TEMPERATURE SENSORS

TEMPERATURE AS A PHYSICAL QUANTITY

Every object or phenomenon existing in the real world may be described by a set of properties. Some of these properties are physical quantities, while others are descriptive ones. Physical quantities must be measurable. In order to make a property measurable, one has to establish a method with which to detect whether a state of a property is higher than another state, to detect if two states are the same, to propose a measure of the state, and finally to find a scale which transforms a given level of the property into an abstract symbol in the form of a number and a unit of measure. Considering temperature as a property of an object, all the problems mentioned above are rather complicated from both theoretical and practical points of view. The human sense of touch enables us to distinguish between higher and lower thermal levels, over a limited range of temperatures and with very limited repeatability, but nothing more, and there was a long way to go from our "feeling of heat" to the definition of temperature and temperature scales. The popular and often-quoted definition of temperature as an "intensity of heat" does not lead directly to solving the problem because of its lack of clarity.

Only the discovery of the fundamental laws of thermodynamics in the middle of nineteenth century allowed us to answer the question, What is temperature? The first law of thermodynamics says that thermal energy transfer is possible only from a system with higher temperature to a system with lower temperature. By observing the direction of thermal energy transfer, we are able both to tell which system is the one of a higher state of temperature and also to confirm the existence of equilibrium of temperature states when the heat transfer between two systems declines to zero. Furthermore, the works by Carnot, Lord Kelvin, and Clausius resulted in the formulation of the laws concerning the reversible thermodynamic cycle, called the Carnot cycle. The Carnot cycle consists of two isothermal heat conversion processes and two adiabatic heat transfer processes as illustrated in Fig. 1. By transferring a heat energy from the system with a higher state of temperature to a system with a lower temperature state, it is possible to transform a part of that energy (although a relatively small one) into mechanical energy. This constitutes a theoretical principle for all heat engines. The theoretical efficiency of a Carnot cycle engine is

$$\eta = \frac{Q_1 - Q_2}{Q_1} \tag{1}$$

where Q_1 is thermal energy transferred from the system with higher temperature in the isothermal expansion process, and Q_2 is thermal energy transferred to the system with lower temperature in the isothermal compression process. The theory of the Carnot cycle does not depend on the medium used, and Eq. (1) is a universal one. The engine efficiency depends only on the ratio Q_2/Q_1 and this ratio was proposed by Lord Kelvin as the basis of a new "absolute" thermodynamic measure of temperature in the form

$$\frac{T_2}{T_1} = \frac{Q_2}{Q_1} \tag{2}$$

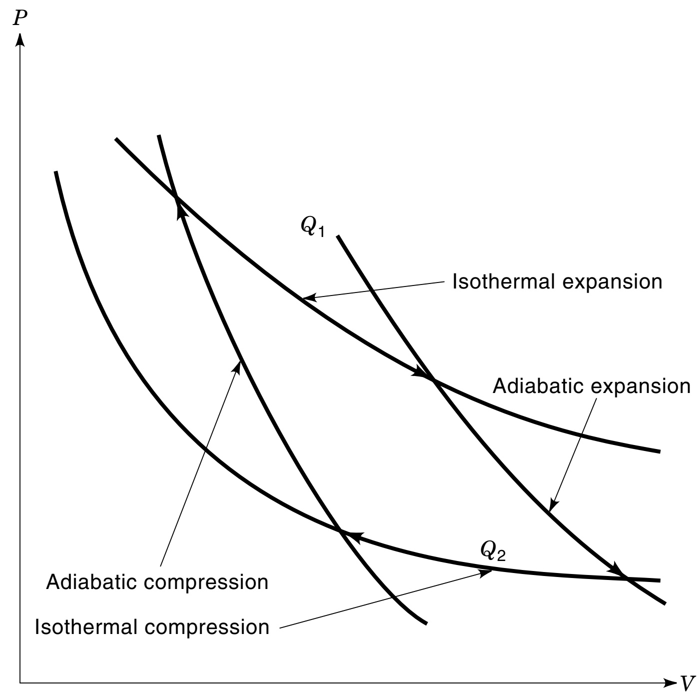


Figure 1. The Carnot cycle for an ideal heat engine. The arrows indicate the subsequent thermal processes.

Such a measure is independent of the thermal properties of any material and requires only one fixed temperature point to create the temperature scale. Equation (2) indicates very clearly that temperature has no physical zero point. In creating any temperature scale the zero point is to be assumed arbitrarily. That is, temperature, in the same manner as time, can be measured only by the interval scale but not by the metric scale. The point defined as 0 K is only a mathematical point on the scale but not a physical null temperature. Even in outer space we are not able to achieve physical null temperature, because the insertion of any material body changes the state of the temperature previously existing.

In Lord Kelvin's lifetime the Celsius scale of temperature had been in use for 100 years, and the temperature differences (e.g., between the ice point and the boiling point of water) had already been expressed in Celsius degrees. Gay-Lussac's gas law had also been known for more than 100 years and expressed as

$$V = V_0[1 + \alpha(t - t_0)]_{p=\text{const}} \tag{3}$$

where V and V_0 are the volumes of an ideal gas at temperatures t and t_0, respectively. Equation (3) proved to give results fitting quite well to the experimental results, especially for rarefied gases at low pressure, and the numerical value of the coefficient α was known with a good accuracy. Taking a Celsius degree as a unit of temperature difference, assuming the ice point of water as a point of $t_0 = 0$, and accepting particularly for these conditions an experimentally obtained value of the coefficient $\alpha = 0.003661$ 1/°C, we are able to create a new temperature scale, with the zero value at the point when an ideal gas volume decreases to zero (Fig. 2). The scale is now known as the absolute or Kelvin scale and is shifted by a

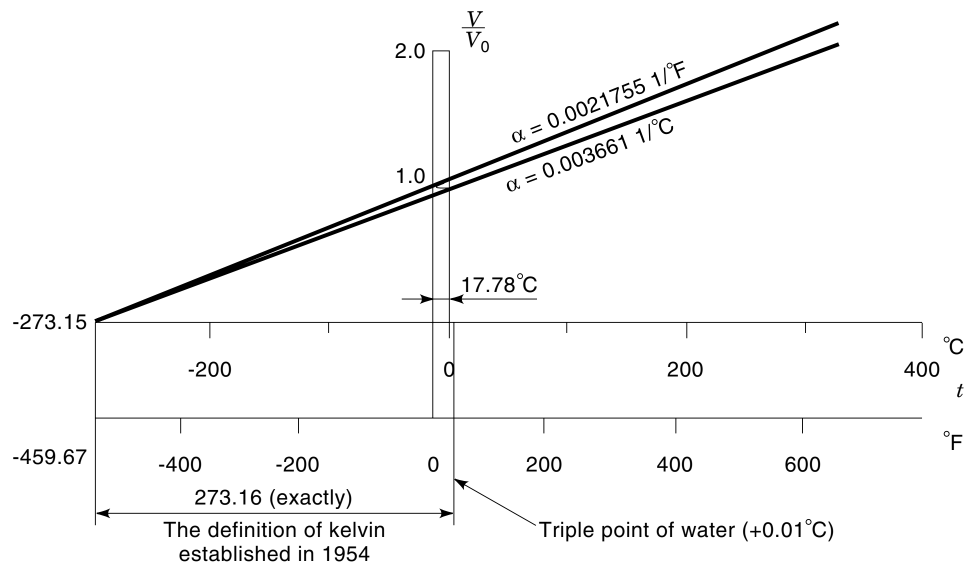


Figure 2. The meaning of absolute temperature scale and its relation to the ideal gas law. The difference between ice point and triple point of water on the temperature scale is excessively enlarged in order to enhance clarity.

value of $1/\alpha = 273.15$ with respect to the Celsius scale. All currently used temperature scales are in linear relations with each other:

$$T[\mathrm{K}] = t[^\circ\mathrm{C}] + 273.15 = (t[^\circ\mathrm{F}] + 459.67)\frac{5}{9}$$
$$t\,[^\circ\mathrm{C}] = T\,[\mathrm{K}] - 273.15 = (t[^\circ\mathrm{F}] - 32)\frac{5}{9}$$
$$t[^\circ\mathrm{F}] = 1.8(t[^\circ\mathrm{C}] + 17.778) = 1.8(T[\mathrm{K}] - 255.37)$$

It is worth noting that Kelvin's idea for measuring an absolute temperature may be used also to formulate other temperature scales, where the ratio of two thermal energy values is related not to the temperature ratio but to the temperature difference, $Q_2/Q_1 = f(\vartheta_2 - \vartheta_1)$, where ϑ are the values of temperature expressed on that new, hypothetical scale. The simplest function which relates ϑ values to the kelvins is logarithmic function $\vartheta = \log T$, and then $Q_2/Q_1 = 10^{(\vartheta_2 - \vartheta_1)}$. Such a scale not only indicates the impossibility of physically reaching a 0 K value (the corresponding value of ϑ is equal to minus infinity) but also indicates in a better way the technical difficulties in reaching very low temperatures. The distance between 0 ϑ unit and 1 ϑ unit (1 K and 10 K) on that scale is the same as between 1 ϑ unit and 2 ϑ units (10 K and 100 K), as it is on the logarithmic scale. Such a scale, however, has never been introduced in practice.

It is evident that Gay-Lussac's law is an excellent basis for developing not only the scale but also a thermometer: a gas thermometer. There is only one problem, albeit a significant one: An ideal gas does not exist. This inconvenience may be overcome either by the use of gases with properties close to the ideal gas (^{4}He, H_2) or by the use of rarefied gases at low pressures and by applying a very special measurement procedure. It has to be pointed out that in Eq. (3) there is an implied condition that p = const. In practically built gas thermometers, however, it is easier to fulfill the requirement of v = const and to observe the changes in p, instead of v. Therefore the majority of gas thermometers work on the constant volume principle.

INTERNATIONAL TEMPERATURE SCALE OF 90

In spite of the great progress in measurement techniques achieved since the days of Lord Kelvin, the use of gas thermometers is not a way to establish a contemporary temperature scale because of the great difficulties regarding their performance. Absolute Kelvin temperature according to Eq. (2) remains the theoretical definition of temperature, but the temperature scale is reproduced with the highest accuracy by means of the International Temperature Scale (ITS) established first in 1927 and recently modified in 1990. Most high accuracy industrial temperature measurement requires the production of a reproducible temperature state rather than its value in terms of its absolute temperature value. ITS-90 allows this by setting up a scale that is highly reproducible but only approximates to an absolute Kelvin scale to the limits of technology available in the late 1980s. Temperatures corresponding to that scale are sometimes marked using the subscript 90 in order to distinguish the differences with respect to the former scales (1927, 1948, 1968) and to the theoretical values of the thermodynamic scale (T [K] and t [°C] with no subscripts).

The ITS-90 describes a set of fixed temperature points (17 points) and the methods of measuring the temperature between these points. Fixed points are freezing or triple points of selected materials (except gallium's melting point). The points and the methods have been chosen to ensure, according to the actual knowledge and technology, the best conformance to the absolute temperature scale. An additional document, "Supplementary Information for the ITS-90," gives a very indepth and exhaustive description of the instruments and the procedures which ensure the highest accuracy and traceability of temperature standard measurements. Figure 3 presents the difference in temperature values expressed by the previous IPTS-68 scale and by the present ITS-90. In some ranges,

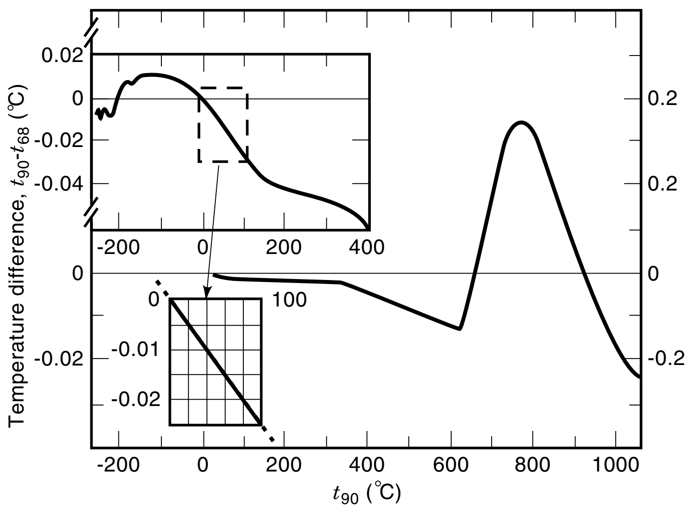


Figure 3. The differences in temperatures expressed by IPTS-68 and ITS-90. (After Ref. 1.)

especially above 630°C, the differences are really great and are mainly caused by the incorrect reference function accepted by the IPTS-68 for the type S standard thermocouple. The correction of that reference function allows us to reduce the differences. Boiling points are rejected by the ITS-90 because of their poor stability and great sensitivity to pressure. The boiling point of water is no longer a fixed point. Some differences in standard instruments and methods have been introduced, too. The most important is that the standard platinum resistance thermometer now covers a much wider range of temperatures than previously, extending from about −260°C up to the freezing point of silver +962°C. Above that temperature the Planck radiation law is used as a principle for standard measurements. Thus, the PtRh–Pt thermocouple is no longer a standard thermometer (1).

Extremely complex reference functions have been defined in order to express sufficiently precisely the ratio of the resistance at a given temperature T_{90} to the resistance at the triple point of water (T_{90} = 273.16 K) and vice versa, to express the temperature as a function of that ratio. The convenience of computerized calculations justify the complex forms of these functions.

They are not used, however, for numerical corrections of temperature values in the industrial, microprocessor-based instruments (e.g., for linearity correction). For that purpose much simpler, yet not so accurate, equations have been developed. Equation (4) is an adequate example.

ITS-90 serves as the best approximation of a realized temperature scale to the absolute thermodynamic scale and determines a highest level of the temperature standards. In every country, several levels of temperature standards are available, which are used for comparisons and to calibrate the thermometers in practical use. The uncertainty is higher as far as the calibration of the technical thermometers is concerned, and it ranges from a few millikelvin or less at the highest accuracy level and in the medium temperature range to the tenths of Kelvin for the case of industrial thermometers and thermometers used in everyday life. The uncertainty of both standard and practical thermometers in the higher temperature range (above 650°C) is always greater. According to the general idea of the ITS-90, it is evident that some modifications are inevitable in the future.

