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CONTENTS

General problems

Designing

Metrology and standardization

Thermoelectric products

L.M. Vykhor, *DSc (Phys-Math)* [1]
P.V. Gorskyi, *DSc (Phys-Math)* [1,2]
V.V. Lysko, *Cand.Sc (Phys-Math)* [1,2]

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METHODS FOR MEASURING CONTACT RESISTANCES OF "METAL – THERMOELECTRIC MATERIAL" STRUCTURES (PART 2)

An overview of existing methods for measuring thermal contact resistance, as well as methods that allow simultaneous determination of thermal and electrical contact resistance values, is presented. Their accuracy, advantages and disadvantages are analyzed, as well as the possibilities of using them in thermoelectricity for the study and optimization of metal-thermoelectric material structures. Bibl. 16, Figs .8.
Key words: thermal contact resistance, electrical contact resistance, measurement, accuracy, thermoelectric power converters.

Introduction

One of the main obstacles to the widespread practical use of thermoelectricity is the high cost of thermoelectric power converters, the largest share of which is the cost of thermoelectric material. Attempts to create miniature modules, and thus significantly reduce their cost, encounter the growing influence of contact resistances, which cause a catastrophic decrease in the quality of the modules.

The development and optimization of technologies for creating contact resistances necessary to meet practical needs is carried out experimentally by studying the influence of various technological factors on the value of contact resistance. The latter is possible only if reliable methods and equipment for measuring contact resistances are available.

The first part of this work present ed an analysis of existing methods and equipment for determining the values of electrical contact resistances and the possibilities of their use for the study and optimization of "metal – thermoelectric material" structures. No less important are the methods for measuring thermal contact resistance, the analysis of which is the subject of the continuation of this work.

1. Specific features of methods for measuring thermal contact resistance

There are a number of methods for measuring thermal contact resistance and the appropriate setups for their implementation. Standard methods are based on measuring the steady heat flux passing through the sample in a specific direction. The basics of the method are set out in the international standard ASTM D5470-06 [1].

In [2], a standard method is described, which is based on the use of a "reference" specimen with a previously known thermal conductivity as a heat flux meter. The diagram of the measuring setup is shown in Fig. 1.

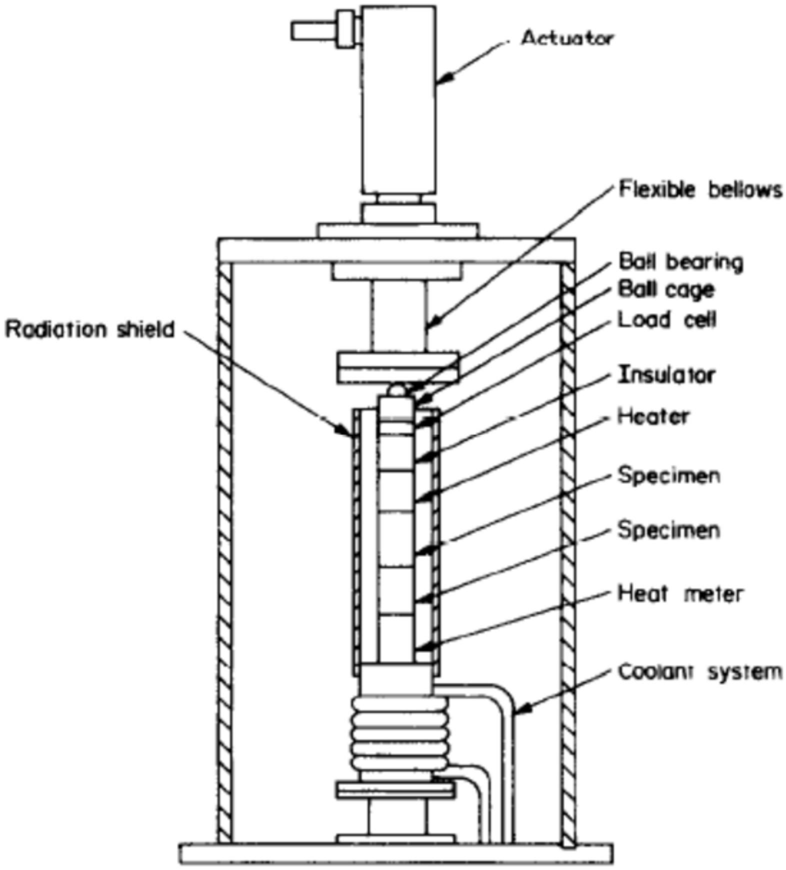

Fig.1. Diagram of a setup for measuring thermal contact resistance using reference specimens as heat meters [2].

The contacting samples are placed between the heater and the heat flux meter. The heat flux is determined by calculation from the known temperature difference and thermal conductivity based on Fourier's law. The calculated power is equal to the heater power. The temperature is measured by three thermocouples mounted in the heat meter at certain distances from the axis. To measure the temperature distribution in the specimens, 36 thermocouples with a diameter of 0.13 mm and a length of 76 cm were used. Thermocouples were placed in holes drilled perpendicular to the specimen axis and fixed in them with epoxy resin. The small diameter of the thermocouples was taken in order to prevent significant disturbance of the heat flux and to fix the position of the thermocouples as accurately as possible. An epoxy resin with a relatively high thermal conductivity was taken so that there was no significant temperature gradient in the bonding layers. The thermocouples partially “wrapped” the heat meter or specimen, which ensured the use of a small piece of the so-called “Kapton tape”. Kapton tape has a very low thermal conductivity. Therefore, using this tape to relax the stresses in the thermocouples does not affect the temperature distribution in the specimen or heat meter. Heat losses in such a setup are no more than 2%.

According to [3], some contacts are characterized by the so-called “directional effect”, which consists in the fact that the contact resistances measured in two opposite directions to the contact plane differ from each other. One of the hypotheses involved in explaining this phenomenon is the change in the contact geometry depending on the direction of heat propagation due to different mechanical properties of the materials. In most cases, this effect is indeed observed in the contact between dissimilar materials. However, it can also be observed in the contact between identical materials. Another explanation is that the potential barrier created by oxide layers near the interface weakens the heat transfer by free charge carriers, such as electrons. Let us assume that ε_1 and ε_2 – are the work functions of electrons from metals 1 and 2. Then, if $\varepsilon_1 > \varepsilon_2$, electrons can pass from metal 2 to metal 1, since electrons in the conduction band of metal 2 are energetically closer to the top of the potential barrier. The ratio of conductivities in opposite directions is then equal to:

$$\frac{\sigma_{12}}{\sigma_{21}} = \frac{\tau_{12}}{\tau_{21}} \frac{T_1^2}{T_2^2} \exp\left\{\left(\frac{\varepsilon_1 - \varepsilon_0}{k}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right\}. \quad (1)$$

In this formula, ε_0 – is the electron work function from the oxide film. If $\tau_{12} \approx \tau_{21}, \varepsilon_1 > \varepsilon_0, T_1 > T_2$ then $\sigma_{12} > \sigma_{21}$. Work functions are sensitive to the state and preparation of the surface, so there is no reason for the absence of a "directional effect" even in contact between identical materials, if the "histories" of the contacting surfaces are different.

The setup for measuring thermal resistance is shown in Fig.2.

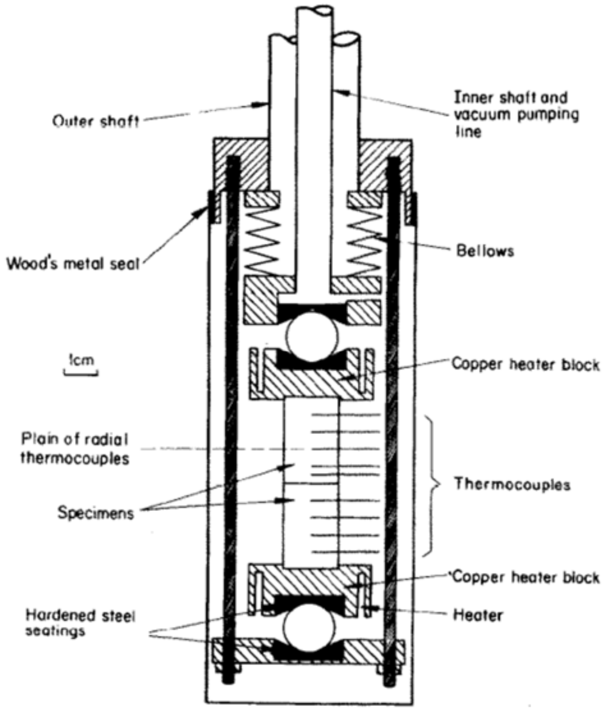

Fig. 2. Schematic diagram of a setup for measuring thermal resistance [3].

The setup is designed to measure contact resistance as a function of load. A load of up to 100 kg is applied kinetically to the contacting specimens, and a heat flux of up to 3 W is "pumped" through them. The heater is powered by a stabilized DC source. The temperature distribution in the specimens is measured by a series of radially placed copper-constantan thermocouples. ThermoEMF is measured with an accuracy of up to 10^{-7} V. The specimens themselves are used as "heat meters". The heat flux through them is calculated from the Fourier law, based on the measured temperature distribution. Under these conditions, the thermal conductivity of the specimens in the temperature range under study is known with sufficient accuracy. The temperature near the interface for each of the contacting specimens, and therefore the temperature jump at the contact, is found by extrapolating the measured temperature distributions along the length of each of the contacting specimens. The design of the setup ensures a minimal radial temperature gradient. This allows measurements to be made even when the contact resistance is strongly dependent on temperature.

The dimensions of the specimens and the location of the thermocouple holes in them are measured with an accuracy of 1 μm by an optical comparator. After switching on the heater (or cooling in the case of measurements at low temperatures), the contacting specimens were kept until a steady state was reached. At room temperature, a steady state was reached 4-5 hours after a change in the load and approximately 10-12 hours after a change in the direction of the heat flux. In the case of measurements at low temperatures, the indicated terms for reaching the steady state were reduced by approximately half. Smoothing of the experimentally obtained dependences was performed by the least squares method. Pairs of contacting specimens of stainless steel and aluminium were studied in the temperature range of 90-300 K. The dependences of thermal contact resistance on time, load, temperature, magnitude and direction of heat flux were measured. It turned out that the "directional effect" is levelled out as the heat flux increases. At the same time, the value of the inverse specific thermal contact resistance itself depends relatively weakly on the value of the heat flux. Thus, even with a sevenfold increase in the value of the heat flux, the specific thermal contact resistance changes by no more than 10%. Therefore, the specific thermal contact resistance is considered invariant with respect to the value of the heat flux.

In [4], specimens of materials pressed against each other, the contact resistance between which must be measured, are placed in a heat-insulated volume between a heater and a cooler, after which the heat flux through the specimens and the temperatures on both sides of the contact in the immediate vicinity of it are measured (Fig. 3).

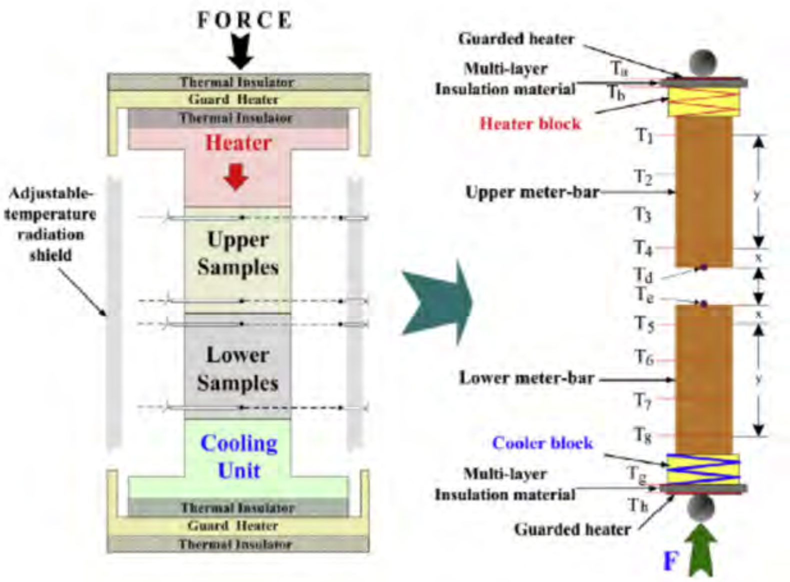

Fig. 3. Schematic diagram of a standard method for measuring contact thermal resistance [4].

A one-dimensional heat flux flows from the upper to the lower specimen and the temperature is distributed linearly, and a jump occurs at the contact. Therefore, the thermal contact resistance is defined as:

$$R = \frac{T_d - T_e}{Q}, \qquad (2)$$

where Q is the average heat flux through the contacting specimens. In this case, the temperatures T_d and T_e are determined by extrapolating the temperatures recorded by local sensors placed in the contacting specimens near the interface, to this very interface.

However, the authors of [4] believe that such a standard method gives too large an error and propose a measurement method based on changing the direction of the heat flux. The method is schematically shown in Fig. 4. This method is based on the use of the average value of the thermal contact resistances in the two directions of the heat flux and the symmetry properties of the measuring system. Let the extrapolated temperatures on both sides in the "forward" direction of the heat flux be equal to T_d' and T_e', and in the reverse direction – to T_d'' and T_e''. Then the thermal contact resistance is equal to:

$$R_T = \left[0.5Q \left(\left| T_d' - T_e' \right|^{-1} + \left| T_d'' - T_e'' \right|^{-1} \right) \right]^{-1} . \tag{3}$$

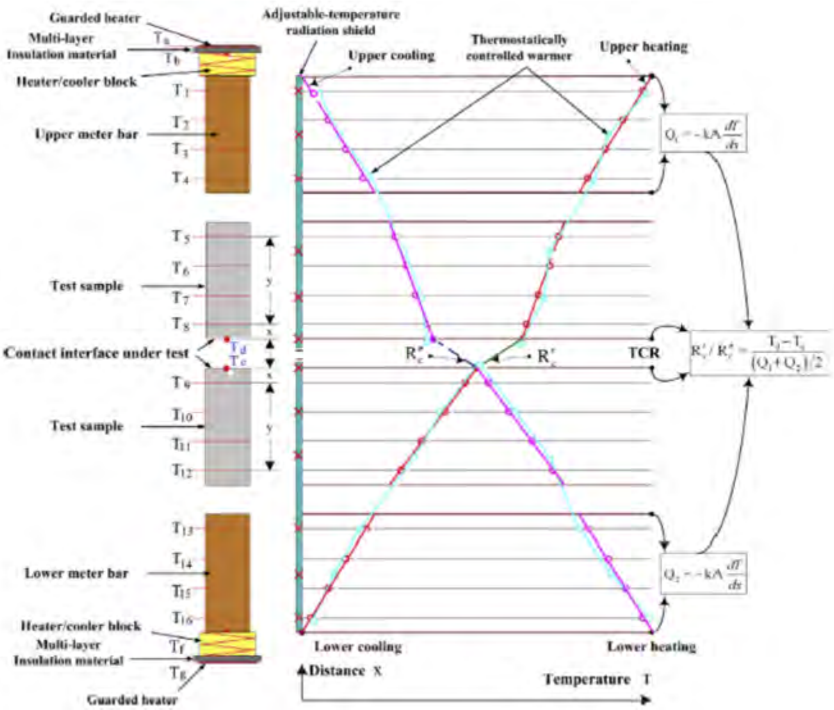

Fig. 4. Schematic diagram for implementation of the variable heat flux method [4].

In [4], it was proven that this method sharply reduces the error, as a result of which the contact resistance ceases to depend on the applied heat flux, while when using the standard method in many cases there is a strong dependence of the results of measuring the thermal contact resistance on the applied heat flux. The temperature in this method is measured by a thermistor.

In general, methods related to measuring thermal characteristics in a steady state are used to measure thermal contact resistance. The disadvantage of these methods is the long waiting time to reach a steady state. In contrast, a number of dynamic methods have been proposed, such as the infrared thermography method [5], the flash method [6], the thermal reflection method [7], the photothermal method [8], and others. [9,10].

As an example, let us consider a non-contact thermographic method described in more detail in [5], which is called the infrared thermography method [5]. According to this method, two contacting specimens are separately heated to different initial temperatures. Immediately after the specimens reach these temperatures, they are brought into contact. The temperature changes and the heat flux from the hot specimen to the cold one are monitored by a high-speed infrared (IR) camera. This camera records IR radiation in the wavelength range from 7.7 to 9.5 μm. This bandwidth is suitable for measuring temperatures above 20°C. To prevent the influence of ambient radiation, the specimens have a high emissivity or blackness ($\varepsilon = 0.95$), which is achieved by a thin layer of black paint with which the samples are coated. To minimize errors, it is important to determine the temperature near the contact line. For this purpose, an optical system with a resolution of 13 μm/px was used, which is the diffraction limit for the specified wavelength range. With a frame size of 60×80 px, i.e. 780×1040 μm, the frame rate was 2500 Hz. The result of these experiments was the time dependence of the temperature distribution near the contact.

The heat transfer coefficient near the contact cannot be measured directly. It must be determined by solving the inverse problem using information about the temperature at a certain point in the spatial domain. Thus, the "cause" (heat flux) is calculated based on the "effect" (temperature field). The mathematical procedure leads to a single, but unstable solution. Therefore, a small "noise" in the temperature measurement results leads to significant errors in the value of the heat flux.

In the case of a one-dimensional problem, the corresponding partial differential equation with the initial and boundary conditions is given by:

$$\frac{\partial T}{\partial t} = \alpha_T \frac{\partial^2 T}{\partial x^2}, \quad T(x, t=0) = T_0, \quad q_c = -k\frac{\partial T}{\partial x}|_{x=0}, \quad \frac{\partial T}{\partial x}|_{x\to\infty}, \tag{4}$$

where α_T is thermal diffusivity. Then the desired heat transfer coefficient is determined as:

$$h_c = \frac{q_c}{\Delta T}. \tag{5}$$

Although the contacting bodies are bounded, the contact time is too short for the heat flux to reach the distant boundaries of the bodies, so the bodies can be considered semi-bounded.

