TEMPERATURE MEASUREMENTS WITH THERMOELECTRIC THERMOMETERS

Thermoelectric thermometers are among the most widely used instruments for measuring temperature. They are used over a wide range of temperature variations. They are characterised by their high adaptability to local conditions and needs. One of their most salient features is that the thermocouple always measures the temperature difference.

1. THE THERMOELECTRIC PHENOMENON – BASIC LAWS

The contact potential difference V_{AB} at the interface between metals A and B (Fig. 1 a) is

$$V_{AB} = V_B - V_A = \frac{k \cdot T}{e} \cdot ln\left(\frac{n_A}{n_B}\right) \tag{1}$$

where: V_A and V_B and n_A and n_B denote the work of output and the numbers of free electrons in 1 cm^3 of metals *A* and *B*, respectively; *k* - Boltzman's constant; *e* - charge of an electron; *T* - absolute temperature. In a closed circuit composed of two metals (Fig.1 b) with different contact temperatures T_1 and T_2, the Seebeck thermoelectric force (TEF) generated at the contacts is given by the formula:

$$E' = V_{AB}(T_1) + V_{BA}(T_2) = \frac{k \cdot T_1}{e} \cdot ln\left(\frac{n_A}{n_B}\right) + \frac{k \cdot T_2}{e} \cdot ln\left(\frac{n_B}{n_A}\right) \tag{2.a}$$

or

$$E' = \frac{k}{e} \cdot (T_1 - T_2) \cdot ln\left(\frac{n_A}{n_B}\right) \tag{2.b}$$

The approximate assumption made here is that the work of output and the number of free electrons are not temperature dependent. The magnitude of E' corresponds to the Peltier electromotive force. In fact, the number of free electrons in a metal is also a function of temperature, which is also the source of the potential gradients arising along the temperature gradient in a homogeneous metal conductor.

In a closed circuit of metals A and B (Fig. 1 c), the so-called Thomson electromotive force is generated

$$E'' = (\sigma_B - \sigma_A) \cdot (T_1 - T_2) \tag{3}$$

with σ_A and σ_B being the Thmson coefficients for metals A and B.

In a normal thermoelectric circuit, both types of thermoelectric force, i.e. Thomson and Peltier, are associated, so we can generally write

$$E = f(T_1 - T_2) \tag{4}$$

The above formula is the basis for using an arrangement of two different metals to measure temperature, or more precisely temperature difference. The system of two different metals for measuring temperature is called a thermocouple, where the measuring or 'hot' junction is the one at the temperature to be measured and the other is the reference junction.

The thermoelectric phenomenon is a reversible thermodynamic process, in contrast to the irreversible phenomenon of heat release when an electric current flows, in proportion to I2R. According to the laws of thermodynamics (1st and 2nd principles), no electromotive force can arise in a circuit with a balanced temperature. The above considerations lead to the conclusion as follows.

In a circuit composed of three different metals A, B and C with junctions 1, 2 and 3, located at temperatures T_1, T_2 and T_3, the thermoelectric force of the whole circuit (Fig. 2) is

$$E = e_{AB}(T_1) + e_{BC}(T_2) + e_{CA}(T_3) \tag{5}$$

where: *e* - is the electromotive force between each pair of metals.

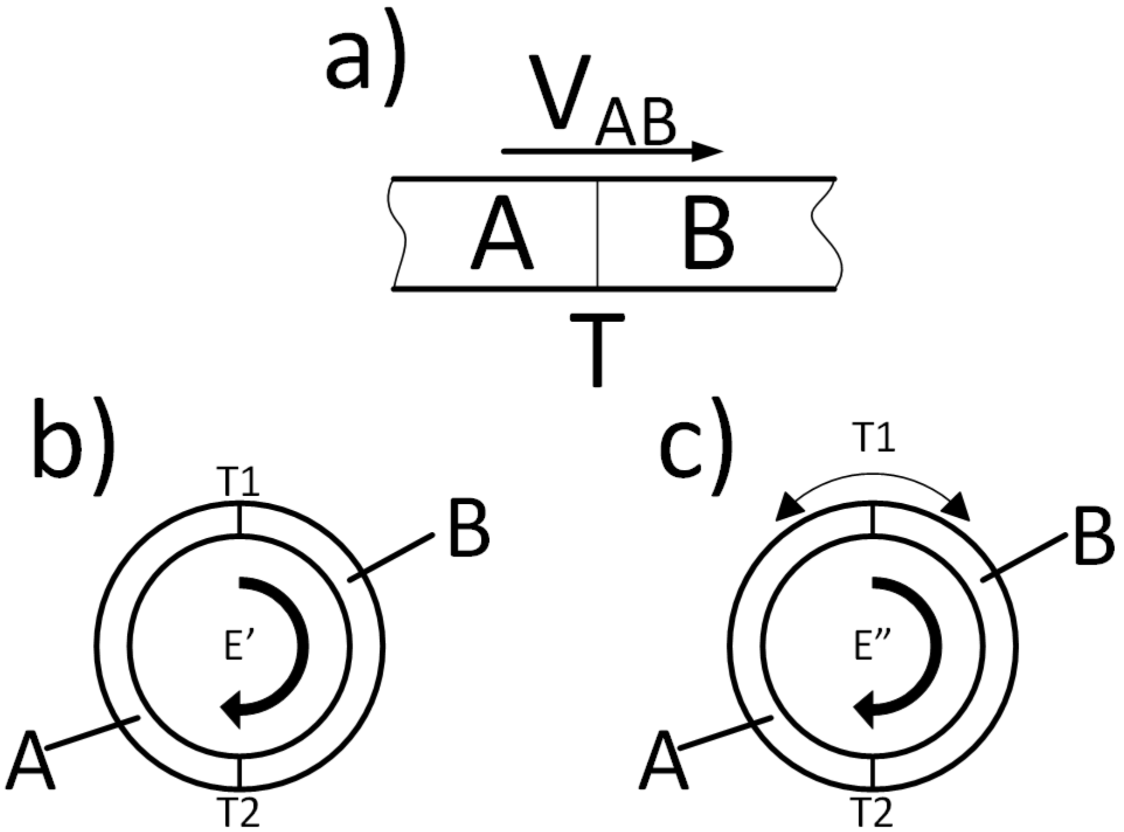

Fig. 1: Thermoelectric phenomena. Supporting formulae: a) $V_{AB} = V_B - V_A = \frac{k \cdot T}{e} \cdot ln\left(\frac{n_A}{n_B}\right)$*; b)* $E' = \left[\frac{k}{e} \cdot ln\left(\frac{n_A}{n_B}\right)\right] \cdot (T_1 - T_2)$*; c)* $E" = (\sigma_B - \sigma_A) \cdot (T_1 - T_2)$*.*

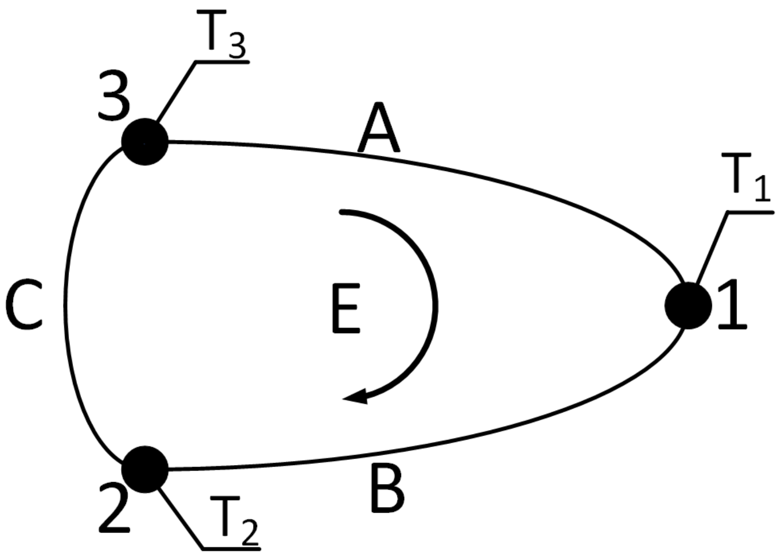

Fig. 2. A thermoelectric circuit made up of three different metals (A,B,C).