THE GENERAL PRINCIPLES OF TEMPERATURE MEASUREMENTS

The measurement of temperature differs from the measurement of other fundamental quantities such as mass, force, longitude, or voltage not only because of the lack of physical zero point of temperature, but primarily because of the inconvenience in direct comparison of the thermal state of the system of unknown temperature with the thermal state of the standard. The temperature is an intrinsic property of a material and hence does not permit scaling in the way of an extrinsic property such as length or mass. To measure temperature it is necessary to find an extrinsic property that varies in a predictable way with temperature and use this to construct a thermometer. That is why the practical measurements of temperature are always performed indirectly. The temperature sensor interfaces with the system whose temperature is to be measured. The interface may be realized by insertion, by point contact, or by visual contact with the system (Fig. 4). The sensor converts the thermal state of a system to a determined state of another quantity, which is defined as an output signal from the sensor. The output signal is then processed in the transducer T and finally presented in numerical form as a result of the temperature measurement. However, it is not the only function that contemporary transducers perform. They are more and more frequently equipped with microprocessors and constitute a system which controls the measurement process, controls range changes, performs the numerical result correction, presents the results in appropriate units, and controls the standard interfaces such as RS 232, IEC 625, or others. Many control systems work according to the two-wire 4–20 mA standard. Therefore it happens very often that a temperature-measuring transducer provides the 4–20 mA output too, or even has an incorporated PID or on/off controller. Sometimes sensors are integrated with transducers either mechanically only or both mechanically and electrically on the same chip. At a large enough scale of integration, the term *integrated sensor* (IS) is justified. (The reading of the acronym IS as “intelligent sensor” is a commercial and marketing abuse.)

It is not the aim of this article to describe transducers but sensors. Therefore only input stages of the transducers—those stages which are directly interfacing with the sensors—will be presented. They are usually analog parts of measuring circuits, because all temperature sensors are analog devices. The principle of sensor operation depends on the physical phenomena used for conversion of temperature to the output signal. There are a lot of physical phenomena where temperature plays a significant role, but only a few of them are used in temperature sensors because they have to meet some additional requirements. These are as follows:

1. The monotonic calibration curve—that is, the relation between the temperature and an output signal over a sufficiently wide temperature range.

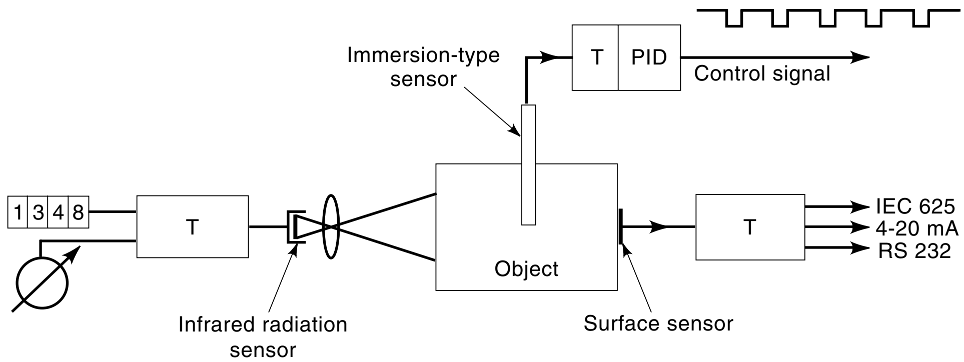


Figure 4. Temperature sensors and transducers. The outputs are arbitrarily assigned to the transducers.

2. Sensitivity to temperature that is much higher than the sensitivity to all other influencing variables.
3. The output signal easily measurable with sufficiently low uncertainty.
4. Interchangeability of the sensors at least within the same type or the same manufacturing technology.
5. Repeatability of the calibration curve over the whole range of operating conditions.

Repeatability is mainly disturbed by hysteresis, relaxation, and aging. Hysteresis is observed when the calibration curve taken for increasing temperatures differs from that taken for decreasing temperatures by the magnitudes exceeding the uncertainty span. Relaxation means a delay in approaching the stable value of measured temperature after a rapid change in the sensor temperature. Aging is a long time process which causes the shift of the calibration curve due to many, sometimes unknown, reasons. Recalibration reduces, at least for a limited period of time, the errors caused by aging.

The linearity of the calibration curve and a large output signal are no longer essential requirements because of the progress in signal conditioning technology.

In order to produce a good sensor, the above requirements have to be fulfilled, but they are not sufficient to ensure a proper temperature measurement. The quality of temperature measurement depends to a great degree on the design of the sensor adequate to the conditions where the temperature has to be measured and on a proper measurement procedure. These two aspects are general ones, and are valid for all measurement techniques, but for the temperature measurements their importance is particularly great. It is due to the fact that every temperature sensor measures its own temperature and, more precisely, the temperature of its own sensitive part (the thermometric body). The designer and the user of a sensor have to ensure the sameness of that temperature with the temperature which is defined as a measurand (that one which has to be measured in the given particular circumstances). For that purpose the sensor should be brought into as close thermal equilibrium with the measurand as possible without disturbing the measurand's thermal state. It requires a good thermal connection to the thermometric body and a poor thermal connection to the environment. The difference in thermal conductivity between thermal isolating and conducting materials is not very high. This involves some difficulties in design of a good thermometer and leads to measurement errors. Errors and uncertainties in temperature measurements will be discussed in more detail in the last section of this article. The problem of the thermal burdening by a sensor does not exist in radiation thermometry, but other sources of errors occur in that case.

RESISTANCE SENSORS

In all resistance sensors the change of their resistance follows the temperature changes, but the way it happens is different in metal sensors and in semiconductor sensors. It is therefore reasonable to separate the considerations about those two groups of resistance sensors. Furthermore, within the group of metal resistance sensors there is a great difference in the design of precise and industrial thermometers. This difference justifies further subdivision of the discussion.

Precise Resistance Sensors

The resistivity of almost all metals depends on temperature, but only a few of them are used in resistance thermometers: those which meet the requirements listed in the previous section. Pure platinum is considered the best material for temperature sensors. It has a relatively high resistivity (15 times greater than copper); thus wires needed to form resistors do not need to be particularly thin. Platinum can be obtained in a pure form with few impurities ensuring repeatability and interchangeability of the sensors. However, the most important reason why platinum is so widely used for temperature sensors is its ability to withstand even severe environmental conditions at high temperatures. For this reason, only pure platinum is used in the standard temperature sensors.

The progress in the technology and in the design of platinum temperature sensors achieved in the past decades made it possible to eliminate the PtRh–Pt thermocouple from the list of standard thermometers, which define temperatures according to ITS-90. Now, the temperatures T_{90} in the range between 13 K and 1233 K (960°C: silver point) are defined by the standard platinum resistance thermometer (SPRT). SPRTs are situated at the top of the hierarchical system of propagation of standards and are used as a first tie, which links ITS with all other temperature standards. They are used only occasionally for measurement of unknown temperature but more frequently for calibration purposes only. It is evident that to satisfy such high demands the quality of SPRTs must be the highest one. The purity of platinum used is secured by meeting two requirements: $R_{Hg}/R_{TP} \leq 0.844235$ and $R_{Ga}/R_{TP} \geq 1.11807$, where R_{Hg}, R_{Ga}, and R_{TP} are resistances at Hg point, Ga point, and triple point of water, respectively. These requirements are much greater than those required for industrial thermometers. In order to achieve such high values, the purity of platinum has to be greater than 99.999%. The influence of impurities is much stronger at lower temperatures, limiting the temperature range of SPRTs. The next limitation is a very low resistance at 13 K with respect to the resistance at the triple point of water, R_{PT} (approximately one-thousandth), which makes the calibration process more complicated and results in decreasing sensitivity.

Standard resistors are always wire-wound, but the cores differ according to the temperature range. For the lowest temperatures, resistors are encapsulated in a hermetically sealed platinum sheath filled with helium under the pressure of 30 kPa. Such a design makes the sensor short and vacuum-protected as required for calibration in cryostats used for realization of ITS-90 fixed points. For higher temperatures, SPRT sensors are fixed at the end of long Inconel or quartz glass tubes, because of the necessity of providing a deeper penetration in the calibration arrangements. For temperatures above 650°C, some special materials such as silica, alumina, or sapphire must be used. The wire diameter of high-temperature SPRTs is greater, exceeding 0.5 mm, resulting in a lower resistance of 2.5 Ω or even 0.25 Ω as compared with 25 Ω for SPRTs used at lower temperatures and wound from 0.05 mm wire.

Each SPRT design has to provide protection from the mechanical stress on the wire and the scratching caused by the different thermal expansion of the core and the platinum wire. At high temperatures the problem is more serious. The upper range for SPRTs seems to be limited by the increasing rate of contamination of the platinum wires, the effect of softening of platinum and by decreasing insulation resistivity. The limit is currently as high as 1000°C, with restriction of the time period of the thermometer exposure to such a high temperature being very short. Nevertheless, some undesirable resistance changes of even the most carefully designed and manufactured SPTRs cannot be completely avoided. Therefore the common procedure of the use of these thermometers is to check the R_0 or R_{TP} resistance before and after each calibration process. The confidence of the values ensures the correctness of calibration. However, it has been found that quenching of the thermometer is already the source of some resistance changes. In spite of the long and intensive experience in preparing better and better SPRTs, many problems are not yet solved and progress in that field has to be expected. For example, it has been found that for the highest temperature, extremely pure platinum is not the best material for the SPRTs (2).

Industrial Metal Resistance Thermometers

The industrial resistance thermometers used for measurement and control purposes in manufacturing plants, in the automotive industry, in housekeeping arrangements, for environmental measurements, and for many other everyday purposes are much less accurate than standard resistive thermometers. Industrial thermometers differ from SPRTs not only by design, technology, and material used, but also by the idea of its implementation. For the purposes of the ITS and of the calibration performed with SPRTs, the ratio of two resistances at two different temperatures is taken as a measure of the temperature. In "normal," not standard, temperature sensors the value of the resistance of the thermometer becomes a measure of temperature. In other words, the output of a standard thermometer is the resistance ratio, and the output of an industrial thermometer is its resistance. The abbreviation for industrial thermometers is PRT (without "S") or more frequently RTD (resistance temperature detector), indicating that sensors in use are not only platinum. Most of the RTDs all over the world are adjusted to the nominal value equal to 100.00 Ω at 0°C, and hence termed as Pt-100 or Ni-100. The relationship between resistance and temperature for platinum RTDs is much simpler than for SPRTs and may be expressed in the form of the following equation:

$$R(t) = R_0[1 + At + Bt^2 + Ct^3(t - 100)] \tag{4}$$

where $A = 3.90802 \times 10^{-3}$ 1/°C, $B = -5.802 \times 10^{-7}$ 1/°C^2, $C = -4.27 \times 10^{-12}$ 1/°C^3 for $t < 0$, and $C = 0$ for $t > 0$. However, it is not the equation but the values of resistances corresponding to appropriate temperatures that are the subject to national and international (IEC) standards, in the form of reference tables. Sometimes a distinction is introduced between "European" sensors with $R_{100}/R_0 = 1.385$ and "American" sensors with $R_{100}/R_0 = 1.392$. Furthermore, the uncertainties allowable for those sensors are also set in national standards, which are normally very close to the international IEC standards (Fig. 5). Standardization secures the reproducibility and hence interchangeability of RTDs, which is one of the most significant advantages of these sensors over all other temperature sensors.

It is a common practice that the repeatability of each individual sensor—especially over a limited temperature span—is in fact much better than the standard uncertainty limits. Therefore the individual recalibration of RTD sensors is recommended, because it allows further improvement of the accuracy. Due to the cost and available technical equipment, such calibration is commonly performed at one or two fixed points only. One-point calibration enables us to take into account an additive component of the difference between the nominal and the actual value of the resistor (i.e., additive systematic error). Two-point calibration enables us to account for the sensitivity difference (i.e., the multiplicative error too). Nonlinearity error remains unknown. If the range of measured temperatures is limited (as is usually the case in practical situations), the nonlinearity of the RTDs has little influence on the total uncertainty and may be ignored. For wider temperature ranges the reference tables or appropriate $R(t)$ equations like Eq. (4) are useful for identifying the nonlinearity component and for applying it for the correction of the measurement result, together with the correction of the additive and multiplicative errors determined during the two-point calibration.

Besides platinum, some other metals and alloys are also used for temperature sensors. Nickel and copper are utilized

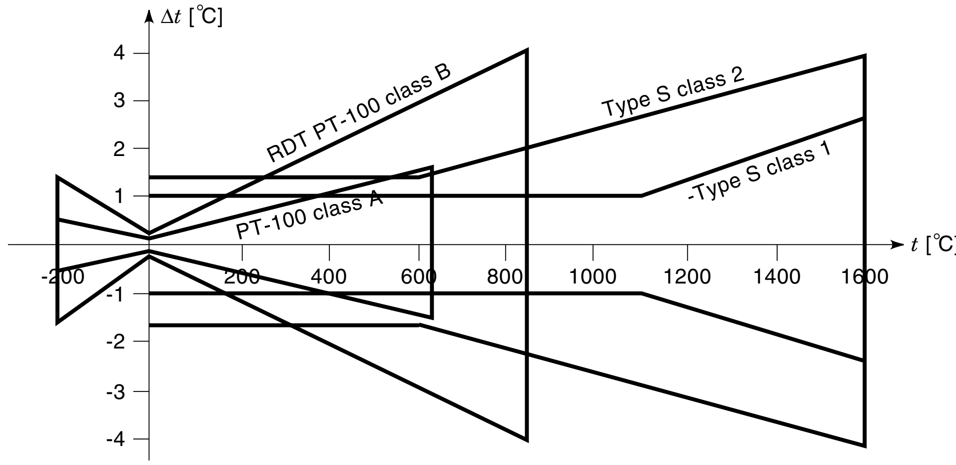


Figure 5. Comparison of allowable uncertainties of RTD Pt-100 after IEC Publication 751 and thermocouple type S after IEC Publication 584. Higher accuracy of resistance thermometers at lower temperatures is evident.

for temperature measurements over a narrow range. The sensitivity of nickel sensors is higher than that of the platinum sensors, but their nonlinearity is greater. Copper sensors are known to be extremely linear, but due to their low resistivity, it takes very long and thin wires to produce a 100 Ω resistor. Therefore, lower nominal values of copper sensors are also allowed by standards.

With the wire wound sensors two designs are usually used. In the first one the wire is bifilarly wound on a glass, quartz, or ceramic rod or pipe and coated with fired glass layer [Fig. 6(b)]. Glass other than quartz glasses is unsuitable as a sensor above about 250°C as electrical insulation properties begin to deteriorate rapidly. For sensors working at temperatures above 600°C, glass is not a proper material and is replaced by alumina (Al_2O_3). The difference in the thermal expansion coefficient of core and platinum causes stress, which influences the long-term stability of the sensors. The second design is stress-free because the helical winding is placed in two holes drilled along the ceramic core and only sealed at the both ends of the core [Fig. 6(c)]. Often, two independent sensors are placed in four separate holes in the body. One of them may be replaced by the second in case of damage, or, more frequently, one serves for measurement and recording purposes while the second serves as a control. It is also very important to ensure the high shunting resistance from the internal mounting structures of the RTDs.