To calculate the heat transfer coefficient, it is necessary to determine the heat flux through the contact area. It is determined using a step-by-step procedure involving a number of "future points in time." The algorithm for calculating the heat flux is illustrated by the following equation:

$$q_c(x=0, t_m) = \frac{\sum_{i=1}^{r}\left(T_{\text{meas},m+i-1} - T_{m+i-1}\right)\Phi_i(x = x_1, t_i)}{\sum_{i=1}^{r}\Phi_i^2(x = x_1, t_i)}, \tag{6}$$

where the step corresponds to a unit jump in the heat flux for a semi-bounded body, which is defined as

$$\Phi_i(x,t) = \frac{x}{k}\sqrt{\frac{4\alpha_T t}{\pi}}\left[\frac{1}{\sqrt{\pi}}\exp\left(-\frac{1}{\sqrt{Fo}}\right) - \frac{1}{2\sqrt{Fo}}\operatorname{erfc}\left(\frac{1}{2\sqrt{Fo}}\right)\right], \tag{7}$$

where $F_0 = \alpha_T t / x^2$ is the Fourier number. Eq. (7) contains only the physical constants of the material and the coordinate and time. Therefore, the corresponding calculation is performed once, namely at the beginning of the procedure. Eq. (6) is obtained from considerations of minimizing the root mean square deviation between the measured ($T_{\text{meas},m}$) and calculated (T_m) temperatures.

Thus, the final contact resistance is calculated based on the measured temperature distribution and the calculated heat flux. The temperature difference is measured not directly at the contact, but at a distance of 50-100 microns from it, since otherwise the data is too "noisy" due to the deformation of the bodies. Under these conditions, the difference between the true temperature jump and the measurement data is neglected. The schematic diagram for determining the heat flux through the contact by the superposition method is shown in Fig. 5. The true heat transfer coefficient is considered to be its steady-state value over time. The sought thermal contact resistance is equal to the inverse heat transfer coefficient.

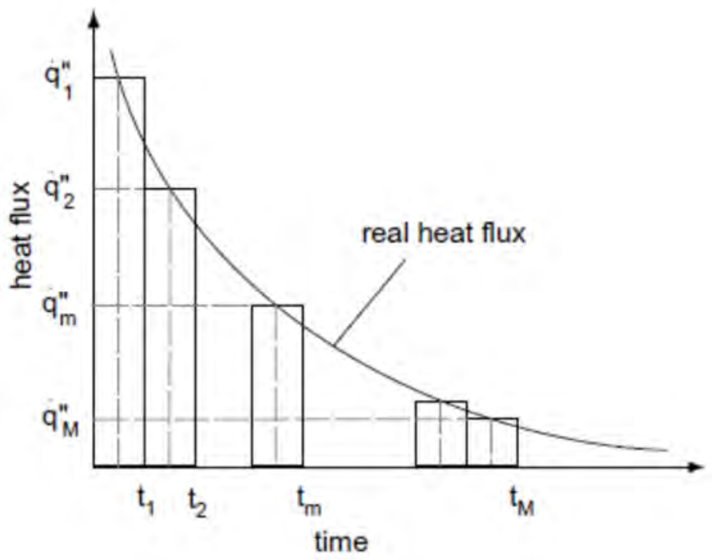

Fig. 5. Schematic diagram for determining the heat flux through the contact by the superposition method [5].

In [11], a method for measuring the thermal resistance between a conductive film and a substrate was proposed, which is suitable for measuring the thermal resistance of contacts created in thermoelectric products in a "microelectronic" design, when a metal contact layer is sprayed or deposited on a thin semiconductor layer. The schematic diagram of the measuring setup for implementing this method is shown in Fig. 6.

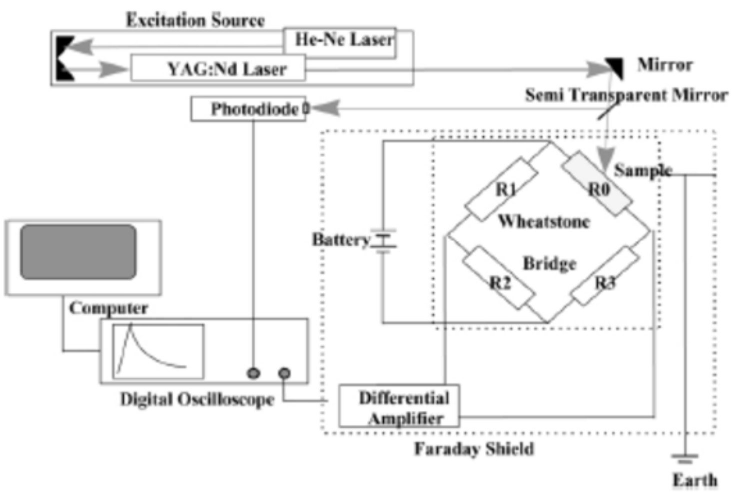

Fig. 6. Schematic diagram for measuring the thermal resistance of a specimen in the form of a thin film on a substrate [11].

In this diagram, the specimen (film on the substrate) was heated by laser pulses with an energy of 4 J and a duration of 20 ns from a neodymium laser with a wavelength of radiation of 1.06 μm. The neodymium laser was pumped by a helium-neon laser. In order to measure the temperature, the specimen was connected to a Wheatstone bridge. A constant voltage was applied to one of the diagonals of the bridge. The voltage removed from the other diagonal of the bridge, as a result of heating and subsequent cooling of the specimen, depended on time. This voltage was fed through a differential amplifier to the input of a digital oscilloscope. The Wheatstone bridge together with the differential amplifier was placed in a Faraday cage. The second input was supplied with a reference voltage from a photodiode, which was illuminated by the same laser that heated the specimen through a semi-transparent mirror. The computer processed the time dependence of this voltage after the peak, since it was it that characterized the cooling of the specimen. Thermal resistance is determined simultaneously with thermal conductivity by fitting experimental thermograms to theoretical ones in the time interval from 10^{-7} to 10^{-6} s. Thermal contact resistance is calculated by the least squares method.

2. Methods for simultaneous measurement of thermal and electrical contact resistances

Methods for simultaneous measurement of thermal R_t and electrical R_c contact resistances are described in [12-14].

In [12], methods for measuring the temperature dependences of thermal and electrical contact resistances are presented. The methods were developed to study the properties of the boundary layer between the thermoelectric oxide material of p-type conductivity $Ca_3Co_4O_3$and the Fe-Cr alloy, which can be used as a material for a connecting plate in the manufacture of generator thermoelectric modules from oxide-based materials. The studied two-layer samples of Fe-Cr/ $Ca_3Co_4O_3$ were obtained using SPS sintering technology. In [13], similar methods were used to study the thermal and electrical contact resistances of two-layer specimens of Ni/ $Ca_3Co_4O_3$.

The thermal contact resistance R_t was determined by measuring the thermal diffusivity by the laser flash method using a special device "Netzch LFA-457 Laser Flash Apparatus". Initially, the thermal diffusivity of each of the Fe-Cr and $Ca_3Co_4O_3$ materials is determined separately. Then measurements are made on two-layer washers. Thin washers (1–2 mm) are used for this. The time t_i is measured during which a strong energy pulse created on the surface of the washer causes half the maximum temperature deviation on the opposite surface of the washer. Thermal diffusivity α is calculated using a simple formula [15]

$$\alpha_i = 1.37a^2 / \pi^2 t_i , \tag{8}$$

where a is washer thickness. Corrections to formula (12) for a more accurate method of calculating thermal diffusivity are described in [16].

The measurement data for single and double-layer washers are automatically used as input data for special computer programs which the Netzch LFA-457 installation is equipped with. This software is designed and configured to determine the thermal contact resistance of the double-layer model.

The electrical contact resistance was measured in the temperature range from 30°C to 800°C on two-layer column-shaped specimens. The measurement diagram is shown in Fig. 7 [12].

This model allows measuring both the resistivity of each specimen component and the contact resistance 4 of the boundary, which is determined by linear extrapolation of the dependence of the resistance R on the distance x to the boundary ($x_{n \text{ to } 0}$) by the formula

$$R_c = \text{extrapolation}\,(R \;\; from \;\; x_{6-3\;to\;0}) - R_{1-2}\frac{x_{1-2}}{x_{2-0}} \tag{9}$$

The last term in formula (9) accounts for the contribution from the influence of the resistance of the *Fe-Cr* alloy between the probe and the boundary.

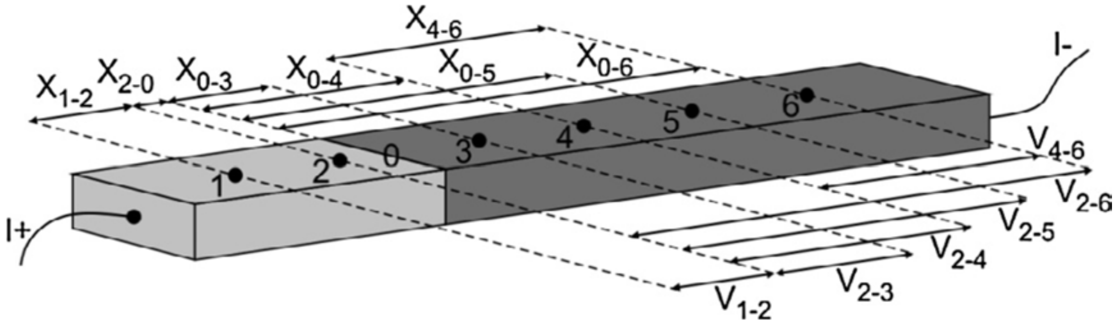

Fig. 7. Schematic diagram for measuring electrical contact resistance [12].

The voltage at different points is measured with a 4-probe Keithley Micro-ohmmeter. The distance from the probes to the boundary is measured using an Olympus SZX9 Stereomicroscope.

Using a micro-ohmmeter, a current was applied to the specimen and the voltage was measured at various points along the surface of the specimen using a probe made of platinum wire with a diameter of 0.1 mm, which was attached with silver paste. The micro-ohmmeter was operated in pulse mode with current passing and voltage measurement for 150 ms. The current was then switched off and the voltage caused by the temperature gradient (due to thermoEMF) was measured and taken into account in determining the resistance. Measurements were made for the forward and reverse directions of the current and the results were averaged. The values of the thermal and electrical resistance of the boundary were multiplied by the cross-sectional area of the measured samples, which gave the value of the specific contact resistance.

[14] describes a setup designed to measure both electrical and thermal contact resistance. Simultaneous measurement of R_c and R_t of a junction is important for understanding the relationship between the quantities and their possible influence on each other. Such data can be useful for designing improved electrical and thermal contacts between materials.

The electrical contact resistance R_c is measured using the 4-probe method (Kelvin method) on direct current. To measure the thermal contact resistance R_t, the heat flux power Q through the contact boundary in steady state is determined using data on a material with known thermal conductivity and the temperature gradient in the unit under study, and ΔT at the boundary is calculated from measurements and extrapolation of the temperature gradient in the specimens. The thermal conductivity of the contact is determined by the formula

$$h_t = \frac{Q}{A\Delta T}, \tag{10}$$

where A is contact area.

The measurement chamber contains two heater-cooler units, two heat flux meters and two test specimens that are joined together, as shown in Fig. 8a. The units and meters are placed symmetrically to the contact boundary of the specimens. The chamber can be evacuated to 10^{-6} mbar or filled with gas. Measurements can be carried out at temperatures from 20 to 150°C. Constant temperatures are created by the heater and the cooling system. The contact of the two specimens is formed by compression using a hydraulic system. The pressure can vary from 0 to 500 kg. Cylindrical samples with a diameter of 10 to 30 mm and a height of 20 to 100 mm can be used for research. The specimen under study is connected to electrical and thermal sensors, as shown in Fig. 8b.

The heater-cooler units are made in the form of copper cylinders. The copper tubes of the cooler are placed in the grooves in the form of a spiral. The nichrome heating elements, inserted into the ceramic washers, are fastened with clamps. The unit can operate as a heater when voltage is supplied to the heating elements, or as a cooler when a coolant is supplied to the copper tubes. In this way, the direction of the heat flux can be changed without disturbing any processes.

Heat flux meters are also cylindrical units made of copper with a known thermal conductivity. The amount of heat flowing through the meter is calculated by measuring the temperature gradients in the direction of the heat flux. The error in determining heat flux using these meters is ±5%.

A digital multimeter (DMM), which measures electrical resistance to an accuracy of 0.1 μΩ, is used to determine electrical contact resistance. The DMM is set up for 4-probe measurements under conditions of minimizing the contribution of wire resistance, including solder joints. The DMM is connected to a computer with special measurement software. The electrical circuit for thermal measurements is completely separated from the electrical circuit, including the DMM and the computer.

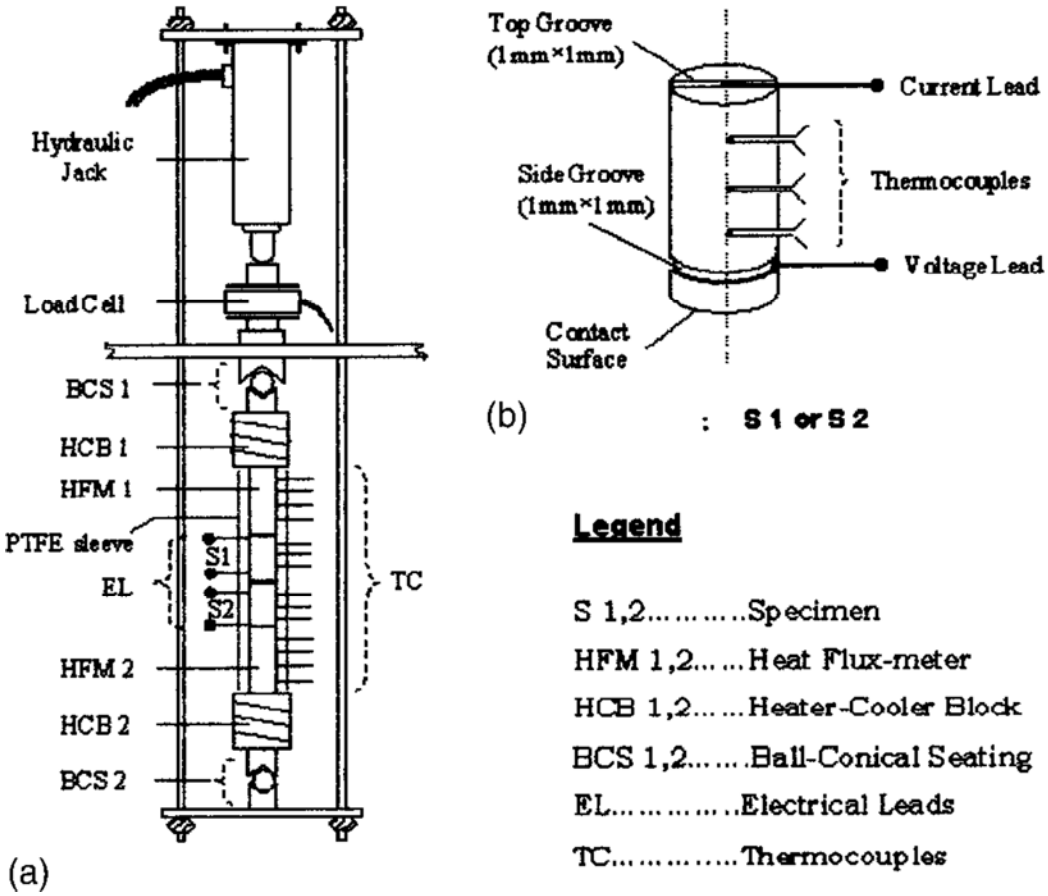

Fig. 8. Schematic of a chamber for measuring contact resistances [14].

In [14], an example of the results of measuring the electrical and thermal contact resistances for a brass/brass pressure contact is presented. It was found that the absolute maximum deviation when measuring the electrical contact resistance on the described setup is ±0.003%, and the thermal conductivity of the contact is ±4.4%. The setup can also be used for measuring the thermal conductivity of materials.

Conclusions

1. The examination and analysis of existing methods for measuring thermal contact resistance, as well as methods that allow the simultaneous determination of thermal and electrical contact resistance values, highlights both the advantages and disadvantages of individual methods.
2. The accuracy and reliability of methods for measuring contact thermal resistance, as well as methods for measuring electrical contact resistance, require significant improvement to implement in practice the possibilities for reducing contact resistances provided by theoretical studies.

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МЕТОДИ ВИМІРЮВАННЯ КОНТАКТНИХ ОПОРІВ СТРУКТУР «МЕТАЛ – ТЕРМОЕЛЕКТРИЧНИЙ МАТЕРІАЛ» (ЧАСТИНА 2)

Наведено огляд існуючих методів вимірювання теплового контактного опору, а також методів, що дозволяють одночасно визначати величини і теплового, і електричного контактних опорів. Проведено аналіз їх точності, переваг та недоліків, а також можливостей використання у термоелектриці для дослідження та оптимізації структур «метал – термоелектричний матеріал». Бібл. 16, рис .8.

Ключові слова: тепловий контактний опір, електричний контактний опір, вимірювання, точність, термоелектричні перетворювачі енергії.

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COMPUTER SIMULATION OF THE WORKING TOOL OF A THERMOELECTRIC DEVICE FOR CRYODESTRUCTION WITH ACCOUNT OF THE PHASE TRANSITION

The paper presents the results of computer simulation of the working tool of a thermoelectric device for cryodestruction with account of the phase transition, as well as cyclic temperature effect on the human skin in dynamic mode. A physical model of the working tool, a three-dimensional computer model of the biological tissue with account of thermophysical processes, blood circulation, heat exchange, metabolic processes and the phase transition, is constructed. As an example, a case is considered when the working tool is on the skin surface, the temperature of which changes cyclically according to a given law in the temperature range [-50 ÷ +50] °C. Temperature distributions in different layers of the human skin in cooling and heating modes were determined. The obtained results make it possible to predict the depth of freezing and warming of the biological tissue at a given temperature effect.