For $T_1=T_2=T_3=T_0$, E=0, so we can write $-e_{AB}(T_1) = -e_{BC}(T_2)+e_{CA}(T_0)$. Since the temperatures of the two junctions T1=T2=T0 are equal, at the third temperature T1 we get

$$E = e_{AB}(T_1) - e_{AB}(T_0) \tag{6}$$

The electromotive force of a circuit consisting of two metals A and B is not altered by the addition of other different metals (e.g. C), provided that all the additional junctions (e.g. BC and CA) are at the same temperature as the BA junction to which the other metals are attached.

It is therefore possible, without causing an error, to attach copper wires to the ends of thermocouples with a reference temperature of T_0, or to immerse unattached thermoelectrodes in a metal bath, or to join (junction) two metals with a third metal, as long as the temperatures of the two resulting new junctions are the same.

The thermoelectric force of a thermocouple measuring the temperature difference $T_3—T_1$ is the algebraic sum of the thermoelectric forces of two identical thermocouples measuring the difference $T_2—T_1$ and $T_3—T_2$.

We sometimes use this law in different systems, e.g. to compensate for changes in reference temperature, to measure temperature and temperature difference (Fig. 3), etc.

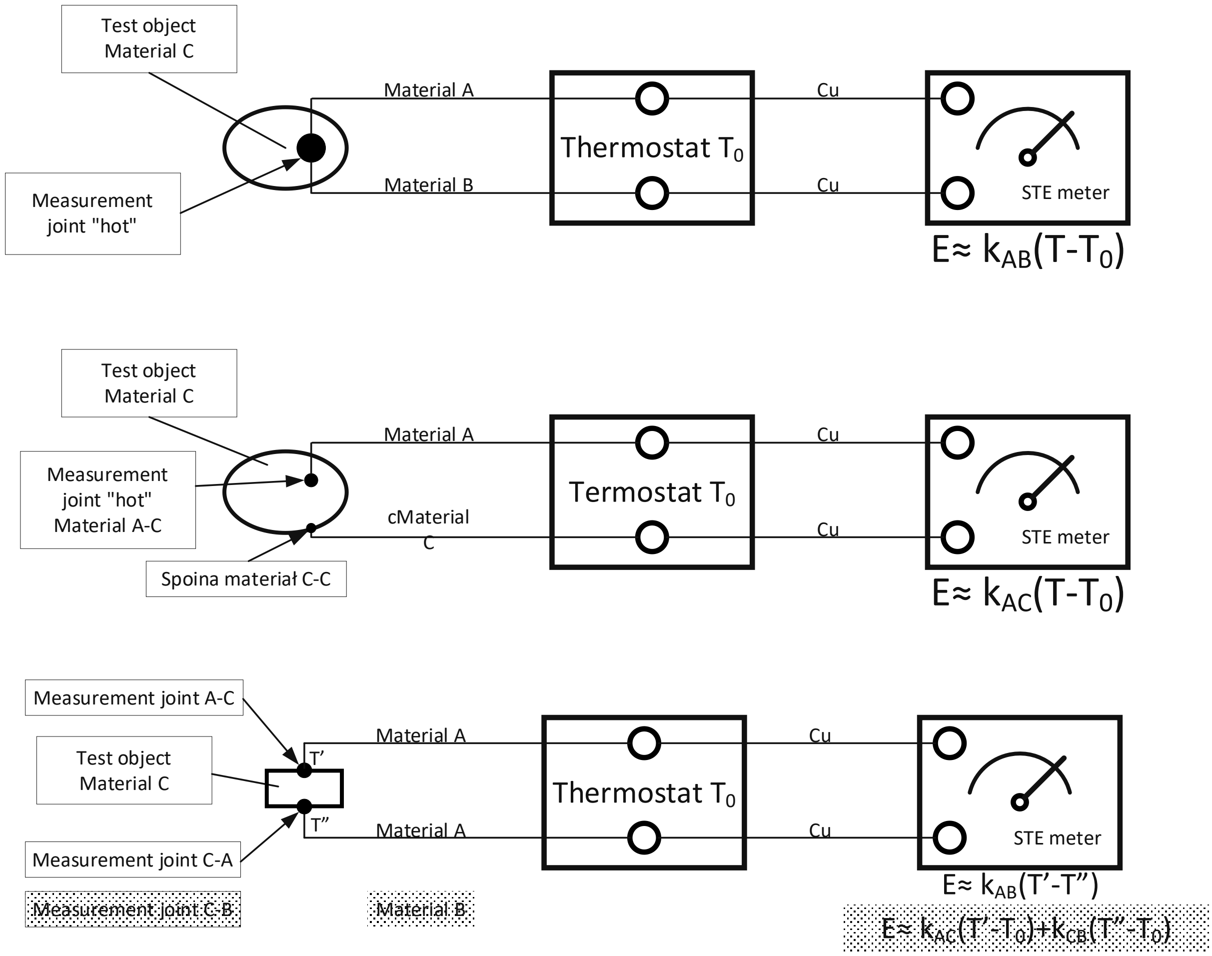

Fig. 3. Idealised diagrams of different variants of temperature measurement of an electrically conductive solid: E - thermoelectric force; k_{AB},k_{AC},k_{CB} - average temperature sensitivity of individual thermocouples in the considered temperature range; T - temperature of the object; T0 - reference temperature.

Table 1. Basic data on the most commonly used thermocouples.

Symbol according to IEC584-1	The type thermocouple[*)]	Temperature range	Average sensitivity [μV/K]	Advantages and disadvantages
J	Iron + Constantan —	−210°C÷+760°C 63K÷1033K	55	The most popular classic thermocouple type. Has relatively high sensitivity in

					the 100÷470°C range. Low repeatability related to iron impurities.
K	Chromel Ni-Cr10 Alumel Ni-Mn2Al2Sil1	+ –	−270°C÷+1372°C 3K÷1645K	41	It is resistant to oxidising atmospheres. Sensitive to sulphur compounds at higher temperatures. Aluminium electrode generally wears out faster than Ni-Cr. The most currently used thermocouple in the range up to 1000°C, with almost linear characteristics.
T	Copper Constantan	+ –	−270°C÷+400°C 3K÷673K	40	It cannot operate in oxidising atmospheres, especially at higher temperatures. Its thermometric characteristics largely depend on the purity of the copper electrode.
E	Chromel Constantan	+ –	−270°C÷+100°C 3K÷1273K	68	Most commonly used at low and very low temperatures. It is non-magnetic.
S	Platinum PtRh10	+ –	−50°C÷+1765°C 223K÷2040K	12	It is the standard of the international temperature scale in the range 630÷1064°C. It is normally used in oxidising atmospheres, but at high temperatures it is sometimes contaminated by Pb, Fe, Zn and Cd. These metals form flammable alloys with Pt, which can contaminate thermoelectrodes.
R	Platinum PtRh13	+ –	−50°C÷+1765°C 223K÷2040K	14	It has properties very similar to an S-type thermocouple.
B	Platinum PtRh30 Platinum PtRh6	+ –	0°C÷+1820°C 273K÷2093K	10	It allows temperature measurements up to 1800°C. Its sensitivity at room temperature is so low that thermostatting of the cold ends is not required.
-	Tungsten WRe5 Tungsten Wre26	+ –	0°C÷+2000°C 273K÷273K	17	Temperature measurement up to 2000°C and above in a reducing, inert atmosphere or vacuum. The low ductility of tungsten alloys does not allow the production of jacketed thermocouples.

