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Theory and Practice of Temperature Measurement by Thermoelectric Transducers

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Abstract

Temperature is one of the main parameters that determine the quantitative and qualitative indicators of products. Therefore, it is difficult to name a field of technology or a branch of industry where it would not be necessary to measure the temperature of solid, liquid, or gaseous substances. Along with this, it should be noted that in each specific field, the choice of methods and means of temperature measurement is determined by its specificity, which is related to the variety of technological objects, the nature of the process, the physical and chemical characteristics of the environment under investigation, the range of measured temperatures, the requirements for the necessary measurement errors, etc. Therefore, choosing a measurement method for a specific technological object is a difficult task, since it is necessary to take into account a large number of factors that can quite often be contradictory. Thus, liquid-in-glass thermometers make it possible to measure the temperature directly near the technological objects. With the help of manometric thermometers, it is possible to measure the temperature at some distance from the research objects. It should also be noted that such thermometers must be constantly connected to the primary transducer by a connecting capillary. Unlike the above, electric thermometers allow for remote temperature measurements at any distance between the primary transducer and the secondary device. Thermoelectric transducers (thermocouples) and resistance thermotransducers have become the most widely used electric thermometers for industrial applications. This is a review paper and contains information on the features of temperature measurement using thermoelectric transducers (thermocouples).

Keywords: temperature; thermocouple; thermoelectric transducer; thermoelectrode; extension and compensation wires; measurement error.

1. Definition of the scientific problem chosen for research

The phenomenon of thermoelectricity (Seebeck effect), discovered in 1821 by Seebeck, is used to measure temperature with thermoelectric transducers (hereinafter referred to as thermocouples). Analysis of design, production and operation problems shows that the quality of thermocouples, their operational and metrological characteristics are determined by the degree of excellence of the structure and chemical composition of thermometric and structural materials, the stability and reproducibility of their electrophysical and mechanical characteristics in a wide range of temperatures. It is also necessary to pay attention to the chemical resistance and mechanical strength of protective fittings for specific research objects. For the effective use of thermocouples, it is necessary to develop criteria for choosing the optimal type for the given measurement conditions and their rational placement on the technological object from the point of view of the necessary time to establish readings in the measured environment. The correct use of thermocouples makes it possible to solve special problems of temperature measurement with fairly simple means.

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2. Analysis of recent publications and studies related to this problem

The results of the authors' analysis show that there is currently sufficient scientific development of the theoretical foundations of temperature measurements using thermocouples [1], [2]. But there is no general theory for creating their optimal construction designs, which would ensure minimal error when they are affected by time-varying disturbances that are random functions of time. Some issues of designing thermocouples for various application conditions have been worked out, but such problems as developing their mathematical model, analysis, forecasting and calculation of component measurement errors and some others have not been sufficiently developed.

One of the directions for creating high-precision and reliable thermocouples for temperature measurement in various industries is the use of thermometric and structural materials with special properties, high stability of their electrochemical, chemical and mechanical properties in a wide range of temperature changes. In particular, publication [3] focuses on the study of structural thermal and electrical insulating materials.

Publications [1], [2], [4] and others focus on the study of thermometric materials, in which their thermoelectric properties, the influence of the studied environments, radiation, high pressure, deformations, thermocyclic influences, etc. on the change of the thermoelectromotive force (thermoEMF) and its stability are sufficiently studied. Therefore, in this review article, we will perform only the analysis and evaluation of thermoelectric materials from the point of view of their possible application during temperature measurement for various analyzed environments.

3. Formulation of the goal of the article

The goal of the article is to review the features of temperature measurement using thermoelectric transducers (thermocouples) and to present the review to scientific, engineering and technical workers dealing with issues of temperature measurements.

To achieve the specified goal, the following main tasks of the research are defined: to formulate the theoretical basis, requirements to materials for thermocouples, the main figures and permissible deviations from them, to substantiate construction design features for the possibility of using thermocouples in various conditions of application.

4. Presentation and discussion of research results

4.1. Theoretical foundations of thermoelectricity

Thermocouples use the phenomenon of thermoelectricity discovered in 1821 by Seebeck (Seebeck effect) to measure temperature. If two conductors of different materials (conductors, semiconductors) A and B are connected at their ends in a closed circuit (Fig. 1a) and the connection points are at different temperatures t_2 and t_1, then an electric current arises in the circuit [1], [4]. Both thermal conductors, which are called thermoelectrodes, form a thermocouple. One of the connection points, placed in the test conditions with the measured temperature, serves as the working (or hot) end of the thermocouple. The other, which is at a constant known temperature, is the free (or cold) end of the thermocouple.

