

OVERVIEW OF BASIC TEMPERATURE MEASUREMENT METHODS AND TECHNIQUES

Temperature is one of the basic quantities characterising the physical state of matter. Next to pressure, the temperature value is a measure of the "quality" of matter. For this reason, it is used, among other things, as one of the main parameters controlling the correct operation of thermal machines and the progress of individual process steps in industry.

As a rule, each temperature measurement requires an individual solution and is an optimisation task due to predefined measurement conditions, technical feasibility and costs.

Correctly measuring temperature requires knowledge of heat transfer, temperature measurement methods and techniques, and types of thermometers and their properties. Basic knowledge of thermometry is given below. Heat transfer issues are only covered to the extent necessary to determine temperature measurement errors.

1. TEMPERATURE AND TEMPERATURE SCALE

The term 'temperature' is not an obvious concept and requires a strict definition. In the literature, temperature is often combined with an adjective, for example: empirical temperature, absolute temperature, total temperature, static temperature, rotational temperature, vibrational temperature, translational temperature, electron temperature, radiation temperature, etc.

The modern engineer, living in the age of the atom, computers, and space flight, is required to freely identify the types of temperature in specific situations, even in cases where an adjective is missing when defining temperature. The listed temperature types are defined below.

Empirical temperature - is a thermodynamic quantity that characterises the thermodynamic equilibrium state of a macroscopic system. It is the same for all parts of an isolated system in thermodynamic equilibrium. The following theorem is also true: for two homogeneous thermal systems to be in diathermic equilibrium, it is necessary and sufficient that their empirical temperatures are equal. The relation allowing the empirical temperature to be expressed by other parameters is called the equation of state. For a perfect gas, it can be of the form $\Theta = pV/mR$, $\Theta = \ln pV/mR$ or more complicated. For liquids, no practical equation of state has been formulated. The Van der Waals equation only allows a qualitative assessment of the state of a liquid below the critical point. For a solid, the equation of state expresses the dependence of the modulus of elasticity in Hooke's law on temperature and pressure. For example, the dependence of Young's modulus on these quantities $E = f(\Theta, p)$. The equation of state for radiation is Planck's law. The form of the equation of state depends on the temperature scale adopted, i.e. the choice of function Θ . Once we have established the equation of state for one system, we can determine Θ for that system from measurements of other parameters entering the equation of state.

Absolute temperature - is the temperature expressed on a scale, whose zero is 273.16 K lower than the temperature of the triple point of water. The parameters of the triple point of a single-component substance (Fig. 2) are invariant.

Static temperature - is the temperature of a fluid moving at speed w , measured by an observer moving in the fluid at the same speed and in the same direction. The observer is stationary relative to the fluid. A practical way of measuring the static temperature T is shown in Fig. 1.

Total temperature - is the temperature of a fluid moving at velocity W , measured immediately after deceleration to velocity $w = 0$. The total temperature is measured assuming that the volume of the fluid under test is an adiabatic-isentropic system and no effective work is observed in the fluid. When we denote by T the static temperature of the fluid and by c , its specific heat, then the total temperature ($T_c = T_0$) is equal to

$$T_c = T_0 = T + \frac{w^2}{2 \cdot c_p} \quad (1)$$

It follows from relation (1) that the total temperature is higher than the static temperature ($w=0$) by the increment ΔT caused by the change of the kinetic energy of the fluid ($m \cdot w^2/2$) into heat ($m \cdot c_p \cdot \Delta T$) when it decelerates to a velocity of zero. A practical way of measuring the total temperature is shown in Fig.1.

For example: air ($c_p \cong 1000 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$) with a static temperature $T = 300 \text{ K}$, moving at 3600 km/h has a total temperature equal to

$$T_c = T_0 = T + \frac{w^2}{2 \cdot c_p} = 300\text{K} + \frac{\left(1000 \frac{\text{m}}{\text{s}}\right)^2}{2 \cdot 1000 \frac{\text{J}}{\text{kg} \cdot \text{K}}} = 300\text{K} + 500\text{K} = 800\text{K}$$

and this temperature should be substituted into Newton's law

$$\dot{q} = \alpha \cdot (T_p - T_{sc}) \quad (2)$$

in place of $T_p = T_c = 800\text{K}$ when calculating the convective heat flux density \dot{q} transferred between a fluid at temperature T_p and a wall perpendicular to the direction of flow at temperature T_{sc} . If the wall were positioned parallel to the flow direction, then $T_p = T = 300 \text{ K}$ should be substituted in (2). For other configurations of flow direction and wall position, the temperature T_p , is calculated from Eq. (1), substituting instead w the value of its component normal to the wall surface.

Radiant temperature - a conventional quantity that characterises the total panchromatic intensity of the radiation flux of a given body. By measuring the total panchromatic intensity of the radiation flux of a body, we treat it as a black body. We calculate the radiation temperature of a given body from the Stefan - Boltzman law.

Electron and lattice temperatures - they are the same in thermodynamic equilibrium, whereas they are different in non-equilibrium states. This situation occurs when the time constant of reaching equilibrium of the body's electron sub-system is much smaller than the time constant of establishing equilibrium between the electrons and the lattice. In practice, such effects are observed in metals and semiconductors subjected to impulsive changes in the boundary condition (e.g. a laser shot into a surface).

Rotational, vibrational, translational temperatures - these are the conventional temperatures associated with particular degrees of freedom of a particle, e.g. in a gas system.

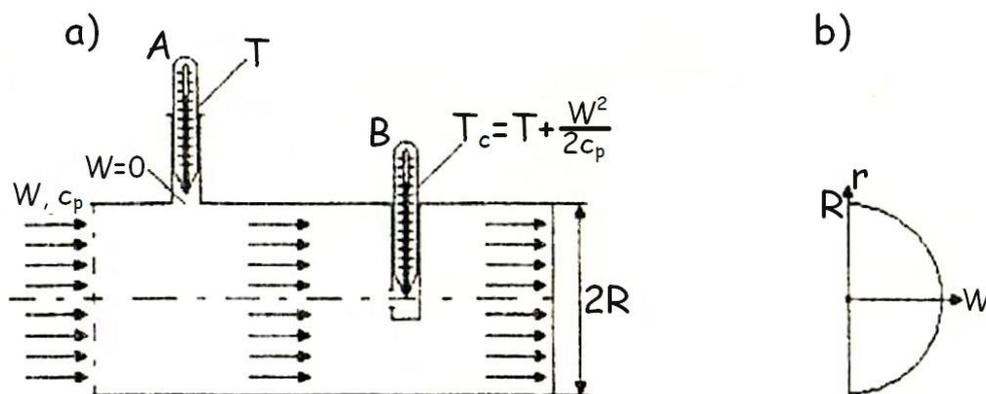
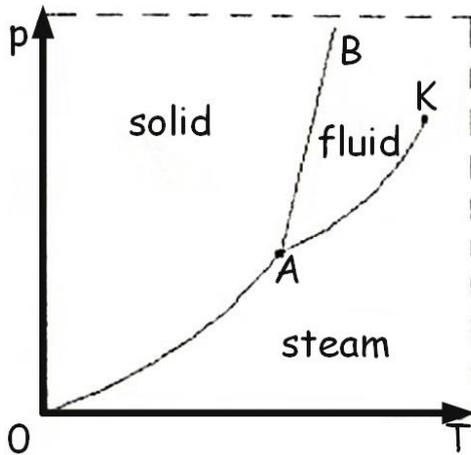


Fig. 1 Figure illustrating: a) how to measure the static (thermometer A) and total (thermometer B) temperature of a fluid; b) the distribution of fluid velocity as a function of radius.