*) in this box the "+" and "-" indicate the polarity of the corresponding electrodes.

2. THERMOCOUPLES

The metals and alloys used in thermocouple construction must meet specific requirements, including linearity, repeatability, and constancy of characteristics, as expressed by the equation E = f(T-T0). Additionally, they should have high sensitivity, resistance to industrial influences across a wide temperature range, and be cost-effective.

Table 1 summarises a few typical thermocouples that meet most industry needs. The thermometric characteristics of the most important thermocouples are shown in Figures 4 and 5.

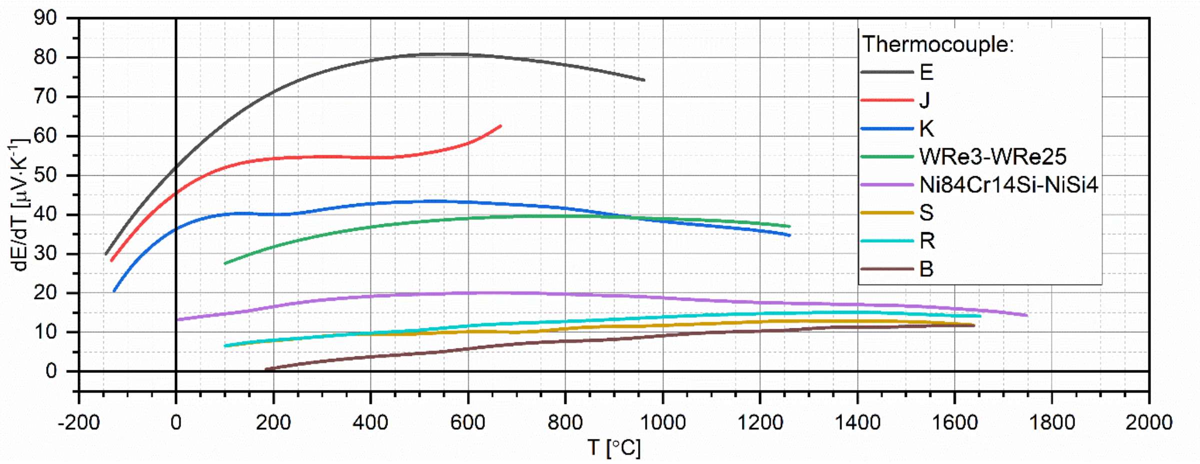

Fig. 4 Temperature dependence of the temperature sensitivity dE/dT, for selected thermocouples.

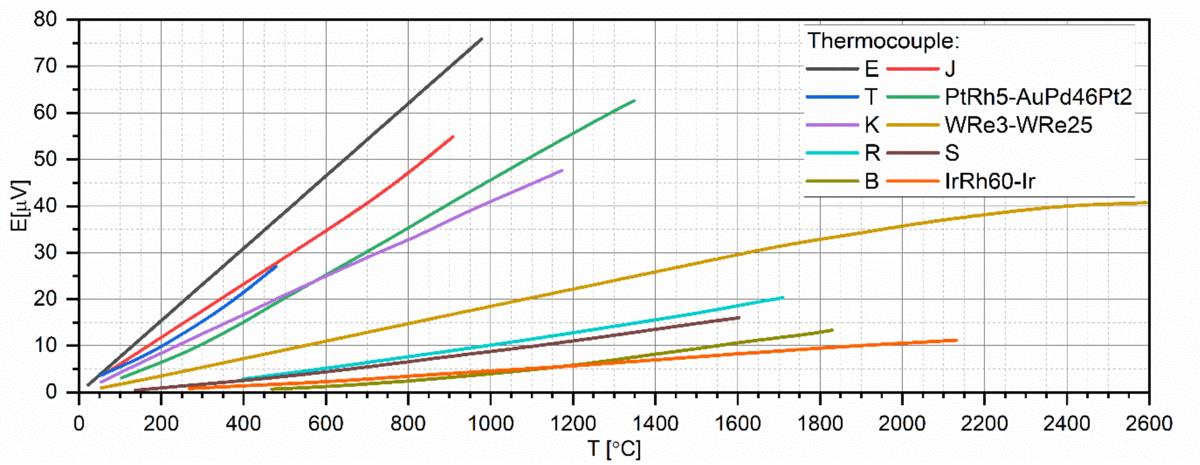

Fig. 5 Thermometric characteristics of selected thermocouples for temperatures higher than 0 ℃.

Special thermocouples are used for temperature measurement under extreme conditions. The PtRh30 - PtRh6 thermocouple (also known as PtRh18 or symbol B according to the IEC standard) is suitable for measuring temperatures up to approximately 1800°C. The addition of rhodium in the second arm reduces the effect of rhodium diffusion. Rhodium-rhodium and iridium-rhodium alloys were used up to about 2000°C, and tungsten-molybdenum alloys up to about 3000°C. Special thermocouples, such as copper-doped-platinum, gold-cobalt-copper, and copper-doped-copper, are used for low-temperature measurements. These thermocouples have a sufficient thermoelectric power gradient, typically ranging from 1 to 4 µV/K, even at temperatures around 4 K.

At high temperatures, thermocouples should not be exposed to oxidising atmospheres. Reducing atmospheres, particularly those containing hydrogen, can cause significant and rapid changes in characteristics and embrittlement of thermocouples. The PtRh-Pt thermocouple is particularly sensitive due to platinum's tendency to absorb metal vapours that are always present in reducing atmospheres, with iron vapours being the most common. At elevated temperatures, the silicon present in the sheaths of the PtRh-Pt thermocouple is also negatively impacted, particularly in the presence of sulphur (e.g. lubricants). Sulphur reacts with silicon to form a volatile compound that decomposes on the platinum.

The use of base metal thermocouples also requires protection from reducing atmospheres, although to a lesser extent. Unprotected thermocouples in hot flue gas atmospheres may experience changes in their characteristics within a few tens of hours. The iron-constantane thermocouple (type J according to IEC standard) is the least sensitive to reducing atmospheres among the widespread thermocouples.

In an oxidising atmosphere, oxidation occurs at a temperature-dependent rate, leading to thermocouple wear. For instance, a chromel-alumel (type K) thermocouple with a 3mm diameter lasts approximately 300 hours at 1200°C and 2000 hours at 1000°C in air. Additionally, selective oxidation of the components causes gradual changes in characteristics. The thermoelectric force of the iron-constantan thermocouple decreases during the first few hours of operation at temperatures up to about 500°C, after which it remains constant. At higher temperatures, a slow decrease occurs. These changes are typically within normal tolerances for an iron-constantan thermocouple. In contrast, NiCr-Ni and chromel-alumel thermocouples behave differently, with their thermoelectric strength gradually increasing. Placing an iron-constantane thermocouple in a sheath tightly filled with pure alumina can significantly reduce its oxidation. This method allows the thermocouple to function properly up to a temperature of approximately 900°C.

If the thermocouple is completely homogeneous, the depth of immersion does not affect the function E = f(T). However, immersion into an area of increased temperature and chemical interactions with the medium can cause the thermocouple to lose homogeneity quickly. Therefore, decreasing the immersion depth can result in errors. This should be taken into account when calibrating thermocouples that are already in use at a different immersion depth than during operation.