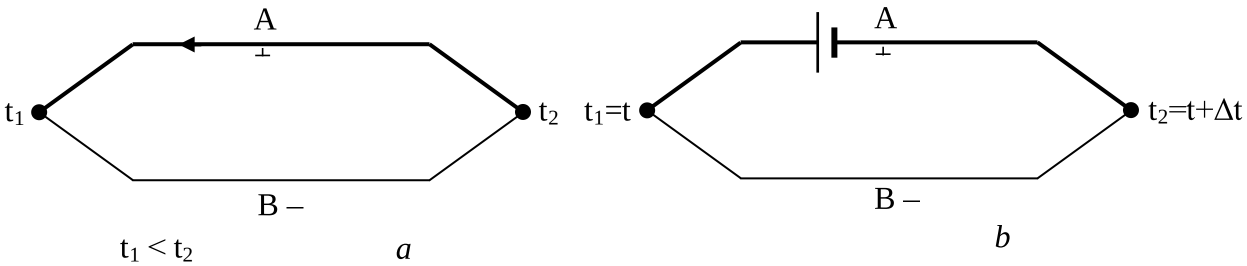

Fig.1. Seebeck (a) and Peltier (b) effect: *a* - thermocircuit with thermoelectrodes A and B; *b* – thermal circuit with a current source; t_1 and t_2 are the connection points temperatures of thermoelectrodes A and B.

The heat flux Φ is determined by the dependence

$$\Phi_P = P \cdot I, \tag{1}$$

where P is the Peltier coefficient, which depends on the material of both thermoelectrodes and the temperatures t_2 and t_1 of the contact points; I is electric current.

During the passage of electric current I in a closed circuit due to the Thompson effect, thermoelectrodes will be heated or cooled if there is a temperature difference in them. This heat flow is also proportional to the current I and the temperature gradient ΔT in both thermoelectrodes:

$$\Phi_T = \sigma \cdot I \cdot \Delta T, \tag{2}$$

where σ is the Thompson coefficient, which depends on the material of the thermoelectrodes and on the measured temperature T.

If the measuring junction of the thermocouple is at temperature $T + \Delta T$, and the reference junction is at temperature T, then thermoEMF

$$E = \frac{dE}{dT}\Delta T \tag{3}$$

and it is determined by the sum of the Peltier and Thompson effects, i.e

$$E = \frac{dE}{dT}\Delta T = P_{(T+\Delta T)} + \sigma_A \Delta T - \sigma_B \Delta T \tag{4}$$

$$\text{or} \quad \frac{dE}{dT} = \frac{P_{(T+\Delta T)} - P_{(T)}}{\Delta T} + \sigma_A - \sigma_B. \tag{5}$$

It follows from equation (5) that

$$\frac{dE}{dT} = \frac{dP}{dT} + (\sigma_A - \sigma_B). \tag{6}$$

After the transformations from (6), we derive the relationship between the thermoEMF E and the Peltier P and Thompson coefficients σ:

$$P = T\frac{dE}{dT} \tag{7}$$

$$\sigma_B - \sigma_A = T\frac{d^2E}{dT^2}. \tag{8}$$

Equations (7) and (8) are the fundamental equations of thermoelectricity. From them, you can get all the thermoelectric properties of the thermocouple, for example, the nonlinear dependence "temperature - thermoEMF":

$$E = aT + bT^2. \tag{9}$$

4.2. Requirements for the selection of alloy components for thermoelectrodes

Different thermoelectric properties of individual thermoelectrode materials are explained based on the electronic theory of solids [5], [6]. However, quantitative assessment is difficult to carry out in most cases. Therefore, the characteristics of thermoelectric properties are studied on the basis of dependencies determined empirically. If the binary thermoelectrode alloy has a small content of some component in the base metal, then it has approximately the same properties as the base metal. If the content of the component increases, then the thermoelectric properties of the thermoelectrode will differ significantly from the base metal in thermoelectric potential. In ternary or more complex alloys, the influence of the components cannot be traced.

Therefore, small changes in the composition of the thermoelectrode alloy do not significantly affect its thermoelectrode potential. So, there are no difficulties in manufacturing thermoelectrode alloys with the same thermoelectric properties in industrial production. It should also be noted that alloying additives should improve the corrosion resistance of the thermoelectrode alloy, but in no case should it deteriorate.

4.3. General requirements for thermoelectrode materials

When measuring temperature using thermocouples, it is preferable that the thermoEMF be large enough and its electrical resistance should be small. This will make it possible to measure the temperature without additional amplifiers, also on a sufficiently large section between the measurement location and the measuring device or regulating device. Materials for thermocouples must have a high melting point, must be able to be manufactured in sufficient quantity with stable quality, and must be easily processed to shape them as necessary. In the working temperature range, thermoelectrode materials should not undergo allotropic transformations that can cause jump-like changes in thermal EMF, thermoelectrodes should have sufficient corrosion resistance and the ability to be operated in oxidizing and restorative environments without changing their thermoelectric properties.