Substance	Triple-point A		Triple-point A	
	p[MPa]	T[K]	p[MPa]	T[K]
CO ₂	0,518	216,65	7,38	304,15
H ₂ O	610,7	273,16	22,13	647,30

Fig. 2 State diagram of single-component systems: OA - sublimation curve; AK - boiling curve; AB - melting curve; A - triple points (solid, liquid and gas equilibrium); K - critical points (end of liquid-vapour equilibrium).

Observations of changes in the volume of gases and liquids under the influence of temperature were the basis for the first definitions of the temperature scale. The next step in this direction was the adoption, by Resolution of the International Committee of Weights and Measures in Paris, of hydrogen as a thermometric body. Changes in the pressure of hydrogen at constant volume were the basis for the definition of a new temperature scale. The base interval of this scale was the interval between the equilibrium temperature of the 'water-ice' system and the 'water-vapour' system at boiling point at a pressure of one physical atmosphere.

The interval between the temperature fixed points ('water-ice', 'water-vapour') was divided into 100 equal parts, assigning a numerical value of 0 to the first part. This scale was called the Celsius rock. This situation lasted until 1948. Subsequent resolutions of international organisations such as the General Conference of Weights and Measures and the International Committee on Weights and Measures then established the principles of the latest temperature scale, called the International Practical Temperature Scale of 1968, abbreviated IPTS-68. This scale was then extended from 630.74°C to 1064.43°C leading to the creation of the Extended Practical Temperature Steel (EPT-76). IPTS-68 and EPT-76 were replaced by the 1990 International Temperature Scale, also known as ITS-90. The differences between ITS-90 and ITS-68 values have no practical impact on industrial measurements.

The ITS-90 scale is defined by a series of temperature fixed points (Table 1) which define the basic standards and give a series of interpolation equations to calculate the temperature between the fixed points. Above the melting point of silver, Planck's law is used to measure temperature. The ITS-90 is characterised by representing the thermodynamic scale with a measurement uncertainty of ± 2 mK for the range from 1 K to 273 K, increasing to ± 7 mK at 900 K. The unit of the ITS - 90 is the kelvin (symbol K). One kelvin is defined as $1/273.16$ of the thermodynamic temperature of the triple point of water.

ITS-90 also defines the Celsius scale based on the thermodynamic scale, where there is a relationship between the temperature expressed in degrees Celsius ($^{\circ}\text{C}$) and the thermodynamic temperature in Kelvin:

$$t[^{\circ}\text{C}] = T[\text{K}] - 273.15 \quad (3)$$

This means that the position of the 0°C point has not changed, i.e. it corresponds to the equilibrium point of liquid and solid water as before. On the Celsius scale, the temperature of the triple point of water is 0.01°C .

The reconstruction of the temperature between fixed points for ITS-90 (Table 1) is carried out as follows:

1. in the range 0.65 K to 5 K using the temperature-pressure relationship for ^3He and ^4He vapours,

2. in the range from 3 K to 24.5561 K (triple neon point), a gas thermometer filled with helium (^3He or ^4He) of constant volume is used. Calibration is carried out at three defined fixed points according to a procedure dedicated to this thermometer,
3. in the range from 13.8033 K (hydrogen triple point) to 961.78°C (silver freezing point), the standard instrument for temperature measurement is a resistance platinum thermometer. Calibration is carried out at defined fixed points according to a procedure dedicated to this thermometer. For correct calibration, the platinum resistance thermometer must be made from pure, stress-free and annealed platinum. For the range from 13.8033 K to 273.16 K (the triple point of water), calibration is performed through the following triple points: hydrogen (13.8033 K), neon (24.5561 K), oxygen (54.3584 K), argon (83.8058 K), mercury (234.3156 K) and water (273.16 K). In addition, a gas thermometer measurement for temperatures of 17 K and 20.3 K is used for calibration. For the 0°C to 961.78°C range, calibrations are performed for the triple point of water and the freezing points of tin (231.928 °C), zinc (419.527°C), aluminium (660.323°C) and silver (961.78°C),
4. above the freezing/melting point of silver, the temperature is defined according to Planck's law. In order to define the temperature, the relationship is used:

$$\frac{L_{\lambda}(T)}{L_{\lambda}(T_x)} = \frac{\exp\left(\frac{c_2}{\lambda T}\right) - 1}{\exp\left(\frac{c_2}{\lambda T_x}\right) - 1} \quad (4)$$

where T_x is the freezing point of silver (Ag), gold (Au) or copper (Cu). $L_{\lambda}(T)$ and $L_{\lambda}(T_x)$ denote the monochromatic flux densities emitted by the blackbody at T and at the solidification temperature T_x (Ag, Au, or Cu), respectively, and the constant $c_2=14388\text{um}\cdot\text{K}$.

Thermometers scaled in Celsius, Kelvin, Fahrenheit and Rankin can be found in the industrial pact, and Table 2 presents the basic data on these temperature scales in relation to the Celsius scale.

In 2000, an additional temperature scale was introduced for measurements at very low temperatures (PLTS-2000) ranging from 0 K to 1 K. In practice, a definition of the temperature scale in accordance with ITS - 90 is used for engineering measurements.

Table 1 Definitive fixed points of the ITS-90 International Temperature Scale.

No.	Types of point (equilibrium)	Temperature [K]	Temperature [°C]
1.	Vapour-pressure point of helium	3 to 5	-270,15 to -268,19
2.	Hydrogen triple point	13,81	-259,34
3.	Equilibrium point of liquid phase and hydrogen vapour at 33330.6 Pa	17,042	-256,108
4.	Triple neon point	24,5561	-248,5939
5.	Oxygen triple point	54,3584	-218,7916
6.	Argon triple point	83,8058	-189,3442
7.	Triple point of mercury	234,3156	-38,8344
8.	Triple water point	273,16	0,01
9.	Gallium melting point	302,9146	29,7646
10.	Indium freezing point	429,7485	156,5985
11.	Tin freezing point	505,078	231,928
12.	Zinc freezing point	692,667	419,527
13.	Aluminium freezing point	933,473	660,323
14.	Freezing point of silver	123,94	961,78
15.	The freezing point of gold	1337,33	1064,18
16.	Copper freezing point	1357,77	1084,62

*) under pressure $p_n = 101325 \text{ Pa}$;

Table 2 Basic data on temperature scales.

Type of thermometer point	Celsius scale	Kelvin scale	Fahrenheit scale	Rankina scale
Absolute zero	273,15°C	0 K	-459,67°F	0°R
Solidification point of water (pn = 101325 Pa)	0°C	273,15 K	32°F	491,67°R
Boiling point of water (pn = 101325 Pa)	100°C	373.15 K	212°F	671,67°R
Translational Patterns:	$T[K] = t[°C] + 273,15$ $t[°C] = \frac{5}{9}(t[°F] - 32)$ $t[°C] = t[°R] - 459,6$			

2. GENERAL COMMENTS ON TEMPERATURE MEASUREMENT METHODS AND TECHNIQUE

Methods for measuring the temperature of solids, liquids and gases can be divided into contact and non-contact.

Contact temperature measurement methods are characterised by the fact that the sensor is in direct contact with the test medium whose temperature needs to be determined (solid, liquid, gas).

Non-contact temperature measurement methods are characterised by the fact that the medium whose temperature is to be determined is not in contact with the temperature sensor, and that the sensor reacts to the value of the intensity of the temperature radiation emitted by the medium under test. The value of this radiation is dependent on the temperature of the medium.

Another division of temperature measurement methods is based on the distinction of the type of effect subject to change with a change in temperature and related to the temperature sensor or the medium under test. For example, if temperature is measured with a thermocouple (sensor) then the thermoelectric voltage of the sensor is dependent on the temperature. If temperature is measured with a thermistor then its resistance changes with temperature.