3. THERMOCOUPLE AND SHIELD DESIGN

In industrial applications, thermocouples require protection from mechanical and chemical effects of the medium. The selection of the sheath, design, and material is a challenging task that involves a compromise between several properties. These properties include resistance to the measured temperature and chemical aggressiveness of the medium, tightness, mechanical strength, electrical insulation, thermal inertia (dynamic properties), and influence on the static temperature measurement error. The final two characteristics are discussed separately as they are particularly important and depend on the properties of the medium, the way the thermocouple is incorporated, and the temperature distribution of the medium and its environment.

The development of nuclear power plants and reactors has led to the creation of new thermocouple designs that are reliable and radiation-resistant. One such design is widely used, particularly in harsh environments.

Thermocouples insulated with pure alumina or magnesium oxide in a metal sheath are depicted in Figure 6 (a and b). They are manufactured by pulling from a large diameter tube filled with insulation (MgO or AlO_3) with rods of thermoelectric material placed inside. The shields are made of various materials, such as heat-resistant or acid-resistant steel, thermoelectric alloys, etc. For temperatures above 1600°C, platinum is used. The diameter of the casings ranges from 0.2 to 6 mm. Between one and four wires are inserted into a single sheath, which can also function as one of the thermoelectrodes. The insulation value between the wires and the sheath is approximately 1011 Ω/m in the cold state, dropping to approximately 100 MΩ/m at 600°C and to 0.03 MΩ/m at 1000°C. Sheathed thermocouples are indispensable in experimentally harsh conditions and aggressive environments, particularly in the temperature range up to about 1000°C.

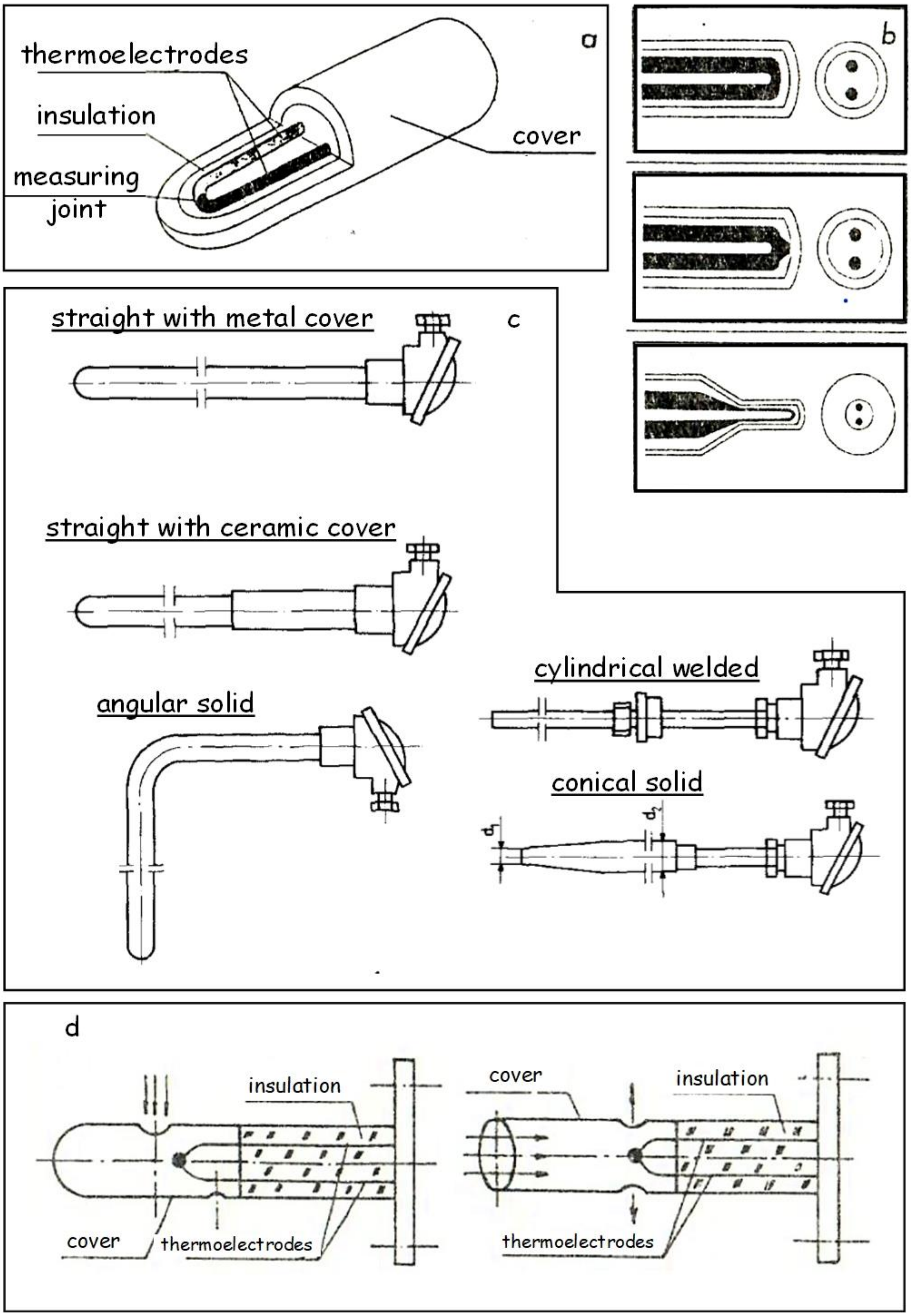

Fig. 6 Examples of thermocouple design solutions: a) sheathed thermocouple; b) types of measuring cells of sheathed thermocouples; c) industrial thermocouple designs ($\varphi_{sheathed}$ = 6 ÷ 30 mm, L=0.2÷2 m); d) aviation thermocouples (for total temperature measurement).

In addition to the standard thermocouple covers, there are various designs available to meet specific requirements (see Fig. 6 c and d).

To ensure accurate measurements, it is important to insulate thermoelectrodes from each other. This can be achieved by using insulating single-hole or double-hole tubes and beads. When working with platinum thermocouples, it is crucial to ensure tight insulation with low silicon content. At high temperatures, ceramic insulation may experience a decrease in resistance value, so it is important to carefully insulate the junction under such conditions. Neglecting this precaution can result in significant errors due to leakage currents.

4. THERMOELECTRIC FORCE (TEF) MEASUREMENT OF THERMOCOUPLES

The primary output signal of the thermocouple is TEF, which is a non-linear function of the difference between the measured and reference temperatures. This signal can be either converted to a normalised signal in an amplifier or fed to a meter or recorder. The former solution is more commonly used, but there are situations where it is advisable to measure the TEF of the thermocouple and the corresponding temperature directly. This is often the case when there are few measuring points, a simple measurement and control system, negligible distances between the thermocouple and the meter, and no sources of interference.

When converting to a digital signal, it is necessary to linearise the signal using one of the methods described in most metrology textbooks.

DC millivoltmeters, automatic compensators, and digital meters and systems are utilized to directly measure the Seebeck thermoelectric force of thermocouples under industrial conditions. The use of the former is justified when an inaccuracy class of 1 to 1.5 is acceptable.

Assuming a certain value of external resistance R_Z, millivoltmeters with a temperature-based scale are described. Changes in R_Z result in alterations in the sensitivity of the millivoltmeter

$$\Delta S = \frac{\Delta U}{E_n} = \frac{\Delta R_Z}{R_Z + R_m} \tag{7}$$

and, consequently, affect the temperature indication error. The thermoelectric force of the thermocouple for the upper limit of the range is denoted by E_n, while R_Z represents the resistance of the millivoltmeter. To maintain the desired accuracy class of measurement with the expected change in ΔR_Z, it is necessary to select an appropriate value of R_m. Therefore, high resistance millivoltmeters (200÷1000 Ω) with low power consumption should be used, and R_Z should be poorly selected (around 5÷10 Ω) from an energy matching perspective.