Sensors are protected from mechanical and chemical influences by metal tubes of different length (up to 2 m) made of stainless steel, nickel alloys, and sintered alumina and

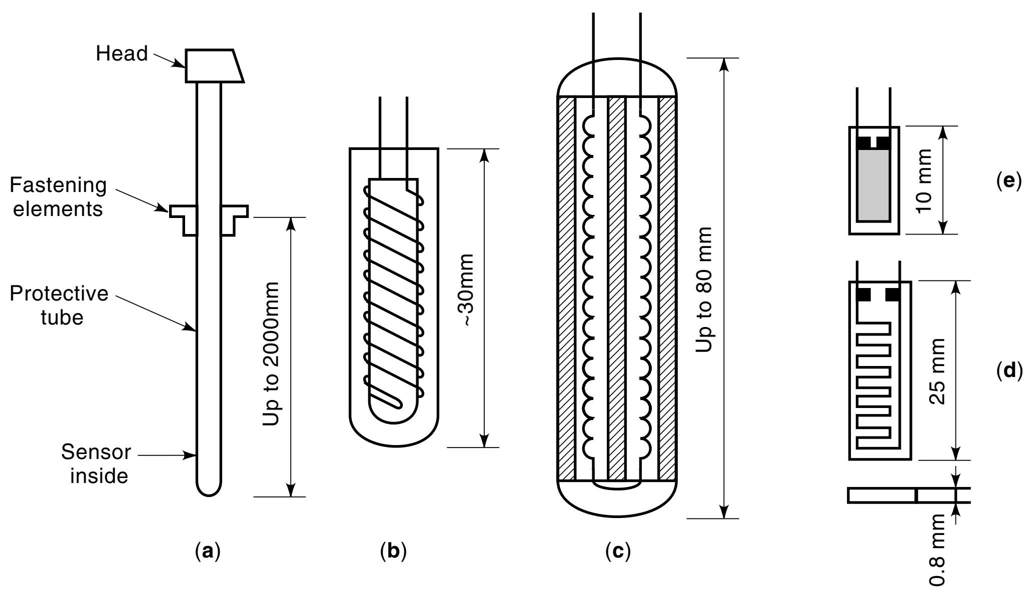


Figure 6. Immersion-type thermometer (a) and four types of sensors: ceramic sealed type (b), free wire type (c), thick film (d), and thin film (e). Types b and c are commonly used in industrial thermometers.

equipped with different kinds of arrangements for fastening them to the objects where the temperature should be measured [Fig. 6(a)]. The choice depends on the kind of object and the range of measured temperatures, pressures, and other environmental conditions. Because the sensor is placed at the bottom of the tube, it is convenient to lead out all the wires from one end of the sensor. In fact, this is the reason why the bifilar winding is used. It protects against the induced noise voltage too. The best thermal contact between the sensor and the protecting tube is highly recommended.

Besides wire-wound RTDs, a group of sensors exists where a metallic layer is deposited on a flat or cylindrical core. The core material most frequently used is alumina, and a metal layer is deposited either as a thick film (5 μm to 10 μm) in a screen printing process [Fig. 6(d)] or as a thin film (1 μm) by sputtering [Fig. 6(e)]. The laser cutting provides the adjustment to the required resistance value. Sensors are coated with a thin protective layer of overglaze. Short response times of such sensors result from the small dimensions and small mass of the sensors. Long-term stability is a bit worse, and the temperature range is restricted to 500°C, but it probably will change with the advances in technology. Deposited RTDs are used in laboratory and service hand-held thermometers and in instruments requiring relatively accurate but small sensors for thermal control or correction. Psychrometric humidity sensing instruments also use deposited sensors. The electric signal which is obtained from these sensors is smaller than the one from traditional sensors because of the lower magnitudes of applied supply current.

SEMICONDUCTOR SENSORS

Semiconductor material may be used in resistance thermometers such as negative temperature coefficient thermistors, linear KTY sensors, and germanium resistance sensors used in cryogenic temperatures, but also in semiconductor devices such as diodes, transistors, and integrated circuits, the operation of which is related to the properties of p–n junction being the essential part of each semiconductor device. Classification and terminology is not established, but for the purposes of this article the distinction will be made between semiconductor resistance sensors and semiconductor active sensors.

Thermistors

Negative temperature coefficient (NTC) thermistors are prepared from a mixture of powdered metal oxides such as $MgTiO_3$ MgO, CuO, NiO, and CoO, along with others sintered at the temperature of 1300°C. During that process, some p- and n-type semiconductor centers are created, thus enabling resistance–temperature relations to be described as semiconductorlike. In semiconductors, both electrons and holes are responsible for the conductivity.

$$s = \frac{1}{\rho} = \frac{ne^2\tau_e}{m_e} + \frac{pe^2\tau_p}{m_p} \tag{5}$$

where: s is the conductivity, reciprocal to resistivity ρ; n and p are the numbers of electrons and holes in the valence band, respectively; τ_p and τ_e are their relaxation times; and m_e and m_p are their effective masses. In the semiconductors, τ_p and

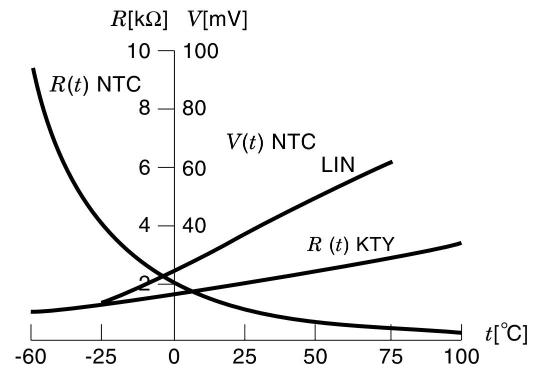


Figure 7. Calibration curves of an NTC thermistor, a KTY temperature sensor, and the output voltage of linearized circuit according to Eq. (15) for temperature span −25° to +75°C. The sensitivity of linearized NTC sensor is twice the sensitivity of KTY which does not need any linearization procedure.

τ_e remain constant but n and p values change with temperature according to the relationship

$$n = p = 2\left(\frac{kT}{2\pi h}\right)^{3/2}(m_e m_p)^{3/4} e^{-E_g/2kT} \tag{6}$$

where E_g is the energy of the band gap, and k and h are Boltzmann's and Planck's constants, respectively. From Eqs. (5) and (6) we obtain

$$\rho = CT^{-3/2}e^{E_g/2kT} \tag{7}$$

In the range of temperature in question (250 K to 400 K), the last term of Eq. (7) dominates. This fact leads to the well-known relationship between temperature and resistance of NTC thermistors in the form of

$$R = R_\infty e^{B/T} \tag{8}$$

R_∞ has a very small value and no physical interpretation. More practical therefore is the equation

$$R = R_{25}e^{B/T - B/298} \tag{9}$$

where R_{25} is the thermistor resistance value at 25°C (500 Ω to 20 kΩ are typical values), and B is a material constant (Fig. 7). The value of B does not correspond strictly to $E_g/2k$ because many other factors influence the resistivity of the semiconductor, and additionally other mechanisms of conduction exist in the thermistor structure. Therefore the value of that constant depends on the material and manufacturing technology of the thermistor, and normally we obtain $B \approx$ 3000 K to 5000 K. By describing the relative sensitivity of the thermistor in the same way as for the metal sensors, one obtains

$$S = \frac{1}{R}\frac{dR}{dt} = -\frac{B}{T^2} \tag{10}$$

from which the value of $S \approx -0.03$ K^{-1} at 25°C is approximately 10 times greater than that for metal sensors.

There are two principal types of thermistors commercially available. The first is the bead type, where the sintered material is formed into a bead of 0.1 mm to 1 mm diameter and sealed in glass stick or epoxy sheath together with two platinum connecting leads. The second and cheaper type is a disk thermistor, where the metal oxides are pressed at 1000°C into the forms of disks, tablets, and bars. Disk-type thermistors are less stable and are used for temperature compensation in electronic circuits. Only bead-type thermistors may be used as temperature sensors because their stability is much better, and after annealing at 60°C repeatability level of ±10 mK may be achieved. Unfortunately, the interchangeability of thermistors is rather poor. Both parameters R_{25} and B differ for individual thermistors, even taken from the same batch (3). This is of particular importance because of the nonlinearity of the calibration curves of the thermistors. The methods of matching the $R(t)$ characteristics are much more complicated for nonlinear characteristics than for the linear ones. The International Standardization Organization (ISO) has attempted to unify thermal calibration curves by introducing the so-called ISO curve thermistors. The standardization concerned the R_{25} value (0.5, 1, 2, 4, 15, 100 kΩ), the shape of the calibration curve, and the admissible limits of interchangeability (from ±0.25% to ±5% of resistance span). Such thermistors are much more expensive than the ordinary ones.

Positive temperature coefficient (PTC) thermistors are used as switching elements rather than as temperature measuring sensors, because of their bistable calibration curve.

Bulk Silicon Sensors

Extremely low doped bulk silicon material shows a different mechanism of conductivity. At temperatures above 100 K, all free electrons become ionized and the temperature influences only the relaxation times, which decrease with the increase of temperature. As a consequence, the resistivity of doped silicon increases, creating a positive slope of the calibration curve of a respective sensor. At higher temperatures, however, the process of thermally excited electrons dislocating from the valence band to the conductivity band becomes more evident and stops the increase in resistivity. The mechanism described above may be practically used only when no p–n junction is created in the bulk material. This is why a special technique of resistance measurement has to be used. The technique is based on a great difference in size between the electrodes used for the measurement. One electrode is only micrometers in diameter, while the other covers the whole counter surface of the semiconductor piece (Fig. 8). This creates a great difference in the electric field density at both electrodes, and therefore only the part of the material with high field density is responsible for the measured resistance R. The relationship between the resistance and the semiconductor resistivity is given in the form

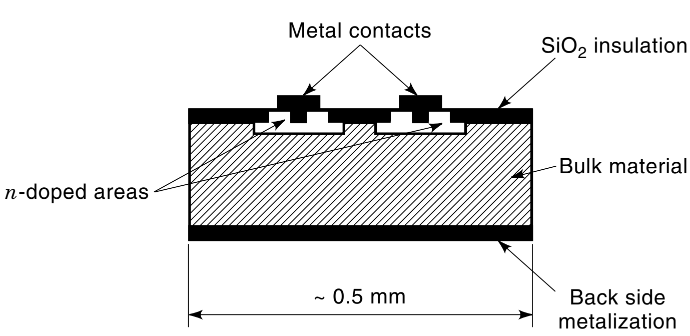


Figure 8. The design of a KTY sensor.

$$\rho = \frac{R}{\pi d} \tag{11}$$

where d is the fine electrode diameter.

The commercially available temperature sensors, which work according to the described principle, are known as KTY linear sensors. In fact there are two small electrodes of 22 μm diameter, and the "back side" of the bulk silicon material is coated by a conductive layer. The very precise doping control of the material is realized by means of neutron implantation in which the silicon atoms are replaced by phosphorus atoms with excellent homogeneity over the whole bulk material. The resistance of KTY sensors at ambient temperatures is about 1 kΩ to 2 kΩ, their sensitivity is about 1%/K, and the operation temperature ranges from −50°C to + 125°C (Fig. 7).

Active Semiconductor Sensors

Active semiconductor sensors are those whose operating principle relies on the potential barrier between the conducting layer and the valence layer in a semiconductor, as in diodes and transistors. The simplest semiconductor device is a diode. According to the Shockley theory, the relationship between current I and voltage V in the forward polarized diode may be expressed as

$$V = V_B + \frac{kT}{nq} \ln \frac{I + I_S(T)}{I_S(T)} \tag{12}$$

where V_B is a barrier voltage, n is a coefficient (not considered in the simplest form of the theory), and $I_S(T)$ is reverse saturation current, many times smaller than forward current I, but very strongly dependent on the temperature. Every temperature increase by 10 K results in its value doubling, and this behavior determines the temperature properties of the diode. In the temperature range of 150 K to 400 K the thermometric calibration curve of the diode is nearly linear, with the negative slope of approximately 2 mV/K to 2.3 mV/K. Unfortunately the I_S value depends not only on the temperature but also on many factors hardly controllable in the manufacturing process. Therefore, the diode sensor's interchangeability is poor. A single diode is the cheapest temperature sensor, but each one has to be individually calibrated at one or better at two points. Even in that case the uncertainty, including nonlinearity and hysteresis, is at the level of ±2 K. In order to improve the properties of diode temperature sensors, two integrated diodes fed from two different current sources I_1 and I_2 should be used (Fig. 9). The difference in voltage drop over these diodes is

$$\Delta V = V_1 - V_2 = \frac{kT}{nq} \ln \frac{I_1}{I_2} \tag{13}$$

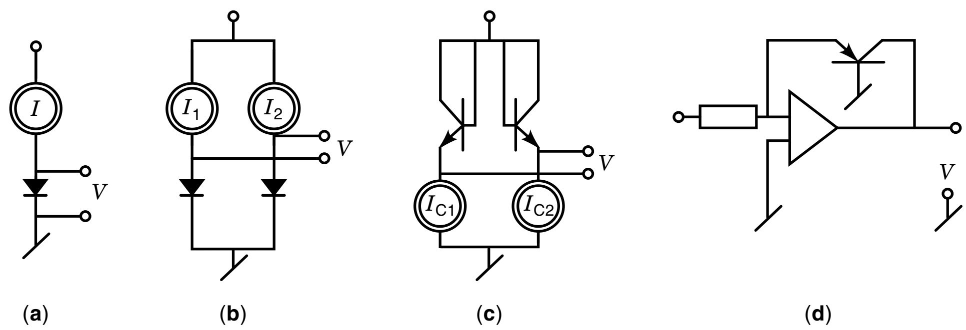


Figure 9. Diode and transistor temperature sensors: simple diode sensor (a), double diode sensor (b), double transistor sensor (c), and simple integrated circuit (d).

and does not depend on the reverse saturation currents because of their similarity due to the integration. Furthermore, the output voltage bias is significally reduced, which leads to simpler measuring circuits.

Transistors are often used instead of diodes, and the base-emitter voltage difference is the output signal of the sensor. Integrated circuit (IC) technology allows us not only to produce temperature-sensitive pairs of transistors but also to include amplifiers and signal conditioning circuits on the same chip. In this way, integrated sensors with precisely trimmed output signal can be produced. The most popular are IC temperature sensors with 1 μA/K output (e.g., Analog Devices AD592), but sensors with voltage output of 1.5 mV/K or even 10 mV/K are manufactured too. The LM75 temperature IC sensor, produced by National Semiconductor, has a silicon band gap sensing element and is equipped with a sigma–delta A/D converter, programmable alarms, and a two-wire I^2C interface. The operating temperature span of diode- or transistor-based IC sensors ranges from −55°C to +125°C.

THE MEASUREMENT OF SENSOR RESISTANCE

Common Problems

The first stage of every transducer consists of the measuring circuit, directly connected to a temperature sensor. A few different measuring circuits are used to transform the resistance changes $\Delta R(t)$ (which follow the measured temperature) to the output signal ΔV, but three problems seem to be common for all those circuits. These are (1) sensor self-heating, (2) lead resistance, and (3) linearity.