Key words: cryodestruction, working tool, temperature effect, human skin, dynamic mode, computer simulation.

Introduction

It is well known in medical practice that temperature effect is an important factor in the treatment of many diseases of the human body [1-11]. However, the devices used for this purpose are in most cases bulky, without adequate temperature regulation and thermal regime reproduction capabilities. To obtain lower temperatures, liquid nitrogen systems are used, which significantly limits the possibilities of their use in medical institutions where the supply of liquid nitrogen is problematic. In addition, the use of liquid nitrogen or the Joule-Thomson effect during gas expansion does not allow for the implementation of precisely required temperature regimes, which reduces the overall efficiency of using cold in treatment.

The use of thermoelectric cooling (heating) can solve this problem [12-21]. The studies of thermal effects on the biological tissue conducted over many years, the creation of thermoelectric devices based on them and their use in medical practice confirm their efficiency. Thermoelectric devices are promising in such areas of medicine as cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, urology, dermatology, etc.

However, the experience of using thermoelectric medical devices revealed a number of their shortcomings. Among them, the most important is the lack of ability to manage cooling and heating processes in time. The latter significantly narrows the possibilities of heat and cold treatment.

Studies show that cooling rates (their dynamics) play a decisive role in treatment [12-27]. Thus, very fast cooling does not lead to the destruction of the biological tissues at all. On the contrary, moderate but cyclical cooling promotes energetic destruction of tumors. The time functions of cooling and heating are also important in the treatment of other diseases.

Therefore, the general problem is to develop a thermoelectric device for the destruction of the biological tissue or oncological neoplasms, which will provide the possibility of cyclic temperature effects on the tumor. This determines the relevance of the problem posed in the present work.

The importance of solving this problem is obvious, otherwise thermoelectric devices for medicine of a new generation with the possibility of cyclic temperature effects on the human skin cannot be developed.

In [28], a computer simulation of the working tool of a thermoelectric device for cryodestruction was performed without taking into account the phase transition. Therefore, the purpose of this work is computer simulation of the working tool of a thermoelectric device for cryodestruction with account of the phase transition.

1. Physical model of the working tool of a thermoelectric device for destruction the walls of which are made of steel

Fig.1 shows a physical model. It consists of housing 1, inside which substance 2 (25% alcohol solution) with a phase transition temperature T_1 is placed. Housing 1 with a hemispherical end 3 touches the skin 4 with a plane 5 with a diameter d. Housing 1 is made of medical grade stainless steel. Skin model 4 takes into account its complex structure.

The model takes into account heat inleak Q_1 at the ambient air temperature T_2=25°C, as well as heat inleak Q_2 from the ambient air. The upper part of housing 1 is adiabatically insulated (q=0). The diameter of the thermal contact 5 is 5 mm.

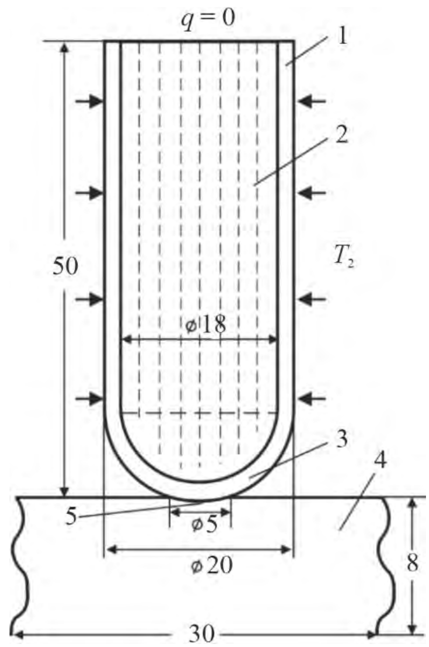

Fig. 1. Physical model of the working tool of a thermoelectric device for cryodestruction, the walls of which are made of steel.

2. Computer model

Three-dimensional computer models were created for the biological tissue in a cylindrical coordinate system, on the surface of which there is a thermoelectric medical device for local cooling. The Comsol Multiphysics package of application programs [29], was used to build computer models, which makes it possible to simulate thermophysical processes in the biological tissue, taking into account blood circulation, heat exchange, metabolic processes, and the phase transition.

The calculation of temperature distributions and the density of heat flows in the biological tissue and the cold accumulator was carried out by the finite element method, the essence of which is that the object under study is divided into a large number of finite elements and in each of them the value of the function is sought, which satisfies the given second order differential equation with the corresponding boundary conditions. The accuracy of solving the given problem depends on the level of division and is ensured by the use of a large number of finite elements [29].

Thermophysical properties of the skin and the biological tissue of the human body in normal [30-38] and frozen states are shown in Tables 1, 2.

The thermal contact resistance between the working tool and human skin is not taken into account in this model, as it is estimated to be insignificant and is $R_c = 2\cdot10^{-3}$ $m^2\cdot K/W$.

Table 1

Thermophysical properties of the biological tissue of the human body [30-38].

Biological tissue layers	Epidermis	Dermis	Subcutaneous layer	Internal tissue
Thickness, *l* (mm)	0.08	2	10	30
Specific heat, *C* ($J\cdot kg^{-1}\cdot K^{-1}$)	3590	3300	2500	4000
Thermal conductivity, κ ($W\cdot m^{-1}\cdot K^{-1}$)	0.24	0.45	0.19	0.5
Density, ρ ($kg\cdot m^{-3}$)	1200	1200	1000	1000
Metabolism, Q_{met} (W/m^3)	368	368	368	368
Blood perfusion rate, ω_b (ml/s·ml)	0	0.0005	0.0005	0.0005
Blood density, ρ_b ($kg\cdot m^{-3}$)	1060	1060	1060	1060
Heat capacity of blood, C_b ($J\cdot kg^{-1}\cdot K^{-1}$)	3770	3770	3770	3770

Table 2

Thermophysical properties of the biological tissue of the human body in normal and frozen states [30-38].

Thermophysical properties of biological tissue	Value	Units of measurement
Heat capacity of normal biological tissue (C_1)	3600	J/m^3 °C
Heat capacity of frozen biological tissue (C_2)	1800	J/m^3 °C
Thermal conductivity of normal biological tissue (κ_1)	0,5	W/m °C
Thermal conductivity of frozen biological tissue (κ_2)	2	W/m °C
Latent heat of phase transition (*L*)	$250\cdot10^3$	J/m^3
Upper temperature of phase transition (T_1)	-1	°C
Lower temperature of phase transition (T_2)	-8	°C

3. Computer simulation results

Fig. 2 shows temperature distributions in the human skin, directly under the center of action of the working tool.

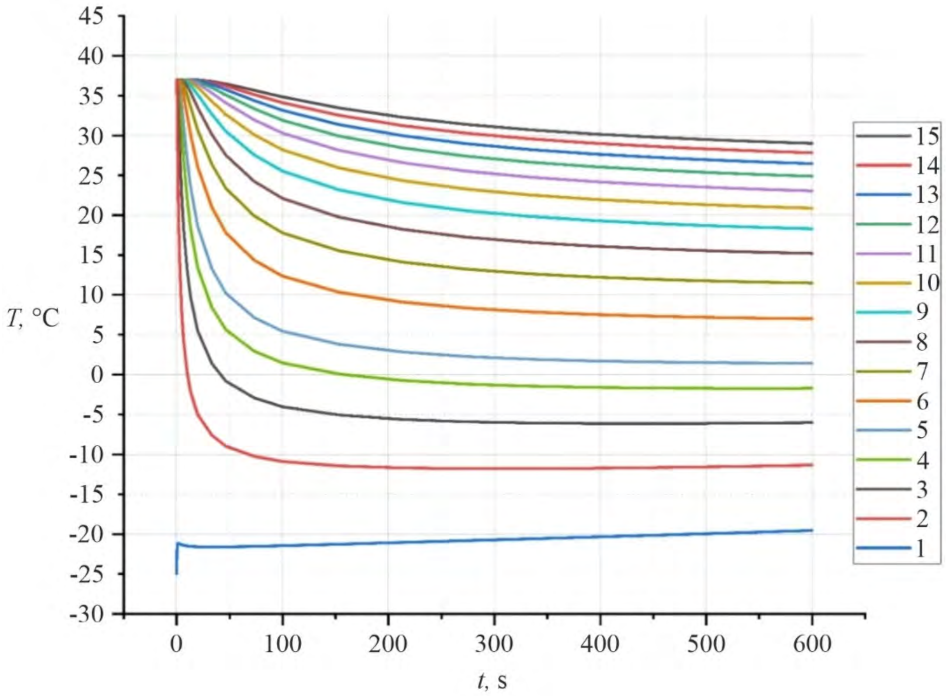

Fig. 2. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig.3 shows temperature distributions in the skin directly under the centre of action of the working tool at time moments: *10 s, 60 s, 140 s, 200 s, 600 s.*

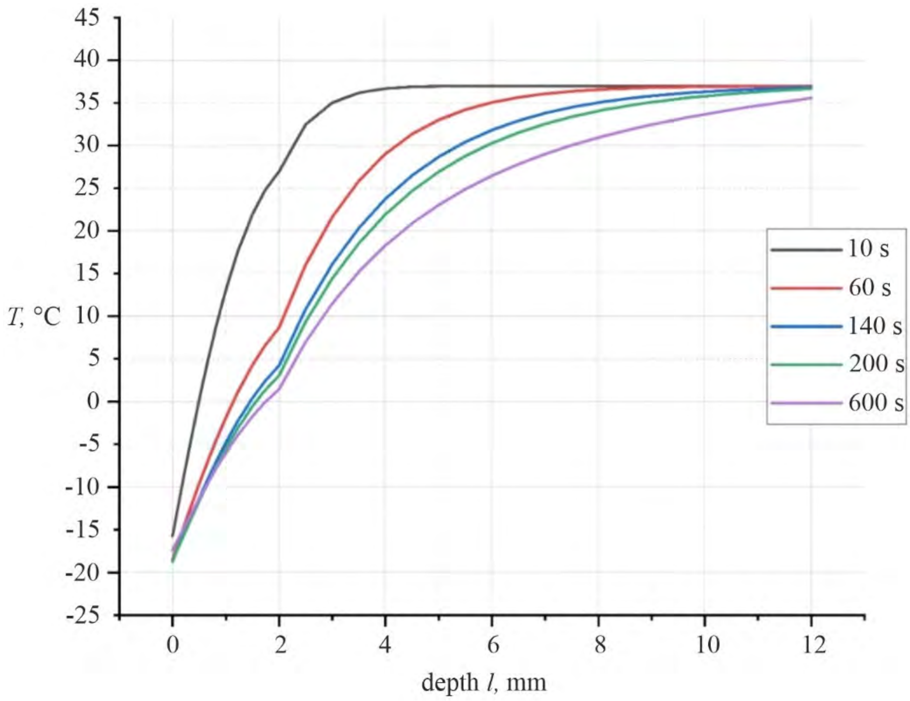

Fig. 3. Dependences of temperature on skin depth at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

Fig. 4 represents temperature distributions in the cold accumulator at different depths.

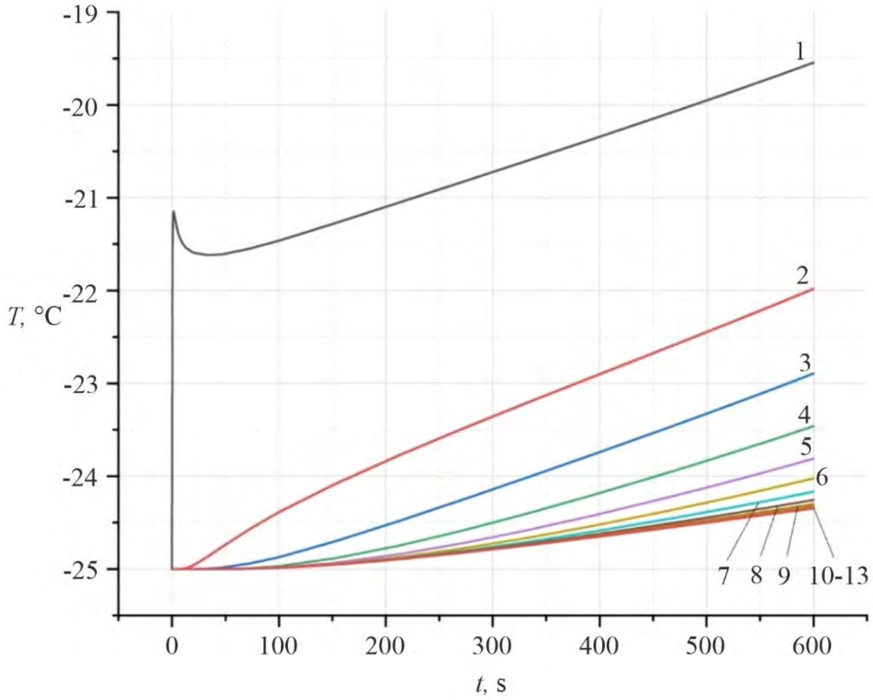

Fig. 4. Dependences of temperature on time in the cold accumulator at different depths: 1 – point of contact between working tool and skin: 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 5 shows the distribution of temperatures in the cold accumulator at the following moments: 10 s, 60 s, 140 s, 200 s, 600 s

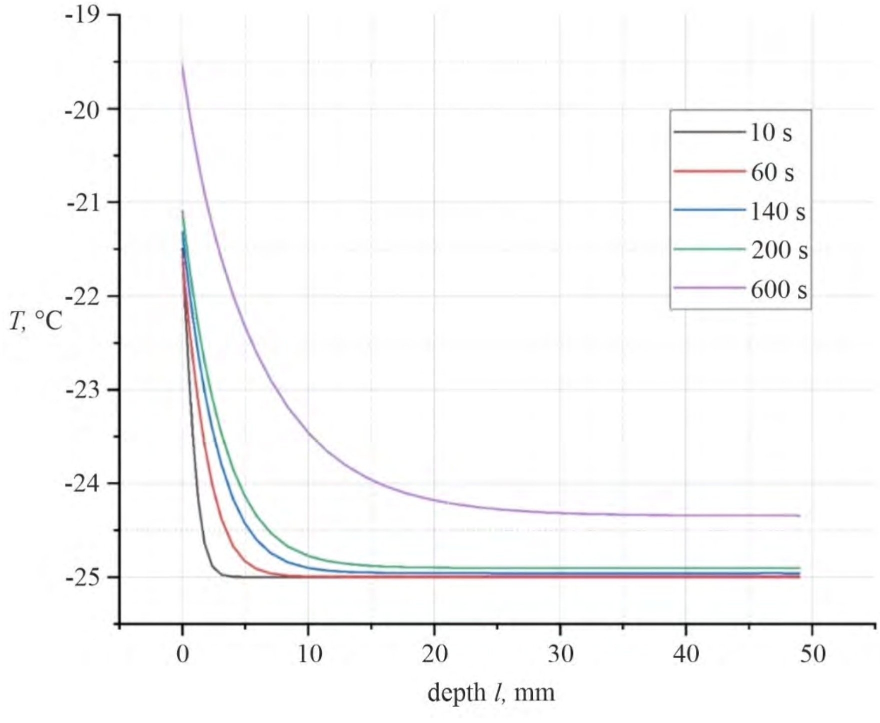

Fig. 5. Dependences of temperature on time in the cold accumulator at time moments:10 s, 60 s, 140 s, 200 s, 600 s.

4. Physical model of the working tool of a thermoelectric device for destruction the walls of which are made of copper

Fig. 6 shows a physical model. It consists of a housing 1, inside which a substance 2 (25% alcohol solution) with a phase transition temperature T_1 is placed. Housing 1 with its hemispherical end 3 touches skin 4 with a plane 5 of diameter d. Housing 1 is made of copper. The complex structure of skin 4 is taken into account in the model.

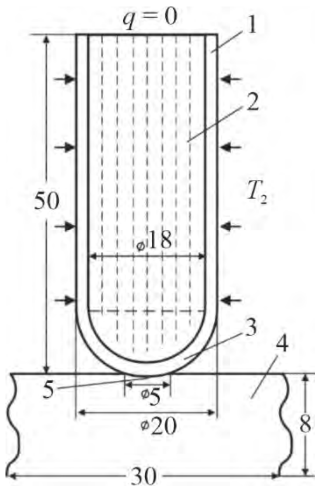

Fig. 6. Physical model of the working tool of thermoelectric device for cryodestruction the walls of which are made of copper.

The model takes into account the heat inleak Q1 at the ambient air temperature T_2 = +25ºC, as well as the heat inleak Q_2 from the ambient air. The upper part of the housing 1 is adiabatically insulated (q=0). The diameter of the thermal contact 5 is 5 mm.

5. Computer simulation results

Fig. 7 shows temperature distributions in the human skin, directly under the center of action of the working tool.