Variations in resistance ΔR_Z occur due to wear of the thermocouple, changes in thermocouple resistance under the influence of the measured temperature, and changes in the resistance of the wires connecting the thermocouple to the meter. The requirements for the leads are contained in the relevant standards. Automatic compensators are required for higher accuracy requirements and high external circuit resistance.

Digital systems are employed for control or central data recording tasks, particularly when there are numerous measuring points or when high precision is required. Digital measurement assumes linearity of characteristics for small temperature changes, while linearisation is necessary for a wide measurement range.

Figure 7 displays a schematic diagram of a converter that transforms the Seebeck Thermoelectric Force (TEF) of a thermocouple into 10÷50 mA DC and 1÷5 A DC output signals that are proportional to the EMF. This converter, as per the Yokogawa General Catalog, has a measurement range of 3 mV to approximately 60 mV with a zero shift from -10 mV to about 60 mV. The input impedance is around 200 Ω and its current output cannot be loaded with an impedance greater than 200 Ω. The converter's accuracy and sensitivity are ±0.5% and ±0.02% of the measuring range, respectively. A linearising circuit can be used to make the converter, ensuring that the non-linearity of the thermocouple characteristics does not exceed 10%.

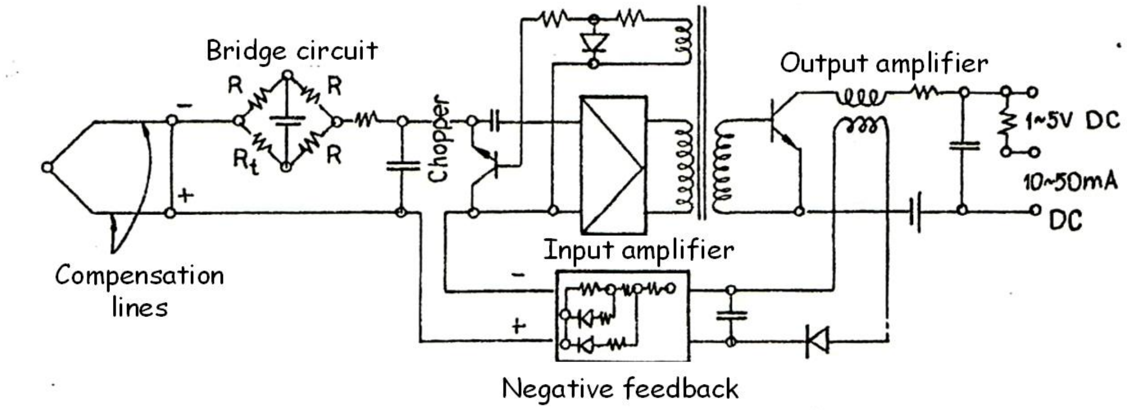

Fig. 7 Schematic diagram of a converter converting the TEF of a thermocouple into a normalised DC current signal proportional to the TEF.

5. COMPENSATION FOR THE EFFECT OF VARIATIONS IN REFERENCE TEMPERATURE

If the reference temperature, T_0, used during calibration is changed to T'_0, an error in the readings will occur (Fig. 8).

$$\Delta \mathrm{T_m} = \frac{\tan\alpha}{\tan\beta}(T_0 - T_0') \qquad (8)$$

where $\tan\alpha = \frac{dE}{dT}$ for temperature $(T_0 + T_0')$ and $\tan\beta = \frac{dE}{dT}$ for temperature $T_m + \Delta T_m/2$.

For rectilinear thermocouple characteristics, $\Delta T_m = -(T_0 - T_0')$ always occurs. As the temperature of the reference junctions tends to fluctuate significantly in real conditions, it is necessary to compensate for its influence. This is achieved by using one of the following methods:

a) by moving the junctions away from the object to an area with little temperature variation;
b) by stabilising the junction temperature of the reference junction;
c) by adding a voltage in the measuring system corresponding to a change in the thermoelectric force $E = f(T - T_0')$;
d) by mechanically shifting the zero of the millivoltmeter.

Ad. a) By using compensating conductors, reference junctions can be moved to a more convenient location. These conductors are wires attached to the thermocouple head, made of a material with thermoelectric properties identical to those of the thermocouple used. For base metal thermocouples, the compensating conductors are made from the same alloy as the corresponding thermocouple arms. For base metal thermocouples, the compensating conductors are made from the same alloy as the corresponding thermocouple arms. For base metal thermocouples, the compensating conductors are made from the same alloy as the corresponding thermocouple arms. For example, for the PtRh-Pt thermocouple, they are made from suitably selected copper and nickel alloys. The use of compensation wires is standardised.

Ad. b) The reference junctions' temperature is stabilised using electrically heated thermostats at a higher temperature than the ambient. The thermostats are standardised, and the temperature stabilisation accuracy ranges from 0.1 to 1 K, depending on the requirements. The mechanical zero of the temperature indicator must correspond to a stabilisation temperature of 50°C (in our climate). For control and laboratory purposes, ice melting is used to stabilise the reference temperature.

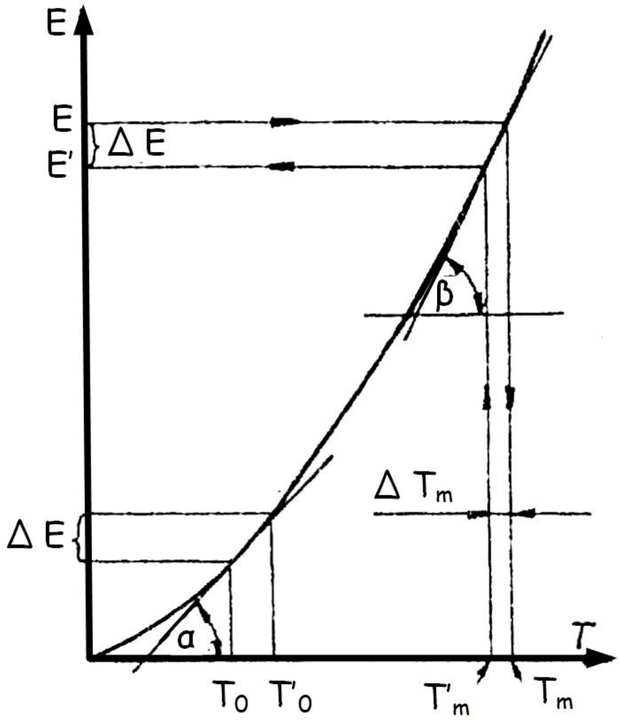

Fig. 8 Graphical method for determining the correction to the measured TEF value when the reference temperature T'_0 is not equal to the rated temperature T_0.

Ad. c) The compensation of the reference temperature can be achieved with sufficient accuracy by introducing a compensating voltage into the circuit, as demonstrated in Figures 9 and 10.

Figure 9, Case A, illustrates compensation using an unbalanced bridge placed at temperature T0 for a reference junction. The bridge comprises three invariant resistors, R, and a resistor with a resistance that varies with temperature, such as copper, where R_0 = R at the normal reference temperature T_0. At T'_0, we have

$$R_t = R_0[1 + \alpha_0(T_0' - T_0)]$$

The temperature coefficient of resistance R, related to T_0, is represented by α_0. Therefore, the bridge is in equilibrium at T_0. At temperature T'_0, the equilibrium voltage is

$$U_N = U_Z\left(\frac{R_t}{R_t + R} - \frac{1}{2}\right) \tag{9}$$

where: U_Z - bridge supply voltage. For small changes in the reference temperature, the change in thermoelectric power of the thermocouple at a constant measuring junction temperature Tm, is determined with sufficient approximation by the formula $\Delta E=k(T_0-T'_0)$, where k=dE/dT. Hence, the compensation condition $\Delta E = U_N$. From equation (9), for a given difference in ambient temperature ΔT_0 and the corresponding ΔE, after neglecting the higher order quantities, the correct value of the bridge supply voltage can be calculated

$$U_z = \frac{4k}{\alpha} \tag{10}$$

A practical application of this way of compensating for changes in reference temperature is shown in Figure 7.