The alloying elements included in the composition of the thermoelectrode alloy should not diffuse to the surface as a result of selective oxidation or evaporate at high temperature. If these conditions are met during a long period of operation, then the thermocouple will have a uniform and stable "temperature - thermoEMF" dependence. At the same time, the thermoEMF values in the entire working range will be within the limits of permissible errors.

It is also necessary to pay attention to the fact that thermoEMF should change as little as possible during mechanical loads on the thermocouple (stretching, bending, twisting, etc.). The properties of thermoelectrodes are significantly affected by cold deformation. Therefore, to achieve consistency of thermoEMF, thermoelectrodes or ready-made thermocouples are often stabilized by electric heating at a sufficiently high temperature.

The thermoelectrodes of the thermocouple may gradually become inhomogeneous during operation due to possible oxidation because of the temperature difference along their length. The degree of such oxidation depends exponentially on the temperature. It sharply decreases when the temperature drops and does not affect the measurement results at a constant depth of immersion of the thermocouple in the medium under study. But when the depth of immersion is changed, the inhomogeneity arising from the oxidation of the thermocouple thermoelectrodes can lead to an increase in the measurement error.

4.4. Technical characteristics and permissible deviations of thermoelectric power

They are regulated by the state standard of Ukraine [7], which fully corresponds to the European standard [8]. This standard establishes common functions (nominal static conversion characteristics) for thermocouples of types R, S, B, J, T, E, K, N, C and A. The temperature is expressed in degrees Celsius, which corresponds to the International Temperature Scale 1990, ITS-90 (symbol t_{90}).

The standard functions are polynomials that express the thermoEMF E as a function of the temperature t_{90} of thermocouples with free ends at a temperature of 0 ℃. This standard also establishes tolerances for thermocouples manufactured in accordance with this standard. The tolerance values apply to thermocouples that are supplied to the consumer and are made of wire with a diameter of 0.13 to 3.2 mm and do not allow for displacement of the graduation during operation. Thermocouples are identified by the materials of the conductors, the positive conductor must be indicated first as: "positive conductor/negative conductor". The positive conductor has a positive electrical potential relative to the second conductor when the measuring junction is at a temperature higher than the reference junction.

Table 1 shows the types of thermocouples. Each letter from the table identifies the standard "thermoEMS-temperature" dependence function.

Table 1. Types of thermoelectric transducers.

Letter designation	Elements and nominal alloy components by weight	
	Positive conductor	Negative conductor
R	Platinum-13% rhodium (platinum rhodium13)	Platinum
S	Platinum-10% rhodium (platinum rhodium 10)	Platinum
B	Platinum-30% rhodium (platinum rhodium 30)	Platinum-6% rhodium (platinum rhodium 6)
J	Iron	Copper-nickel (constantan)
T	Copper	Copper-nickel (constantan)
E	Nickel-chromium (chromel)	Copper-nickel (constantan)
K	Nickel-chromium (chromel)	Nickel-aluminum (alumel)
N	Nickel-chromium-silicon (Nicrosil)	Nickel-Silicon (Nisyl)
C	Tungsten-5% rhenium	Tungsten-26% rhenium
A	Tungsten-5% rhenium	Tungsten-20% rhenium

It should be noted that, in addition to the above, thermoelectric converter type L (chromel-copel) is used in Ukrainian industry. Positive electrode – nickel-chromium (chromel); negative – copper-nickel (copel).

The relationship between temperature and thermoEMF in this standard is determined by standard functions that give the dependence of thermoEMF as a function of temperature t_{90} at a temperature of free ends of 0 ℃. The standard functions in the form of a polynomial for each type of thermocouple, except for type K, in the temperature range from 0 to 1300 ℃ are defined by the following equation:

$$E = \sum_{i=0}^{n} a_i \, t_{90}^{i}, \tag{10}$$

where a_i are polynomial coefficients; n is the degree of the polynomial.

The values of a_i and n depend on the type of thermocouple and its temperature range and are given in the standard [7].

For a K-type thermocouple in the temperature range from 0 to 1300 ℃, the standard function is defined by the following equation:

$$E = \sum_{i=0}^{n} a_i \, t_{90}^{i} + c_0 \exp[c_1(t_{90} - 126.9686)]^2, \tag{11}$$

where c_0 and c_1 are constants specified in the standard.