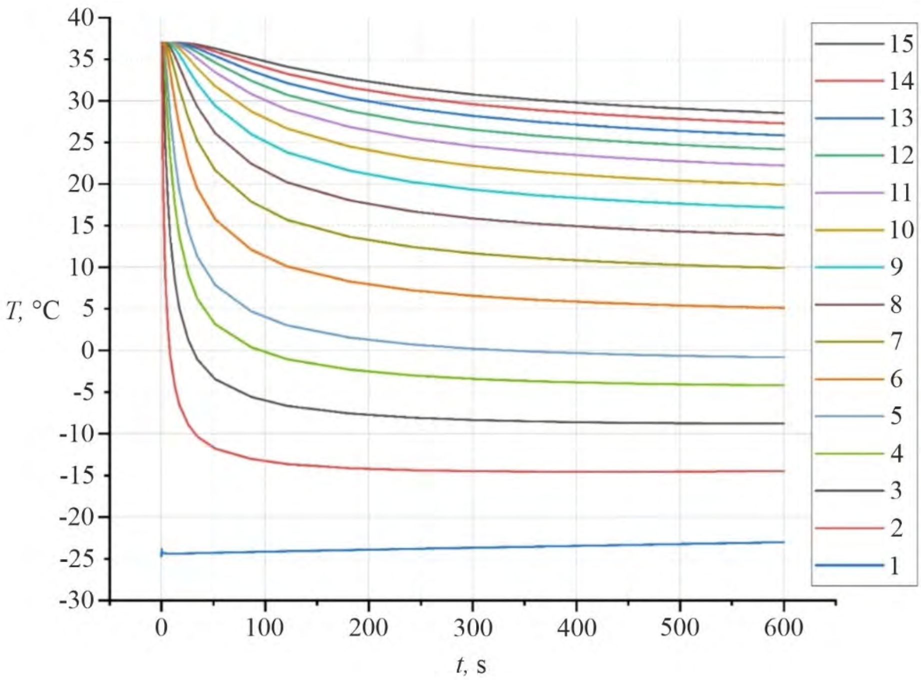

Fig. 7. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between the working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig. 8 shows temperature distributions in the skin directly under the center of action of the working tool at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

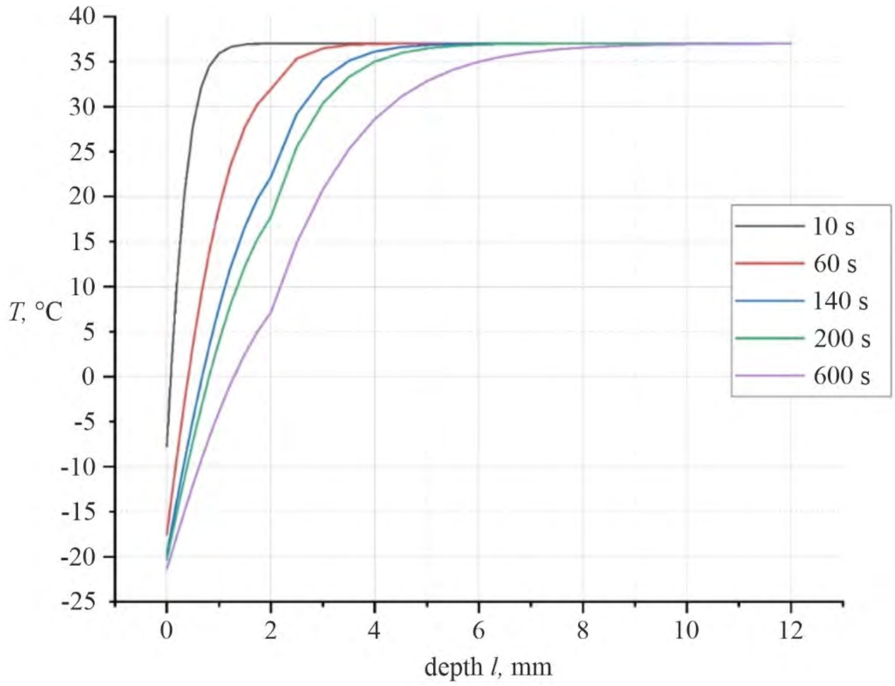

Fig. 8. Dependences of temperature on the skin depth at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

Fig. 9 shows temperature distributions in the cold accumulator at different depths.

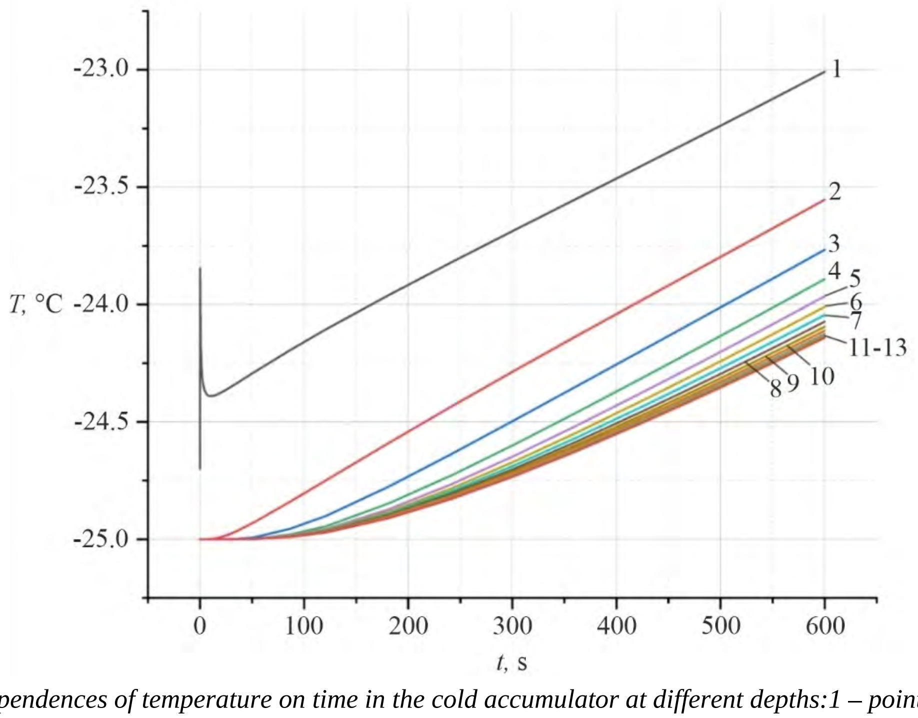

Fig. 9. Dependences of temperature on time in the cold accumulator at different depths:1 – point of contact between working tool and skin; 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 10 shows temperature distributions in the cold accumulator at time moments: *10 s, 60 s, 140 s, 200 s, 600 s.*

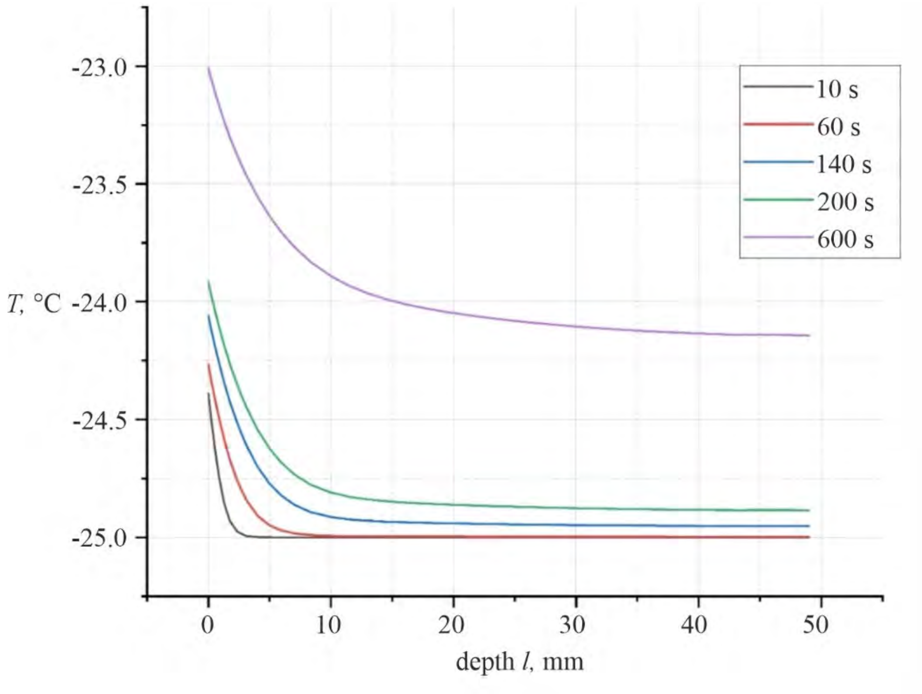

Fig. 10. Dependences of temperature on time in the cold accumulator at time moments:10 s, 60 s, 140 s, 200 s, 600 s.

Conclusions

1. A method for computer simulation of temperature distribution in the human skin in a dynamic mode, with account of the phase transition, has been developed, which makes it possible to predict the results of local temperature effects on the skin and determine at any moment in time the temperature distribution in different layers of the skin for a given arbitrary time function of change in the temperature of the working tool $T_f(t)$.

2. A computer model was developed and computer simulation of the working tool of a thermoelectric device for destruction was carried out for two design options in order to determine the temperature in the skin and the cold accumulator, taking into account the phase transition: the working tool is made of medical steel without an inner cylinder; the working tool is made of copper without an inner cylinder.

3. Using computer simulation, temperature distributions in different layers of the skin and in the cold accumulator of the working tool of a thermoelectric device for destruction at an initial temperature of -25 °C were determined, taking into account the phase transition. The results obtained make it possible to predict the depth of freezing of biological tissue.

4. With the aid of computer simulation, it was established that account of the phase transitions increases the accuracy of temperature determination in the biological tissue and the cold accumulator.

5. Using a tool design with an inner cylinder made of copper has been found to increase cooling efficiency by 10%.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ РОБОЧОГО ІНСТРУМЕНТУ ТЕРМОЕЛЕКТРИЧНОГО ПРИЛАДУ ДЛЯ КРІОДЕСТРУКЦІЇ З ВРАХУВАННЯМ ФАЗОВОГО ПЕРЕХОДУ

У роботі наведено результати комп'ютерного моделювання робочого інструменту термоелектричного приладу для кріодеструкції з врахуванням фазового переходу, а також циклічного температурного впливу на шкіру людини у динамічному режимі. Побудовано фізичну модель робочого інструменту, тривимірну комп'ютерну модель біологічної тканини з врахуванням теплофізичних процесів, кровообігу, теплообміну, процесів метаболізму та фазового переходу. Як приклад, розглянуто випадок, коли на поверхні шкіри знаходиться робочий інструмент, температура якого змінюється циклічно за наперед заданим законом у діапазоні температур [-50 ÷ +50] °C. Визначено розподіли температури у різних шарах шкіри людини в режимах охолодження та нагріву. Отримані результати дають можливість прогнозувати глибину промерзання і прогрівання біологічної тканини при заданому температурному впливі.

Ключові слова: кріодеструкція, робочий інструмент, температурний вплив, шкіра людини, динамічний режим, комп'ютерне моделювання.

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METHODS AND EQUIPMENT FOR THE PREPARATION OF THERMOELECTRIC MATERIAL SAMPLES FOR MEASURING THEIR PROPERTIES BY THE ABSOLUTE METHOD

The importance of high-quality preparation of the studied samples of thermoelectric materials for measuring their properties using a complex absolute method is shown. The requirements for the samples under study are given, as well as a description of the methods and equipment for producing samples that meet these requirements. Bibl. 27, Figs. 11.
Key words: measurement, electric conductivity, Seebeck coefficient, thermal conductivity, figure of merit, absolute method.

Introduction

The importance of improving methods and equipment for measuring the properties of thermoelectric materials cannot be overestimated. High requirements for the accuracy of measuring equipment are put forward both when solving the problems of finding new and optimizing known thermoelectric materials to increase their thermoelectric figure of merit [1-3], and when choosing the optimal thermoelectric material for specific practical applications of thermoelectric energy converters [4-13].

One of the best for determining the thermoelectric properties of materials (electrical conductivity, Seebeck coefficient, thermal conductivity and figure of merit Z) is the complex absolute method [14-16]. It is widely used in creating standards and has important advantages: measurements of σ, α, κ, Z are performed simultaneously on the same sample, which reduces errors; small samples can be used for measurements; thermoelectric parameters are found from classical formulae without making amendments.

Papers [17-26] give the results of comprehensive research conducted at the Institute of Thermoelectricity of the National Academy of Sciences of Ukraine and the Ministry of Education and Science of Ukraine, aimed at developing methods for minimizing the errors of the absolute method. The result of these studies is the creation of "ALTEC-10001" measuring equipment (Fig. 1), the accuracy of which in determining the figure of merit is 3-5 times higher than the accuracy of measurement when using other methods, in particular, the Harman method [27].

Fig. 1. "ALTEC-10001" installation for measuring the thermoelectric properties of materials by the complex absolute method, developed at the Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine.

From the analysis of possible measurement errors, it follows that it is necessary to ensure high requirements for the sample being measured - the accuracy of its dimensions, the correctness of its shape, the quality of its surface, uniformity, etc. It is extremely important to create high-quality electrical and thermal contacts on the end surfaces of the sample and install thermocouples on its side surface. However, ensuring compliance with these requirements is not always given due attention, although deviations from them lead to such significant errors that the use of all necessary methods to improve measurement accuracy may become useless.

Therefore, *the purpose of this work* was to develop special methods and equipment for preparing samples for measurements.

1. Requirements for the studied samples of thermoelectric material

Fig. 2 shows a diagram of the complex absolute method taken as a basis when creating the “ALTEC-10001” installation. The thermoelectric parameters of the sample under study are determined from the formulae

$$\sigma = \frac{I}{U}\frac{l}{S}, \tag{1}$$

$$\alpha = \frac{E_\alpha}{T_h - T_c}, \tag{2}$$

$$\kappa = \frac{I_0 \cdot U_0}{T_h - T_c}\frac{l}{S}, \tag{3}$$

$$Z = \frac{\alpha^2 \sigma}{\kappa}, \tag{4}$$

where l is the distance between thermocouple probes; S is cross-sectional area of the sample; I, U are current through the sample and voltage drop between measuring probes when determining electrical conductivity; E_α is thermoEMF between identical legs of thermocouple probes; T_h and T_c are the “hot” and “cold” temperatures in the sample; I_0, U_0 are current and supply voltage of the reference heater.

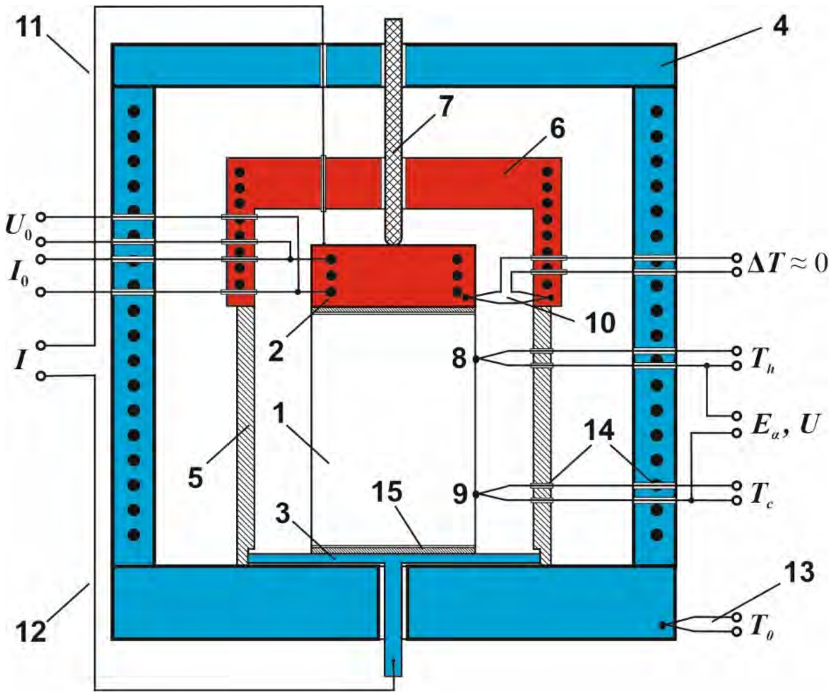

Fig. 2. Complex absolute method of measuring thermoelectric parameters of materials: 1 – sample under study; 2 – reference heater; 3 – mounting pad; 4 – thermostat; 5 – screen; 6 – screen heater; 7 – clamp; 8, 9 – measuring probes-thermocouples; 10 – zero thermocouple; 11, 12 – current leads of the sample; 13 – thermocouple of the thermostat thermoregulator; 14 – thermal keys; 15 – contact structures.

Papers [17, 18] examined in detail the influence of various physical factors on the accuracy of measurements of parameters of thermoelectric materials, primarily thermal conductivity and electrical conductivity, depending on the geometric dimensions of the samples and structural elements of the measuring cell. It has been shown that measurement errors can be significant, more than 50%, if special means are not used to eliminate them.

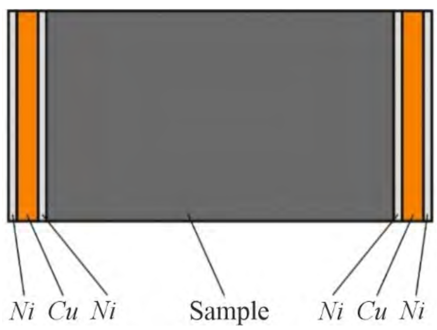

Fig. 3. Contact structures for measuring the thermoelectric properties of material by the absolute method.

It has been established that cylindrical samples with a diameter of 6-8 mm are optimal for ensuring minimal measurement errors and time to establish stationary conditions. In doing so, the length of the sample should be at least 2 times greater than the diameter of the sample, and the distance between the probes should not exceed ⅓ of the length of the sample.

In addition, as shown in [19], in order to achieve a one-dimensional distribution of electric current and heat flow in the sample, it is necessary to metallize the ends of the sample. The layers must be resistant to temperature effects in the entire working interval of measurements and have fairly good adhesion and anti-diffusion properties. A set of metal coatings was determined (Fig. 3), which ensures acceptable values of errors in thermal conductivity and electrical conductivity measurements. The optimal contact structure created on the ends of the sample consists of anti-diffusion nickel layers with a thickness of ~ 10 μm and a copper layer with a thickness of ~ 100 μm.

2. Production of thermoelectric material samples

The process of cutting thermoelectric material has its own specific features, so the direct use of modern serial equipment for cutting semiconductors is not always justified in relation to thermoelectric material.

The Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine has developed a small-sized desktop machine "ALTEC-13009" for cutting thermoelectric material with free and bound abrasive.

The basis of the cutting tool is the replaceable frame 1 (Fig. 4), made of high-strength aluminum alloy. Tungsten wire 3 is wound on the frame. The distance between the wires is set by the grooves of the size bars 2. Diamond micropowder is applied to the surface of the wire.