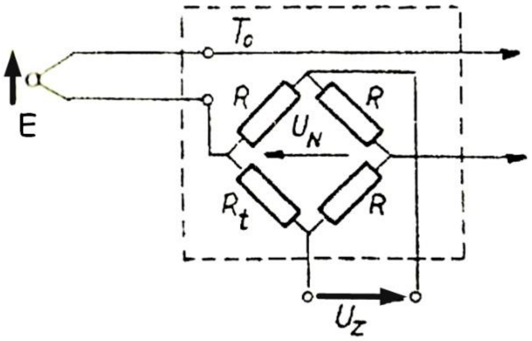

Fig. 9 Bridge circuit to compensate for variations in ambient temperature T_0 with T_0-dependent resistance.

Figure 10, Case B, depicts a compensating system with an equilibrium condition defined by the relation.

$$E - E_0 = U_Z\left(\frac{R_1}{R_1 + R_2} - \frac{R_t}{R_t + R_3}\right) \tag{11}$$

where: $R_1=R'_1+r_1$ and $R_2=R'_2+r_2$ denote the resistances at the measured temperature T_m and

$$R_t = R_0[1 + \alpha_0(T'_0 - T_0)]$$

where R_0 and α_0 refer to the normal ambient temperature T_0, while T'_0 denotes the actual ambient temperature and E and E_0 the thermoelectric force of the measuring junction and the reference junction. Assuming that R=idem and E0=var, the condition for correct compensation is obtained as follows

$$\frac{d(E - E_0)}{dT} = U_Z \frac{d\left(\frac{R_1}{R_1 + R_2} - \frac{R_t}{R_t + R_3}\right)}{dT} \tag{12}$$

After completing the actions, the result is obtained

$$\frac{dE_0}{dT} = k = U_Z 2\alpha_0 R_0 \frac{R_3}{R_3 + R_0} \tag{13}$$

The expression $\alpha_0 R_0(T'_0-T_0)$ is omitted here as it is a small quantity in the denominator. It is assumed that $r_1 \ll R'_1$ and $r_2 \ll R'_2$ and that both $k=dE_0/dT$ and α_0 are linear over the range of ambient temperature changes. Formula (13) can be used to calculate α. To select the ratio of manganese to copper or nickel for the R_t branch, or to calculate the value of R_0 given a certain α, formula (13) can also be used.

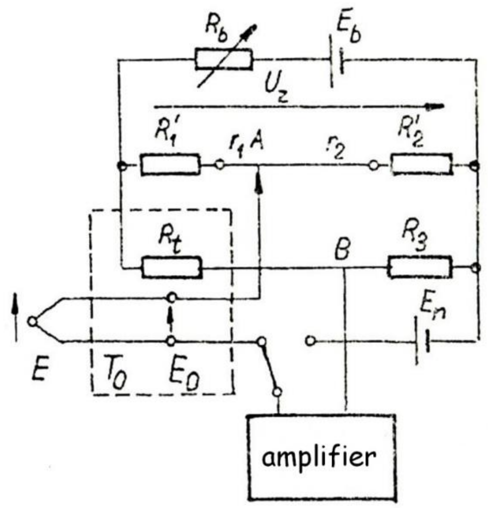

Fig. 10 Compensating bridge circuit with ambient temperature-dependent resistance used in compensators.

Ad. d) To measure thermoelectric force, compensation can be achieved by adjusting the mechanical zero to ensure that the pointer constantly indicates the actual reference temperature when the circuit is open. This adjustment is made using a bimetal strip to move one of the millivoltmeter's return springs accordingly.

6. SYSTEM OF CONNECTIONS OF MEASURING INSTALLATIONS

In multi-point metering installations, significant savings can be made on expensive and highly resistive compensating cables by using junction boxes close to the metering points. The boxes can be thermostatically controlled. With a larger number of points, it is more convenient to use the temperature of a separate thermostat as a reference temperature and to compensate for the difference (Fig. 11) between the temperature T'_0 of the box and T_0 of the reference (thermostat) by means of a thermocouple in series with the measuring thermocouples, whose thermoelectric force adds up to the measuring one.

The use of a common conductor for one of the poles is only acceptable at low temperatures and with excellent insulation, as serious errors can easily occur due to stray currents.

Several thermocouples placed at different points in the medium can be used to measure the average temperature of the medium by connecting them in series or in parallel. In the first case, for $R_m \approx \infty$ (Fig. 11), we have $E = \sum_{i=1}^{n} E_i$ so, assuming a linear thermocouple characteristic E=cT, we obtain $\bar{T} = \frac{E}{cn}$. In the second case (Fig. 13) we have $E = \frac{1}{n}\sum_{i=1}^{n} E_i$ or for $E_1 = cT_1$, also $T = \frac{1}{n}\sum_{i=1}^{n} T_i$ where $R_m \approx \infty$ or there must be equality of resistance of all circuits. The quantity R_m is the resistance of the meter and n is the number of thermocouples.