Self-heating of resistance sensors is unavoidable because the flow of the current creating the output signal causes automatic heat dissipation in the sensor, subsequent increase of its temperature, and consequent measurement error Δt:

$$\Delta t = Pk_w = I^2R(t)k_w \tag{14}$$

where k_w is a dissipation factor. The dissipation factor depends on the design of the sensor and on its materials, dimensions, and shape, but it depends primarily on the environment of the sensor. Its magnitude changes dramatically with the kind of medium surrounding the sensor and with the velocity of that medium, as presented in Table 1. Theoretically, the error due to self-heating belongs to the systematic errors category and should be able to be removed from the measurement result by means of a correction procedure, but our knowledge about the value k_w is insufficient to calculate the correction value because of the unstability of the environmental conditions. It is sometimes possible to correct for self-heating effects by measurement at two currents and extrapolating to zero current. The best way, however, is to limit the error due to self-heating by keeping the current at the allowable level, but it results in lowering of the output signal.

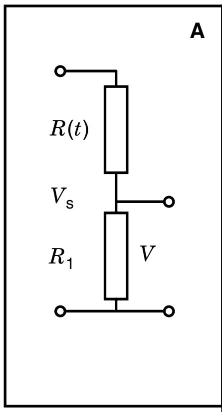
The second problem is the change of lead resistances with temperature. The problem becomes serious in situations when the distance between the sensor and the transducer reaches up to hundreds of meters and the long leads are exposed to great temperature differences (e.g., outdoor temperatures in summer and winter). For a 10 Ω copper lead the temperature change of 60 K (from −30°C to +30°C) causes a 2.4 Ω resistance change which is observed as a 6 K temperature error if a Pt 100 sensor is used. The best way to avoid this kind of error is to feed the sensor from a current source by one pair of leads and to sense the voltage from the sensor by another pair of leads. This solution is called a four-wire line and is commonly used in transducers with standard analog 4–20 mA output and in all high accuracy transducers. A three-wire line instead of a four-wire line is also used, especially in bridgelike measuring circuits. Three-wire installation cancels the additive errors caused by the thermal change of lead resistance, but the multiplicative part of the error remains. The higher the sensor resistance, the lower the influence of the lead resistance. There is no need to use four- or three-wire lines for thermistors or KTY sensors.

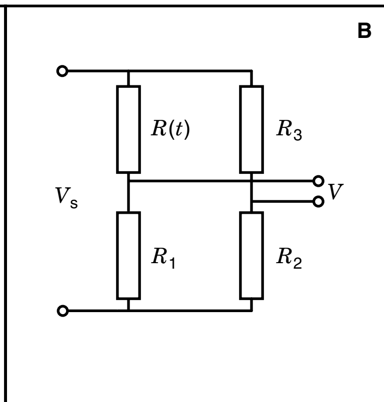
Table 1. Dissipation Factors of Resistance Sensors Without Protective Sheath

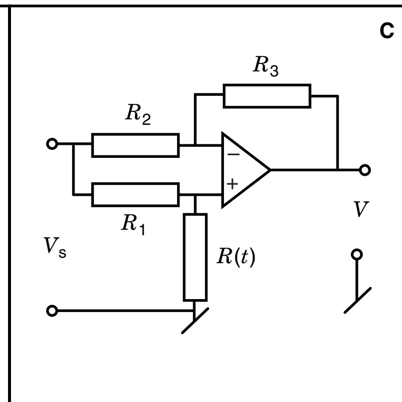
Sensor	Environment	k_w (mW/K)
Wire-wound RTD[a]	Still air	3–5
	Air 1 m/s	10–20
Thin-film RTD	Still air	2
	Still water	75
NTC bead-type thermistor	Still air	1
	Stirred oil	8

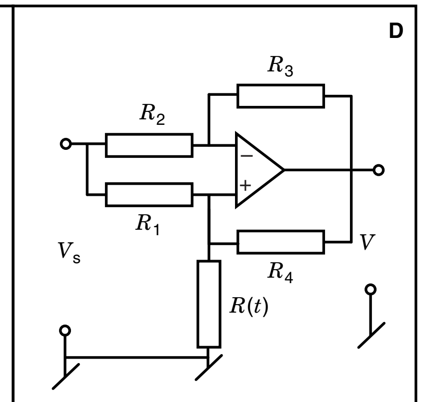
[a] RTD, resistance temperature detector.
[b] NTC, negative temperature coefficient.

Table 2. Some Examples of Linearizing Circuits for Resistance Sensors. Values of *k*, *A*, and *B* given in the third row correspond to Eq. (15). Circuit A (potentiometric), B (bridge circuit), and C (active bridge circuit) may be used for NTC thermistors or RTD nickel sensors. Circuit D (positive feedback circuit) may be used for RTD platin sensor.









A	B	C	D
$V = V_S \frac{R_1}{R_1 + R(t)}$	$V = \frac{V_S}{R_2 + R_3} \cdot \frac{R_1R_3 - R_2R(t)}{R_1 + R(t)}$	$V = \frac{V_S}{R_2} \cdot \frac{R_1R_3 - R_2R(t)}{R_1 + R(t)}$	$V = V_S \frac{R_1R_3R_4 + R(t)[R_1R_3 - R_2R_4]}{R_1R_2R_4 - R(t)[R_1R_3 - R_2R_4]}$
$k = V_S, A = 0, B = \frac{1}{R_1}$	$k = V_S \frac{R_3}{R_2 + R_3}$, $A = -\frac{R_2}{R_1R_3}$, $B = \frac{1}{R_1}$	$k = V_S \frac{R_3}{R_2}$, $A = -\frac{R_2}{R_1R_3}$, $B = \frac{1}{R_1}$	$k = V_S \frac{R_3}{R_2}$, $A = \frac{1}{R_4} - \frac{R_2}{R_1R_3}$, $B = \frac{1}{R_1} - \frac{R_3}{R_2R_4}$

The third problem, linearity, is common for all transducers working with more or less nonlinear sensors. While most transducers are equipped with microprocessor-controlled systems, the linearity corrections are commonly performed numerically. The look-up table method is preferred. In that method, appropriate corrected values or the values of corrections which have to be added to the directly measured uncorrected results are written in memory. The linearization algorithm consists of a simple readout from the memory. At 0.1% resolution the method requires only 1 kB of memory. Some other methods of numerical linearity correction, utilizing the reduced tables containing only node point correction values, are also used. The correction data for all the results falling in between the node points are calculated by linear interpolation.

In spite of the simplicity of the numerical linearization, the possibility of analog linearization ought to be taken into consideration in measuring circuits where no microprocessor is used or where we use one of the lower-performance microprocessors carrying out many other functions related to the organization of the measuring process or to the presentation of the results. The analog linearization stems from the general law known from circuit theory, which says that in every linear circuit, each signal (either current or voltage) between any two points of the circuit is related to the circuit parameter R by a bilinear equation

$$V\,(\text{or } I) = k\frac{1 + AR}{1 + BR} \tag{15}$$

where the constants k, A, and B depend on the circuit configuration (see Table 2). It needs to be pointed out that the expression "linear circuit" is used here in a meaning of circuit theory and is completely unrelated to the linearity or nonlinearity of the sensor. These circuits enable a nonlinear relationship between the output signal V and the sensor resistance R, in order to compensate the nonlinear relationship between the sensor output and the temperature. Some examples are presented in Table 2. The limitation of the method concerns the constant value of B. For circuits with no active elements, B is always positive. In that case, if the sensor resistance increases with temperature, the denominator of Eq. (15) increases too and the sensitivity of the circuit decreases. The circuit compensates for the nonlinearity of sensors whose sensitivity increases with temperature (like Ni-100 or KTY sensors) only and is useless for Pt-100 sensors in which the sensitivity decreases with temperature. Otherwise, if the sensor resistance decreases with temperature, the denominator of Eq. (15) decreases and the circuit may be used as a compensating circuit for sensors with sensitivity decreasing with temperature (like NTC thermistors). In order to use that method for the most popular Pt-100 sensor, the constant B in Eq. (15) has to be negative. This may be achieved only by the use of an active element with positive feedback (case D in Table 2). In the technical literature and application notes, these circuits are called "current control supply" or "current source with negative resistance" or simply "feedback compensation." The above described method does not lead to the canceling of the nonlinearity error but only to its reduction.

The Most Popular Measuring Circuits for Resistance Temperature Sensors

Generally the resistance sensors are manufactured with high accuracy. Transducers have to be matched to the sensors in order not to increase the total uncertainty. It is evident that for SPRTs the most accurate methods and instruments should be used for measuring the resistance and more exactly the resistance ratio. Costs and compactness are less important. The uncertainty of modern precise resistance ratio measurements is as low as a few parts per million, but only with

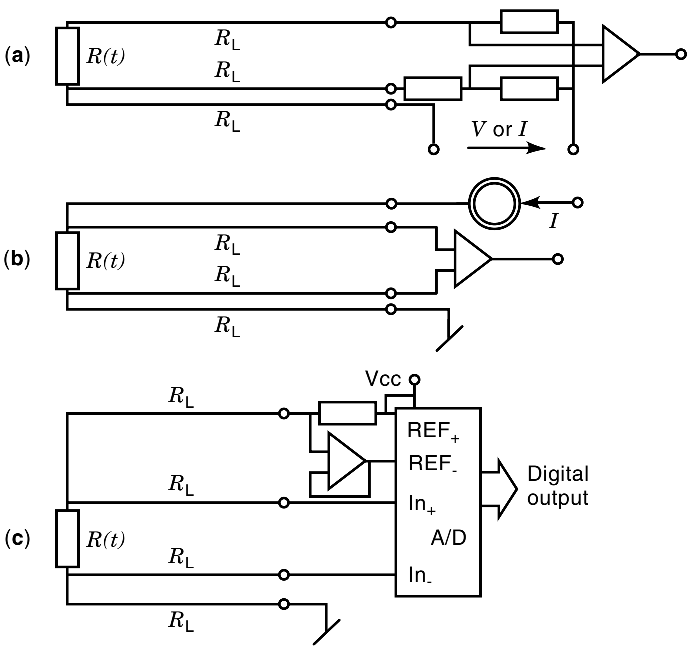


Figure 10. The measuring circuits which reduce the influence of the leads resistances R_L. (a) Three-wire bridge circuit makes it possible to connect one lead to the sensor and the second to the resistor in opposite bridge arm and then to reduce their influence. (b) Four-wire circuit with the current source enables canceling of the lead resistance influence. (c) The implementation of an A/D converter in the four-wire circuit provides direct conversion of the analog signal to the digital one.

very special arrangements used in advanced well-equipped laboratories. Such measurement circuits will be not presented here. However, with conventional temperature measuring transducers the accuracy of resistance measurements has to be high too. Let us note that according to IEC 751 standard, the Pt-100 uncertainty at 0°C is only ±0.1 K, which means ±0.04 Ω. In order to protect the sensor accuracy, the uncertainty of the transducer ought to be less than, say, ±0.01 Ω, which gives 0.01% with respect to a 100 Ω sensor. For resistance-measuring instruments in common use, it is a rather high requirement and a bridge circuit is therefore the one which has to be primarily considered as the input stage of the transducer.

Balanced bridges are contemporarily used almost only in self-balancing chart recorders or *x–y–t* recorders. The complicated mechanical design of such instruments together with the need for the precise potentiometer, which decides about the quality and accuracy, makes these instruments rather expensive. There is a reason why those instruments are equipped with multiplexers in order to record up to 16 temperatures from different sensors located in different points of a plant. Such instruments have been formerly widely used not only in industrial applications, but also in laboratories and research. High cost and the absence of an electrical output signal (which may eventually be obtained from an additional potentiometer) make those instruments not very suitable for modern instrumentation systems.

To the contrary, unbalanced bridges are very often used as the first stages of contemporary transducers working with resistance temperature sensors [Fig. 10(a)]. The differential structure of any unbalanced bridge circuit enables easy adjustment to the desired temperature range. The output voltage is not strictly proportional to the resistance, because the unbalanced bridge belongs to the class of the circuits described by Eq. (15) and presented in Table 2 as cases B and C. Therefore, an unbalanced bridge may also be used as a linearizing circuit for some types of sensors. To do that, an appropriate matching of the bridge branches have to be performed. Unbalanced bridges are supplied either from a voltage source or from current sources. The constant current supply is preferred especially for low-resistance sensors, as Pt-100 or Ni-100, where the three-wire connection between the sensor and the transducer is needed in order to reduce the line temperature error. The reduction is four times better using a current source than using a voltage source.

The output voltage from a bridge is fed to a direct-current (dc) differential amplifier. The signal is usually high enough for a conventional low-noise operational amplifier with a proper compensation of bias currents. In some extremely precise instruments the switched-capacitor-based instrumentation amplifiers are used (i.e., Linear Technology LTC 1043). The aim of the amplifier is not only to increase the signal but also to allow the transition from differential to a single-ended signal. It is a general requirement, especially in the industrial measuring installations, that the sensor must be grounded. When the three-wire configuration is used, two of them are close to ground potential, but according to the principles of noise protection they must not to be grounded at two points (at sensor's side and at transducer's side) in order to avoid the ground loop which introduces additional unknown voltages. The circuit with floating voltage supply and grounded one-amplifier input is less convenient because of the limitations in scaling the circuit parameters. The greatest comfort in circuit parameters scaling is provided by a four-wire installation because it consists of two almost separated circuits [Fig. 10(b)]. The only problem to solve is the subtraction of that part of voltage which corresponds to the low limit of the measured temperature. It may be done either by a bias voltage or by another differential structure containing a sufficiently stable voltage source. Integrated circuits, which incorporate a controlled gain amplifier, a linearization circuit, and isolated output (i.e., Analog Devices 1B41), facilitate the design of the measuring system. A/D converters with reference input may be used for direct four-wire connection to the sensor supplied from the voltage source instead of a more complicated current source [Fig. 10(c)].

Some completely different temperature measuring circuits—that is, circuits with frequency output, where the sensor resistance influences either the oscillator frequency or the duty cycle of square-wave output voltage—are also known. The practical implementation of such circuits are limited mostly to those in a form of integrated circuits—for example, the SMT 160-30 produced by Smartec.

RESISTIVE SENSORS FOR LOW TEMPERATURE RANGES

The range of temperatures below 20 K becomes more and more interesting not only for the researchers but also for the technologists. The practical use of the superconductivity requires the precise temperature measurements and control of temperatures as low as 4 K. In some cryogenic technologies the high magnetic fields and nuclear radiation are simultaneously present. Temperature sensors destined for low-temperature applications have to be resistant to those environmental conditions too. It is reasonable to distinguish a special group of sensors working at low temperatures in spite of their different principles of operation and design.