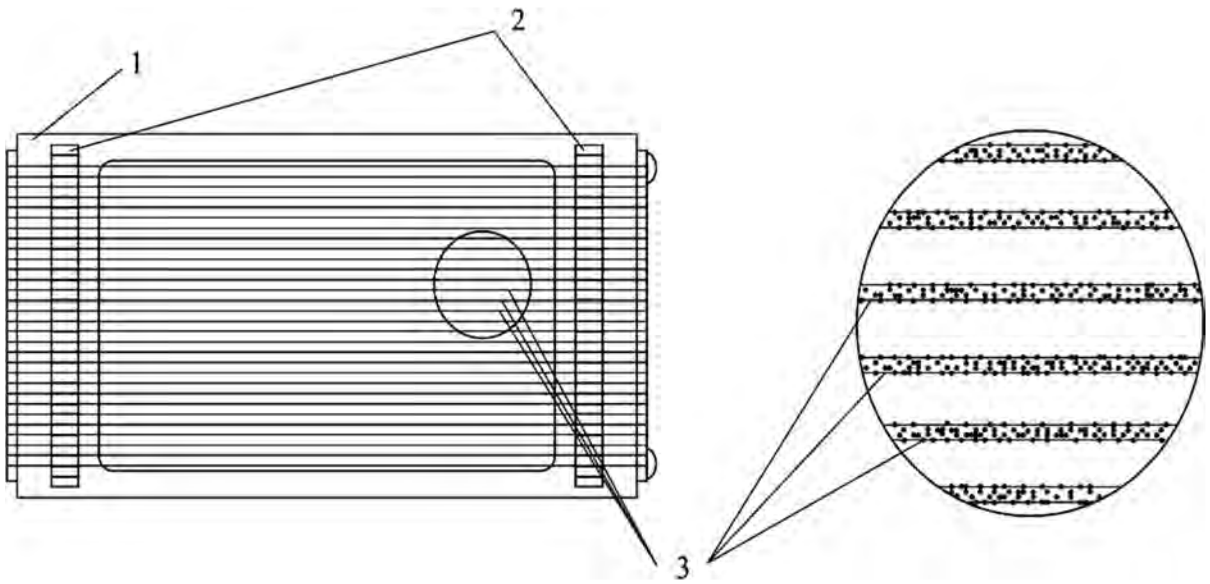

Fig. 4. Tool for cutting with wires with fixed diamond grains: 1 – tool, 2 – size bars; 3 – wires with fixed diamond grains.

A small-sized desktop machine is designed for producing rectangular-shaped samples from thermoelectric material in laboratory conditions (Fig. 5). The machine is schematically shown in Fig. 6.

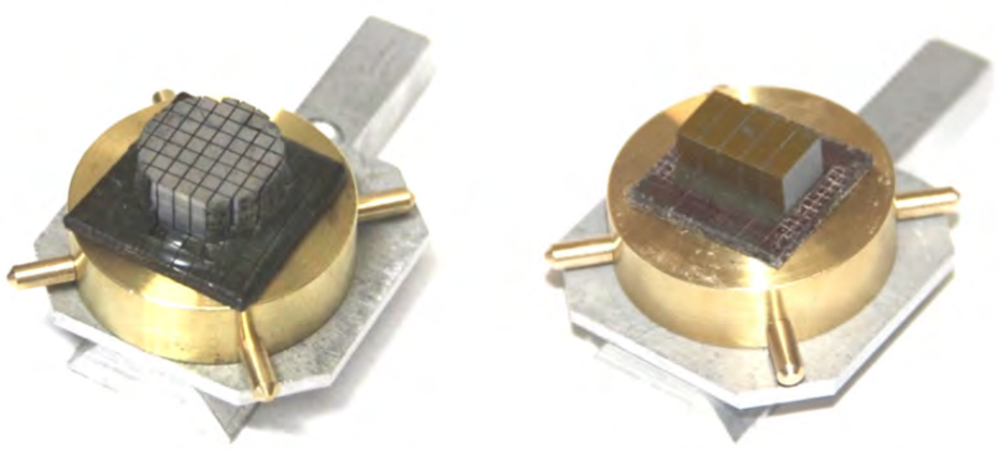

Fig. 5. Appearance of the result of cutting the thermoelectric material with the "ALTEC-13009" desktop machine.

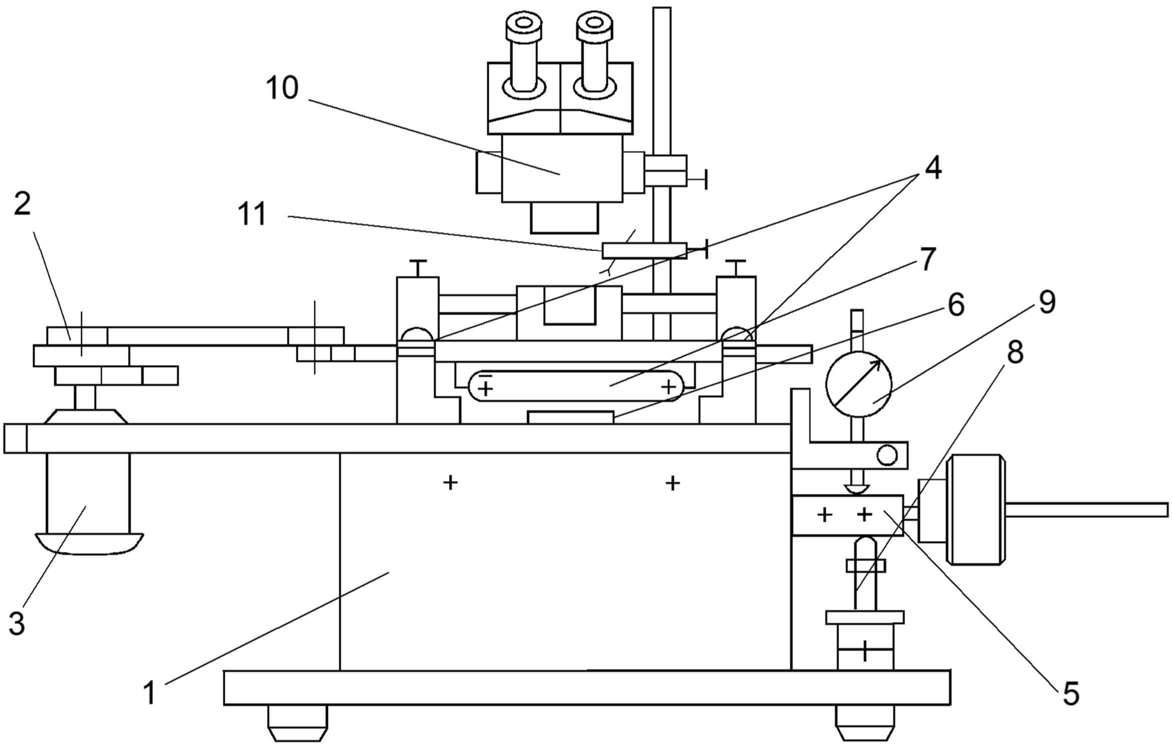

Fig. 6. Schematic of a small-sized desktop machine for cutting thermoelectric material: 1 – bed; 2 – drive unit; 3 – electric motor; 4 – carriage fastening unit; 5 – mechanism for raising and lowering the table; 6 – material to be cut; 7 – cutting tool; 8 – system for regulation and control of cutting depth; 9 – indicator; 10 – microscope; 11 – coolant supply.

The working tool of the machine is a frame with wires arranged parallel to it. Guides installed on the frame set the required distance between the wires and, accordingly, the dimensions of the samples. The machine allows cutting under conditions of small deforming influences. This achieves minor violations of the surface layers of the material.

The frame is secured to the movable carriage using two clamping nuts. Using the same nuts, the cutting wires are aligned parallel to the direction of movement of the tool. Bearing sliding of the carriage guides ensures the accuracy and ease of their reciprocating movement.

The machine consists of a carriage with a cutting tool 7, the reciprocating movement of which is carried out by the drive unit 2 from the electric motor 3; carriage fastening units 4; mechanism for raising and lowering the table 5 with a counterweight for adjusting the pressure on the edge of the cutting tool; system for control of cutting depth 8, indicator 9 for controlling the cutting depth; device for supplying coolant 11. The beginning and end of the cutting process is controlled by the indicator 9. The appearance of the small-sized desktop machine "ALTEC-13009" is shown in Fig. 7.

The error when cutting a thermoelectric material with a free abrasive is 0.01 mm with a depth of violation of the surface layer of 5-15 µm; when using a cutting tool coated with diamond abrasive - 0.02 mm with a depth of violation of the surface layer of 10-25 microns.

To create round samples, first a workpiece in the form of a polyhedron is created on the “ALTEC-13009” machine (Fig. 8), which is manually brought to a cylinder using the grinding equipment shown in Fig. 9.

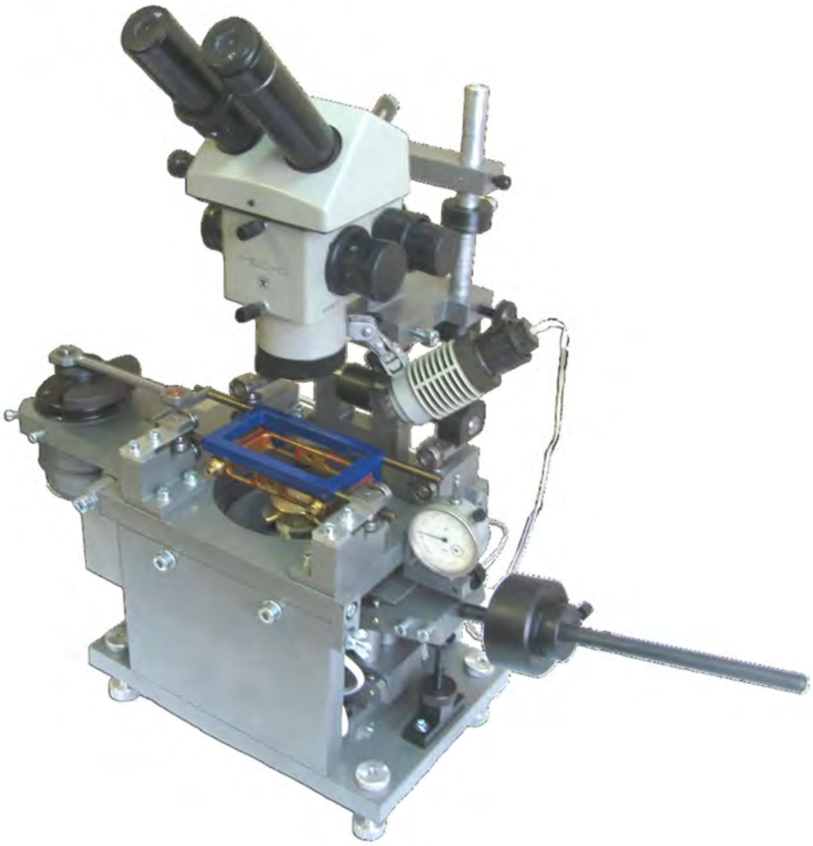

Fig. 7. Appearance of the small-sized desktop machine "ALTEC-13009".

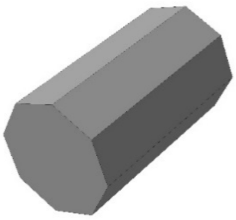

Fig. 8. A workpiece of thermoelectric material in the form of a polyhedron.

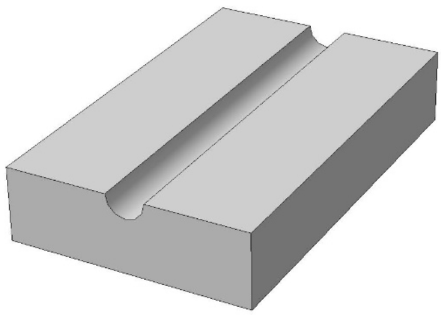

Fig. 9. Equipment for grinding the side surface of a multifaceted workpiece.

The accuracy of the geometric dimensions of the sample is controlled by an instrument microscope 10 with a resolution of 0.001 mm.

3. Creation of contact structures on the end surfaces of the studied samples

Before applying metal coatings, the surfaces of the ends of the sample should be freed from damaged deformed layers formed when cutting the material. Depending on the cutting methods, the depth of the damaged layers varies. An example of the effect of the cutting method on the depth of the damaged layer is given in Table 1.

Damaged layers significantly affect the value of contact electrical and thermal resistances and, therefore, the reproducibility and error of measurements. Therefore, before applying metal coatings, the damaged layers should be removed by mechanical processing followed by chemical or electrochemical etching.

Table 1

Effect of cutting method on the depth of deformed layers of thermoelectric material based on Bi_2Te_3.

№	Cutting method	Depth of deformed layers *h*, μm	
		n-type	*p*-type
1.	Electroerosion	2 – 5	5 – 10
2.	Wire with free abrasive	15 – 20	20 – 30
3.	Diamond disc	40 – 50	50 – 80

The appearance of the installation for creating contact structures on the measured samples is shown in Fig. 10.

The installation comprises: three vessels with electrolytes – for applying nickel and copper coatings, as well as preliminary etching of the surface of the sample; direct current source; measuring devices for controlling the amount of current during etching and applying coatings.

Fig. 10. Appearance of the installation for creating contact structures on measured samples of thermoelectric materials.

The process of creating a contact structure includes the following stages:

– mechanical treatment of the surface of the sample ends by grinding with powder with a fraction of up to 20 μm;
– placing the sample in equipment that protects the side surface of the sample and creates an electrical outlet from the side surface of the sample to the current source;
– electrochemical etching of sample ends;
– ultrasonic cleaning of the surface of sample ends;
– application of a nickel layer with a thickness of about 10 μm;

– application of a copper layer with a thickness of at least 100 μm;
– application of a nickel layer with a thickness of about 10 μm.

The composition of electrolytes is selected individually for each thermoelectric material. For example, for thermoelectric materials based on Bi_2Te_3, an aqueous solution of potassium hydroxide (KOH - 150 g/l) and sodium citrate ($NaC_3H_4(CO_2H)_3$ - 100 g/l) can be used for electrochemical etching; solution temperature 18-25 °C, current density Dk = 20 A/dm^2, anodes made of stainless steel. To apply nickel layers, an electrolyte composition is used: nickel (II) heptahydrate sulfate ($NiSO_4{\cdot}7H_2O$) – 150 g/l; potassium chloride (KCl) – 14 g/l; sodium sulfate dihydrate ($Na_2SO_4{\cdot}10H_2O$) – 70 g/l; magnesium sulfate heptahydrate ($MgSO_4{\cdot}10H_2O$) – 15 g/l; boric acid (H_3BO_3) – 25 g/l. Cathodic current density = D_k = 0.5-1.5 A/dm^2, electrolyte temperature = 18-25 °C; pH 4.5-5.5, electrolyte deposition rate ~ 10 μm/h. Nickel plates are used as anodes, the ratio of the anode area to the cathode area is ~ 2:1. Nickel plating is carried out with continuous filtration and intensive mixing of the electrolyte. The copper coating is applied with an electrolyte of the following composition: copper sulfate (II) pentahydrate ($CuSO_4{\cdot}5H_2O$) – 200 g/l; sulfuric acid (H_2SO_4 – 50 g/l. Electrolyte temperature = 18-25 °C, cathodic current density $D_к$ = 1-2 A /dm^2, electrolyte deposition rate ~ 10-15 μm/h, pure electrolytic copper anodes.

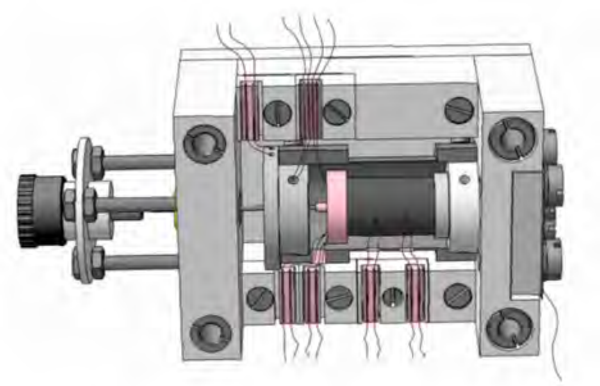

Fig. 11. Placement of the studied sample of thermoelectric material in the measuring cell of the “ALTEC-10001” installation.

The estimated total time for applying the Ni (~10 μm) – Cu (~100 μm) – Ni (~10 μm) contact structure is about 8-10 hours.

The thermoelectric material sample prepared in this way is placed in the measuring cell of the "ALTEC-10001" installation (Fig. 11).

The specified sample preparation equipment provides the measurement conditions necessary to realize the capabilities of the complex absolute method, and is an integral part of the overall measurement strategy.

Conclusions

1. The requirements for the preparation of the studied samples of thermoelectric materials for measuring their properties by the complex absolute method are given.
2. Optimal for ensuring minimal measurement errors and time for establishing stationary conditions are cylindrical samples with a diameter of 6-8 mm, a length of at least 2 times the diameter of the sample and a distance between probes equal to ~ ⅓ of the length of the sample. A description of a small-sized desktop machine for cutting thermoelectric material is presented, allowing the production of samples of the required geometry.
3. To achieve a one-dimensional distribution of electric current and heat flow in the sample, it is necessary to metallize the ends of the sample. The optimal contact structure created on the ends of the sample consists of anti-diffusion nickel layers with a thickness of ~ 10 μm and a copper layer with a thickness of ~ 100 μm. A description of the installation for galvanic application of the necessary contact structures and the method of its use are given.

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МЕТОДИ ТА ОБЛАДНАННЯ ДЛЯ ПІДГОТОВКИ ЗРАЗКІВ ТЕРМОЕЛЕКТРИЧНОГО МАТЕРІАЛУ ДО ВИМІРЮВАНЬ ЇХ ВЛАСТИВОСТЕЙ АБСОЛЮТНИМ МЕТОДОМ

Показана важливість якісної підготовки досліджуваних зразків термоелектричних матеріалів до вимірювань їх властивостей комплексним абсолютним методом. Наведено вимоги до досліджуваних зразків, а також опис методів та обладнання для виготовлення зразків, які задовольнятимуть цим вимогам. Бібл. 27, рис. 11.