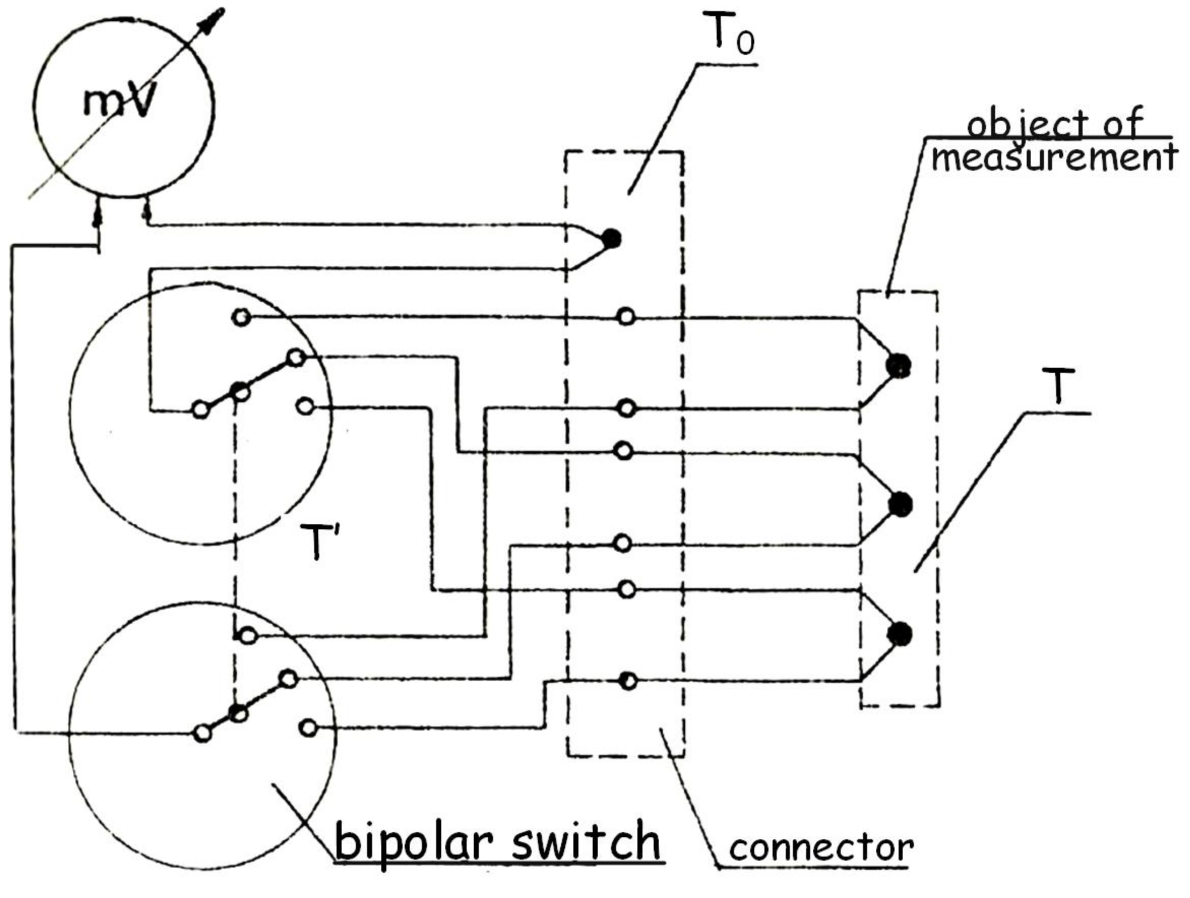

Fig. 11 Box with connector and bipolar switching and reference thermocouple

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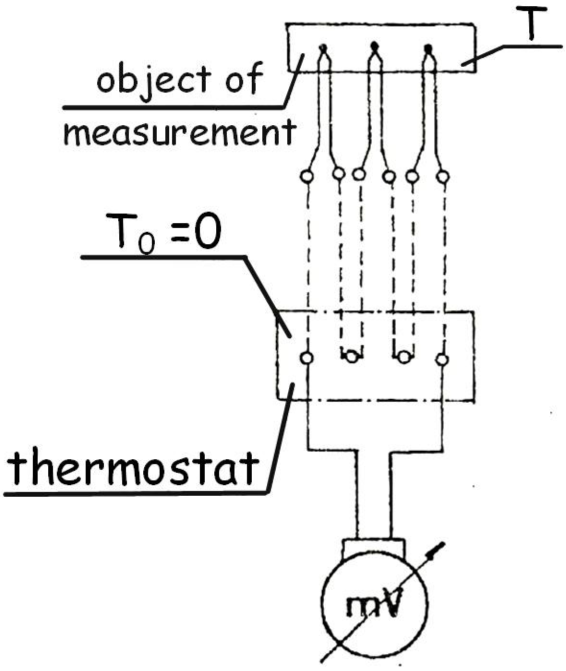

Fig. 12 Serial thermocouple array to measure average temperature.

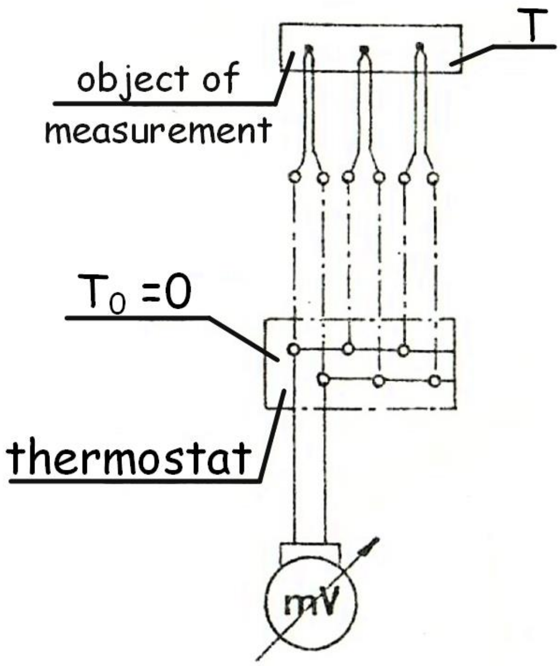

Fig. 13 Parallel thermocouple array for average temperature measurement.

The installation of resistance thermometer and thermocouple leads must be carried out with great care. Detailed requirements are given in the relevant standards. The cross-section of the wires should be at least 1.5 mm^2. The cables should be laid in such a way as to avoid damage and the influence of high-voltage networks. Connections should be made with terminals protected against corrosion and damage. The insulation resistance between conductors and earth must be greater than 3 MΩ. In systems using electronic compensators or digital millivoltmeters, measures must be taken to eliminate noise and variable components.

7. THERMOCOUPLE CALIBRATION

In order to determine the thermoelectric properties of the thermocouple, it is necessary to characterise it, i.e. to determine the dependence of the thermoelectric voltage value generated by the thermocouple as a function of the temperature difference between the measurement junction and the reference junction.

Figure 14 shows a typical block diagram of a thermocouple calibration system under laboratory conditions. The junctions of the thermocouple under test and the thermocouple to be calibrated are placed in the measuring chamber of the electric furnace. The reference junctions of the thermocouples are placed in a thermostat which maintains a constant and known temperature. The indicated voltages of the two thermocouples are read on a digital voltmeter via a special switch. By varying the temperature of the furnace and determining its value with a reference thermocouple, the voltage value for the thermocouple under test is read. This allows the thermocouple to be characterised - E=E(ΔT).

The exercise uses an electronic thermostat that maintains an internal temperature of 50°C with a tolerance of ±0.2°C. It is sometimes useful to place the reference junctions in a thermos flask containing a mixture of distilled water and ice to ensure a constant temperature of 0°C.

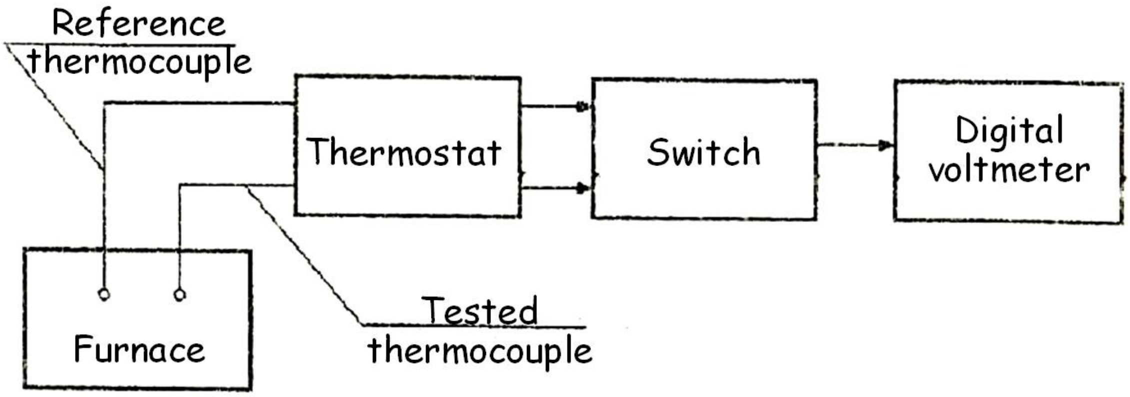

Fig. 14 Schematic diagram of the thermocouple calibration system.

8. DETERMINATION OF THE TIME CONSTANT OF THE THERMOCOUPLE

The thermoelectric force TEF of a thermocouple E(t) exposed to a step change in temperature $\Delta T = T_1 - T_0$ as shown in Fig. 15 is given by a function of type

$$E(t) - E_0 = (E_1 - E_0)\left(1 - e^{-\frac{t}{\tau}}\right) \quad (14)$$

where:

E_0 - thermoelectric force corresponding to the initial temperature T_0;

E_1 - thermoelectric force corresponding to the end temperature T_1;

t - time; τ - time constant.

