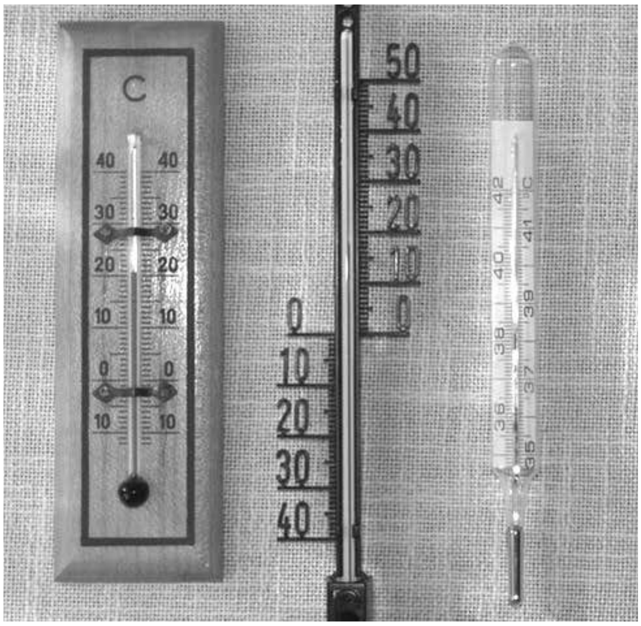


Fig. 14 Liquid-in-glass thermometer

b) Electrical detection

Utilization of the temperature-dependent electrical resistance of electrical conductors, semiconductors or ceramic elements:

- Resistance thermometer (e.g. Pt 100), PTC thermistor (PTC) and NTC thermistor (NTC).
- Use of thermoelectricity
- Electronic sensors that use the linear temperature dependence of the band gap of semiconductors to generate a signal proportional to temperature.

c) Indirect measurement

Based on temperature-dependent changes in the state of materials (e.g. tabulated material data), fiber-optic temperature measurement with optical fibers, Seger cones, temperature measurement by color change (at a certain temperature), observation of solidification, melting, annealing or tarnishing.

Fig. 15 Resistance thermometers

16. RELATIONSHIP BETWEEN TEMPERATURE IN °C AND RESISTANCE IN OHMS

As already described in section 1.4, the Callendar-van Duesen equation contained in the DIN EN 60 751:2009 standard establishes the mathematical relationship between the temperature in °C and the resistance in ohms. Although the table covers the range from -200°C to +850°C, the restrictions listed in the standard apply to technical resistance thermometers.