Ключові слова: вимірювання, електропровідність, коефіцієнт термоЕРС, теплопровідність, добротність, абсолютний метод.

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RATIONAL AREAS OF USING THERMOELECTRIC HEAT RECUPERATORS

An analysis of the literature devoted to the methods of recovery of waste heat from various energy-intensive devices is presented. A comparative analysis of existing methods of recuperation of low-temperature waste heat is presented – the conventional and organic Rankine cycles, the Kalina cycle, etc. The characteristics of the existing thermoelectric heat recuperators are given, as well as the analysis of the possibilities of their further development and the most rational areas of their application.
Key words: recuperator, waste heat, efficiency, power, specific cost.

Introduction

General characterization of the problem. Most types of equipment for technological processes in industry, heat engines (turbines, internal combustion engines, etc.) disperse a huge amount of heat waste during their operation. At the same time, more than half of this heat is not only not used in any way, but also leads to negative consequences for the environment – to its thermal pollution [1 – 4].

Table 1 shows the main sources of waste heat and their characteristic temperatures. Waste heat is conventionally divided into three groups according to the temperature range [5]:

- high-temperature (> 650 °C);
- medium-temperature (230 – 650 °C);
- low-temperature (< 230 °C).

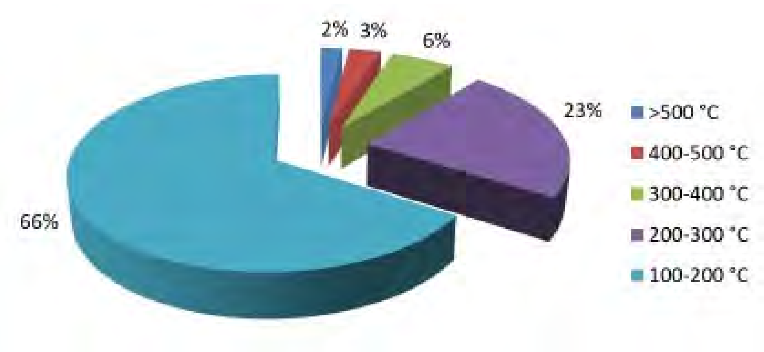

Fig. 1. Distribution of waste heat sources by temperature range [6].

Wherein, as can be seen from the diagram shown in Fig. 1, the majority of thermal waste (more than 66 %) falls in the low-temperature range [6]. Another 23 % of waste heat has a temperature of up to 300 °C. This temperature range is favourable for heat recovery through thermoelectric conversion of thermal into electrical energy.

At the same time, other methods of heat waste recovery work at such temperatures, including the generation of electrical energy through mechanical work.

Therefore, *the purpose of the work* is to analyze the possibilities of practical use of thermoelectricity for heat waste recovery and to determine the most rational areas for this, where thermoelectric energy conversion has a competitive advantage over other methods.

Table 1

Main sources of thermal waste and their temperature range [5].

Sources of thermal waste		Temperature range, °C
High-temperature waste heat (> 650 °C)	Nickel processing furnace	1.370 – 1.650
	Steel electric arc furnace	1.370 – 1.650
	Basic oxygen furnace	1.200
	Aluminum reverberation furnace	1.100 – 1.200
	Copper refining furnace	760 – 820
	Steel heating furnace	930 – 1.040
	Copper reverberation furnace	900 – 1.090
	Hydrogen installations	650 – 980
	Incinerators	650 – 1.430
	Glass melting furnace	1.300 – 1.540
	Coke oven	650 – 1.000
	Iron dome	820 – 980
Medium-temperature waste heat (230 – 650 °C)	Steam boiler exhaust	230 – 480
	Gas turbine exhaust	370 – 540
	Piston engine exhaust	320 – 590
	Ovens for heat treatment	430 – 650
	Drying and baking	230 – 590
	Cement kiln processes	450 – 620
Low-temperature waste heat (< 230 °C)	Exhaust gases from recovery devices in gas boilers, ethylene furnaces, etc	70 – 230
	Process steam condensate	
	Cooling water from:	50 – 90
	oven door	
	annealing furnaces	30 – 50
	air compressors	70 – 230
	internal combustion engines	30 – 50
	air conditioning	70 – 120
	Ovens for drying, baking and hardening	30 – 40
	Hot processed liquids / solids	90 – 230
		30 – 230

1. Traditional methods of waste heat recovery

1.1. Generation of electrical energy through mechanical work

The Rankine cycle [7, 8]. The most commonly used system for generating electricity from waste heat involves using the heat to generate steam, which then drives a steam turbine. The scheme of waste heat recovery with the Rankine cycle is shown in Fig. 2.

The conventional Rankine cycle is the most efficient option for the utilization of waste heat from exhaust gas streams at temperatures above 340 – 370 °C.

At low waste heat temperatures, steam cycles become less economical, as low-pressure steam will require more bulky equipment. Moreover, the low temperature of the waste heat cannot provide sufficient energy to superheat the steam, which is a requirement to prevent steam condensation and erosion of the turbine blades. Therefore, low-temperature heat is better suited for the organic Rankine cycle or the Kalina cycle, which use liquids with lower boiling points compared to water.

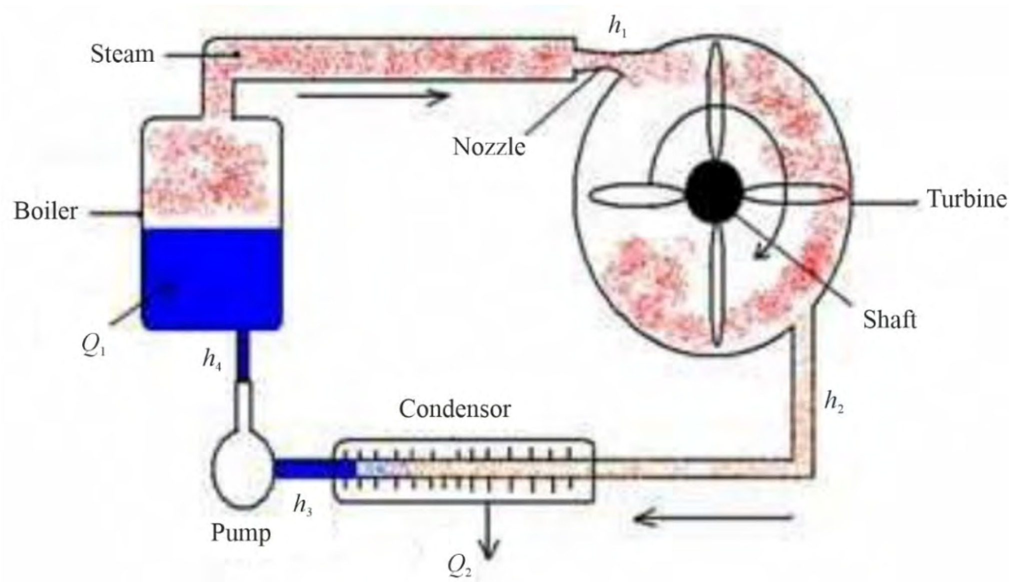

Fig. 2. Waste heat recovery according to the Rankine cycle.

The organic Rankine cycle – ORC [7, 9 – 11] operates similarly to the steam Rankine cycle, but uses an organic working fluid instead of steam. Options include silicon oil, propane, haloalkanes (such as "CFCs"), isopentane, isobutane, and toluene, which have lower boiling points and higher vapor pressures than water. This allows the Rankine cycle to operate at much lower waste heat temperatures - sometimes as low as 65 ºC. The most appropriate temperature range for an ORC will depend on the fluid used, as the thermodynamic properties of the fluids will affect cycle efficiency at different temperatures.

Compared to steam, the fluids used in ORCs have a higher molecular weight, allowing for compact designs, higher mass flow, and higher turbine efficiency (up to 80 – 85 %). However, since the cycle operates at lower temperatures, the overall efficiency is only about 10 – 20 %, depending on the condenser and evaporator temperatures. Although this efficiency is much lower than that of a high temperature steam power plant (30 – 40 %), it is important to remember that low temperature cycles are less efficient than high temperature cycles. Efficiency limits can be expressed by the Carnot efficiency - the maximum possible efficiency of a heat engine operating between two temperatures. A Carnot engine operating with a heat source at 150 ºC and releasing it at 25 ºC is only 30 % efficient. In this light, an efficiency of 10 – 20 % is a significant percentage of the theoretical efficiency, especially compared to other low-temperature options, such as the use of piezoelectrics, which are only 1 % efficient.

The Kalina cycle [7, 11] is a variation of the Rankine cycle, which uses a mixture of ammonia and water as the working fluid. A key difference between single-fluid cycles and cycles that use dual fluids is the temperature profile during boiling and condensation. For single-fluid cycles (e.g., steam or organic Rankine cycles), the temperature remains constant during boiling. As heat is transferred to the working medium (such as water), the temperature of the water slowly rises to its boiling point, where the temperature remains constant until all the water evaporates. In contrast, a binary mixture of water and ammonia (each of which has a different boiling point) will increase its temperature during evaporation. This makes it possible to better match the thermal compatibility with the waste heat source and the cooling medium in the condenser. Consequently, these systems provide significantly greater energy efficiency.

The cycle was invented in the 1980s, and the first power plant based on the Kalina cycle was built in Canoga Park, California in 1991.

<u>*Table 2*</u>

Methods of converting waste heat into electrical energy through mechanical work [7-11].

№	Method	Efficiency	Working temperatures	Electric energy cost	Service life
1.	The Rankine cycle	20 – 30 %	> 350 °C	0.8 – 1.8 $ / W	15 – 20 years
2.	The Kalina cycle	~ 15 %	100 – 540 °C	1.2 – 1.8 $/W	20 – 30 years
3.	The organic Rankine cycle	~ 8 – 15 %	100 – 590 °C	1.4 – 2.2 $/W	20 – 30 years

A comparison of the main parameters of mechanical methods of converting the energy of waste heat into electrical energy is given in table. 2. As can be seen from the table, for successful competition in the low-temperature region, thermoelectric energy recuperators need to reach a cost of no more than $1/W.

1.2. Direct conversion of thermal into electrical energy

For the recovery of low-temperature waste heat, the most favorable among the methods of direct conversion of thermal into electrical energy is thermoelectric [12 – 16].

In addition to thermoelectric energy conversion, other technologies are being developed that allow generation of electricity directly from heat. These include methods such as thermoacoustic, pyroelectric, thermomagnetic, thermoelastic, piezoelectric, and others. [6, 7, 17 – 22]. There is no information in the literature on testing such systems in industrial heat recovery devices, although some have undergone prototype testing in applications, such as automotive heat recovery.

2. Existing thermoelectric waste heat recuperators

Based on the analysis of the literature data, it is possible to single out the currently most common areas of use of thermoelectric heat recuperators: industrial plants, internal combustion engines, thermal power plants, boilers, gas turbines, domestic heat.

2.1. Thermoelectric heat recuperators for industrial installations

It should be noted that heat recovery from stationary industrial plants (especially at temperatures below 600 K) is of great interest for thermoelectricity, as it allows to fully realize its advantages. Estimates show that only in the USA, from thousands of industrial processes, about 3300 TJ of energy is wasted annually [38, 53], part of which can be returned to the active balance with the help of direct thermoelectric energy conversion. Moreover, thermoelectric recuperators can be used not only to increase the overall efficiency of energy conversion, but also to provide backup power to the most important nodes of industrial installations, which significantly increases their reliability [110].

Today, active research is underway of the recovery of waste heat [43 – 51] from such energy-intensive industrial facilities as steel mills [26, 36 – 41, 54, 55], cement kilns [24, 27 – 35, 38 – 40, 52, 54], glass melting furnaces [38 – 40, 52], lime annealing furnaces [38, 39, 52], furnaces for the production of ethylene [38, 39], waste processing plants [104, 105], furnaces for smelting aluminum and other metals [38, 39, 52], etc.

Thus, the scientists of KELK Ltd. and JFE Steel Corporation (Japan) [36, 37] jointly created and tested a thermoelectric recuperator using waste heat from a steel furnace (Fig. 3). Its power is about 9 kW with an efficiency of 8 %.

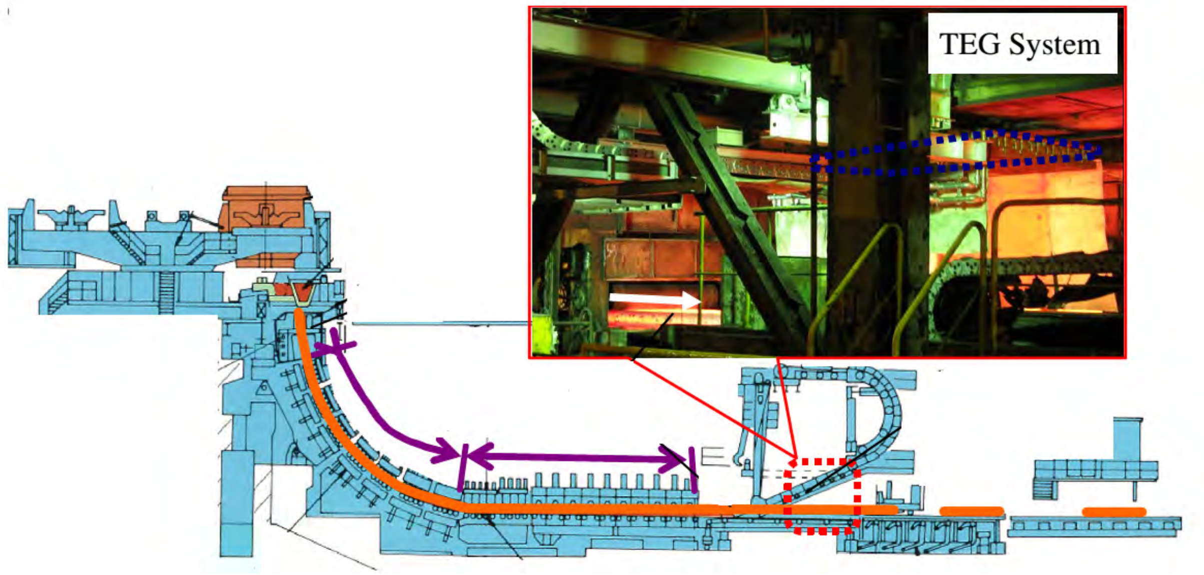

Fig. 3. Thermoelectric generator installed on steel production line of company JFE (Japan) [36].

A thermoelectric recuperator using waste heat from the kiln to produce cement was installed at the cement kiln at the Awazu plant of Komatsu (Japan) (Fig. 4). The power of such a recuperator is about 10 kW.

The waste heat recuperator of cement kilns [35] was also developed by scientists of the Industrial Technology Research Institute (Taiwan) and the Institute of Thermoelectricity (Ukraine). The peculiarity of such a generator is its placement at some distance from the rotating cement kiln, while it does not affect the technological processes inside the kiln.

A project to recover waste heat from waste recycling plants using thermoelectricity was jointly implemented by Fudzitaka (Japan) and the Institute of Thermoelectricity (Ukraine) [104, 105]. The power of one block of such a recuperator installed at the Tokio Gas plant was 1 kW.

The US Department of Energy is showing interest in the use of waste heat from various technological processes in industry. With its support, a group of works dedicated to the recovery of waste heat [38, 39, 52] from steel plants, cement furnaces, glass furnaces, lime kilns, ethylene production furnaces, aluminum and other metal smelting furnaces was created [38, 39, 52]. Economic and technical assessments of the possibility of creating such equipment are given in these works. However, it did not come to real use.

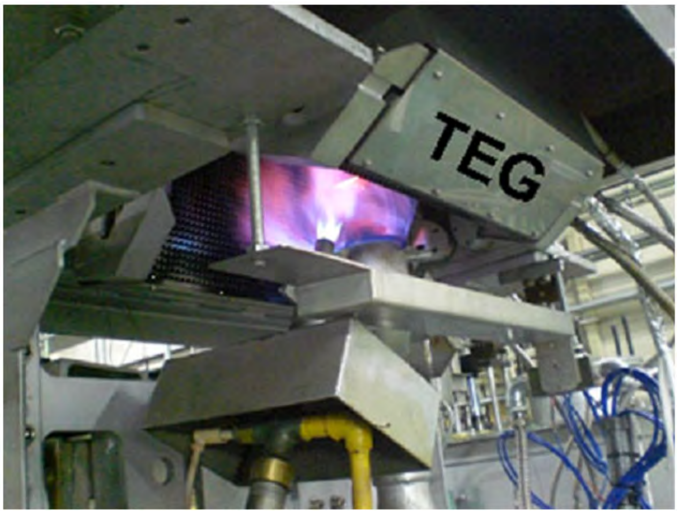

Fig. 4. Installation of thermoelectric generator on cement kiln of the Awazu plant of company Komatsu (Japan) [31].

Very interesting are the works devoted to the use of waste heat from industry using a combined method that unites thermoelectric energy conversion and the organic Rankine cycle [50, 51]. This allows increasing the conversion efficiency up to 13 %.

2.2. Thermoelectric heat recuperators from internal combustion engines

Recently, a large number of publications have been devoted to the topic of heat recovery from internal combustion engines [28, 29, 52, 56 – 103]. These are works related to the recovery of waste heat mainly from passenger car engines (Fig. 5).

In the studies of Japanese scientists [28, 29], the use of a thermoelectric recuperator that employs the thermal energy of the exhaust gases of a Suzuki motorcycle is considered. The power generated in this way is 10 W at a weight of 3 kg and does not allow talking about the prospects of its mass use.

The BMW company [63, 64] conducted a series of studies and tests of a thermoelectric energy recuperator for passenger car exhaust gases. A power of 200 W was achieved with a recuperator weight of 13 kg.

The thermoelectric recuperator manufactured by Nissan Motors [56, 61, 77] showed rather low efficiency. Its efficiency was only 0.1% at a generated power of about 36 W. However, the authors believe that increasing the efficiency to 5% under the same conditions will allow the output power to increase to 950 W.