A further division of measurement methods is made according to the movement of the body whose temperature we are determining (body in motion or at rest). We can also divide measurement methods into those concerning time-fixed temperature and transient temperature.

The possibilities of the various, most popular methods of measuring the surface temperature of solids, taking into account the division outlined above, are summarised and listed in Table 3, while Table 4 presents the basic sensors most commonly used to measure temperature, their principle of operation and range of applicability.

A method related to the use of the thermoelectric effect. It involves measuring the thermoelectric force TEF (thermoelectric voltage) that is generated between two different metals with junctions at different temperatures. The differential STE changes as the temperature of the two junctions changes.

A method related to the use of the change in electrical resistance of a material as a function of temperature. It involves measuring the electrical resistance of a temperature sensor, placed at a location (point, surface, volume), whose temperature needs to be determined.

A method related to the use of the variation of thermal radiation flux density from a surface as a function of temperature. It involves measuring the intensity of total radiation, monochromatic radiation, a specific range or ranges of radiation. The main advantage of this method is that the measurement is non-contact. This avoids the calculation of error values associated with the disruption of the temperature field of the object under test by the sensor in situ. The object whose surface temperature is being determined can vary in position relative to the detector from single centimetres to several metres. In contrast, the biggest disadvantage is that the measured temperature is usually subject to an error that depends on the emissivity value of the surface under test. Generally, pyrometers are calibrated on the basis of blackbody

emissivity ($\varepsilon = 1$), while the surface of the object under test usually has $\varepsilon < 1$. For this reason, the temperature recorded by a meter calibrated in this way is underestimated. Emissivity is a thermophysical parameter whose value under real conditions can vary over a wide range. Its value depends on the temperature value, the intensity of surface corrosion, surface cleanliness (e.g. presence of lubricant), etc. Sometimes, in order to eliminate the measurement error associated with the influence of an unknown or known approximation of the emissivity of the surface, it is advisable to cover the surface with carbon black. Covering with carbon black eliminates the error associated with the influence of the unknown emissivity value, but, on the other hand, causes a change in the heat flux density of the transmitted radiation with the environment, so that the actual body surface temperature will in this case be lower than before the carbon black covering. When only process temperature control is involved, i.e. maintaining a constant temperature, knowledge of emissivity is not relevant.

Table 3: Methods and techniques used to measure the surface temperature of solids

Physical quantity subject to a change in temperature and measurement technique	Temperature measuring range [K]	Accuracy [%]
THERMOELECTRIC FORCE (TEF)		
- two wires made of different metals	70÷1900	1
- one wire + body as second material		
- thin layer of metal (1 material) applied to body surface (2 material)		
- two bodies of different metals in contact with each other		
ELECTRICAL RESISTANCE		
- three-dimensional coil	30÷870	1
- two-dimensional grid, coil or tape	30÷870	1
- one-dimensional cable	30÷870	1
- thermistor (spherical, etc.)	250÷870	1
THERMAL RADIATION		
- comparison of the optical brightness of a heated reference with the surface of the object	320÷2270	1÷2
- measurement of total radiation or in-band	290÷4270	1÷2
- measurement of emitted infrared radiation	>370	1÷2
- reflectance pyrometer	>570	1÷2
- two-colour pyrometer	470÷4270	1÷2
- thermal imaging	250÷1900	-
OTHER TECHNIQUES		
- thermal expansion (expansion thermometer, bimetal)	400÷1200	2
- resonance frequency of a piezosquartz crystal	190÷520	0,01
- crayons (sudden colour change of a substance at a known temperature)	340÷940	2
- paints (sudden colour change of a substance at a known temperature)	310÷1620	2
- fusible indicators (change of colour after melting)	330÷1700	2

Table 4. Basic specifications of sensors most commonly used for temperature measurement.

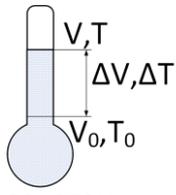
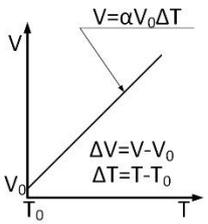
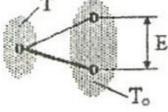
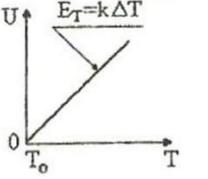
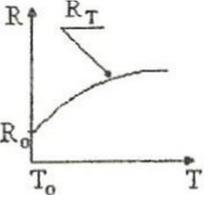
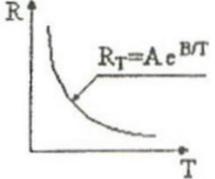
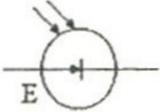
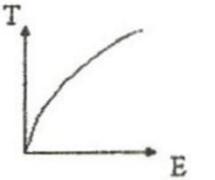
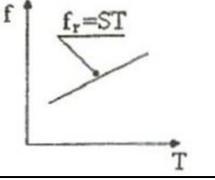
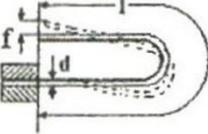
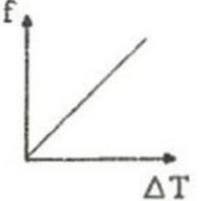
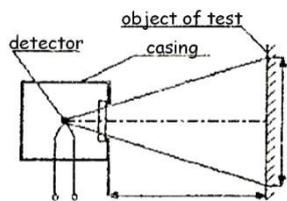
No.	Temperature detector type	Detector symbol and typical measured temperature range	Detector output and its relationship to temperature	Static detector characteristics
1	2	3	4	5
1	Glass, filled with thermometric liquid (mercury, alcohols, pentane, ether...).	 <p>73÷273K -200÷500°C</p>	Change in ΔV of the thermometric fluid $\Delta V = \alpha \cdot V_0 \cdot \Delta T$ α – apparent coefficient of volumetric expansion of liquids; V – volume of the thermometer tank; ΔT – change in liquid temperature.	
2	Thermocouple	 <p>150÷1900 K -123÷1627°C</p>	Thermoelectric force E_T of the thermocouple $E_T = k \cdot (T - T_0) = k \cdot \Delta T$ k – material coefficient; T – measuring junction temperature; T_0 – reference junction temperature.	
3	Metal thermoelectric resistor (platinum, copper, nickel...)	 Pt100 50÷1100 K -223÷827°C	R_T resistance of thermoelectric resistor at temperature T $R_T = R_0 \cdot (1 + A \cdot T + B \cdot T^2)$ R_0 – resistance of the resistor at temperature T_0 ; A, B – standard constants of the resistor.	
4	Semiconductor thermoelectric resistor (thermistor)	 <p>193÷573 K -80÷300°C</p>	R_T resistance of thermoelectric resistor at temperature T $R_T = A \cdot \exp\left(\frac{B}{T}\right)$ A – thermistor resistance for $T = \infty$; B – a constant depending on the thermistor material.	
5	Photoelement (photocell, single junction photodiode)	 <p>323÷2273 K -80÷300°C</p>	Current I in the photodiode circuit $I = k \cdot E; E = f(T)$ k – coefficient dependent on photodiode material and design; E – illumination intensity of the photodiode; T – temperature of the test object.	
6	Quartz resonator	 <p>263÷328 K -10÷55°C</p>	Resonant frequency f_r resonator $f_r = ST$ S – constant factor; T – resonant temperature.	
7	Bimetal	 <p>473÷673 K 200÷400°C</p>	Displacement f of the bimetal $f = 10^{-4} \cdot K \cdot \frac{l^2}{2 \cdot d} \cdot \Delta T$ K – specific deflection [K^{-1}]; ΔT – temperature difference[K]; l, d – dimensions in [mm].	

Table 5 Features and specifications of pyrometers.