t_{90} in °C	0	1	2	3	4	5	6	7	8	9
-200	18.520	18.952	19.384	19.815	20.247	20.677	21.108	21.538	21.967	22.397
-190	22.825	23.254	23.682	24.110	24.538	24.965	25.392	25.819	26.245	26.671
-180	27.096	27.522	27.947	28.371	28.796	29.220	29.643	30.067	30.490	30.913
-170	31.335	31.757	32.179	32.601	33.022	33.443	33.864	34.284	34.704	35.124
-160	35.543	35.963	36.382	36.800	37.219	37.637	38.055	38.472	38.889	39.306
-150	39.723	40.140	40.556	40.972	41.388	41.803	42.218	42.633	43.048	43.462
-140	43.876	44.290	44.704	45.117	45.531	45.944	46.356	46.769	47.181	47.593
-130	48.005	48.416	48.828	49.239	49.649	50.060	50.470	50.881	51.291	51.700
-120	52.110	52.519	52.928	53.337	53.746	54.154	54.562	54.970	55.378	55.786
-110	56.193	56.600	57.007	57.414	57.821	58.227	58.633	59.039	59.445	59.850
-100	60.256	60.661	61.066	61.471	61.876	62.280	62.684	63.088	63.492	63.896
-90	64.300	64.703	65.106	65.509	65.912	66.315	66.717	67.120	67.522	67.924
-80	68.325	68.727	69.129	69.530	69.931	70.332	70.733	71.134	71.534	71.934
-70	72.335	72.735	73.134	73.534	73.934	74.333	74.732	75.131	75.530	75.929
-60	76.328	76.726	77.125	77.523	77.921	78.319	78.717	79.114	79.512	79.909
-50	80.306	80.703	81.100	81.497	81.894	82.290	82.687	83.083	83.479	83.875
-40	84.271	84.666	85.062	85.457	85.853	86.248	86.643	87.038	87.432	87.827
-30	88.222	88.616	89.010	89.404	89.798	90.192	90.586	90.980	91.373	91.767
-20	92.160	92.553	92.946	93.339	93.732	94.124	94.517	94.909	95.302	95.694
-10	96.086	96.478	96.870	97.261	97.653	98.044	98.436	98.827	99.218	99.609
0	100.000	100.391	100.781	101.172	101.562	101.953	102.343	102.733	103.123	103.513
10	103.903	104.292	104.682	105.071	105.460	105.849	106.238	106.627	107.016	107.405
20	107.794	108.182	108.570	108.959	109.347	109.735	110.123	110.510	110.898	111.286
30	111.673	112.060	112.447	112.835	113.221	113.608	113.995	114.382	114.768	115.155
40	115.541	115.927	116.313	116.699	117.085	117.470	117.856	118.241	118.627	119.012
50	119.397	119.782	120.167	120.552	120.936	121.321	121.705	122.090	122.474	122.858
60	123.242	123.626	124.009	124.393	124.777	125.160	125.543	125.926	126.309	126.692
70	127.075	127.458	127.840	128.223	128.605	128.987	129.370	129.752	130.133	130.515
80	130.897	131.278	131.660	132.041	132.422	132.803	133.184	133.565	133.946	134.326
90	134.707	135.087	135.468	135.848	136.228	136.608	136.987	137.367	137.747	138.126
100	138.506	138.885	139.264	139.643	140.022	140.400	140.779	141.158	141.536	141.914
110	142.293	142.671	143.049	143.426	143.804	144.182	144.559	144.937	145.314	145.691
120	146.068	146.445	146.822	147.198	147.575	147.951	148.328	148.704	149.080	149.456
130	149.832	150.208	150.583	150.959	151.334	151.710	152.085	152.460	152.835	153.210
140	153.584	153.959	154.333	154.708	155.082	155.456	155.830	156.204	156.578	156.952
150	157.325	157.699	158.072	158.445	158.818	159.191	159.564	159.937	160.309	160.682
160	161.054	161.427	161.799	162.171	162.543	162.915	163.286	163.658	164.030	164.401
170	164.772	165.143	165.514	165.885	166.256	166.627	166.997	167.368	167.738	168.108
180	168.478	168.848	169.218	169.588	169.958	170.327	170.696	171.066	171.435	171.804
190	172.173	172.542	172.910	173.279	173.648	174.016	174.384	174.752	175.120	175.488
200	175.856	176.224	176.591	176.959	177.326	177.693	178.060	178.427	178.794	179.161
210	179.528	179.894	180.260	180.627	180.993	181.359	181.725	182.091	182.456	182.822
220	183.188	183.553	183.918	184.283	184.648	185.013	185.378	185.743	186.107	186.472
230	186.836	187.200	187.564	187.928	188.292	188.656	189.019	189.383	189.746	190.110
240	190.473	190.836	191.199	191.562	191.924	192.287	192.649	193.012	193.374	193.736
250	194.098	194.460	194.822	195.183	195.545	195.906	196.268	196.629	196.990	197.351
260	197.712	198.073	198.433	198.794	199.154	199.514	199.875	200.235	200.595	200.954
270	201.314	201.674	202.033	202.393	202.752	203.111	203.470	203.829	204.188	204.546
280	204.905	205.263	205.622	205.980	206.338	206.696	207.054	207.411	207.769	208.127
290	208.484	208.841	209.198	209.555	209.912	210.269	210.626	210.982	211.339	211.695

Temperature resistance table cont.