As stated before, a platinum resistance thermometer does not work properly at temperatures below 10 K. For that range a different alloy has been developed, namely rhodium with 0.5% iron (2,3). The technology of preparing thin, 0.05-mm-diameter rhodium–iron wires is complicated. It includes chemical iron deposition on powdered rhodium and then a series of metallurgical processes. The helically wound sensor is hermetically encapsulated similarly to SPRT sensors. The most useful operating range is 0.3 K to 30 K; but due to its relatively low slope of resistance versus temperature, it may be used up to the normal ambient temperatures too. The stability of an Rh–Fe sensor is relatively good, much better than that of low-temperature semiconductor sensors. Semiconductor sensors, however, are much simpler and smaller, and for that reason they are used too.

Some specially prepared and composed thermistors, usually made from iron oxide, are able to measure temperatures as low as 5 K. According to Eq. (8), thermistor sensitivity and nonlinearity increases dramatically at lower temperatures, creating problems with covering a wider range of temperatures. This is a common problem of all low-temperature sensors related to the "wrong" representation of temperatures on the linear scale, as discussed in the first section of this article. The greatest advantage of thermistors is their low sensitivity to the magnetic fields. Germanium was previously used in electronic semiconductor devices to the same degree as silicon. The physical principles of its conductivity remain the same as those described for silicon. Germanium temperature sensors have been used for measurement purposes for a much longer time than bulk silicon sensors. Their operating area, however, is shifted toward the very low, cryogenic temperature range. The bulk germanium with a very small amount of added impurities forms a low-temperature sensor which may be used down to 1.6 K; but due to the very strong dependence of its properties on the amount of the impurities introduced, the individual calibration of each sensor is necessary. The calibration process at extremely low temperatures is always a complicated and expensive one. Other problems related to the use of the germanium sensor are (1) rapid and unexpected changes in resistance of the magnitude corresponding to a few millikelvins, (2) high sensitivity to the mechanical stress, and (3) a strong Peltier effect causing an additional heat distribution along the sensor. The instability exhibited by many low temperature Ge resistance thermometers is thought to be due to the difficulty of attaching leads in a way that defines the resistor without subjecting it to strain effects. A long-lasting experience with this kind of sensor (since 1960) has resulted in gathering a considerable amount of information, which enables us to reduce the effects of all inconveniences listed above. Specially doped germanium resistors are insensitive to magnetic fields (3).

Individually calibrated diode sensors may also be used in the very low temperature region, down to 10 K. Sensitivity is not the same as at medium temperatures, and it increases rapidly below a certain temperature (approximately 25 K for silicon diodes), but the sensor calibration curve remains repeatable with the uncertainty of ±10 mK. Commercially available diode sensors are produced with a wider uncertainty span, exceeding ±0.25 K but with quite good reproducibility of ±50 mK (4).

THERMOCOUPLE SENSORS

Physical Principles

A temperature difference between two points of a conducting wire forces free electron diffusion from the point of higher temperature to the point of lower temperature. Such dislocation of electrons produces a voltage difference, which forces the electron flow in the opposite direction. In the state of dynamic equilibrium, both processes are in balance. A voltage difference caused by the temperature difference is known as thermal electromotive force (emf), and it provides a measure of temperature difference between any two points of the wire. Thermal conductivity of the metal wire causes temperature distribution along the wire, and hence the thermal emf may be considered as continuously distributed along the wire too. The problem of how to measure the thermal emf arises because each electrical contact of the connecting leads with the heated wire is also a thermal contact and generates subsequent thermal emf corresponding to the temperature difference at the ends of the connecting leads. If the materials of the heated wire and connecting leads are the same, two emfs appear in the loop with the opposite signs and are reduced to zero. However, the magnitude of the thermal emf depends on the material; and it is possible to find a pair of materials (A and B) with essentially different emfs, thereby generating relatively high voltages in the loop (Fig. 11).

By denoting the thermal emf sensitivities to the temperature of both wires as $S_A(t)$ and $S_B(t)$, one obtains

$$E_{AB} = \int_{t_1}^{t_2} [S_A(t) - S_B(t)]\,dt = \int_{t_1}^{t_2} S_{AB}(t)\,dt \tag{16}$$

where $S_{AB}(t)$ is the sensitivity of a thermocouple known as a Seebeck coefficient or "thermoelectric power." In other words, a temperature difference produces thermal emf, and the inhomogeneity of the materials in the loop allows us to detect it. The greatest inhomogeneity appears at the contact points of two different materials. These points constitute "hot junction" and "cold junction," or more properly, a measuring junction and reference junction. Any other material (C in Fig. 11) included in the thermocouple loop but not exposed to the temperature difference does not produce any additional emf in the loop. Otherwise, each unexpected inhomogeneity, caused not only by inclusion of any additional material D but also by chemical reactions or annealing processes in the material under temperature difference, is a source of additional thermal emf. Therefore the whole of the thermocouple loop ought to be considered as the sensor not just the tip and this makes the consideration of sources of uncertainty much different to most other temperature sensors.

The thermal emf effect discovered by Seebeck in 1821 is superposed by two other effects related to the current flow in the loop: (1) Thomson effect and (2) Peltier effect. In the Thomson effect an additional emf is induced by current flow in the presence of a temperature difference in the conductor,

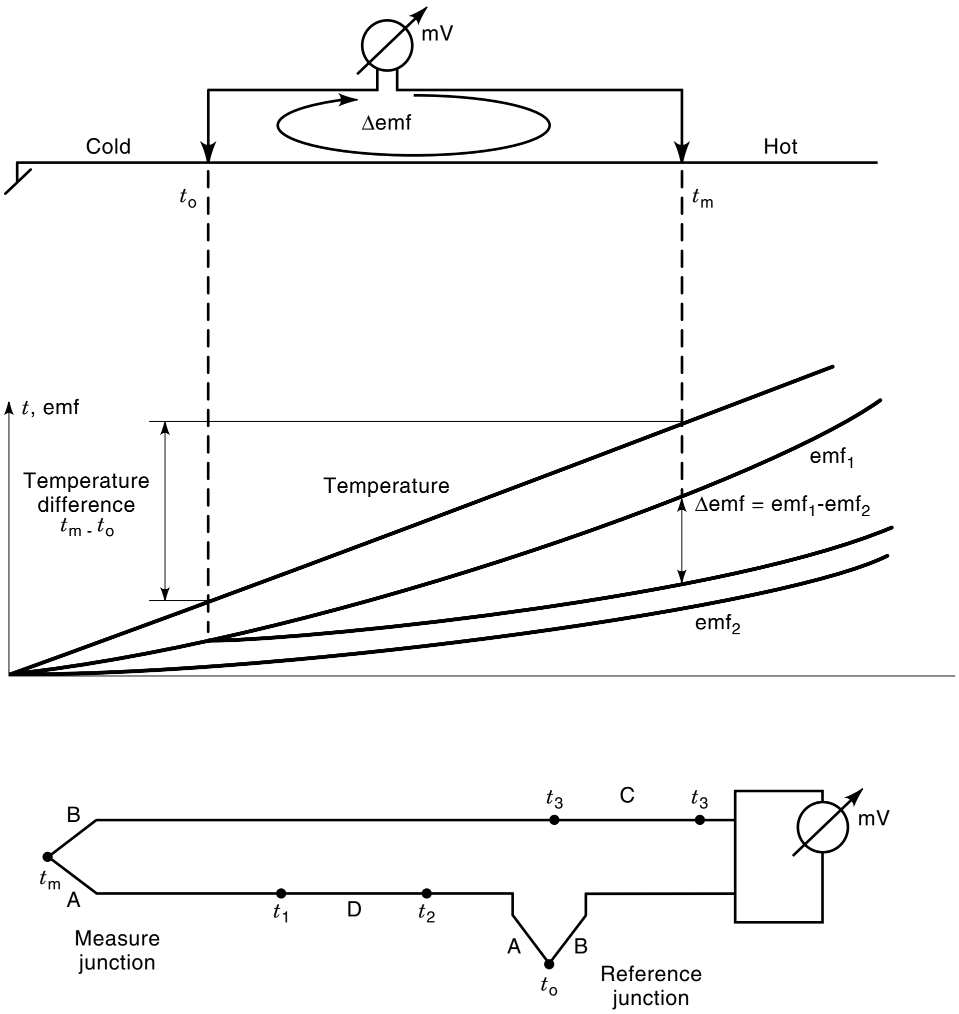


Figure 11. Temperature difference measurement by a thermocouple circuit. Temperature difference $t_m - t_0$ corresponds to the emf difference Δemf.

involving heat liberation or absorption by the conductor at the rate

$$Q = \int_{t_1}^{t_2} S_{TA} I \, dt \tag{17}$$

where S_{TA} is a Thomson coefficient of the particular material A. For the same reason as with Seebeck effect, the Thomson emf in the whole loop is different from zero only in a case when two different materials make two branches of the loop. The Peltier effect reveals in the additional heat absorption or heat generation forced by the current flowing through a junction of different materials $Q_P = V_{P_{AB}} I$, where V_P is called the Peltier coefficient (Peltier emf).

Three effects described above are interrelated according to the equation

$$E_{AB} = V_{P_{AB}}(t_1) - V_{P_{AB}}(t_2) + \int_{t_1}^{t_2} S_A(t)\,dt + \int_{t_2}^{t_1} S_B(t)\,dt \tag{18}$$

Because of the low currents flowing in the temperature-measuring thermocouple loops, the effects of additional heat emitted in the Thomson and Peltier effects may be normally neglected.

Thermocouples

It is evident that a thermocouple has to be composed of thermowires, which reveal a large spread in their respective thermal emfs. In measurement practice, however, a lot of additional requirements are of a great importance. Most of them stem from the fact that thermocouples are usually used at high temperatures. Therefore the wires themselves have to be resistant to high temperatures. Their melting points must be at least by 150 K higher than the upper temperature of the measuring range. At high temperatures the atmosphere is usually corrosive and hence much more aggressive than at low temperatures. The degeneration of the lattice structure and the chemical changes observed at the surface of the wires cause the inhomogeneity of the wire materials and lead to the successively arising measurement errors. This is a reason why thermocouple wires are rather thick, and the upper temperature limit for continuous work case depends on their diameters. The cost of wires, especially those made of noble metals, is important too. Very special alloys have been developed in order to meet the above-mentioned requirements. The work in this area is still going on, and the result has been continuous improvements and modifications of the thermocouple wires. Table 3 presents the most popular thermocouples and their essential properties.

Table 3. Thermocouple Data

Type	+Wire	−Wire	Long-Time Temperature Span (°C)	Short Time Allowable Temperature (°C)	Thermal emf Span at 0°C Reference Junction (mV)	Allowable Uncertainty (IEC) Class 1 at 0°C (°C)	Class 1 at Upper Limit (°C)	Class 2 at 0°C (°C)	Class 2 at Upper Limit (°C)	Properties
S	PtRh10	Pt	−50 to +1600	1760	−0.23 to +18.6	1	2.5	1.5	4	Stable. For oxidation and insert atmosphere. Sensitive to contamination.
R	PtRh13	Pt	−50 to +1600	1760	−0.23 to +21	1	2.5	1.5	4	
B	PtRh30	PtRh6	+100 to +1600	1800	-- to 13.8	—	—	—	4.27	Negligible thermal emf up to 60°C.
K	NiCr Chromel	NiAl Alumel	−270 to +1000	1250	−6.46 to +50.6	1.5	4	2.5	9	Most frequently used. Linear for $t > 0$°C. For clean oxidizing and inert atmosphere.
N	NiCrSi	NiSi	−270 to +1000	1300	−4.3 to +47.5	1.5	4	2.5	9	More stable than type K at high temperatures.
T	Cu	CuNi Constantan	−270 to +350	400	−6.26 to +20.9	0.5	1.4	1	2.6	For oxidizing and reducing atmosphere at low temperatures. Moisture-resistant.
J	Fe	CuNi	−210 to +750	1200	−8.1 to +69.5	1.5	3	2.5	5.6	For reducing and inert atmospheres.
E	NiCr	CuNi	−270 to +700	1000	−9.8 to +76.4	1.5	3.2	2.5	6.75	High thermal emf, also at low temperatures.
—	WRe5	WRe26	0 to +2400	2700	0 to +40.7	No standards				For highest temperatures. For neutral and reducing atmospheres only.
—	NiCr	Au	−273 to 0	—	−5.3 to 0					Linear for low temperatures, also below 4.2 K.

The calibration curves of some thermocouples are subject to standardization in the form of reference tables, similar to the corresponding tables for resistance sensors. Worse stability of thermocouples results in their much greater uncertainties as compared to resistance sensors (see Fig. 5). When a lower uncertainty is required, the individual calibration of thermocouples is not recommended because the validity of the results is rather short-lived.

Thermocouple Sensors

A great variety of thermocouple sensors with different sizes and designs are destined for a wide range of applications, such as power plants, nuclear installations, metallurgy, chemical reactors, and the glass industry, as well as laboratories, research works, and communal applications (5).

Industrial-immersion-type thermocouple sensors look like thick resistance sensors because they are manufactured in a similar form, with a long protective pipe and a head on one end. The sensor element (wires with the junction) are mounted inside and may be replaced if necessary. However, the materials used for shields differ considerably. For high-temperature sensors a conventional carbon steel protective pipe is insufficient. Either stainless steel (18% Cr, 8% Ni), inconel (NiCr, 15% Fe), hastelloy, or bronze has to be used depending on the environmental conditions. Sometimes there is a need for molybdenum or tungsten sheath (for highest temperatures). Noble metal thermocouples have to be additionally protected by means of an internal ceramic (alumina Al_2O_3) coating, against the contamination of the thermocouple wires by the particles of pipe material that occurs at high temperatures. Some outer porous ceramic protection tubes are used with the sensors for open fire furnaces.

A special type of sensor is produced in the form of a metal shielded double thermowire cable with MgO or Al_2O_3 insulation. These are called shielded thermocouples or mineral insulated metal sheathed (MIMS) sensors. The same type of insulation is used in resistance heaters. The thermocouple junction is formed by connecting both wires. The external diameter of the MIMS may be as low as 0.25 mm (more commonly 0.6 mm to 3 mm), and the bonding radius allowed is normally twice that of the diameter. This constitutes a great advantage of the sensor, being an ability to penetrate hardly accessible spots. This kind of sensor is now obtainable in up to lengths of a tenth of a meter, with the sensing junction, as well as the plug on the opposite end, formed and sealed by the producer. Former MIMS were produced in a form simply cut from one piece of cable, but the hygroscopic properties of the insulation material made it very hard for the user to provide the proper hermetic sealing.

The next group of thermocouple sensors are those designated for the measurements of moving surface temperatures and designed as free thermowires or thermostrips, either suspended on elastic arms or shaped into a form of an elastic arch. The measuring junction is situated in the middle of the free part of the thermostrips and should be pressed to the surface during measurement. The smoothness of the thermojunction allows the measurement of the moving or rotating elements without heat generating by friction. The elasticity of the sensor ensures a good thermal contact with the surfaces of different shapes (e.g., with rollers of different diameters).