Type of pyrometer	Measurement area[K]	Accuracy	Value time ¹⁾ 98% [s]	Distance factor ²⁾
Radiation				
1. lenticular a) glass lens	970÷2270	±15÷±25 K	0,5÷2	7÷20 (50)
b) quartz lens	670÷1470		5	
c) fluoride lens	320÷870			
2. With optical fibre	970÷2270		0,5÷2	-
3. Mirror	-230÷870	±2%	2÷5	7÷20 (40)
Photoelectric				
1. Monochroma- type	320÷2700	±2÷±1,5%	0,001 ³⁾	20÷300
2. Band-type				
Monochrome with disappearing fibre				
Monochrome disappearing fibre	970÷1770 1670÷2270	±6÷±15 K	-	130 (micropirometer 5000)
Two-colours				
1. Manually adjustable	970÷2470	±2 K	-	20÷50
2. Automatic electric	1070÷2470	±1÷±1,5%	0,001 ³⁾	
3. Electromechanical automatic			-	
¹⁾ The 98 % value time is the time taken for the pyrometer readings to reach 98 % of the value corresponding to a steady state, assuming the input signal (forcing) is in the form of a unit stroke 1(t).				
²⁾ The distance coefficient is the ratio of the distance l of the front edge of the pyrometer telescope from the test surface to the minimum required diameter of the test body surface d(fig. ²⁾).				
³⁾ Values not taking into account meter inertia.				

Also, the medium between the test surface and the detector must be essentially transparent to the band(s) of radiation being measured. Thus, it is unacceptable for the test surface to be immersed in a liquid or even covered by a liquid film. The detector must be located so that it "sees" the surface under test directly or through a window (e.g. the surface of a piston in an internal combustion engine). If a window is used, the absorption of radiation by the window material must be taken into account.

Depending on the principle of operation, a distinction is made between radiation pyrometers, monochromatic with disappearing filament, photoelectric and two-colour pyrometers.

Basic technical data on the properties and metrological capabilities of the pyrometers are presented in Table 5.

Radiation pyrometer (Fig. 3) - is a total radiation pyrometer. Its operation consists in focusing (lens, mirror) on the detector panchromatic radiation (in the whole spectral range) emitted by the surface of the tested object. Currently, in most cases, a thermosack (a miniaturised serial connection of several or more thermocouples) is used as the radiation detector. In their various models, radiation pyrometers make it possible to measure temperatures in the range 230 ÷ 2270K with an accuracy of ± (15 ÷ 20) K. They are used, among other things, for continuous temperature measurements of the surface of solids (which may be in motion), large volumes of gases, the internal surfaces of engine combustion chambers (window).

Monochromatic pyrometer with disappearing filament (Fig. 4) - its principle of operation consists in comparing by eye the luminance of the surface of the test body with the luminance of the filament of the pyrometer bulb, which is regulated by an adjustable resistor controlling the current flow through the

filament. The current is adjusted until the apparent image of the bulb fibre against the surface of the test body disappears. The ammeter incorporated in the bulb circuit is calibrated in temperature units. The typical range of applicability is $970 \div 2270$ K with an accuracy of $\pm (5 \div 15)$ K. It is increasingly less used due to the subjectivity of the measurement. Due to its manual operation, it is not suitable for use in automatic systems.

Photoelectric (band) pyrometer - this uses the dependence of the averaged radiation flux density in a band, the range of which is imposed by the spectral characteristics of the detector, on temperature. Typical radiation detectors in bandpass pyrometers are photoresistors made of PbS, CdS, PbTe and PbSe and germanium or silicon photodiodes, photoemission or photovoltaic elements. The range of wavelengths to which the detector responds is called the operating bandwidth of the pyrometer, e.g. for a PbS photodetector it is $0.4 \div 4.7$ μm , and for a germanium photodiode it is $0.4 \div 1.7$ μm . Typical metrology solutions of this type of pyrometers (Fig. 3) include an electrical transducer or a radiation flux modulator. Some commercial versions of pyrometers are equipped with a memory circuit, allowing the maximum temperature value to be stored. The typical measuring range of a band pyrometer is $320 \div 2270$ K, with an inaccuracy of $\pm (0.2 \div 1.5\%)$ of the measuring range. Band pyrometers are most often used in systems for the measurement and control of rapidly changing temperatures, e.g. in induction heating, hot rolling of metal sheets, etc.

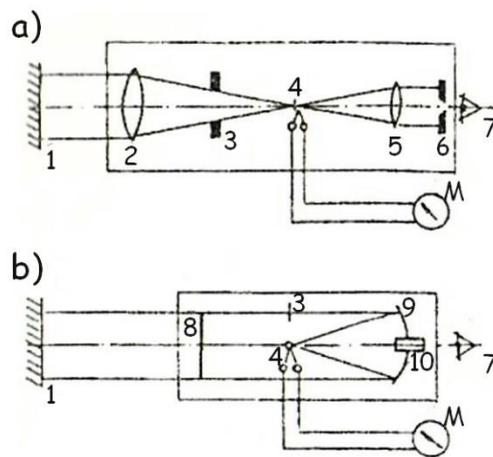


Fig. 3 Block diagram of a radiation pyrometer: a) lenticular; b) specular. 1-test body; 2-lens; 3,6-screen; 4-thermostat; 5-eyepiece; 7-observer; 8-transparent screen; 9-mirror; 10-mirror; M-meter.

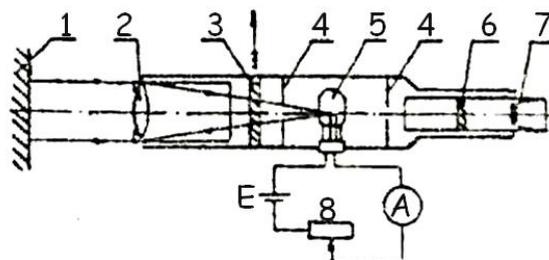


Fig. 4 Schematic of the construction of a monochromatic fading pyrometer: 1-test object; 2-lens; 3-grey filter; 4-diaphragm; 5-bulb; 6-red filter; 7-eyepiece; 8-adjustment resistor.

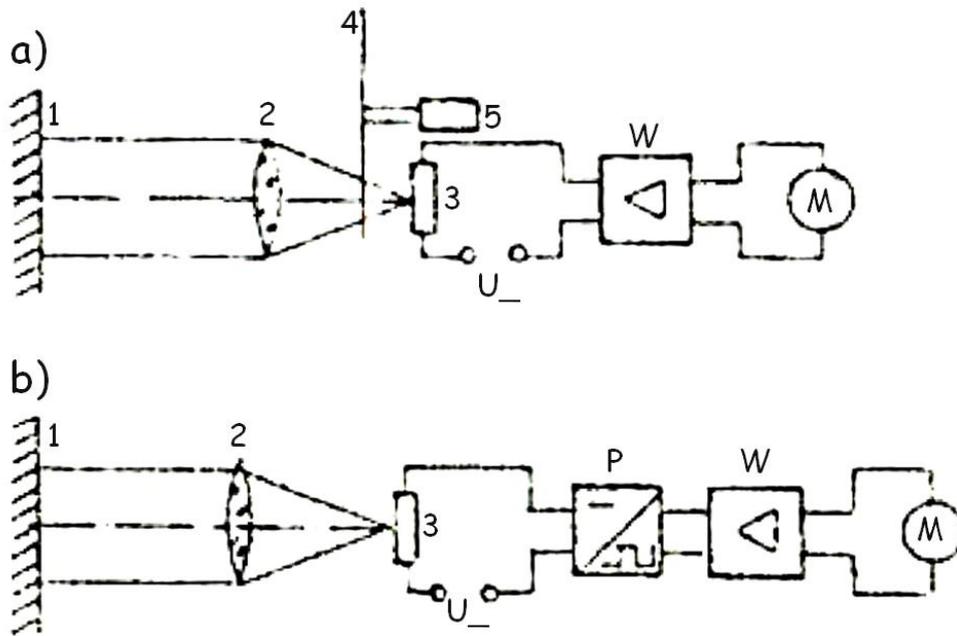


Fig. 5 Schematic of photoelectric pyrometer construction: a) with flux modulation; b) with electrical transducer. 1-test body; 2-lens; 3 photoelectric detector; 4-spinning disc with holes; 5-motor driving the disc; P-transducer; W-amplifier; M-measurer.