4.5. Permissible deviations of thermocouples

The standard [7] establishes permissible deviations of thermoEMF from the nominal values depending on the temperature range and tolerance class of the thermocouple (Table 2).

Table 2. Values of tolerances (±°C) and temperature ranges of measurement.

Thermoelectric transducer type	Values of tolerances (±°C) and temperature ranges of measurement		
	Class 1	Class 2	Class 3
	0.5 or 0.004|t|	1 or 0.0075|t|	1 or 0.015|t|
Type T	From - 40 °C to 350 °C	From - 40 °C to 350 °C	From - 200 °C to 40 °C
	1.5 or 0.004| t|	2.5 or 0.0075| t|	2.5 or 0.015| t|
Type E	From - 40 °C to 800 °C	From - 40 °C to 900 °C	From - 200 °C to 40 °C
Type J	From - 40 °C to 750 °C	From - 40 °C to 750 °C	—
Type K	From - 40 °C to 1000 °C	From - 40 °C to 1200 °C	From -200 °C to 40 °C
Type N	From -40 °C to 1000 °C	From - 40 °C to 1200 °C	From - 200 °C to 40 °C
	1 for t < 1100 °C or [1 + 0.003(t -1100)] for t > 1 100 °C	1.5 or 0.0025|t|	4 or 0.005|t|
Type R or S	From 0 °C to 1600 °C	From 0 °C to 1600 °C	—
Type B	—	From 600 °C to 1700 °C	From 600 °C to 1700 °C
	—	0.01|t|	—
Type C	—	From 426 °C to 2315 °C	—
	—	0.01|t|	—
Type A	—	From 1000 °C to 2500 °C	—

It is noted that consumers should take into account that the permissible deviations specified in Table 2 apply only to new thermoelectrodes and do not allow for changes in thermoEMF that may occur during the operation of thermocouples. Values of permissible deviations and measurement ranges that differ from the values in table 2 must be agreed between the manufacturer and the consumer. In Table 2 |t| is absolute value of temperature.

4.6. Thermocouples made of non-noble materials

To measure the temperature in the range from 0 to 1300 ℃, in most cases, thermocouples from non-noble materials are used [1], [4]. According to [7], thermocouples of types T, J, K, E, N and in Ukraine type L are standardized from non-noble materials.

Type T thermocouple (copper/copper-nickel or nickel/constantan). The operating temperature range of the thermocouple is from -200 (250) to 400 ºC (600 ºC). Hereinafter, the values in parentheses are for short-term use. Such thermocouples are mainly used for measurements in the range not higher than 200 ºC, since copper oxidizes at higher temperatures. In a renewable environment, they can be used for temperature measurements up to 600 ºC for a long time. Due to the low thermal conductivity of thermoelectrodes, such thermocouples are used to measure the temperature of small objects to ensure low errors due to heat dissipation [9]. It should be noted that copper is transformed into zinc and nickel under the influence of neutron radiation. Therefore, such thermocouples cannot be used for measurements in nuclear reactors.

Type J thermocouple (iron/constantan). Such thermocouples are used for measurements in the temperature range from -200 (250) to 700 ºC (900 ºC). Above 700 ºC, the iron thermoelectrode begins to oxidize, but in a renewable environment its corrosion is minimal. In wet environments, the iron thermoelectrode is subject to rust. In industrial gases containing sulfur at a content of up to 0.01%, the constantan thermoelectrode may become fragile due to the formation of nickel sulfides, but the thermal EMF practically does not change. Such thermocouples can be used for temperature measurements in salt baths. But for such measurements, the thermocouple must be constructed in the form of tubular thermoelectrodes. The constantan thermoelectrode must be placed inside a thin-walled iron tube, which will serve as the second thermoelectrode. The use of this construction design makes it possible to measure the temperature of the salt bath up to 900 ºC.

Type K thermocouple (nickel-chromium/nickel-aluminum). Such thermocouples are known as chromel-alumel and are the most common and have the best temperature resistance among thermocouples made of non-noble materials. The temperature range of thermocouples is from 0 (-250) to 1000 ºC (1300 ºC). To reduce the oxidation of nickel in the air, aluminum is added to the alumelthermoelectrode, due to which a dense oxide layer is formed. In addition, manganese and silicon are added to the chromelthermoelectrode, which protects it from the influence of sulfur, since these elements bind sulfur on the surface into sulfides. Therefore, it is less susceptible to oxidation and sulfurization. At a higher temperature and increased concentration of sulfur, embrittlement of thermoelectrodes is possible.