In metallurgy, two kinds of immersion-type sensors are commonly used for measurement of the molten metals temperature. Both kinds work under the transient state conditions. The construction must be strong enough to pierce the layer of the blast furnace slag. In the first design, two sharp-cut thick bars from thermocouple materials are placed near each other at the end of a long handle. The stick is immersed in the molten metal, thereby creating a junction. In the second design the exchangeable cap with very thin thermocouple wires (50 μm to 100 μm) and a protective cover is placed at the end of the handle. The cover is damaged when immersed in the molten metal, and after each measurement the cap is replaced by the new one.

Many other thermocouple sensors are present on the market or are custom-designed for particular purposes. The use of a thermocouple sensor instead of another sensor type is motivated in a case when most important are (1) high temperature range, (2) the small dimensions of the sensor, and (3) relatively low cost.

Thermocouple Measuring Circuits

At a first glance, the task seems to be easy: Create a reference junction and measure a dc voltage. However, some problems arise particularly in the industrial environment and at high temperatures. In the large area plants the distance between the sensors and the transducers is long, and at high temperatures the sensor head temperature is usually unstable to such a degree that it is impossible to treat it as a reference junction. Therefore, the thermocouple wires are contained in the space where the temperature is constant, say in the transducer (6,7). For evident reasons it is not a good solution, especially if noble metal wires are used. In such a case, extension wires are used as a connection between the sensor head and the reference junction. These are special compensation leads having the same thermal emf as the thermocouple wires, but with a much lower temperature range, namely that expected to occur at the sensor head (Fig. 12). Compensation leads have to be matched to the thermocouple; and in order to avoid misconnections, the colors of their insulation are subject to standardization. Compensating wires are much cheaper than thermocouple wires. A special noble metal thermocouple has been developed (Type B, Table 3), which does not require any compensation leads because its thermal emf at temperatures up to 50°C is practically equal to zero and with temperatures up to 120°C it is very low. For that thermocouple, neither a reference junction nor the compensating leads are needed, assuming that the ambient temperature of the transducer and the sensor head temperature do not exceed 50°C and 120°C, respectively.

For all other thermocouples, however, the reference junction is necessary. In laboratory practice ice-water baths, and in industrial measurements, thermostats may be used. Both are unpractical. Instead of stabilizing the temperature of a reference junction, it is more convenient to measure it and to introduce a compensating voltage into an emf measurement loop. Such a method is now used in almost all instruments and transducers. The most common compensating circuit is shown in Fig. 12. At nominal temperature of the reference junction (say 25°C), $R(t) = R$ and $V_C = 0$. As the reference temperature increases, $R(t)$ increases accordingly, producing a compensating voltage V_C, equal to the change of the thermal

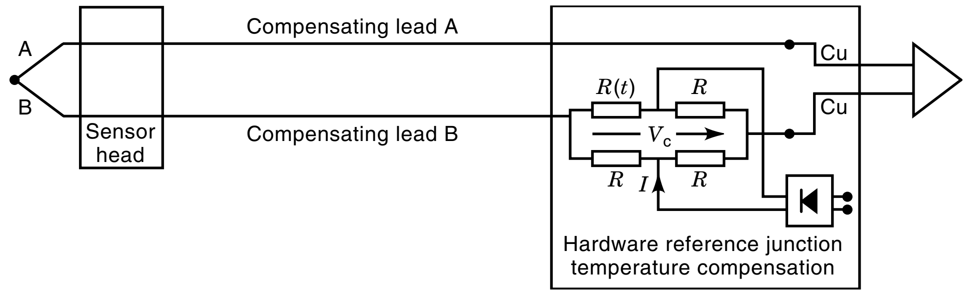


Figure 12. Basic thermocouple circuit with compensating leads which eliminate the influence of the head temperature variations and with reference junction temperature compensation circuit. Resistances R and supply current I are matched according to the type of the thermocouple.

emf corresponding to the difference between the actual temperature and 25°C. The supply current I is matched according to the sensitivity of particular thermocouple. There exist also a great number of integrated circuits for compensation of the reference junction temperature where a diode sensor is used instead of the temperature-sensitive resistor (i.e., Linear Technology 1025). The amplification of a thermocouple signal, together with the reference junction compensation and with some additional functions, is performed by integrated circuits such as Analog Devices AD594, or Linear Technology LTK001.

A method of reference junction voltage correction instead of compensation is also used. It is based on the measurement of the reference junction temperature (for example, by means of a semiconductor sensor), followed by a numerical calculation of the correction value. There is also a common need for the numerical correction of a result in all instruments working with thermocouples, because of the nonlinearity of these sensors. The correction is usually performed by the look-up table method described before.

Another problem encountered in thermal emf measuring circuit is caused by the noise superposing on a relatively weak dc signal transmitted over long compensating leads. In order to avoid the electromagneticaly induced voltages, the wires in the compensating leads should be twisted. The protection against the common mode noise is provided by shielding the wires and connecting the shield to a guard terminal of the instrument or transducer. In this way the current flowing through the stray capacitance between the leads and the supply power lines or induced by any source in the grounding loop is shunted and does not affect the measured voltage. The noise voltage may also be suppressed by filtering of the output signal.

A very successful method eliminating all problems due to long compensation leads is to place the whole transducer in the thermometer's head. The current developments in electronic components technology enables building compact and temperature-resistant transducers comprising all compensating and linearizing elements and delivering the standard 4–20 mA output signal. Many companies offer such a solution now, and this design seems to be very promising for all immersion-type thermocouple thermometers.

QUARTZ TEMPERATURE SENSORS

The piezoelectric properties of quartz crystal (SiO_2) are applied in the design of extremely precise, stable, and relatively cheap oscillators. The applications of those oscillators are very widespread, from counters and frequency meters to precise timers in clocks and computers. The most important requirement for all those purposes is temperature stability. It is achieved by appropriate cut of the oscillator plate from the quartz crystal. For temperature-invariant oscillators the so-called AT cut is used with the cutting plane inclined to a z axis (optical axis) of the crystal at +35°. Any other cut results in a smaller or greater dependence of the oscillator frequency on the temperature. This very property is used in quartz temperature sensors. A plate obtained by a Y cut with the inclination of −4° called HT cut has the highest value of temperature coefficient. The relation between the frequency and temperature may be written as

$$f(t) = f_0(1 + 90 \times 10^{-6}\Delta t + 60 \times 10^{-9}\Delta t^2 + 30 \times 10^{-12}\Delta t^3) \quad (19)$$

where f_0 is frequency at temperature $t = t_0$ and $\Delta t = t - t_0$. The third and the fourth terms in parentheses introduce nonlinearity, which in this particular case is a great disadvantage because a conventional frequency meter cannot be used as a temperature indicating instrument. Therefore, the LC cut, not the HT cut, is used for quartz temperature sensors. The LC cut of a quartz crystal with the cut plane inclined at +11° 10′ to the x axis and at +9° 24′ to the z axis forms an oscillator with frequency linearly depending on the temperature but with a lower sensitivity (35×10^{-6} 1/K instead of about 100×10^{-6} 1/K with HT cut).

A quartz plate with two electrodes forms a resonator which may be presented in the simplest form as an equivalent electrical circuit, as shown in Fig 13. In the circuit, C_0 is a geometrical capacity between two electrodes and L_1, C_1, and R_1 are quartz plate parameters, which depend on its mechanical properties. Two resonance frequencies exist for this circuit: Serial resonance frequency $f_S = 1/2\pi\sqrt{L_1C_1}$ and parallel reso-

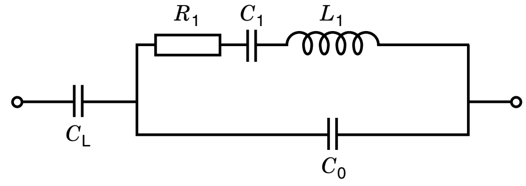


Figure 13. An equivalent circuit of a piezoelectric resonator. C_0 is a geometrical capacity between two electrodes and L_1, C_1, R_1 are quartz plate parameters which depend on its mechanical properties. C_L is a load capacity for tuning of the resonance frequency.

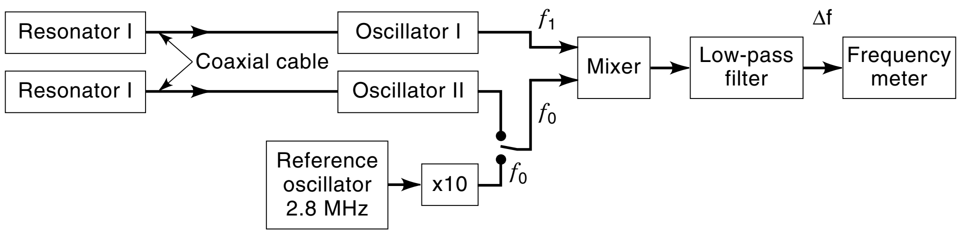


Figure 14. The differential structure of a quartz thermometer.

nance frequency $f_G = 1/2\pi\sqrt{L_1C_E}$, where $C_E = C_0C_1/C_0 + C_1$. Both frequencies have close values, because the capacities C_1 and C_E are of the same order. Using of an additional load capacity C_L, the resonance frequency of the plate may be tuned in a limited range between f_S and f_G. Two opposite surfaces of the resonator are coated with thin gold layers. The resonator is mounted in a hermetical case protecting it from atmospheric air moisture. Spring contact elements ensure a low level of mechanical damping. The oscillator frequency f_0 depends on the dimensions of the resonator. It is very convenient to adjust that frequency to such a value that the relationship between the frequency and the temperature may be obtained by simply shifting a decimal point on the frequency meter. Hence if the sensitivity coefficient α is equal to 35×10^{-6} 1/K, the condition is fulfilled for $f_0 \approx 28.6$ MHz, because in that case $f_0\alpha = 1000$ Hz/K. The tuning feature of the oscillator allows us to meet the above requirement in spite of some differences in individual plates parameters (3). The connection between the sensor and the oscillator must be performed by high-frequency coaxial cable. By the use of frequency meters with high resolution, high resolution of temperature measurements may be achieved too. Much better solution, however, is application of a differential structure of the measuring circuit (Fig. 14) where a mixer forms a low-frequency signal Δf, which corresponds to the difference between the measured temperature t and a reference temperature t_0: $\Delta f = f - f_0 = f_0\alpha(t - t_0)$. In such a state the resolution of the frequency meter may be much more effectively used. Taking as an example the temperature range from 0°C to 200°C, the value of $f_0\alpha$ equal to 1000 Hz/K, and the 61/2 digit resolution of the frequency meter (which is a common practice), a 0.1 mK temperature resolution is achieved. This extremely high resolution is a reason why quartz thermometers are commonly equipped with two sensors allowing the measurement of temperature difference. In many practical cases, it is not the absolute value of temperature but the difference of temperatures that has to be known with a great accuracy. A double quartz thermometer is an excellent instrument for this purpose. Please note that the meaning of the term "absolute value" is used here differently than "absolute temperature scale." The uncertainty of the quartz thermometers depends primarily on aging and relaxation. Single-point recalibration from time to time and avoidance rapid temperature shocks are therefore highly recommended. With these conditions met, the uncertainty of ±50 mK may be sustained for a long time.

RADIATION THERMOMETRY

The principle of radiation thermometry is the measurement of the thermal energy emitted by radiation from the object under inspection. It is not the whole energy that is measured but only its very little part, corresponding to the radiation focused on the radiation-sensitive element placed in the thermometer. The essential difference between the radiation thermometry and all other methods of temperature measurements is the lack of the thermal equilibrium between the object and the sensor. With radiation thermometry the only way of thermal energy transfer from the object to a sensor would be electromagnetic wave propagation in the range from ultra-violet radiation (0.2 μm wavelength) through visible spectrum (0.38 μm to 0.78 μm) up to far-infrared radiation (50 μm). Thermal energy transfer does not lead to equalizing of the temperatures but only excites the sensor. The excitation level, and consequently the output signal of the sensor, depends on the portion of the received energy. Proper design, together with the proper use of a radiation thermometer, ensures a strictly defined dependence of that portion of energy and the temperature of the object. All other object properties and radiation parameters such as emissivity, dimensions, the distance to the sensor, atmosphere composition and temperature, and radiation of other objects including the thermometer body and many others, either have to be kept at the same level as during the thermometer calibration or must have no influence on the sensor. These requirements seem to be more serious than in conventional thermometers since they are related to the environment in which the measurement is performed, rather than to the sensor and the instrument themselves.

In order to answer the question of how to meet the above requirements, some essential properties of thermal radiation have to be considered. The spectral density of heat energy emitted by a black body is given by Planck's law

$$M(\lambda) = C_1\lambda^{-5}\frac{1}{e^{C_2/\lambda T} - 1} \tag{20}$$

or in a simplified (but sufficient for our discussion) form of Wien's law

$$M(\lambda) = C_1\lambda^{-5}e^{-C_2/\lambda T} \tag{21}$$

In both equations, $C_1 = 37.4$ mW·μm^4/cm^2 and $C_2 = 14{,}388$ K·μm. The lower the temperature of the radiation source, the longer the wavelength of the emitted radiation (Fig. 15). The product of the temperature and the wavelength corresponding to the maximum of spectral density remains constant, according to Wien's law of displacement: $T\lambda_{max} = 2899$ K·μm. The measurement of low temperatures requires the use of the sensors and of the methods which detect the radiation in far-infrared spectrum.

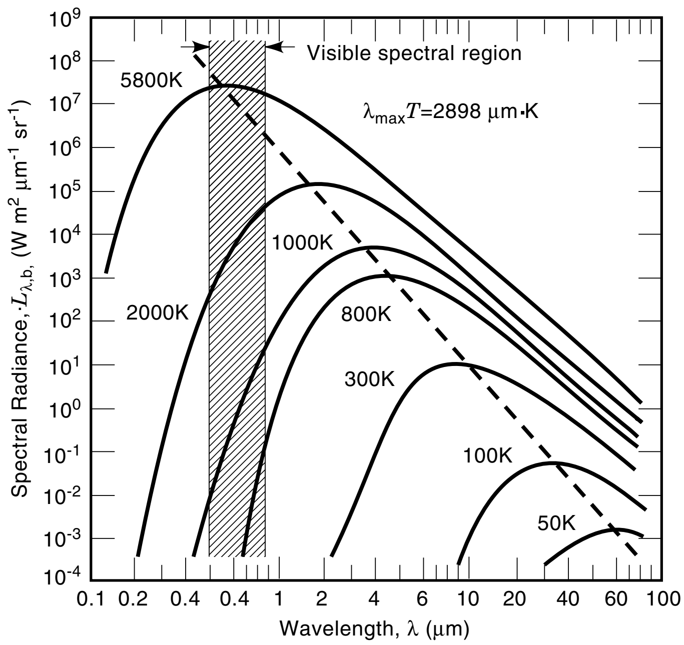


Figure 15. Spectral heat radiation density. Dotted line indicates the Wien's law. After Ref. 8. The radiance energy declines dramatically with the temperature. It is the main reason why low temperature radiation thermometers were developed many years later than high temperatures ones.