300	212.052	212.408	212.764	213.120	213.475	213.831	214.187	214.542	214.897	215.252
310	215.608	215.962	216.317	216.672	217.027	217.381	217.736	218.090	218.444	218.798
320	219.152	219.506	219.860	220.213	220.567	220.920	221.273	221.626	221.979	222.332
330	222.685	223.038	223.390	223.743	224.095	224.447	224.799	225.151	225.503	225.855
340	226.206	226.558	226.909	227.260	227.612	227.963	228.314	228.664	229.015	229.366
350	229.716	230.066	230.417	230.767	231.117	231.467	231.816	232.166	232.516	232.865
360	233.214	233.564	233.913	234.262	234.610	234.959	235.308	235.656	236.005	236.353
370	236.701	237.049	237.397	237.745	238.093	238.440	238.788	239.135	239.482	239.829
380	240.176	240.523	240.870	241.217	241.563	241.910	242.256	242.602	242.948	243.294
390	243.640	243.986	244.331	244.677	245.022	245.367	245.713	246.058	246.403	246.747
400	247.092	247.437	247.781	248.125	248.470	248.814	249.158	249.502	249.845	250.189
410	250.533	250.876	251.219	251.562	251.906	252.248	252.591	252.934	253.277	253.619
420	253.962	254.304	254.646	254.988	255.330	255.672	256.013	256.355	256.696	257.038
430	257.379	257.720	258.061	258.402	258.743	259.083	259.424	259.764	260.105	260.445
440	260.785	261.125	261.465	261.804	262.144	262.483	262.823	263.162	263.501	263.840
450	264.179	264.518	264.857	265.195	265.534	265.872	266.210	266.548	266.886	267.224
460	267.562	267.900	268.237	268.574	268.912	269.249	269.586	269.923	270.260	270.597
470	270.933	271.270	271.606	271.942	272.278	272.614	272.950	273.286	273.622	273.957
480	274.293	274.628	274.963	275.298	275.633	275.968	276.303	276.638	276.972	277.307
490	277.641	277.975	278.309	278.643	278.977	279.311	279.644	279.978	280.311	280.644
500	280.978	281.311	281.643	281.976	282.309	282.641	282.974	283.306	283.638	283.971
510	284.303	284.634	284.966	285.298	285.629	285.961	286.292	286.623	286.954	287.285
520	287.616	287.947	288.277	288.608	288.938	289.268	289.599	289.929	290.258	290.588
530	290.918	291.247	291.577	291.906	292.235	292.565	292.894	293.222	293.551	293.880
540	294.208	294.537	294.865	295.193	295.521	295.849	296.177	296.505	296.832	297.160
550	297.487	297.814	298.142	298.469	298.795	299.122	299.449	299.775	300.102	300.428
560	300.754	301.080	301.406	301.732	302.058	302.384	302.709	303.035	303.360	303.685
570	304.010	304.335	304.660	304.985	305.309	305.634	305.958	306.282	306.606	306.930
580	307.254	307.578	307.902	308.225	308.549	308.872	309.195	309.518	309.841	310.164
590	310.487	310.810	311.132	311.454	311.777	312.099	312.421	312.743	313.065	313.386
600	313.708	314.029	314.351	314.672	314.993	315.314	315.635	315.956	316.277	316.597
610	316.918	317.238	317.558	317.878	318.198	318.518	318.838	319.157	319.477	319.796
620	320.116	320.435	320.754	321.073	321.391	321.710	322.029	322.347	322.666	322.984
630	323.302	323.620	323.938	324.256	324.573	324.891	325.208	325.526	325.843	326.160
640	326.477	326.794	327.110	327.427	327.744	328.060	328.376	328.692	329.008	329.324
650	329.640	329.956	330.271	330.587	330.902	331.217	331.533	331.848	332.162	332.477
660	332.792	333.106	333.421	333.735	334.049	334.363	334.677	334.991	335.305	335.619
670	335.932	336.246	336.559	336.872	337.185	337.498	337.811	338.123	338.436	338.748
680	339.061	339.373	339.685	339.997	340.309	340.621	340.932	341.244	341.555	341.867
690	342.178	342.489	342.800	343.111	343.422	343.732	344.043	344.353	344.663	344.973
700	345.284	345.593	345.903	346.213	346.522	346.832	347.141	347.451	347.760	348.069
710	348.378	348.686	348.995	349.303	349.612	349.920	350.228	350.536	350.844	351.152
720	351.460	351.768	352.075	352.382	352.690	352.997	353.304	353.611	353.918	354.224
730	354.531	354.837	355.144	355.450	355.756	356.062	356.368	356.674	356.979	357.285
740	357.590	357.896	358.201	358.506	358.811	359.116	359.420	359.725	360.029	360.334
750	360.638	360.942	361.246	361.550	361.854	362.158	362.461	362.765	363.068	363.371
760	363.674	363.977	364.280	364.583	364.886	365.188	365.491	365.793	366.095	366.397
770	366.699	367.001	367.303	367.604	367.906	368.207	368.508	368.810	369.111	369.412
780	369.712	370.013	370.314	370.614	370.914	371.215	371.515	371.815	372.115	372.414
790	372.714	373.013	373.313	373.612	373.911	374.210	374.509	374.808	375.107	375.406
800	375.704	376.002	376.301	376.599	376.897	377.195	377.493	377.790	378.088	378.385
810	378.683	378.980	379.277	379.574	379.871	380.167	380.464	380.761	381.057	381.353
820	381.650	381.946	382.242	382.537	382.833	383.129	383.424	383.720	384.015	384.310
830	384.605	384.900	385.195	385.489	385.784	386.078	386.373	386.667	386.961	387.255
840	387.549	387.843	388.136	388.430	388.723	389.016	389.310	389.603	389.896	390.188
850	390.481									