The Hi-Z company [56, 61, 82, 83] presented the design of a thermoelectric heat recuperator installed on a GM Sierra car. The maximum power generated by such a device was 255 W with an efficiency of 2 %.

The results of research aimed at optimizing the parameters of a thermoelectric heat energy recuperator from a car engine are presented in [66]. The design power of 600 W with an efficiency of 4 – 5 % was confirmed by a series of experiments

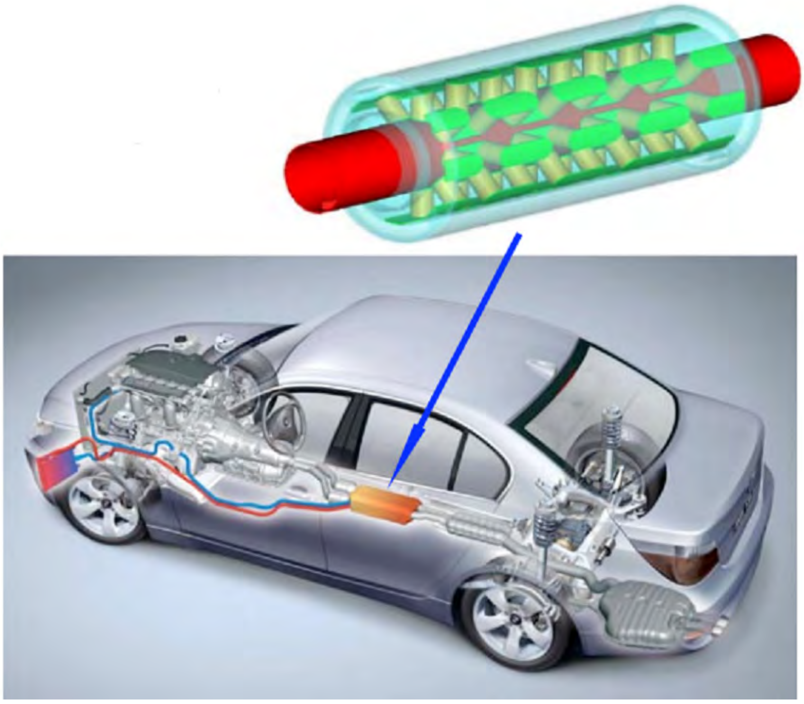

Fig. 5. Thermoelectric recuperator for cars [52].

However, it should be noted that the use of thermoelectric recuperators in passenger cars has a number of disadvantages [60, 70, 71]. The real gain in power is not significant enough. This leads to the search for more efficient applications of thermoelectricity. First of all, heat recovery from diesel engines of large ships (in addition to high power, their advantage is the possibility of heat removal from the cold side of the thermoelectric converter into the surrounding water), as well as large trucks and special equipment [75, 80, 82, 93, 97].

Thus, the Hi-Z company [61, 75, 80, 82] presented a thermoelectric energy recuperator of exhaust gases from the NTC-350 truck diesel engine. After a cycle of tests and refinements, a power of 1 kW was achieved. The efficiency of such a recuperator was as low as 1.3 %.

Also interesting are the works devoted to the use of thermoelectric recuperators in hybrid cars [71], where the energy generated during the operation of the internal combustion engine is used to recharge car batteries. In [100, 103], the results of calculations of a combined recuperator using thermoelectric conversion in combination with the organic Rankine cycle are given.

2.3. Thermoelectric recuperators for thermal power plants

Increasing the efficiency of energy conversion at thermal power plants is an extremely important task.

Paper [106] presents the results of studies of a thermoelectric heat recuperator using waste thermal energy from power plants of the Tokyo Electric Power company. Through the joint efforts of the Komatsu Research Center and KELK [107], such a thermoelectric recuperator was created and its experimental studies were carried out (Fig. 6).

Economic and technical assessments of the possibility of creating similar recuperators were also carried out in [38, 39], but the project was not implemented in practice.

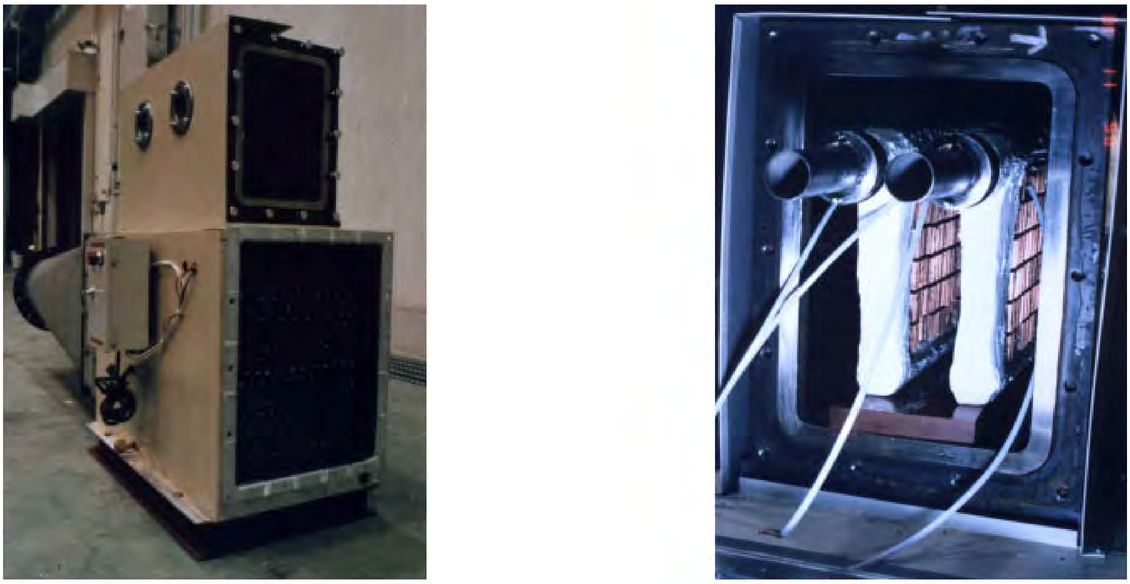

Fig. 6. Thermoelectric recuperator installed at the thermal power plant of the Tokyo Electric Power Company [106].

2.4. Thermoelectric recuperators of waste heat from boilers

Boilers for obtaining steam and hot water are used in almost all large enterprises, in schools and hospitals, large office buildings and for household needs [109]. The heat source for such boilers is usually the combustion energy of gas or other fuel.

In [38, 39], research was carried out and the design of a thermoelectric recuperator was developed, which uses waste thermal energy from industrial boilers (Fig. 7). The efficiency of this converter was realized at the level of 2 %.

Scientists from the Brno University of Technology (Czech Republic) developed and tested a thermoelectric recuperator for the utilization of waste heat from a boiler that uses biomass as fuel [108]. The power generated by such a device is 8.5 W, and the overall efficiency of the boiler increases to 76 %.

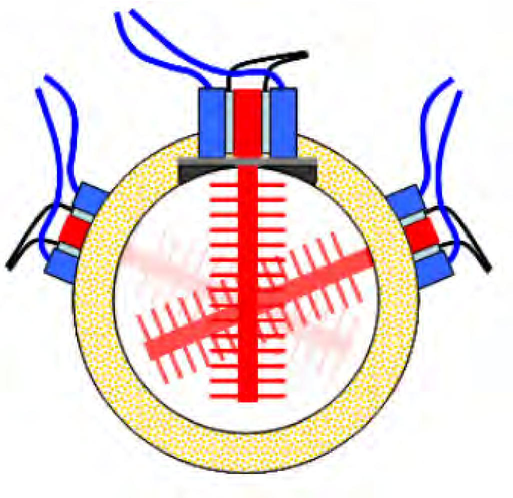

Fig. 7. Installation of a thermoelectric generator in the air duct of the boiler [38].

2.5. Thermoelectric recuperators of heat from gas turbines

Papers [23 – 25, 110] are devoted to the topic of waste heat utilization from gas turbines. Exhaust gases from turbines of pumping stations on gas mains were used as a source of thermal energy.

The design of such a recuperator (Fig. 8) ensures the generation of electric power at the level of 7 kW, which is enough to power gas pumping stations in emergency modes of operation. In this way, the backup power supply of the stations is provided, which significantly increases the reliability of its operation.

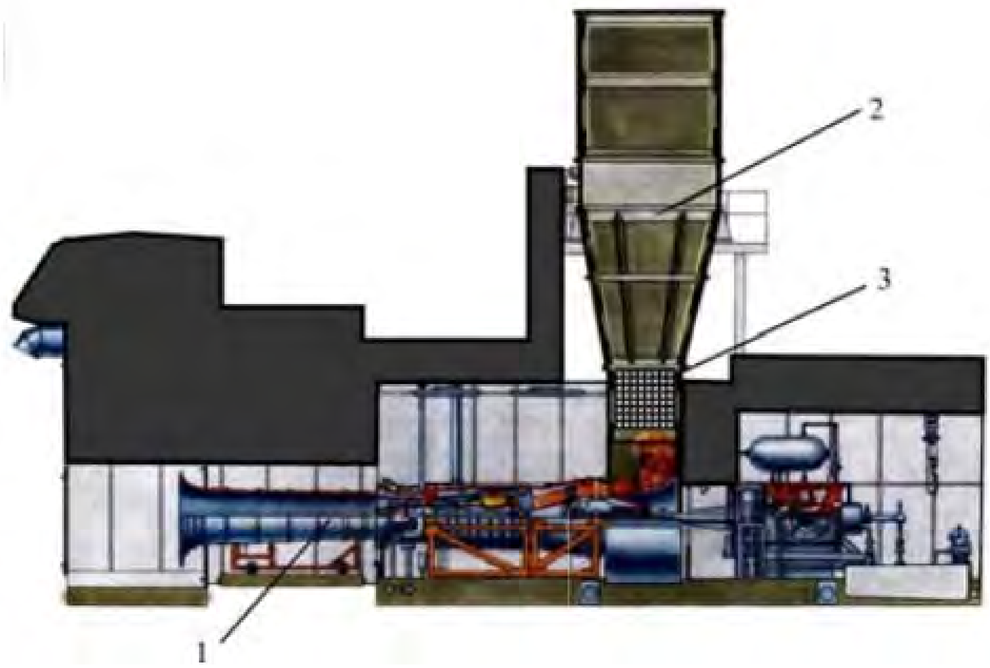

Fig. 8. Gas pumping unit. 1 – gas turbine, 2 – exhaust device, 3 – thermoelectric heat recuperator [110].

2.6. Thermoelectric recuperators of household waste heat

Possibilities of thermoelectric recovery are not limited exclusively to large industrial sources of thermal energy. Recently, the direction of utilization of thermal energy of various household devices to obtain electrical energy, which is necessary for powering low-power equipment (lighting the room with a safe voltage of 12 V, charging batteries of household devices, ensuring air circulation through the use of fans, powering LCD TVs and other radio equipment) [16] has been intensively developing.

Papers [111-115] present the results of the development of a thermoelectric heat recuperator from biomass combustion in a household kitchen stove (Fig. 9). The temperature difference on the thermoelectric modules is created on one side by the flame C, and on the other by the water tank A. The efficiency of such generators is about 4 – 5 %, and the specific cost of the generated electricity is $ 2.7 – $5/W.

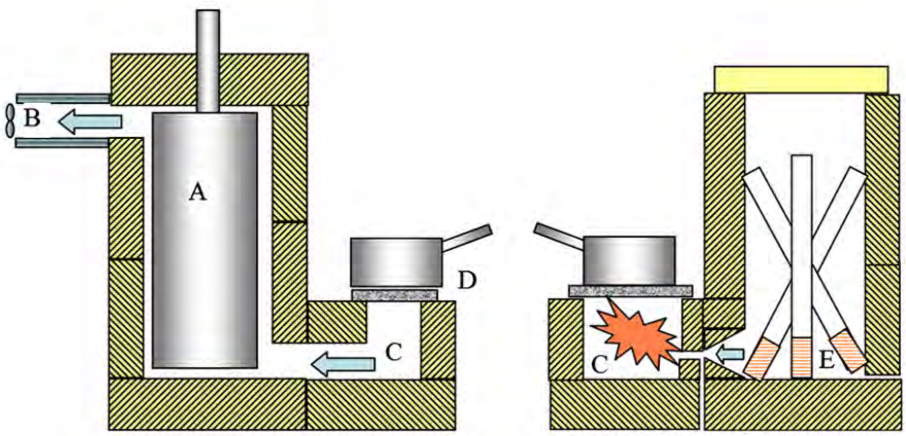

Fig. 9. Heat recovery system from biomass combustion in a household stove (A – water tank, B – gas outlet and fan, C – hot gases from fuel combustion, D – stove, E – combustion chamber) [112].

Similar devices that make it possible to utilize household heat waste are being developed by many organizations, however, unfortunately, it is too early to talk about their mass production and availability of such products.

1.7. Alternative uses of thermoelectric heat recuperators

One of the applications of thermoelectricity for the utilization of waste heat is a recuperator that uses waste heat from the biomass drying process [116]. Such a recuperator is schematically shown in Fig. 11. The power generated by it is used to power fans that circulate hot air in such a system.

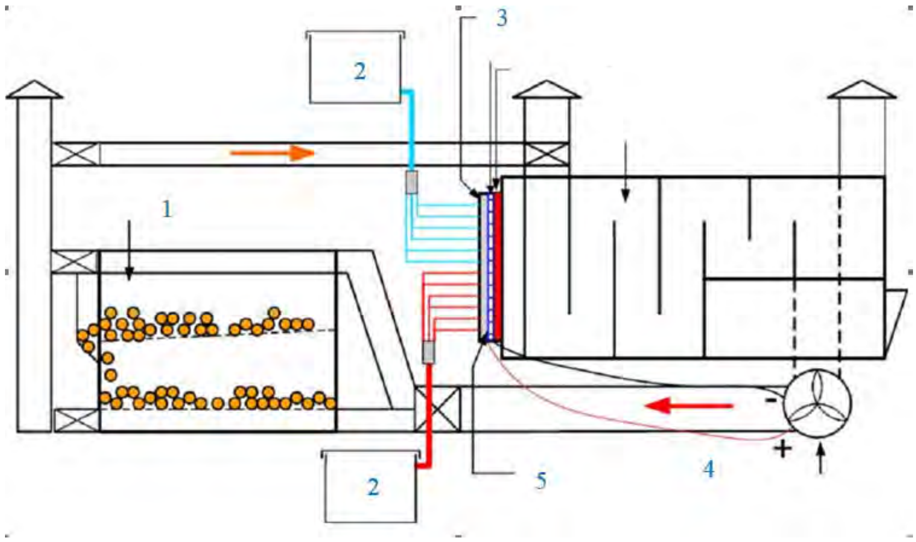

Fig. 11. Thermoelectric recuperator using waste heat from the biomass drying process: 1 – drying chamber, 2 – container with hot water, 3 – generator cooling system, 4 – hot air supply, 5 – thermoelectric converter [116].

Toshiba has developed a 55 W thermoelectric recuperator with an efficiency of 1.8 % [111]. For the conversion, it uses waste heat from the operation of an electrical transformer.

An interesting direction in the development of thermoelectricity is its use to power low-power devices. Reduced power consumption and the emergence of highly efficient voltage converters that begin operating at a level of 30 mV have determined the emergence of a new solution for powering low-power devices on the market. It works by converting waste heat into electrical energy. This makes it possible to increase the service life and reliability of a wide range of autonomous devices that require regular replacement of batteries [124].

In particular, in this way, the power supply of wireless detectors, sensors, indicator meters, parameter monitoring systems and information transmission systems in hard-to-reach or moving parts of equipment is solved, which makes it possible to monitor the condition of the equipment and plan its maintenance. Another promising area is the use of space heating control systems inside the house and reading indicators from various resource consumption meters.

Miniature thermoelectric recuperators used to power low-power equipment and sensors on board the aircraft are considered in [117-122]. Fig. 12 shows the installation of such a device under the wing of the aircraft. The authors present the results of a series of tests of such sources, which confirms their high efficiency.

Thus, the efficiency of currently created thermoelectric energy recuperators is within 1 – 7 % in the range of waste heat temperatures of 50 – 500 °C. The cost of such generators is from 2.7 to 13.5 $ / W with a service life of 10 – 30 years.

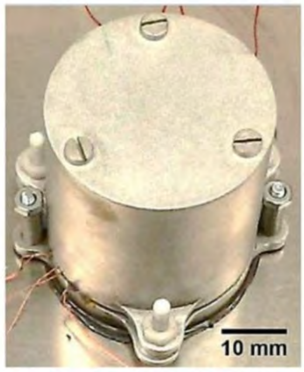

Fig. 12. Place of installation and appearance of a thermoelectric recuperator using waste heat from an Airbus A 380 aircraft turbine [116].

Such indicators do not allow thermoelectricity to compete with the Rankine and Kalina steam cycles and indicate the need for further improvement of thermoelectric recuperators.

A detailed analysis of the possibilities of reducing the cost of thermoelectric waste heat recuperators is given in [125]. It follows from it that achieving the required cost of 1 $/W is possible, provided that heat exchange systems are created with a cost of up to 1 $/(W/K).

Conclusions

1. The most common areas of using thermoelectric heat recuperators are considered, namely - industrial installations, internal combustion engines, thermal power plants, boilers, gas turbines, domestic heat.
2. It has been established that the most effective is the use of thermoelectric recuperators of waste eat from energy-intensive industrial facilities, as well as from powerful internal combustion engines installed, for example, on large trucks or ships.
3. The use of miniature thermoelectric recuperators for powering low-power equipment, as well as the recycling of household waste heat, is also promising.
4. A comparative analysis of existing methods of recuperation of low-temperature waste heat is provided – the conventional and organic Rankine cycles, the Kalina cycle, etc. It is shown that for successful competition in the low-temperature region, thermoelectric energy recuperators need to reach a cost no higher than $1/W, which is possible if heat exchange systems with a cost of up to $1/(W/K) are created.