The total thermal energy emitted by a surface of a black body with the area F is an integral of the Wien's equation:

$$E_{\mathrm{BB}} = F \int_0^\infty M(\lambda)\, d\lambda \tag{22}$$

The black body is defined as an object which does not reflect thermal radiation and therefore, according to Kirchhoff's law of radiation (absorptive power = emissive power), emits the whole radiant energy relative to its temperature. The emissivity factor ϵ of a black body is equal to 1. To simulate a black body (e.g., for the calibration of radiation thermometer), a closed cavity with a relatively small aperture may be used. The inner surface of the cavity has to be specially shaped. In the radiation thermometry practice, only some objects (such as a hearth of a furnace) may be treated as black cavities. All other objects, and especially all objects in the air, have the emissivity ϵ smaller than 1, and their radiation density has to be multiplied by ϵ. The magnitude of emissivity depends on the material, surface finish (polishing, oxidization, roughening, deadening), its temperature, incident and viewed angles of heat flux direction, and polarization of radiation. Furthermore, the emissivity depends on the wavelength too. Therefore, the whole heat energy emitted by a uniform surface F observed by the radiation thermometer may be expressed as

$$E = F \int_0^\infty \epsilon(\lambda) M(\lambda)\, d\lambda \tag{23}$$

where $\epsilon(\lambda)$ is usually known with a very poor accuracy.

Next we take into consideration the properties of the atmosphere that the radiation is passing through. Application of radiation thermometers with high-temperature objects is always disturbed by the presence of smoke and dust particles absorbing the radiation. The blow of purging air is used to clear the optical path between the object and the thermometer and to protect the optical parts from contamination with dust. Nevertheless, the outer surface of the instrument optics has to be cleaned from time to time.

In measurements performed in open air the concentration of absorbing gases is considerably lower, but the distance between the object and the instrument is much greater so the absorption plays a significant role too. The contents of CO, CO_2, and water vapor in the air are most significant. The spectral distribution of the absorption caused by these gases is not uniform and shows extremely great variations. Only two bands of thermal radiation wavelength may be indicated as almost free from absorption. These are 3.5 μm to 4.5 μm (near atmospheric window) and 8 μm to 13 μm (far atmospheric window). Hot gases disturb the measurement process by their own radiation too. According to Kirchhoff's law, the spectral distribution of emissivity is the same as the distribution of absorption, and it declines in the spectral ranges of atmospheric window. For these two reasons, it is highly recommended that radiation thermometers operate within one of those windows.

Considering the spectral disturbances, two additional aspects must not be overlooked: (1) the spectral transmitance of the materials used for optical parts of the thermometers (lenses, windows, and filters) and (2) the spectral sensitivity of radiation detectors. Glass optic elements may be used in the range of visible and near-infrared radiation up to 2 μm wavelength that corresponds to measured temperatures over above 500°C. Quartz lenses enable slight widening of that range (up to 3.5 μm). For these thermometers, however, which cover a much lower temperature range, very special materials have to be used. These are ZnSe (0.6 μm to 16 μm), GaAs (1.2 μm to 12 μm), or CdTe (1.7 μm to 25 μm) and some other materials, such as Chalcogenid, KRS-5, or specially prepared ZnS. All of them (except ZnSe) are not transparent to visible light, and therefore the optical path for visual radiation must be simultaneously used to aim at the target.

Infrared Radiation Detectors

Two groups of infrared (IR) detectors are presently used in radiation thermometry. These are thermal detectors with low but spectrum-independent sensitivity and semiconductor photon detectors (IR diodes and IR photovoltaic sensors), much more sensitive but working in the limited spectral zones. Thermopiles, bolometers, and pyroelectric detectors are the thermal detectors.

Thermopiles consists of a large number (of up to 66) of thermocouples with hot junctions concentrated on a small surface and exposed to the thermal radiation flux, along with reference junctions kept at a temperature close to the ambient temperature (Fig. 16). The thermocouple materials are Bi–Sb or Ag–poly Si, with a hot junction deposited on a very thin (0.7 μm to 1 μm) silicon membrane isolated with an SiO_2 layer and with a reference junction deposited on bulk silicon material, which forms a frame around the membrane. A low thermal conductivity of the thin membrane secures

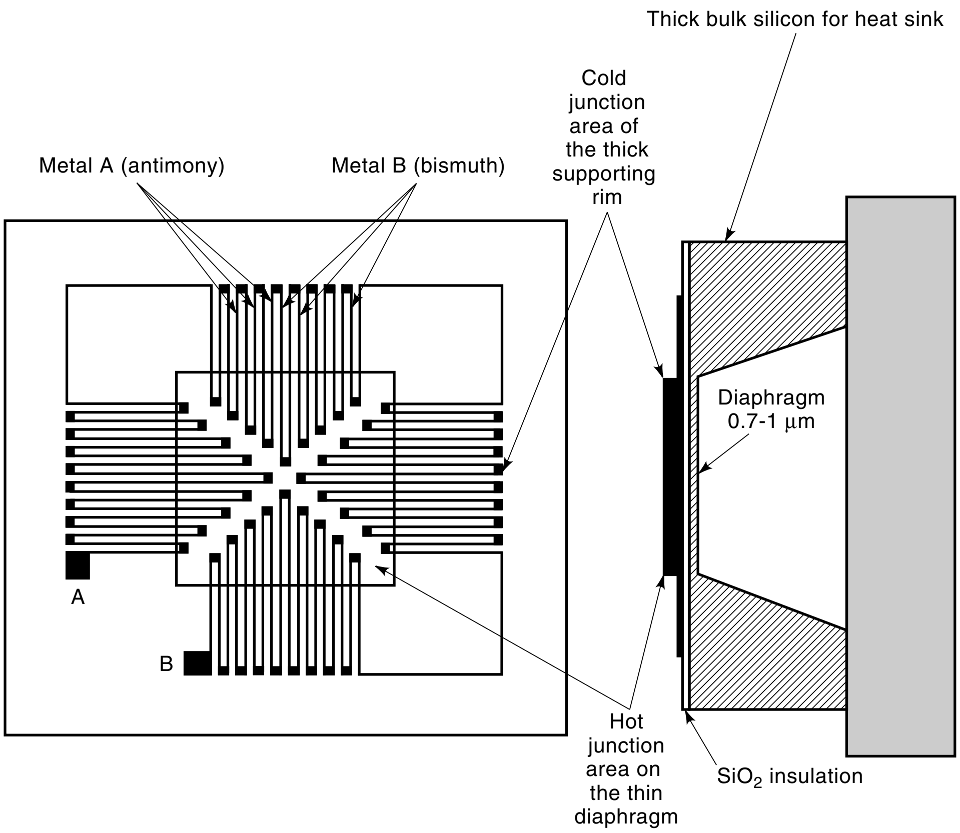


Figure 16. Thermopile manufactured in Micro Machining Technology.

proper thermal insulation between hot and reference junctions. The detector is fabricated by Micro Systems Technology (MST) and may be integrated with signal conditioning elements or even A/D converters on one chip with dimensions not exceeding a few millimeters. These thermocouples possess a very high thermoelectric power of approximately 100 μV/K, comparing with a few μV/K for conventional metal thermocouples. This ensures high sensitivity of the detector expressed in volts per watt of thermal energy:

$$S_D = \frac{V_{out}}{E} \tag{24}$$

Thermal noise is the factor limiting the possibilities of thermal energy measurement. The Johnson noise equivalent voltage is given by

$$V_N = 2\sqrt{kTR\Delta f} \tag{25}$$

where k is Boltzmann's constant, R is the detector resistance, T is the detector temperature, and Δf is the bandwidth of the associated amplifier, determined either by the chopper frequency or by the detector speed. Substituting Eq. (24) in Eq. (25), one achieves the noise equivalent power (NEP) in the form

$$\text{NEP} = E_{N\,min} = \frac{2\sqrt{kTR\Delta f}}{S_D} \tag{26}$$

The reciprocal of NEP is called detectivity $D(\lambda)$. Hence the sensitivity S_D is proportional to the square root of detector area A, and the frequency band Δf is determined by the amplifier rather than by the detector itself. The properties of the detector are better described by specific spectral detectivity $D^*(\lambda)$, defined as

$$D^*(\lambda) = D(\lambda)\sqrt{A\Delta f} \tag{27}$$

Thermopile specific spectral detectivity is usually about 10^8 $\text{cm}\cdot\text{Hz}^{1/2}\,\text{W}^{-1}$ (Fig. 17).

Bolometers with thermistors used as temperature-sensing elements have the same detectivity but are less frequently used. Pyroelectric detectors where the electrical charge evoked on the piezoelectric plate follow the temperature changes are a few times more sensitive, but they do not work at steady-state conditions and the thermal flux must be mechanically modulated by means of a rotating disk with slots or holes. Mechanical chopping enables the use of alternating-current (ac) amplifiers; this is more convenient than using direct-current (dc) ones and additionally cuts off a large portion of low-frequency noise (red noise), thus increasing the specific spectral detectivity. For this reason, the chopping technique is not only used with pyroelectric detectors.

Photon detectors are much more sensitive than thermal detectors and are mostly used when the limited range of wavelength is preferred. They are manufactured as semiconductor photodiodes or photovoltaic elements. The most sensitive Si detectors [$D^*(\lambda) = 10^{13}$ $\text{cm}\cdot\text{Hz}^{1/2}\,\text{W}^{-1}$] are suitable for

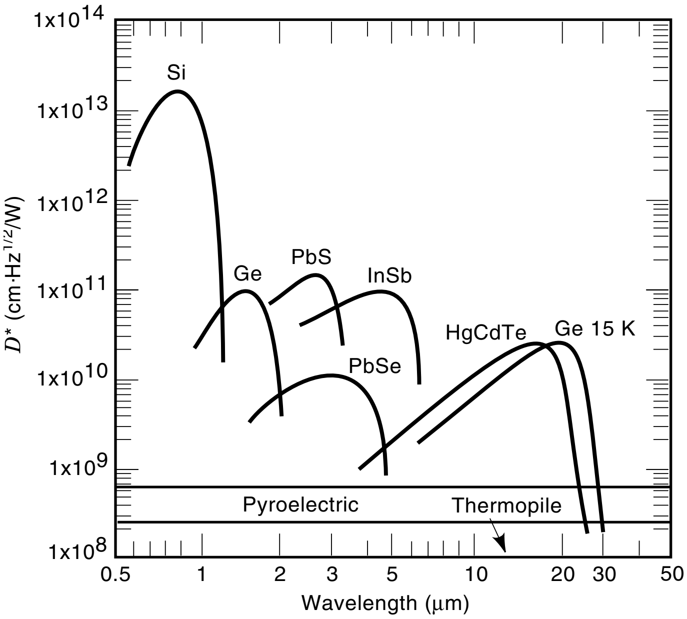


Figure 17. Specific spectral detectivity of thermal and photon infrared detectors. The design of low temperature radiation thermometers is more complicated not only because of the lower radiance energy but by the lower sensitivity of the photon detectors working in the far IR region.

visual spectra only; PbS, InAs, and InSb detectors [$D^*(\lambda) = 10^{11}$ cm $\cdot$ Hz$^{1/2}$ W^{-1}] cover the range up to 3 μm to 5 μm; and only an Hg–Cd–Te detector may be used up to the 20 μm range, achieving its maximum detectivity [$D^*(\lambda) = 5 \times 10^{10}$ cm $\cdot$ Hz$^{1/2}$ W^{-1}] in the far-infrared radiation region. Cooling of detectors in order to improve their detectivity by noise reduction results sometimes in shifting of the spectral characteristics toward longer wavelengths. This effect is observed in particular for Ge detectors. Therefore, in comparing the spectral detectivities of various detectors, precise specification of their operating temperatures must be taken into account (8). Detector cooling is frequently performed by single-stage or multistage Peltier coolers, which are compact and easy to use. The only problem to solve in their design is providing quick dissipation of the heat to enable the continuous cooling of the detector. Stirling coolers which require pumps are seldom used. It is quite possible, however, that in the near future, micropumps for that purpose will be produced by Micro Machining Technology.

Wide-Band Radiation Thermometers

Conceptually the simplest method of radiation thermometry is to detect the thermal energy emitted by an object toward a sensor regardless of its spectral distribution. This energy depends on the temperature according to the Stefan–Boltzmann law:

$$E = \epsilon_0 \sigma T^4 - \epsilon_t \sigma T_t^4 \qquad (28)$$

where σ is the Stefan–Boltzman constant, T and T_t are the object and thermometer temperatures, respectively, and ϵ_0 and ϵ_t are the emissivities of the object and the thermometer, respectively. The exponent 4 in Eq. (28) makes the calibration curve nonlinear and increases the uncertainty at the lower range of measured temperatures where the sensitivity is also low. This form of relationship, however, decreases the influence of the object emissivity ϵ_0. The thermometer calibrated with the use of a black body ($\epsilon_0 = 1$) always indicates lower temperature T_{in} than is actually existent at the observed surface with the emitance ϵ_0. By the comparision of equal states of the detector output signals during calibration and measurement, and assuming that all other factors are the same, one obtains

$$T = \frac{1}{4\sqrt{\epsilon_0}} T_{in} \qquad (29)$$

[The second term in Eq. (28) has been neglected, which is allowed in case of higher object temperatures.] For example, taking $\epsilon_0 = 0.5$, the real temperature is not twice the indicated temperature but only 19% higher, as expressed in kelvins. Nevertheless, such a great difference is not negligible and has to be corrected. The simplest and the most common way is to adjust the emissivity value in the instrument which calculates and introduces the appropriate result correction. It would be a good method if the values of ϵ_0 were known with sufficient accuracy, but usually this does not take place. Furthermore, ϵ_0 is used here in the meaning of average emissivity over the whole spectral range. It has been shown before that for many reasons the heat flux incident at the sensor is spectrally disturbed, and hence the averaging should be weighted with regard to all these disturbances. Calculations become complicated to such a degree that their practical usefulness becomes questionable. The only way is then to calibrate the thermometer at the same environmental conditions as its operational conditions. The calibration is more effective when influence variables are stable. Higher stability may be achieved by narrowing the wavelength band. For this reason the class of wide-band thermometers includes not only total radiation thermometers but also thermometers with intentionally limited spectral bands. Total radiation thermometers are commonly equipped with thermal detectors and are used for measurements inside closed cavities as tanks or ovens where the emissivity is equal to 1 and the distance to the target is relatively low and stable. For applications in open air the thermometers with narrowed band and adjustable emissivity are used. They work in the first atmospheric window (for higher temperatures) or in the second atmospheric window (for lower temperatures). For lower temperature ranges the compensation of ambient temperature [T_t in Eq. (28)] is commonly performed. Some of the devices are referred to as "near touch" radiation thermometers, in which an infrared detector is placed immediately over the surface, and the mirror optic is used to focus the radiant energy at the detector.