17. CONCLUDING REMARKS

Resistance thermometers are not a modern development. H.-C. Oersted discovered the dependence of the electrical resistance of metals on temperature back in 1818 at the beginning of the industrial revolution. However, it was not until 1871 that Werner von Siemens presented the first industrially usable platinum resistance thermometer. The first endeavors to create standardized criteria – scales – for temperature measurement were made as early as the beginning of the 18th century. These endeavors are still ongoing today, in the 21st century. Now, though, the discussion revolves around millikelvins and microkelvins.

Temperature has become by far the most frequently measured parameter of all, way ahead of pressure measurement. Resistance thermometers play a key role here – they account for around 40% of the production and application figures for temperature sensors. In certain industrial sectors, e.g. the petrochemical and general chemical industries, pharmaceuticals and the food and beverage sector, the usage figures reach 90% and above.

The trend towards ever smaller, faster and more accurate resistance thermometers is also unbroken. At the same time, the usable temperature ranges are constantly being extended upwards.

The traditional boundary between resistance thermometers and thermocouples in terms of temperature range and measurement uncertainty is becoming increasingly blurred and the overlaps are getting bigger.

Naturally, this brochure cannot cover every single aspect of temperature measurement with resistance thermometers. Our aim was to provide enthusiasts with as complete an overview as possible of the conditions that enable reliable temperature measurement in an industrial environment. Anything beyond this is reserved for the relevant publications, guidelines and standards.

18. BIBLIOGRAPHY

Fischer, H.: „Werkstoffe in der Elektrotechnik“ (Materials in electrical engineering), 3rd Edition, Carl Hanser Verlag, Munich/Vienna 1987

Michalowsky, L: „Neue Technische Keramikwerkstoffe" (New technical ceramic materials), Wiley-VCH-Verlag 1994

Bergmann, W.: „Werkstofftechnik" (Materials engineering), Part 2, Carl Hanser Verlag, Munich/Vienna 1987

Kittel, Ch.: „Einführung in die Festkörperphysik" (Introduction to solid state physics), Oldenbourg-Verlag, Munich/Vienna 1970

Philippow, E.: „Grundlagen der Elektrotechnik" (Fundamentals of electrical engineering), 9th Edition, Verlag Technik, Berlin/Munich 1992

Beckerath, A. von, et al: WIKA Manual „Druck- und Temperaturmesstechnik" (Pressure and temperature measurement technology), ISBN 3-9804074-0-3

Alfa Aesar, A.: Johnson Matthey Company „Forschungschemikalien, Metalle und Materialien (Research chemicals, metals and materials) 1999-2000"

Weber, D.; Nau, M.: „Elektrische Temperaturmessungen" (Electrical temperature measurements), M. K. Juchheim, Fulda, 6th Edition. Nov. 1997

Körtvelyessy L.V.: „Thermoelement Praxis" (Thermocouple practice), Vulkan Verlag, Essen 1987

Weichert, L.: „Temperaturmessung in der Technik" (Temperature measurement in engineering), Expert Verlag, Sindelfingen 1992

Lieneweg, F.: „Handbuch - Technische Temperaturmessung" (Manual – Technical temperature measurement), Vieweg Verlag, Braunschweig 1976

Author collective VDI Reports 1379, „Temperatur 98" (Temperature 98), VDI Verlag GmbH, Düsseldorf 1998

VDI/DE Directives 3511 „Technische Temperaturmessungen" (Technical temperature measurements), Pages 1-5, Düsseldorf 1993

VDI/DE Directives 3522 „Zeitverhalten von Berührungsthermometern", (Time behavior of contact thermometers),

Bonfig, K.W. et al: „Technische Temperaturmessung" (Technical temperature measurements), Event documentation, Haus der Technik e.V., Essen, 1999

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