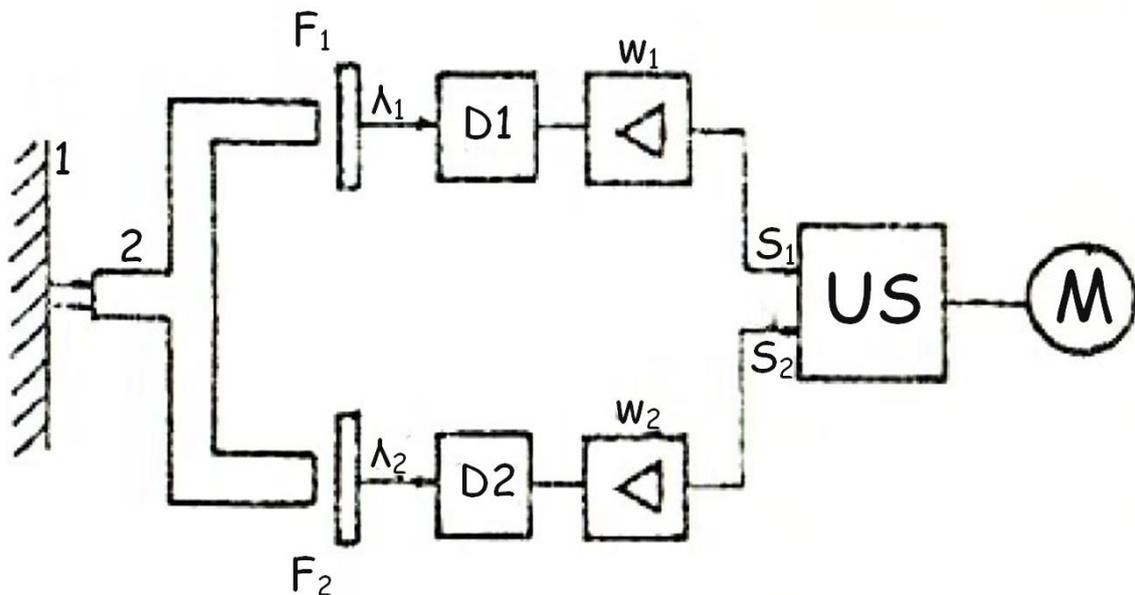


Fig. 6 Schematic of the construction of a dual-colour pyrometer: 1-object under test; 2-port-type fiber F1, F2-narrow-band filters; W1, W2-amplifiers; S1, S2-output signals from amplifiers; US-circuit realizing S1/S2-function; M-measurer.

Two-colour pyrometer (Fig. 6) - a pyrometer whose principle of operation is based on the use of the temperature dependence of the quotient of the radiation flux density of very narrow bands around the

wavelengths λ_1 and λ_2 . It is usually assumed that $\lambda_1 = 0.55 \mu\text{m}$ (green colour) and $\lambda_2 = 0.65 \mu\text{m}$ (red colour). The design solutions of this type of pyrometer vary, but most commonly interference filters and separate detectors are used to separate the narrow radiation bands around λ_1 and λ_2 , and the quotient of the measurement signals is realised in a special electronic circuit or by numerical calculation. Even now, versions with a two-colour filter are encountered. In this case, the observer adjusts the two-colour sliding filter so that the body observed through the filter appears grey. The measuring range of the dual-colour pyrometer is $970 \div 2470 \text{ K}$, and the error of measurement usually does not exceed $\pm 10 \text{ K}$. Two-colour pyrometers can work independently with temperature controllers and recorders. Their output signal practically does not depend on the emissivity of the surface. They are used for temperature measurements of surfaces whose emissivity varies within large range, as well as for temperature measurements in heat-absorbing media (vapours, gases). They are relatively expensive.

Thermal imaging camera (thermal imaging) - is a device that allows the imaging (visualisation) of the distribution of the temperature field occurring on a specific area of the surface of the object under investigation. More precisely, it is the visualisation of the density of the infrared radiation flux emitted independently by individual points (together with their surroundings) forming the visible surface through the camera's optical system. The basic assembly of such a camera is the sampling system (observing the surface), whose task is to transmit the signal amplitude information to the detector point by point (Fig. 7). For this purpose, in most cases, an optomechanical system consisting of rotating or swinging mirrors or prisms made of a material transparent to the dedicated radiation band is used. The sweep frequency of the surface of the test object is 25 Hz . The signal from a specific point (with the nearest surroundings) of the surface under examination falling on a detector (e.g. InSb) is converted into an electrical signal. The amplitude of the measurement signal incident at a given moment (and therefore from a specific location of the test object) on the detector determines the intensity of the glowing spot on the screen (brightness level) or can be encoded on a colour scale of e.g. 10 degrees. The image of the surface temperature field of the object under test is called a thermogram. This image can be stored in the memory of the device with the possibility of its reconstruction. The radiation detector should be selected so that its detection band lies in the range of $3 \div 5 \mu\text{m}$ or $8 \div 14 \mu\text{m}$, as in these ranges the absorption of radiation by the atmosphere is negligibly small. With thermal imaging, it is possible to visualise the temperature field in the range of 250 to $1,900 \text{ K}$. The resolution capability of this type of equipment depends on the range of temperature measured. Thermal imaging is used for detecting leaks in thermal insulation, in medical diagnostics, in forecasting the condition of agricultural crops (from space), for detecting underground exploration (from space), submerged submarines (aircraft, space), and for detecting mineral deposits.

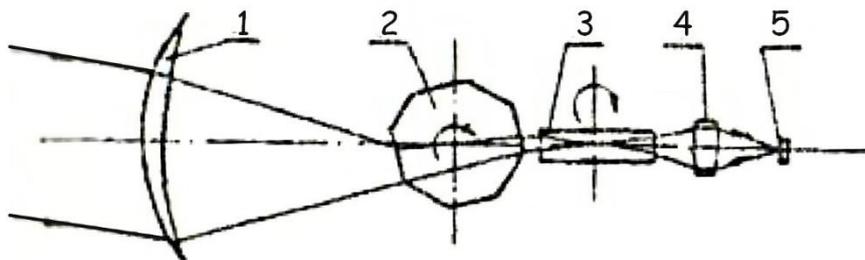


Fig. 7 Optomechanical system of the thermal imaging device: 1,4-lens; 2-vertical rotating prism; 3-horizontal rotating prism; 5-infrared detector.