The majority of wide-band radiation thermometers are produced as hand-held or tripod-based instruments, commonly equipped with optical or laser aiming facility. Because of the progress in noiseless amplification of weak electric signals, the lowest temperature range of the discussed instruments has been pushed down to the level of -50°C or even -100°C. It is no longer true that those radiation thermometers are destined for high temperatures only, as it was in the past. It still remains true, however, that accurate measurements may be obtained only in the case of sufficiently stable conditions. The responsibility for ensuring repeatable conditions is with the user. The accuracy of the measurement depends rather on his skills and experience than on the quality of an instrument.

Monochromatic Radiation Thermometers

The name for the device derives from the times when radiation thermometers were used in the visual band only and indicates that a very narrow spectral band $\Delta\lambda$ of emitted heat flux is used for measurement purposes. In optical pyrometers the narrow band was being filtered using colored windows. Now the infrared interference filters are used for that purpose. Interference filters consist of a number of thin transparent layers deposited on a substrate. The optical properties and the thicknesses of the layers are specially matched to transmit through only a desired wavelength band $\Delta\lambda$ with the middle wavelength equal to λ_1, as well as to reflect all higher and lower band frequencies. The filter remains cool because the undesired heat energy is reflected and not absorbed. The filtered bands are matched first of all with respect to the temperature range of the thermometer, but also with respect to the atmospheric windows. The part of energy emitted in wavelength band $\Delta\lambda$ may be described as

$$E_{\lambda_1} = \epsilon_{\lambda_1} C_1 \lambda^{-5} e^{-C_2/\lambda_1 T} \Delta\lambda \tag{30}$$

where ϵ_{λ_1} is the emissivity at wavelength λ_1. The volume of energy incident at the detector is much lower than that in wide-band thermometers, but narrow-band photon detectors with much higher detectivity may be used in this case. Assuming the same calibration procedure as described before for wide-band thermometers, one obtains the relationship between the real temperature T and indicated temperature T_{in} in the form of

$$\frac{1}{T} = \frac{1}{T_{\text{in}}} + \frac{\lambda_1}{C_2} \ln \epsilon_{\lambda_1} \tag{31}$$

and for the small differences between T and T_{in} in the form of

$$T \approx T_{\text{in}} \left(1 - \frac{T_{\text{in}} \lambda_1}{C_2} \ln \epsilon_{\lambda_1} \right) \tag{32}$$

The differences between real and indicated temperatures are lower than in wide-band thermometers [Eq. (29)]. However, it is more important that the value of ϵ_λ be better defined and more stable than an average emissivity ϵ_0 which has been used for calculations in the case of wide-band thermometers. Furthermore, all disturbances such as atmospheric absorption, hot gas radiation, contamination of optical parts by dust particles, and variations in detector properties have no influence on the output signal so far, because they do not concern directly the filtered band $\Delta\lambda$. The maintenance of the monochromatic thermometers is therefore simpler and their stability is much better, but the problem of emissivity correction remains.

Radiation Ratio Thermometers

The idea of radiation ratio thermometers is based on simultaneous measurement of radiation in two narrow wavelength bands followed by calculating the temperature from the ratio of the results. Both bands have to be chosen on the "increasing" part of the Wien's spectral energy distribution curve (see Fig. 15), and they differ for each temperature range. Denoting the energy ratio at wavelength λ_2 and λ_1 by R, one obtains

$$T = \frac{\lambda_2 - \lambda_1}{\lambda_2 \lambda_1} C_2 \left[\ln R \left(\frac{\lambda_2}{\lambda_1} \right)^5 \right]^{-1} \tag{33}$$

for all gray bodies independent from their emissivity. For nongray bodies, like all metals, in which the emissivity is a function of wavelength, a very small correction is needed:

$$T \approx T_{\text{in}} \left(1 - T_{\text{in}} \frac{\lambda_2 \lambda_1}{C_2(\lambda_2 - \lambda_1)} \ln \frac{\epsilon_1}{\epsilon_2} \right) \tag{34}$$

where ϵ_1 and ϵ_2 are emissivities for wavelength λ_1 and λ_2, respectively. The difference between ϵ_1 and ϵ_2 is very low, even in metals, which causes, according to Eq. (34), a very little difference between T and T_{in}. The ratio thermometers may be considered emissivity-independent instruments. The design of radiation ratio thermometers is much more complicated than other radiation thermometers, and special requirements for low chromatance optic elements have to be fulfilled. Therefore this kind of instruments is rather expensive.

In summary, it is worthwhile to point out that in the last decade an intensive progress in radiation thermometry has been achieved. The basic ideas remain unchanged, an optical pyrometer with disappearing filament remains a prototype of narrow band thermometers, and a two-color pyrometer is an ancestor of the ratio thermometers, but the progress in detector technology, the introduction of interference filters, the possibilities of low noise signal amplification, and numerical result corrections make the use of these instruments simpler and allow moving the operational temperature range toward lower temperatures. The use of fiber optics to transmit the thermal energy from hardly accessible places or through the areas with nuclear radiation or strong electromagnetic fields creates the next step of development which cannot be underestimated. Up to now the optical fibers work at short wavelengths only (up to 2.5 μm), but with low distances the temperatures as low as 100°C may be measured; further progress in that field is expected.

ERRORS AND UNCERTAINTIES

First of all we have to distinguish between errors and uncertainties. According to its definition, an error is a difference between a true value of a measurand and a result of measurement. Errors always have certain values and a sign, but they remain unknown. In order to determine an error, we can try to calculate it or to measure it. Errors are measured in the calibration process. A determined error added to the result with the opposite sign as a correction makes the result free from that particular error. Many errors exist which are very hard to determine, even if their sources are theoretically known. In radiation thermometry we know exactly how the emissivity influences the result, but we do not know the particular value of the target emissivity. We are only able to estimate the range of results which is affected by more or less unknown sources of errors. It is a range of uncertainty, and the most probable value of the result is commonly (but not always) placed in the middle of this range. Therefore, uncertainty is denoted as $\pm\Delta t$, where Δt is half of the estimated range.

All predictable errors in sensors or transducers are normally accounted by the producer by means of compensations and corrections. The accuracy data which are found in transducer specifications or in standards are uncertainty limits. ISO Guide For Expression of Uncertainties (10) distinguishes two kinds of uncertainties: type A and type B. Type A uncertainties are easy to detect and estimate by repetition of measurements performed in the same conditions and then by calculating the variancy of the results (classical random uncertainties). Type A uncertainties dominate in high accuracy measurements. Random effects observed in industrial measurements are caused by measurand instability and environmental variations rather than by measuring instruments themselves. Type B uncertainties are those which remain constant by repetition of measurements. They may be caused by residuals remaining after nonlinearity compensation hysteresis effects, or they may be caused by the influence of variables such as pressure, nuclear radiation, electromagnetic fields, humidity, dust, lead temperature variations, ambient temperature variations, velocity of the medium under measurement, aging, and many others. Type B uncertainties dominate in medium accuracy thermometers. Estimation of type B uncertainties needs some investigations performed either by the manufacturer of the thermometer or by the user, and some amount of experience too. It is a more complicated task than a type A estimation but the uncertainty data given in thermometer specification may be adequately used here. The calibration of a particular sensor or transducer transforms some uncertainties into errors, allowing us to account for them in a form of correction. All the rest remains as a part of a type B uncertainty. Laboratory calibration of temperature sensors is expensive, but calibration performed at the site of thermometer installation is more expensive and sometimes even impossible. On the other hand, it is impossible to restore all measurement conditions during laboratory calibration, and thus the improvement of accuracy by the recalibration is always limited.

Two remarks dealing with specification sheets ought to be pointed out here. In thermometry the uncertainty data referred to as "% of reading" or "% of full scale" (%FS) have no sense because temperature scales have no physical zero, and ±2% of 273 K gives ±6 K but ±2% of 0°C gives ±0°C. All uncertainties have to be referred to in temperature units.

The next remark is concerned with resolution. Resolution is not a measure of accuracy and normally has nothing to do with uncertainty. It is only the ability to indicate small differences in temperature. High resolution may sometimes be very useful, but we ought to have in our minds that by the use of numerical result display the resolution is commonly 10 times better than the uncertainty involved.

In the sensor–transducer pair the uncertainty of sensor usually dominates. Excluding standards from our considerations, it may be stated that of all temperature sensors, metal resistance thermometers are the ones with the lowest uncertainty. In the temperature range of −50°C to +150°C, quartz thermometers are much more accurate and stable than all semiconductor sensors (the fact is reflected in their price). Traditional NTC thermistors seem to be less attractive in comparison with modern linear semiconductor sensors and more and more cheap integrated sensors which have the advantage of standarized calibrated output signal. However, the uncertainty of all semiconductor sensors is not better than ±0.5°C to 1°C. Thermocouples are the less accurate sensors. Their uncertainty is rapidly increasing, with the measured temperature reaching up to ±10 K at temperatures above 1000°C. This is a much higher value than for radiation thermometers where the uncertainty is rather optimistically referred to as ±1 K to 2 K. The advantage of thermocouple sensors is their lower cost, but the costs of transducers are comparable now. Some radiation sensors are equipped with such a signal conditioning system that their output signal fits to conventional thermocouple transducers. The thermocouples, however, are the unique sensors which have to be immersed in the high-temperature medium.

The discussion presented above deals with the instrument uncertainty, but more serious sources of uncertainty are related to the methods of temperature measurement. Generally, the problem is in the difference between the temperature of a sensor and the temperature which ought to be measured. This problem will be considered separately for steady-state conditions and for dynamic conditions.

Steady-State Errors of Temperature Measurement

In order to provide the same temperature of an object and of a sensor, the conditions for easy heat transfer from the object to the sensor and simultaneously for the difficult heat transfer from the sensor to the ambient environment should be created. For immersion-type sensors the length of the immersed part should be as large as possible because the heat runs away from the sensor through the protective tube, and a higher temperature gradient along the shield facilitates the transfer. Thermal insulation of the tank or pipe line where the temperature is measured lowers the gradient, and therefore the error too. The problem is much more serious in the case of gas media because of their low heat transmission coefficient and the possibility of heat escape to the pipe walls by radiation. The problem weight increases with the measured temperature, not only because of the higher temperature gradient but also due to the need for increasing shield thickness and for better thermal insulation of the sensor by protective ceramics.

The measurement of surface temperature is the best case for obtaining a false result. The sources of errors are the same, but the available remedies are very limited. The typical situation is schematically presented in Fig. 18. The sensor ought to have the best thermal contact with the surface but simultaneously should be insulated from the environment. The heat is accumulated in the silver plate with high thermal conductivity in order to equalize the surface and sensor temperatures. The air gap between the surface and the plate ought to be filled with silicon gel. The connection leads act as radiators and therefore run along the surface to a distance far enough to avoid the surface temperature disturbance near the sensor. The thermal insulation provides protection from the temperature decrease at the point of measurement, but perhaps it may cause a local increase of the temperature especially when the surface was intensively cooled. Touching of the surface by the sensor involves thermal effects which are different in each particular case and practically unpredict-

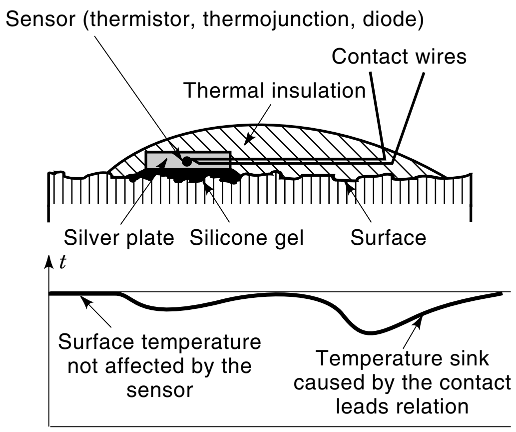


Figure 18. The measurement of surface temperature. The heat is accumulated in the silver plate with high thermal conductivity in order to equalize the surface and sensor temperatures. The air gap between the surface and the plate ought to be filled with silicon gel. The connection leads act as radiators and therefore run along the surface to a distance far enough to avoid the surface temperature disturbance near the sensor.

able. From this point of view, the advantage of radiation thermometry for surface temperature measurements is evident.

Dynamic Errors

Dynamic errors are caused by the thermal inertia of the sensors and become important while transient temperatures have to be measured. The dynamic properties of a sensor are described by the response time of the output signal after a rapid change of sensor temperature, or by the time constant. The response time is usually defined as the time elapsing between 10% and 90% of the output signal change, but other definitions are also used. The response time depends on the sensor properties such as its material, shape, and dimensions, but depends first of all on the environment surrounding the sensor, characterized by the heat transmission coefficient. That coefficient is a few times greater in liquids than in gases, and it increases with the velocity of the medium. With any comparison of the sensor dynamic properties, exactly the same conditions have to be secured.

Assuming the linearity of the thermometer the idea of Laplace transformation and transfer function may be used for describing the thermometer dynamic properties. The simplest model of the dynamic behavior of a sensor may be presented in a form of the first-order transfer function:

$$K(s) = \frac{T_T(s)}{T_0(s)} = \frac{1}{1 + s\tau_1} \tag{35}$$

where $T_T(s)$ is the Laplace transformation of thermometer temperature, $T_O(s)$ is the Laplace transformation of the object temperature, s is the Laplace operator and τ_1 is a time constant. The model is valid for nonembedded sensors only, which are rather seldom used. Two other models are also used. The second-order model

$$K_{\mathrm{II}}(s) = \frac{1}{(1 + s\tau_1)(1 + s\tau_2)} \tag{36}$$

accounts for the delay of the output signal and better describes the thermometer with the shielded sensors. A model with the differential action

$$K_{\mathrm{III}}(s) = \frac{1 + s\tau_{\mathrm{D}}}{(1 + s\tau_1)(1 + \tau_2)} \tag{37}$$

may in turn be used for surface temperature thermometers.

All those models may be treated as rough approximations because in fact the dynamic properties of temperature sensors are nonlinear. The experiment has shown that even for a nonembedded thermocouple sensor the time constant at 400°C has been three times larger than at that 1200°C (4). Also the warming curves and quenching curves always differ from one another.

For dynamically nonlinear sensors, it is not so easy to transform the results from one operating condition to other. One of the methods for estimation of dynamic behaviors of a sensor under its operating conditions uses an intentionally generated self-heating impulse in order to record the thermometer answer and then to calculate its dynamic parameters.

The dynamic behavior of the radiation thermometers depends on the dynamic properties of the infrared sensors which are rather slow, with the response time varying from 0.2 s to 2 s, and which are dynamically nonlinear too.

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