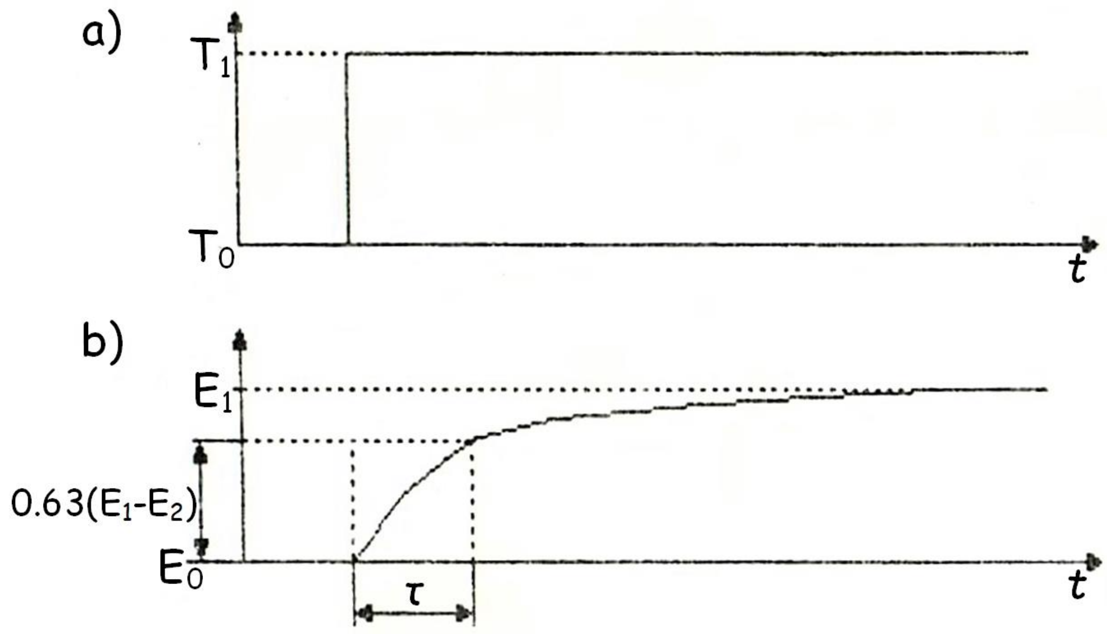

Fig. 15. Figure illustrating the concept of time constant of a thermocouple: (a) temperature step forcing; (b) sensor response.

Relationship (14) is only valid under the assumption that the thermocouple (more precisely, the thermocouple junction) can be treated as an element with concentrated parameters. For the value t=τ we have

$$E(\tau) - E_0 \cong 0{,}63 \cdot (E_1 - E_0) \tag{15}$$

i.e. that the TEF reaches approximately 63% of the maximum amplitude (E_1- E_0) of the variation in its value.

The time τ, after which the TEF reaches 63 % of its change from the value (E_1-E_0), is commonly used to determine other values for the percentage change in TEF relative to the total TEF. These values are presented in below table.

Value of (E_1-E_0) [%]	63%	80%	90%	95%	98%	99%
Time from the start of the forcing	τ	1,6τ	2,3τ	3,0τ	4,0τ	5,0τ

The response time is shorter when the medium in which the sensor is placed has a high heat capacity, conducts heat well and when the thermal resistance between the medium and the thermocouple is low.

These conditions occur when a thermocouple is placed in a liquid metal stream. The response time is then reduced to a minimum and depends only on the type of thermocouple, its geometry, thermal conductivity coefficients, and the thermal capacity of the sheath and insulation.

The response time of the sheathed thermocouple decreases with better insulation compaction (improved thermal conductivity), smaller thermocouple diameter, and closer thermocouple junction to the sheath.

A schematic of Figure 16 shows a test station used to measure response times in the gas stream.

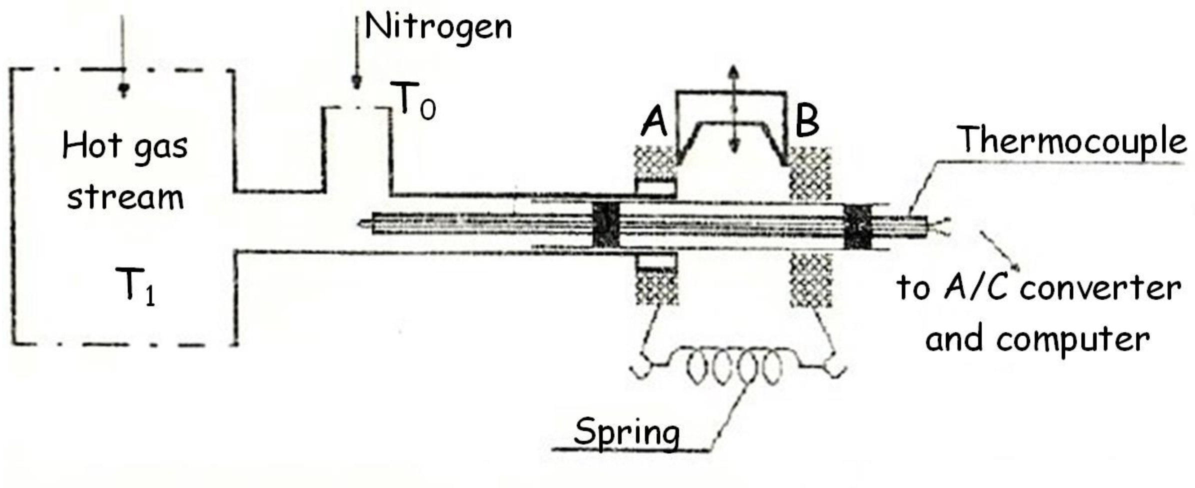

Fig. 16. Schematic diagram of a device for injecting a measuring sensor into a hot gas stream for determining the time constant.

A thermocouple device is used to measure the temperature of a gas stream (T_1 temperature of about 350÷500 K). The device consists of a thermocouple placed in a small tube that can be inserted into a channel or duct with the help of a spring mechanism. The spring is tensioned and set in the 'shot' position by a metal pin pressed between the A and B rings. In this position, a small channel is available to hold the junction of the thermocouple in a stream of nitrogen, which is considered the ambient temperature T_0. The thermocouple's thermoelectric force is then transmitted to the computer input through an amplifier and analogue-to-digital converter. The measurement begins when the A and B rings make contact. The monitor screen displays the STE change curve and stores it in the computer's memory.

9. PROCEDURE FOR CARRYING OUT THE MEASUREMENTS

1. Start the measuring system.
2. Prepare the thermocouple to be injected into the hot air flow - stretch the thermocouple spring.
3. Start DAS-TC Datalogger software.
4. Set the software parameters as directed by the laboratory instructor.
5. Start data recording in DAS-TC Datalogger software while injecting the thermocouple.
6. After completion of the measurement (approx. 100 seconds), save and download the results for further processing.

What the class report should contain:

1. Title page with group number and list, details of the instructor.
2. A short theoretical introduction about thermocouples - maximum 1 page.
3. Purpose and scope of measurements.
4. Description of the measurement procedure and measuring site.
5. Presented results of measurements - calculations, measurement errors, tables, graphs, etc.
6. Conclusions - conclusions should include the results obtained and a commentary on these results. Description of any errors made by the measurer.

LITERATURE

[1] Michalski L. Eckersdorf K. Temperature measurements. WILEY. New York 2001.

[2] Wiśniewski S. Pomiary temperatury w badaniach silników i urządzeń cieplnych. WNT. W-wa 1983.