For all thermocouples made of non-noble materials, the repeated change of the oxidizing and reducing medium leads to a change in thermoEMF. And for a K-type thermocouple, these changes at a temperature above 1000 ºC can be significant already in a short period of time. In a neutral or renewable environment in the temperature range from 800 to 1000 ºC, oxidation of chromium in the chromelthermoelectrode is possible, which can lead to its destruction. It is important that chromel-alumel thermocouples are practically insensitive to neutron radiation and are used for temperature measurements in nuclear reactors.

Thermocouples of type E (chromel/constantan) and type N (nicrosil/nisyl) can be compared to chromel-alumel thermocouples in terms of their technical characteristics and temperature range, but it should be noted that the thermocouple of type N has increased stability due to the high content of chromium and silicon, which reduce the rate of oxidation of nickel alloys.

Type L (chromel/droplet) type thermocouple. These thermocouples are used in Ukraine to measure temperatures in the range from 200 to 800 ºC. It is advisable to use them for measurements in oxidizing environments. Sulfur-containing and renewable environment corrode the thermocouple and it quickly fails. Due to the high value of thermoEMF and low thermal conductivity of both thermoelectrodes, these thermocouples, in addition to industrial measurements, are used as radiation receivers in radiation pyrometers and for measuring small temperature gradients.

4.7. Thermocouples made of noble materials

Thermocouples made of noble materials are used to measure temperatures in the range from 1000 to 1800 ºC. These include S, R and B type thermocouples.

Type S thermocouple (platinum rhodium 10/platinum). It is mainly used for accurate measurements of high temperatures in the range from 0 to 1300 ºC. It is sufficiently stable in an oxidizing environment up to 1300 ºC. Gas environments with the presence of hydrogen, sulfur, and carbon, as well as impurities of lead, zinc, iron, and phosphorus, lead to a change in thermoelectric power. Silicon impurities lead to fragility of the platinum thermoelectrode. Therefore, silicon-containing insulating tubes or protective covers cannot be used to protect such thermocouples. Therefore, it is advisable to use protective tubes and covers made of pure aluminum oxide (alumina) Al_2O_3.

When measuring temperatures above 1000 ºC, rhodium may partially evaporate from the platinum rhodium thermoelectrode and settle on the platinum thermoelectrode. Due to this phenomenon, thermoEMF can decrease. Therefore, both thermoelectrodes must be well insulated from each other by protective insulating tubes to the working end of the thermocouple. Note that the platinum rhodium thermoelectrode is significantly less affected by various impurities. But under the influence of neutron radiation, rhodium turns into palladium. Therefore, thermoelectrodes containing rhodium should not be used in nuclear reactors. Platinum is quite resistant to neutron radiation.

Type R thermocouple (platinum rhodium 13/platinum). It is mainly used in Anglo-Saxon countries. It has almost the same properties as the S-type thermocouple, but it can work for a longer time in an oxidizing environment at a temperature of up to 1400 ºC.

Type B thermocouple (platinum rhodium 30/platinum rhodium 6). The thermocouple has a working temperature range from 0 to 1600 ºC (1800 ºC) and a lower thermal EMF than S and R type thermocouples. In the temperature range from 0 to 100 ºC, the thermal EMF changes very little and the temperature change in this range practically does not affect the measurement result. Therefore, the thermocouple is recommended to be used for measuring temperatures not lower than 300 ºC. The thermocouple is most widely used in the steelmaking industry for measuring the temperature of molten metals. The advantage of the thermocouple is also that thermoelectrodes are less prone to embrittlement compared to types S and R and to a much smaller effect on the change of thermoEMF from impurities of other metals. Evaporation of rhodium, which can settle on another thermoelectrode, also slightly changes thermoEMF in the temperature range up to 1000 ºC. At higher temperatures, this effect is already noticeable. It is advisable to use the thermocouple in an oxidizing environment. It can also be used in a renewable environment, but at temperatures not higher than 1200 ºC. Compared to thermocouples of type S and R, the thermocouple has higher stability at high temperatures and greater resistance to mechanical and chemical influences, but its thermal EMF is lower.

Other thermocouples from noble materials. An iridium-rhodium 60/iridium thermocouple is used for measurements in neutral and oxidizing environments up to a temperature of 2100°C. It is not standardized according to [7], but it is the only thermocouple made of iridium rhodium alloys that can be operated for a long time (up to 25 hours) in aggressive environments at temperatures from 1800 to 2100 ºC and is used mainly in laboratory and scientific research. With longer use, thermoelectrodes become fragile and can get destroyed. They are not used for measurements in nuclear reactors.