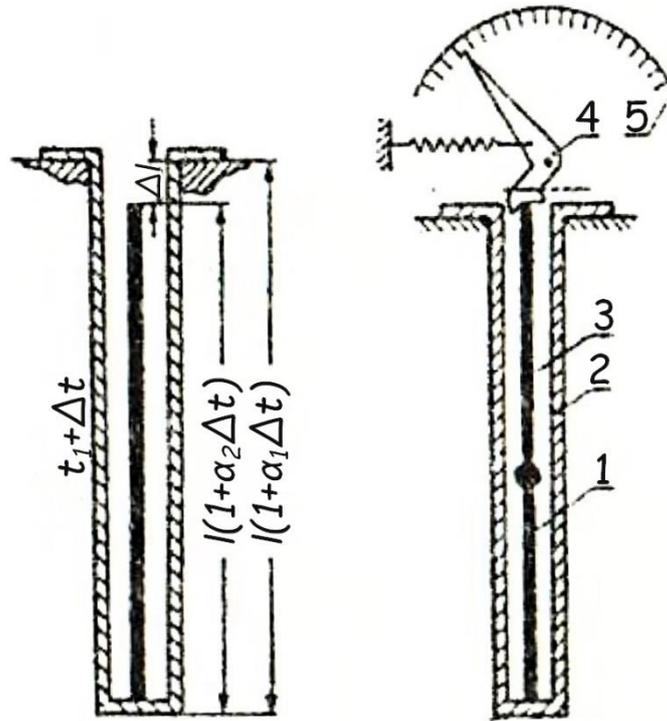


Fig. 8 (a) principle of the dilatation thermometer - state at temperature $(t - \Delta T)$; (b) cross-section through the thermometer: 1-passive material; 2-active material; 3-bar extension; 4-mechanical transmission guide; 5-temperature scale.

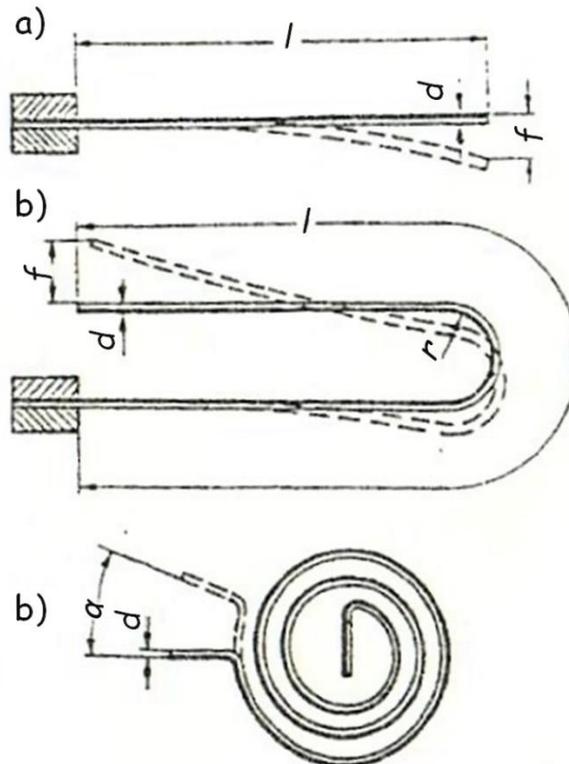


Fig. 9 The most common shapes of bimetals: a) flat tape; b) U-shaped tape; c) flat spiral.

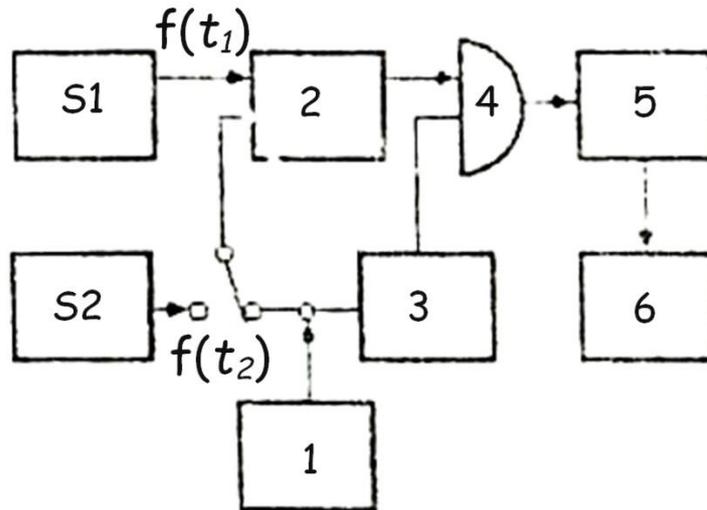


Fig. 10 Block diagram of the quartz thermometer: S1, S2-temperature sensors; 1-frequency generator f_0 ; 2-mixer; 3-clock pulse generator; 4-differential frequency detector circuit with A/D converter; 5-counter; 6-display.

The method is related to the use of the difference in linear expansion of different materials as a function of temperature. This difference is expressed by the formula

$$\Delta l = l \cdot (1 + \alpha_1 \Delta T) - l \cdot (1 + \alpha_2 \Delta T) = l \cdot (\alpha_1 - \alpha_2) \cdot \Delta T \quad (5)$$

where: l - length of the sensor at temperature T ; α_1 and α_2 , - coefficients of linear expansion of the materials used; ΔT - temperature change. An example of a dilatation thermometer solution is shown in Fig. 8 The sensors of these thermometers are usually made in the form of a tube with a high value of coefficient α_1 with a rod coaxially placed in it, made of a material with a small coefficient α_2 . The pairs of materials used in expansion thermometers should be characterised by the highest possible operating temperature, high differential ($\alpha_1 - \alpha_2$) and resistance to corrosion and oxidation (Al, Ni, brass, NiCr, porcelain, FeNi36, quartz). The maximum measured temperatures reach 1200 K (NiCr - porcelain) and the measurement error does not exceed 2 %.

This phenomenon is also used in the design of the bimetal thermometer (Fig. 9). The basic element of this type of thermometer is the bimetal, which is two hot-welded or hot-rolled strips of metals or alloys with different linear coefficients of expansion. As the temperature changes, the bimetal bends towards the strip with the smaller coefficient of expansion. In the case of a flat bimetal strip, the displacement f [mm] at the end of the bimetal is expressed as follows

$$f = 10^{-4} \cdot K \cdot \frac{l^2}{d} \cdot \Delta T \quad (6)$$

where: K - specific deflection in [K]; l - length of bimetal in [mm]; d - thickness of bimetal in [mm]; ΔT - temperature rise above rest temperature. The unattached end of the bimetal moves the pointer on the thermometer scale. Typical application temperature range for this type of thermometer is 200÷400°C. Measurement accuracy 1÷2%. They can replace technical liquid thermometers. Bimetal is sometimes used in other thermometers as a compensating element for ambient temperature effects.

A method related to the use of the frequency dependence of a piezoelectric crystal on temperature and other effects.

Quartz thermometers. The natural frequency of the quartz oscillator depends on the temperature T and can be written as

$$f(\theta) = f_0 \cdot (1 + \alpha \cdot \theta + \beta \cdot \theta^2 + \gamma \cdot \theta^3) \quad (7)$$

where: f_0 , - frequency at reference temperature T_0 , $\theta = T - T_0$; α , β , γ - coefficients depending on the location of the quartz monocrystalline axis to the cutting plane.

In typical oscillators, the piezoelectric quartz monocrystal is cut in such a way that its frequency is practically independent of temperature, i.e. $\alpha = 0$. However, when used in thermometry, the mutual positioning of the axis and the cutting plane is selected so that $\beta = 0$ and $\gamma = 0$, in which case $f(\vartheta)$ is a linear function of ϑ . One possible system solution for a quartz thermometer is the arrangement shown in Figure 10. Such a solution is used in a thermometer from Hewlett-Packard and allows both the measurement of the temperature T_1 (sensor S_1) and the temperature difference T_1 and T_2 (sensors S_1 and S_2). The quartz plates in the temperature sensors are typically a few millimetres in diameter, with a resonance frequency of a few tens of MHz and its variation as a function of temperature of about $1 \text{ kHz}\cdot\text{K}^{-1}$. The resolution of the thermometer is dependent on the duration of the measurement, e.g. for 10 s it is 10^{-4}K and for 0.1 s it is 10^{-2}K . The typical temperature range measured with this thermometer is -80°C to 250°C , and the measurement error should be determined individually for each specific measurement problem.