4.8. Thermocouples made of refractory metals and alloys

For temperature measurements in high-temperature reactors, jet engines, for regulation of high-temperature furnaces, etc., thermocouples with a range of operating temperatures above 2000 ºC are required. Thermocouples made of refractory metals and alloys are suitable for such measurements. The standard [7] provides tungsten/tungsten thermocouples of types A and C with a range of operating temperatures from 0 to 2200 ºC (2500 ºC). Thermocouples are suitable for temperature measurements in neutral and weakly renewable environments and in vacuum. Thermocouples are destroyed in an oxidizing environment. When operating in environments with the presence of carbon, silicon or in carbon-containing gases, tungsten carbides are formed on the thermal electrodes and thermocouples are destroyed. They can be used for measurements in nuclear reactors, but measurements must be made in an inert shielding gas environment.

4.9. Construction design features

When choosing a thermocouple for industrial measurements, it is necessary to proceed from the conditions of its operation. The maximum permissible temperatures largely depend on the diameter of the thermoelectrodes, as well as on the chemical interaction with the subject of research. To reduce the chemical impact of the thermocouple, it is necessary to place it in a hermetic case or fill the case with an inert gas.

The diameter of the thermoelectrodes should be chosen in such a way that the error due to heat removal because of thermal conductivity is insignificant and the inertia of the displays satisfies the consumer. For thermocouples made of non-noble metals and alloys, thermoelectrodes with a diameter of 0.2 to 3.2 mm are used in most cases, for noble ones – from 0.35 to 0.5 mm. In special cases, for example, when measuring the temperature of liquid steel, thermoelectrodes with a diameter of 0.03 to 0.08 mm are used.

For thermoelectrodes made of metals and their alloys for temperature measurement up to 150 ºC, the measuring junction can be formed by soldering with soft solders, for higher temperatures, thermoelectrodes are most often welded together in a neutral environment (in an argon environment). To measure the temperature of metal surfaces, it is enough to press the pointed ends thermoelectrodes into this surface (needle thermocouples). Thermoelectrodes of a very small diameter should be connected to each other through a thin galvanically deposited metal layer.

Structurally, thermocouples can be unprotected, which are used without protective fittings, and protected thermocouples with protective fittings made of different materials. Thermocouples without protective fittings should be used when there is no danger of their damage due to mechanical loads or due to chemical influences. It should be noted that thermocouples from all contact thermometers, due to the point shape of the measuring junction, can be quite easily adapted to specific application conditions. Therefore, they have found the widest application in the practice of technical temperature measurements.

When manufacturing and using thermocouples, it should be taken into account that they must be resistant to mechanical loads and chemical effects of gases and vapors, metal melts, etc. It is also necessary that the error due to the removal of heat due to thermal conductivity from the structure to the environment be as small as possible. When measuring rapidly changing temperatures, the readings of the thermocouple should quickly follow the changes in the temperature of the object under study [9].

Thermocouples are widely used in various industries – general industrial applications, for measuring high temperatures, converters with a unified output signal, for work in emergency and post-accident monitoring systems of nuclear reactors, etc. Detailed information on the designs of converters, which are mass-produced in Ukraine, can be obtained from the link [10].

Successful implementation of automation systems in metallurgical production is impossible without reliable and credible primary information about the temperature of the technological process. Temperature is one of the main parameters that determines the quantitative and qualitative indicators of finished products. Therefore, the technological processes of the metallurgical industry require the availability of a sufficient and diverse number of primary temperature transducers with high accuracy, sensitivity, stability and resistance to interference. Thermoelectric transducers for temperature measurement in metallurgy, including for measuring the temperature of metal melts, are described in detail in [11].

4.10. Cable thermocouples

Such thermocouples consist of one or more thermocouples placed in a metal shell, which is filled with a highly compressed powdery oxide insulating mass. In most cases, magnesium or aluminum oxides are used. In special cases, zirconium, thorium or beryllium oxides are used to measure high temperatures. The metal shell protects the thermocouple from possible chemical and mechanical impacts. Most often, it is made of stainless steel, as well as copper-nickel alloys or platinum rhodium, depending on the required temperature range.

The measuring junction of the thermocouple is generally isolated from the shell (Fig.2). The reference junctions of the thermocouple can be connected to a connection block in the thermometer head or connected to a connector. If, for example, only part of the thermocouple needs to be inserted into the pipeline, then it can be fixed anywhere along its length with the help of flanges, movable blocks with terminals, etc.

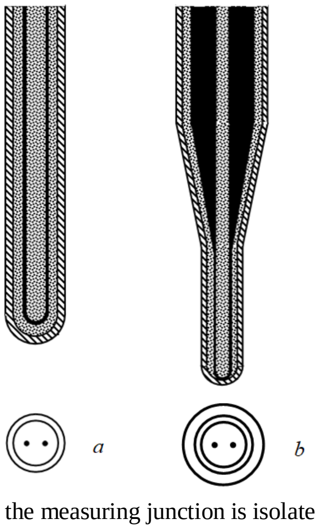

Fig.2. Cable thermocouple (section): *a* – the measuring junction is isolated from the shell; *b* – the measuring junction is narrowed and connected to the shell.