Colour. Thermosensitive coatings, which change colour rapidly when the critical temperature is exceeded, are often used to study the temperature distribution on the surface of solids. Heat-sensitive coatings should change colour in less than one second, cannot change their properties when exposed to the fluid surrounding the covered surface and cannot emit noxious gases when heated. Heat-sensitive coatings can be divided into:

- those that change colour reversibly or irreversibly due to changes in the chemical composition or crystal lattice structure of temperature-sensitive pigments. By using mixtures of different pigments, colour-sensitive paints can be obtained that change colour many times, up to 12 times;
- colour changing due to the melting of one of the components;
- liquid crystals (most often cholesterols), which have the properties of liquids (liquidity) and solid crystals (non-isotropy), changing colour when the temperature changes by hundredths of a degree.

As an example of the use of heat-sensitive coatings, there are crayons and heat-sensitive paints from Faber-Castell (Stein bei Numberg, Germany). This company produces Thermochrom crayons, 18 of which cover a temperature range of $65^\circ\text{C}\div 670^\circ\text{C}$, and Thermocolor paints, 34 of which cover a temperature range of $40^\circ\text{C}\div 1350^\circ\text{C}$. The measurement accuracy is $\pm 5\%$. Advantages of these paints and crayons include the low cost of determining temperature distributions on the surfaces under test and the ability to determine isotherms immediately after the object has cooled. The paints are supplied as powders dissolved in alcohol.

Among the 34 Thermocolor paints, 5 change colour twice, 4 change colour three times and 2 change colour four times.

Thermochrom crayons are used for fast and inexpensive temperature determination in welding, extrusion, ageing, etc., technological processes and for the monitoring of heated parts during operation. Thermocolor paints are used for determining the temperature distribution on large surfaces, e.g. chemical apparatus, furnace walls, aircraft plating, rocket engine walls, gas turbine blades, flow channel walls, etc. In special cases, paints are used to determine the maximum temperature of pistons and air-cooled cylinders and heads of internal combustion engines or to determine cutting temperatures. Unlike crayons, paints must be applied to surfaces before the body is heated.

Fusible indicators - are chemical compounds with different melting points, commercially available as fast-drying liquids or crayons. A surface painted with such a substance at a temperature below its melting point is dull, as if it had been scratched with chalk. When the surface reaches its rated (melting) temperature and above, and after it has cooled, the substance on the surface becomes glassy and bears the marks of over-melting. Flux indicators They are manufactured in a temperature range from 330 to 1700 K with gradations from 5 to 30 K. The error of indication is specified to a maximum of $\pm 1\%$.

3. CONDITIONS FOR CORRECT TEMPERATURE MEASUREMENT

The great variety of thermodynamic phenomena that occur in different media (solid, liquid, gas) entails the need to choose the most appropriate temperature measurement method in each individual case.

Nowadays, every engineer has a large variety of temperature measurement methods and techniques at his or her disposal, and the problem comes down only to the optimal choice of measurement method and how to implement it in practice.

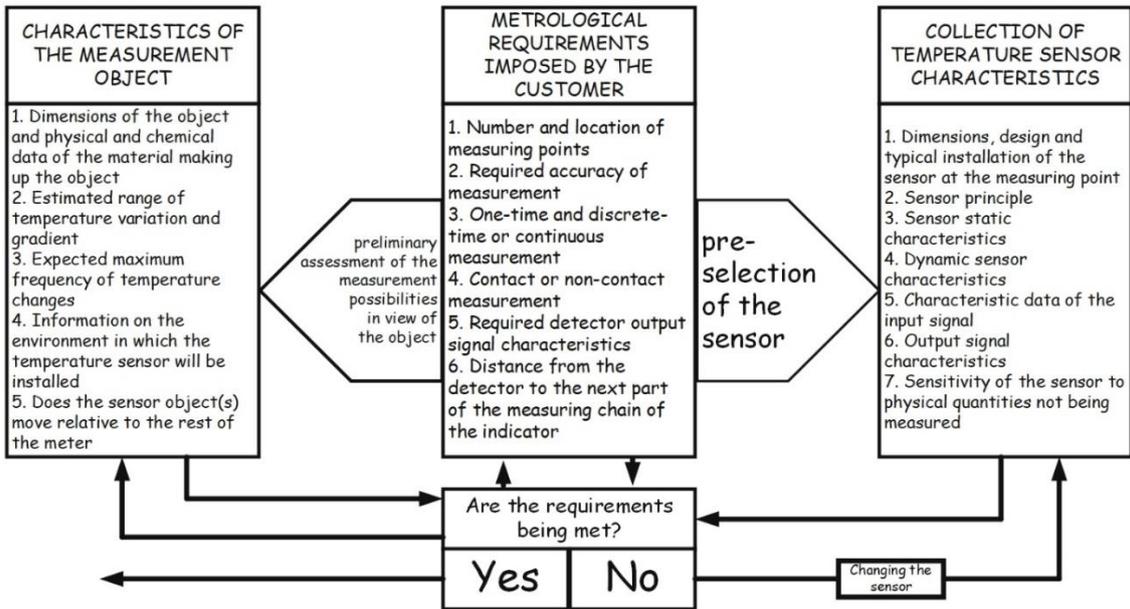


Fig. 11. Procedure for selecting the type and type of sensor for temperature measurement.

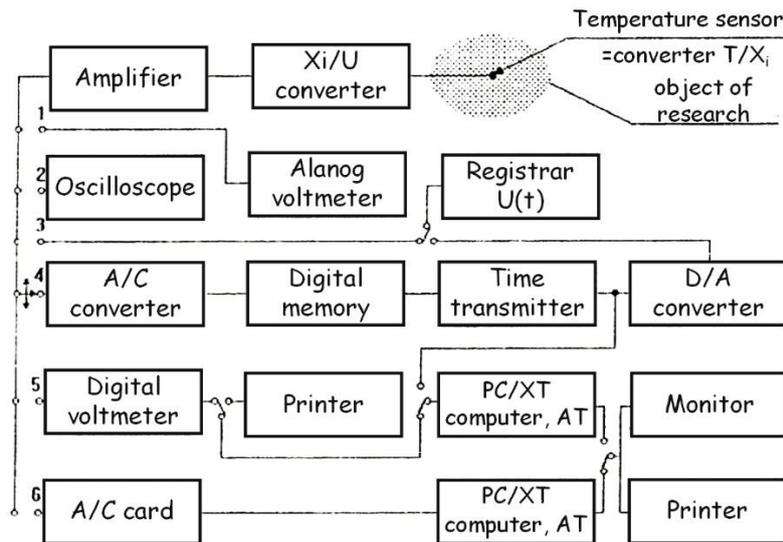


Fig. 12: Block diagram of the connections of the most commonly used systems for temperature measurement and recording.

Before measuring the temperature, it is first necessary to establish:

- the location of the point in the measuring space where the measuring sensor will be placed;
- the operating conditions of the sensor, i.e. the approximate range of variations of the measurand, the nature of these variations, the operating time of the sensor, the chemical properties of the environment in which the sensor will be placed;
- the measurement error of the measurand.

Knowledge of the above data allows the selection of the most appropriate sensor whose properties will guarantee that these requirements are fulfilled. A framework that guarantees the selection of the optimal temperature sensor given the pre-imposed experimental conditions and the currently available range of methods and associated temperature sensors is shown in Figure 11.

The measuring system that works with the sensor intended to measure temperature is selected depending on the type and thermoelectric parameters of the sensor itself.

The measurement system working with a given temperature sensor must be selected with regard to

- the nature of the variation of the measurand (constant or time-varying temperature)
- the requirement of the measurand (average, minimum, maximum or instantaneous transient temperature is measured);
- the nature of the measurement (continuous or discrete time). This is particularly important when measuring the temperature of rotating or reciprocating parts;
- the method of processing the measurement signal (analogue reading, digital, analogue or digital recording).

The criterion that determines the details of the measurement system is usually a predetermined measurement error and whether the temperature measurement system cooperates with the control and automation system of the facility as a wider whole.

Figure 12 shows a diagram of the temperature sensor, which is a T/X_i transducer (where X can be the thermoelectric force E , electrical resistance R , radiant flux density I , elongation l , ...), connected to another X_i/U transducer. The system consisting of the temperature sensor and the X_i/U transducer is responsible for converting changes in temperature-dependent quantities into electrical voltage. For instance, in the case of a resistive sensor, the sensor converts a temperature change into an electrical resistance change (T/R), while the following component (the X_i/U transducer) converts the resistance change into an electrical voltage change (R/U). In contrast, a thermocouple does not require the X_i/U transducer since the sensor directly converts the temperature change into a thermoelectric voltage change (T/U).

The correct measurement of the temperature of a given object, with a given measuring sensor together with the associated measurement and visualisation system, requires a separate error analysis each time. An illustration of this problem can be, for example, the measurement of surface temperature. Accurately measuring the surface temperature of a solid body is, contrary to appearances, not a trivial problem. Particularly if the surface of the body exchanges heat with its surroundings (fluid) by convection (Fig. 13). A characteristic feature of such heat exchange is the occurrence of a large temperature gradient in the fluid boundary layer and, therefore, in order to reduce measurement errors to a minimum, the sensor (thermocouple, thermistor) on the surface of the solid must be placed in a special way. The different ways in which thermocouples designed to measure the surface temperature of a solid are placed are shown in Fig. 14.

Placing the sensor on a surface causes a disturbance in the local body temperature field near the attachment point. This disturbance is due to changes in heat transfer conditions between the fluid and the surface, as well as heat dissipation through the sensor wires. The error in measuring the sensor surface temperature depends on the disturbance in the temperature field. To illustrate the complexity of determining the measurement error, consider the case shown in Fig. 14(d), assuming infinite resistance for heat flow from the body to the sensor.

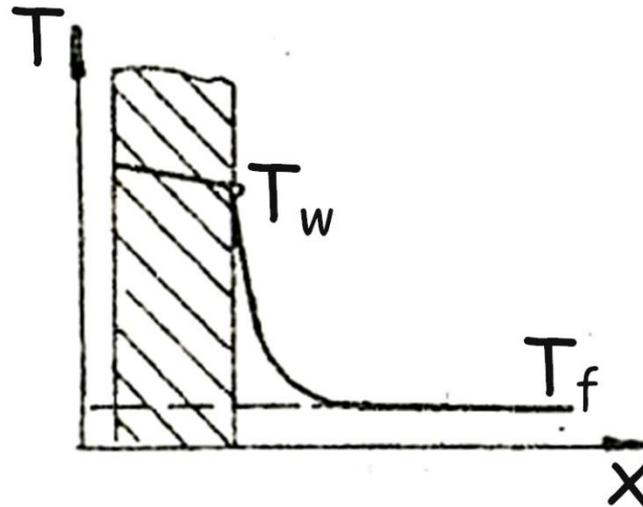


Fig. 13 Temperature change in the plate and the boundary.

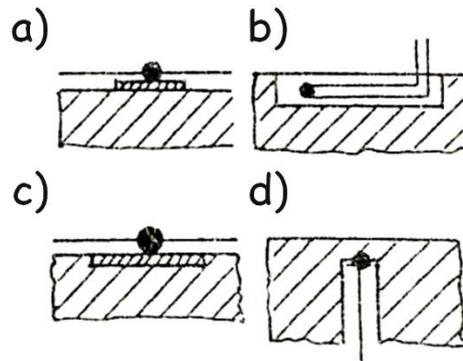


Fig. 14 Ways of placing thermocouples to measure surface temperature: P - plate made of a good heat conductor; \bullet - junction of thermocouple.

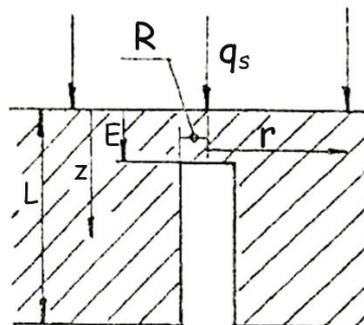


Fig. 15 Geometry of surface temperature measurement with a thermometer inserted into a hole below the surface.

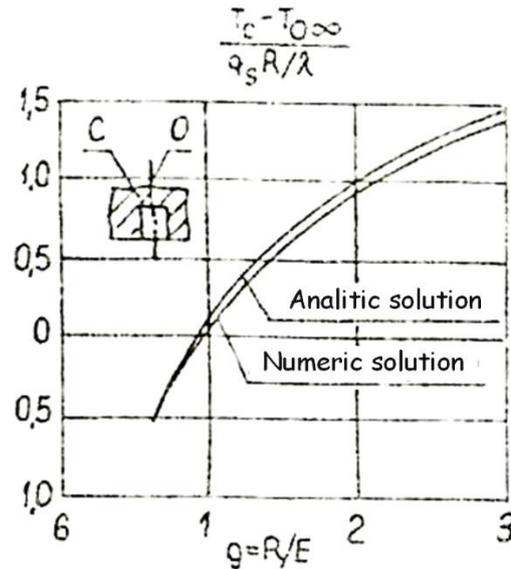


Fig. 16 Dependence of the error in measuring the surface temperature with a thermometer placed at point C on g .

When it is necessary to measure the temperature of a surface where a temperature sensor cannot be directly installed, such as the inner surface of a high-pressure tank wall or the cylinder sleeve of an internal combustion engine, the method shown in Fig. 14(d) is used. A thermometer is placed perpendicular to the surface in a small cylindrical hole drilled from the outside of the wall. Beck and Hurwicz (1960) determined the error in surface temperature measurement using this method. Based on their findings, it is recommended to use this method with caution. They took determinations as shown in Fig. 15, assuming a steady heat transfer and an infinitely long hole, and that the thermometer does not dissipate heat, they obtained that

$$\frac{T_0 - T_g}{g \dot{q} \frac{R}{\lambda}} = 0,5$$

gdzie:

- $T_0 = T(r = 0, z = 0)$ - is the temperature at point O (Figure 1);
- $T_g = T(r = \infty, z = 0)$ - is the surface temperature undisturbed by the hole;
- $g = R/E$ - dimensionless ratio;
- \dot{q} - heat flux density at the surface;
- λ - thermal conductivity coefficient of the wall material.

The same authors also determined the absolute error of determining the surface temperature when measuring the temperature at point C, to which the temperature $T_c = T(r=0, z=E)$ corresponds, as a function of g , under the same assumptions as above. A graph of this relationship is shown in Fig. 16. From the graph shown, it can be seen that this error is equal to zero if $g = 1$. Since the thermometer does not measure the temperature at point C, but the average temperature at the face of the hole, it is recommended to use $g = 1.1$.

4. PROCEDURE FOR CARRYING OUT THE EXERCISE

The aim of this exercise is to introduce students to various temperature measurement methods and techniques, along with their associated nuances.

The instructor will review selected temperature measurement methods used in technology where they are essential, using audio-visual material in the first part.

The instructor will introduce students to various types of temperature sensors and instruments and provide practical demonstrations of their operation.

The second part of the course is focused on demonstration. The exercise requires the group to develop a topic assigned by the instructor, related to a specific temperature measurement issue, by the end of the semester. The exercise leader will determine the scope, content, and volume of the report on the assigned topic.

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