If the protruding end is too long, it can be bent and laid accordingly. Cable thermocouples from base metals and alloys can be made up to 400 m long, and from noble ones – up to 10 m. The outer diameter can be from 0.15 to 8 mm. Thermocouples with an outer diameter of 3 mm or more are widely used in practice.

Due to their design, such thermocouples have low inertia, minimal error from heat conduction to the environment, high resistance to cyclic temperature changes, strength to shock loads and pressures, as well as good flexibility. Thermocouple insulation does not break when twisted, stretched or bent. The permissible bending radius is one or two diameters of the outer shell.

Due to their flexibility, they can be placed in hard-to-reach places, welded, glued or simply pressed when measuring surface temperatures, as well as measure temperatures of bearings, turbines, etc. When measuring in nuclear reactors or high-pressure autoclaves, the required number of thermocouples can be introduced through one common inlet with a hermetic seal. Operation at static pressures up to 100 MPa is allowed. To measure the temperature along the height of the object under investigation, it is advisable to use the required number of thermocouples in a protective cover and distribute their working ends evenly along the length of the cover.

The technical characteristics of cable thermocouples are regulated by the state standard of Ukraine [12], which fully corresponds to the European standard [13]. This standard specifies requirements for simplex, duplex and triplex metal-sheathed mineral insulated thermocouple cables and thermocouples intended for use in general industrial applications. It covers thermocouple cables and thermocouples with T, J, E, K, and N non-precious material conductors only.

4.11. Extension and compensation wires

In order to exclude the influence of the ambient temperature on the readings of the thermocouple and to connect it to the measuring device, the reference junction must be separated by a considerable distance. At the same time, it is not necessary to use long thermocouples, it is more rational to extend them with flexible insulated wires or cables. They must be identical to the thermoelectrodes of the thermocouple, therefore they are called extension or compensation thermoelectrodes.

In Ukraine, extension and compensating wires are standardized by the national standard [14], which is an identical translation of the European standard [15]. The standard [14] establishes requirements for extension and compensation wires, which are used in the management of technological processes. According to the standard, wires made of conductors having the same nominal composition as the corresponding thermocouple are called extension wires. They are marked with the letter "X", which is placed after the thermocouple designation, for example, "KX". Compensating wires are made of conductors with a composition that differs from the composition of the corresponding thermocouple. They are designated by the letter "C", which is placed after the designation of the thermocouple, for example, "KC". Sometimes different tolerances are used for the same thermocouple for different temperature ranges. They are distinguished by additional letters, for example, "KCA" and "KCB". The extension or compensation lead tolerance is defined as the maximum additional deviation in microvolts caused by the introduction of the extension or compensation lead into the measuring circuit. Table 3 shows the established tolerances for extension and compensation wires used at temperatures indicated as "Wire Temperature Range".

Table 3. Tolerance classes of extension and compensating wires.

Type	Tolerance class		Wire temperature range	Measuring junction temperature
	1	2		
JX	± 85 µV (± 1.5 °C)	± 140 µV (± 2.5 °C)	From – 25 °C to 200 °C	500 °C
TX	± 30 µV (± 0.5 °C)	± 60 µV (± 1.0 °C)	» – 25 °C » 100 °C	300 °C
EX	± 120 µV (± 1.5 °C)	± 200 µV (± 2.5 °C)	» – 25 °C » 200 °C	500 °C
KX	± 60 µV (± 1.5 °C)	± 100 µV (± 2.5 °C)	» – 25 °C » 200 °C	900 °C
NX	± 60 µV (± 1.5 °C)	± 100 µV (± 2.5 °C)	» – 25 °C » 200 °C	900 °C
KCA	–	± 100 µV (± 2.5 °C)	» 0 °C » 150 °C	900 °C
KCB	–	± 100 µV (± 2.5 °C)	» 0 °C » 100 °C	900 °C
NC	–	± 100 µV (± 2.5 °C)	» 0 °C » 150 °C	900 °C
RCA	–	± 30 µV (± 2.5 °C)	» 0 °C » 100 °C	1000 °C
RCB	–	± 60 µV (± 5 °C)	» 0 °C » 200 °C	1000 °C
SCA	–	± 30 µV (± 2.5 °C)	» 0 °C » 100 °C	1000 °C
SCB	–	± 60 µV (± 5 °C)	» 0 °C » 200 °C	1000 °C

The notes to Table 3 indicate that the temperature range of the wire may be reduced relative to the values given due to temperature limitations that determine the properties of the insulation.

Extension and compensating wires are identified by color. The color of the insulation of the negative conductor for all types of thermocouples must be WHITE. The color of the insulation of the positive conductor is determined depending on the type of thermocouple. So, for T type thermocouple – BROWN, for E type – PURPLE, for J type – BLACK, for K type – GREEN, for N type – PINK, for B type – GRAY and for R and S types – ORANGE.

The dimensions of the wires must be agreed upon between the consumer and the manufacturer, taking into account, for example, the breaking strength and flexibility of the cable. Typical nominal values of the diameter of a single-core wire and the diameter of the cores of a multi-core wire are set by the standard from 0.1 to 1.6 mm. The nominal cross-sectional area of a stranded wire is from 0.05 to 2.3 mm2, depending on its structure, which is determined by the number of wires and diameter. The number of cores can be from 3 (for example, with nominal diameter values of 0.3; 0.65 and 0.8 mm) to 48 with a nominal diameter value of 0.2 mm.

It is also established that wires are made from pairs of twisted conductors or flat parallel conductors. It is also advisable to use additional shielding for the thermoelectric circuit to reduce susceptibility to electrical interference.

4.12. Errors of thermocouples

When evaluating the errors that occur when measuring temperature using thermocouples, the following must be taken into account:

- thermocouples must be made from pairs of thermoelectrodes to ensure permissible deviations of thermoEMF not exceeding the values given in Table 2;
- permissible errors of compensating wires should also not exceed the values given in Table 2;
- errors due to incorrect selection and different thermoEMF of thermocouples and compensating wires;
- incorrect connection of the poles of compensation wires and thermocouple is possible;
- influence of the temperature of the reference junctions of the thermocouple;
- errors due to changes in the electrical resistance of the thermocouple circuit;
- errors that may arise as a result of correcting the influence of the temperature of reference junctions in the measuring circuits of secondary devices;
- the error of the measuring device, which is determined by its accuracy class.

In addition, there may also be errors due to shunting of the thermocouple due to poor insulation of its thermoelectrodes, compensating and extension wires, as well as due to the possible occurrence of galvanic couples between them.

5. Conclusion

This is a review paper and it contains information on the features of temperature measurement using thermoelectric transducers (thermocouples). The theoretical basis, requirements for materials for thermocouples, basic values and permissible deviations from them are formulated. The main types and characteristics of thermocouples made of noble, non-noble and refractory metals and alloys are given. Design features are justified for the possibility of using thermocouples in various technological conditions and environments.

In order to exclude the influence of ambient temperature on the readings of thermocouples, the requirements for compensating and extension wires are given, which are standardized in Ukraine and used in the control of technological processes.

A general assessment of the errors that occur when measuring temperature using thermocouples, and which must be taken into account, is given.

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Теорія і практика вимірювання температури термоелектричними перетворювачами

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Анотація

Температура є одним із головних параметрів, що визначають кількісні і якісні показники продукції. Тому важко назвати сферу техніки або галузь промисловості, де не потрібно було би вимірювати температуру твердих, рідких чи газоподібних речовин. Поряд з цим необхідно відмітити, що в кожній конкретній галузі вибір методів і засобів вимірювання температури визначається її специфікою, що пов’язана з різноманітністю технологічних об’єктів, характером протікання процесу, фізико-хімічними властивостями досліджуваного середовища, діапазоном вимірюваних температур, вимогами до необхідної похибки вимірювання, тощо. Тому вибір методу вимірювання для конкретного технологічного об’єкта є складною проблемою, оскільки необхідно враховувати велику кількість факторів, які досить часто можуть бути суперечливими. Так, скляні термометри розширення дають змогу виміряти температуру безпосередньо поблизу технологічних об’єктів. За допомогою манометричних термометрів можна виміряти температуру на деякій відстані від об’єктів дослідження. Необхідно також відмітити, що такі термометри постійно повинні бути з’єднані з первинним перетворювачем з’єднувальним капіляром. На відміну від наведених вище, електричні термометри дають змогу здійснювати дистанційні вимірювання температури на будь-якій віддалі між первинним перетворювачем і вторинним приладом. Із електричних термометрів найбільше поширення в промислових умовах отримали термоелектричні перетворювачі (термопари) і термоперетворювачі опору. Ця робота є оглядовою і містить інформацію про особливості вимірювання температури за допомогою термоелектричних перетворювачів (термопар).

Ключові слова: температура; термопара; термоелектричний перетворювач; термоелектрод; подовжувальні та компенсаційні проводи; похибка вимірювання.