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РАЦІОНАЛЬНІ ОБЛАСТІ ВИКОРИСТАННЯ ТЕРМОЕЛЕКТРИЧНИХ РЕКУПЕРАТОРІВ ТЕПЛА

Приведено аналіз літератури, присвяченої методам рекуперації відпрацьованого тепла від різних енергоємних. Представлено порівняльний аналіз існуючих методів рекуперації

низькотемпературних відходів тепла – традиційного та органічного циклів Ренкіна, циклу Калини та ін. Наведено характеристики існуючих термоелектричних рекуператорів тепла, а також аналіз можливостей їх подальшого розвитку та найбільш раціональні області їх застосування.
Ключові слова: рекуператор, відпрацьоване тепло, ККД, потужність, питома вартість.

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RESULTS OF EXPERIMENTAL RESEARCH ON THERMOELECTRIC MEDICAL HEAT FLOW SENSORS

The paper presents the results of experimental studies and medical tests of local heat release of the human body using a thermoelectric medical heat flow sensor. The study was conducted in the intensive care and surgical departments of the Vyzhnytskyi Central District Hospital. The device uses a multi-element thermoelectric sensor with high sensitivity and accuracy in a wide temperature range. Medical tests have confirmed that inflammatory processes are accompanied by increased heat release in certain areas, even if the general body temperature remains normal. At the same time, with oncological diseases and thrombosis, there is a reduced heat release in the corresponding parts of the body. The obtained results show the potential of using thermoelectric heat flow sensors for early diagnostics of various pathological conditions, including inflammation and oncological processes. The introduction of thermoelectric heat meters into medical practice will provide an accessible and effective tool for detecting diseases at early stages, which will significantly simplify diagnostic procedures and increase their effectiveness.

Key words: heat flow sensor, thermoelectric heat meter, local heat release, diagnostics of diseases, thermoelectric sensor, body heat release, early diagnostics, inflammatory processes, oncological diseases.

Introduction

The human body has its own thermoregulation system capable of maintaining a stable body temperature regardless of external or internal changes. This creates conditions in which the general body temperature is not always an indicator of existing pathological processes. For example, local inflammatory processes may not lead to an increase in the general body temperature due to the active work of the body's thermoregulatory devices, which is why such conditions may remain hidden during routine temperature measurements. However, these processes are accompanied by increased local thermal release, which can be easily detected using superconductor thermoelectric heat flow sensors [1–3]. These devices are distinguished by high accuracy in measured heat flows and are widely used in medical diagnostics.

In Ukraine, cancer is one of the main causes of mortality among the population. According to the National Cancer Registry of Ukraine, there has been an increase in the incidence of cancer in recent years. In particular, in 2023, more than 200,000 new cases of cancer diagnosis were registered, which shows an increasing trend. The most common types of cancer include breast cancer, lung cancer, stomach cancer, and prostate cancer.

Mortality from oncological diseases in Ukraine remains high (Fig. 1), which is due to insufficient early diagnostics and limited access to modern treatment methods. The survival rate of patients depends on the stage of the disease at the time of diagnostics. Early diagnostics significantly increases the chances of successful treatment and improves the prognosis.

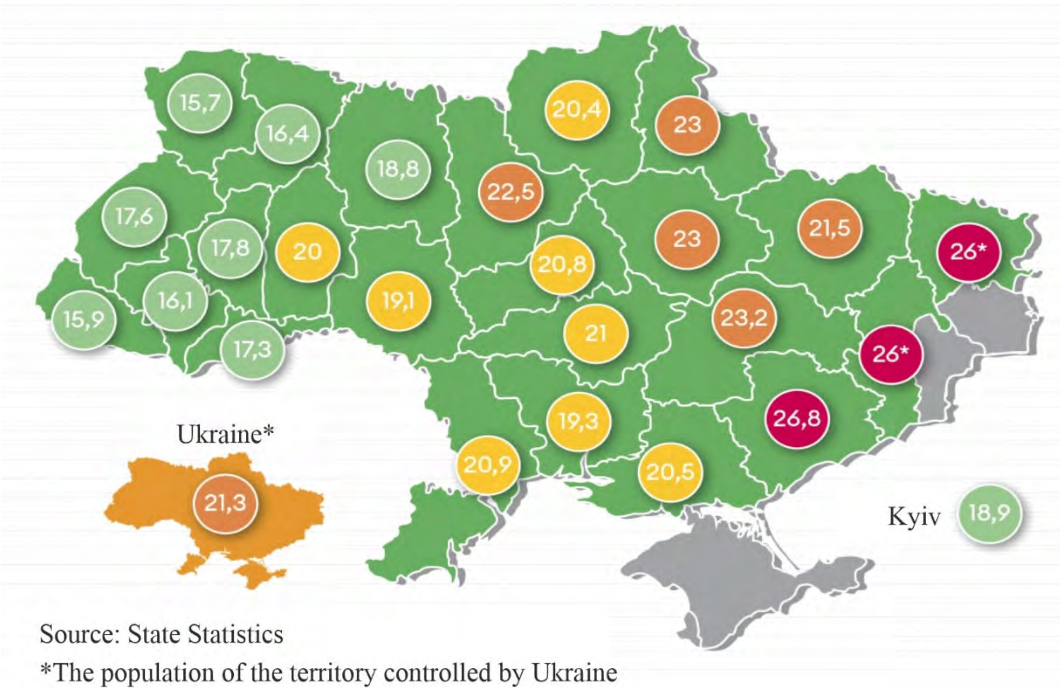

Fig. 1. The number of deaths from oncological diseases in Ukraine per 10,000 population in 2020.

The importance of early diagnostics cannot be overstated. Timely detection of oncological diseases allows us to prevent the progression of the disease, apply effective treatment methods and reduce mortality. To achieve these goals, it is necessary to improve screening methods, raise awareness among the population and ensure access to quality medical services.

Considering the above, constant improvement of the system of diagnostics and treatment of oncological diseases is critically important for improving the general situation in medical diagnostics in Ukraine.

Analysis of the literature. The paper [4] presents the development of a highly sensitive thermoelectric semiconductor heat flow sensor, specially created for medical and biological research, in particular, for measuring heat flows from the surface of the human body. This paper presents the results of using such sensors for the diagnostics and treatment of joint diseases and establishes that it is the heat flow density that is the key parameter that best reflects the degree of expression of inflammatory processes in the human body.

In addition, a heat meter designed to detect oncological diseases of the mammary glands was developed in [5, 6]. Such a device allows diagnosing tumors at early stages, thanks to the analysis of changes in the heat production of mammary gland tissue. Also, a medical thermoelectric heat meter [7] was developed at the Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine, which is used to measure the density of heat flow from the body surface in order to detect inflammatory processes, assess the state of the body in extreme conditions and determine the permissible level of physical activity.

The accuracy and speed of recording signals from thermoelectric sensors are key factors in measuring heat flows from the human body using medical heat meters [8 – 12]. In [13 – 15], modern electronic systems for recording signals from such sensors were developed, which allows monitoring the thermal state of the body in real time.

Studies of the influence of thermoelectric heat meters on the recording of heat flows from human skin were conducted in [16 – 21]. Using computer simulation, the features of using these devices to study local heat release in real operating conditions were analyzed [22, 23]. In [24 – 29], modern multichannel thermoelectric devices were developed that allow real-time measurement of both the temperature and the density of heat flows of the human body, and a method for calibrating thermoelectric sensors for medical purposes was presented [30 – 32].

However, to date, the correlation between the readings of thermoelectric heat flow sensors and the general state of human health has not been sufficiently studied. Therefore, the purpose of this work is to determine the local heat release of the human body using a thermoelectric heat meter for early diagnostics of diseases.

1. Method of measurement

Gradient semiconductor heat flow sensors, which work on the basis of the "auxiliary wall" principle [1, 2] (Fig. 2), are actively used to determine the heat release of the object under study.

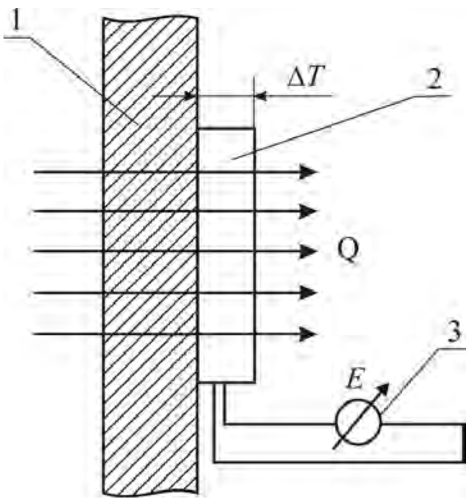

Fig. 2. "Auxiliary wall" method:
1 – surface under study, 2 – gradient heat meter; 3 – galvanometer.

This method consists in measuring the change in temperature ΔT along the heat flow Q on the "auxiliary plane" (plate) located on the surface of the object under study. Due to the Seebeck effect, a thermoelectric power E arises in the thermopile used as an "auxiliary wall", proportional to the temperature difference between its faces. This allows the thermopile to be pre-calibrated and the thermoelectric power value to be used to determine the heat flow density.

The temperature distribution $T(r)$ in the thermoelements of the auxiliary plate can be found by solving the differential equation of thermal conductivity in the quasi-stationary approximation, written in the isotropic situation for the legs of *n*- and *p*-type [1, 2]:

$$\nabla(\kappa\nabla T)+\frac{i^2}{\sigma}-Ti\nabla\alpha=0\,, \tag{1}$$

where κ, σ, α are thermal conductivity, electric conductivity and thermoEMF of legs material, *i* is electric current density.

The solution of the differential equation (1) makes it possible to determine the temperature distribution $T(r)$ and specific heat flows $q(r)$ from the relationship:

$$q(r)=\alpha iT-\kappa\nabla T=0\,. \tag{2}$$

The amount of heat flow on the surface of the plate is determined by the ratio:

$$Q=\int_S q(r)ds\,, \tag{3}$$

where *S* is free surface of the plate.

Ratios (1) – (3) make it possible to determine the relationship between the heat flow and the temperature distribution on the surface of the plate. In the case of small temperature differences, which are often encountered in engineering applications, the heat flow value is determined by averaging the parameters of relations (1) – (3) from the following equation [1, 2]:

$$Q=\frac{\lambda}{l}\cdot S\cdot\Delta T\,, \tag{4}$$

where *Q* is the value of the measured heat flow, λ is the effective coefficient of thermal conductivity of the "wall" – the primary heat flow converter, *l* is the thickness of the "wall", *S* is the surface area of the plate, ΔT is the average temperature difference between the heat exchange sides of the "wall", which is measured by the battery of thermoelements of the primary converter.

The quantities λ, *l*, *S* have constant values, and the ratio $\frac{\lambda}{l}\cdot S=C$ is a fixed characteristic of the sensor determined through experiment. In this case, the heat flow is calculated by the formula:

$$Q=C\cdot\Delta T\,. \tag{5}$$

Therefore, this method involves placing a heat flow sensor on the object being studied, obtaining readings from the heat meter in a steady state, and measuring the thermoelectric force (thermoEMF) of the heat meter.

2. Operating principle and structure of a thermoelectric heat flow sensor

The recorder is designed to measure and automatically record temperature and DC voltage, ambient temperature (room temperature). The general appearance of the device is shown in Fig. 3.

When developing the electronic indicator, special attention was paid to its reliability and low cost, which provides the possibility of wide implementation of thermoelectric heat flow sensors in medical practice.

Before carrying out measurements, it is necessary to fulfill the following requirements, in particular, to determine the temperature of the human body T_{body}, °C. For each measurement of the heat flow on the surface of the human body, the same conditions should be ensured:

- ambient temperature T_{room},°C
- vertical or horizontal arrangement of thermoelectric heat flow sensor on the surface of the body;
- body position during measurement.

a)

b)

Fig. 3. Appearance of heat flow (voltage) and temperature measuring and recording devices. a – measuring device version with a heat flow sensor; b – measuring device version with temperature sensors.

When developing the electronic indicator, special attention was paid to its reliability and economic availability, which contributes to the widespread introduction of thermoelectric heat flow sensors in medicine.

3. Results of experimental studies

Experimental studies of the thermoelectric medical heat flow sensor were carried out in the intensive care and surgical departments of the Vyzhnytskyi Central District Hospital. The results of the conducted studies are presented below in Fig. 4 – 7 for various patient diagnoses.

The first stage of the tests was the study of postoperative processes accompanied by increased values of heat flow density of inflamed areas of the human body. This is especially noticeable when analyzing heat flows on the surface of the human body in the area of the liver when diagnosing a patient with cirrhosis of the liver (ascites) (Fig. 4). It should be noted that the patient's body temperature before and after the operation was T = 36.6 °C.

From Fig. 4 it is clear that after the operation the heat release in the liver area stabilized, the inflammatory process stopped and the patient is recovering.

Let us consider in more detail the heat release on the surface of the human body for patient diagnoses – cirrhosis of the liver (ascites) and atrophic cirrhosis of the liver (Fig. 5). The figure shows that heat release in the area of the liver almost did not change with atrophic cirrhosis of the liver.

However, heat release in the intestine and spleen is reduced by 3 – 4 times due to blood stagnation in the portal vein (thrombotic condition).

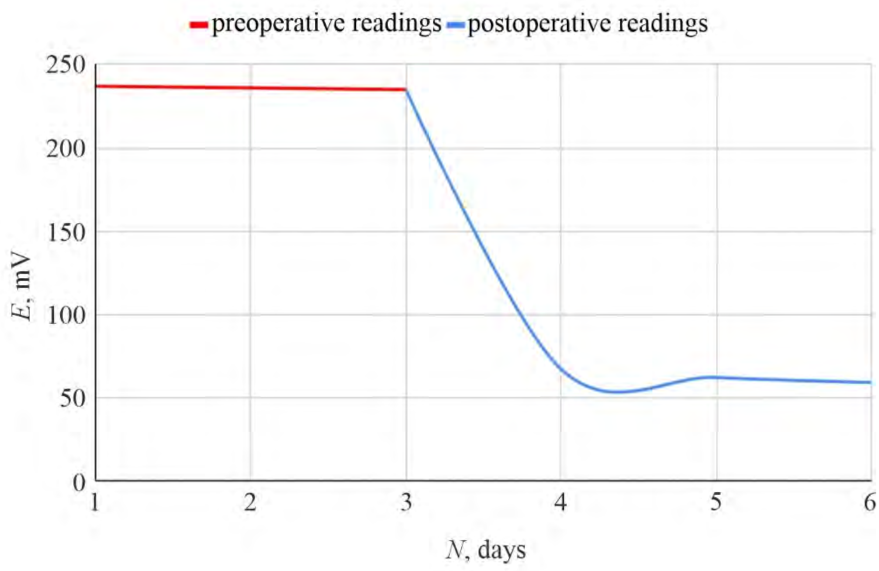

Fig. 4. Results of experimental studies of heat flows of the human body surface in the liver area with a patient diagnosed with liver cirrhosis (ascid).

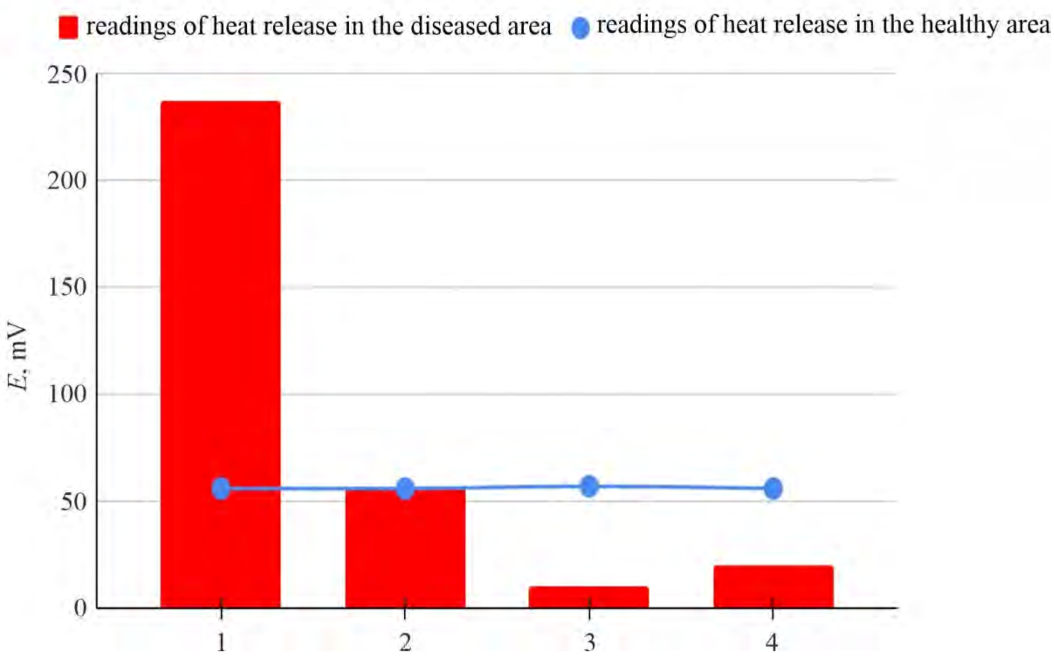

Fig. 5. Results of experimental studies of heat flows of the human body surface with a patient diagnosed with liver cirrhosis: 1 – liver cirrhosis (ascites); 2 – atrophic liver cirrhosis (liver readings); 3 – atrophic liver cirrhosis (intestine readings); 4 – atrophic liver cirrhosis (spleen readings).

Fig. 6 shows a diagram of average readings of a thermoelectric heat flow sensor for healthy areas of the body.

The diagram (Fig. 6) shows that the readings of the thermoelectric heat flow sensor for healthy areas of the body vary within 50 – 70 mV. In some areas, such as the temple, the readings can reach 81 mV. This is due to the presence of the temporal artery, through which a large amount of blood passes, causing intense heat release. However, when measuring the heat flow in the shin and knee area, reduced heat generation was observed, which is probably due to the lower blood supply to these areas.

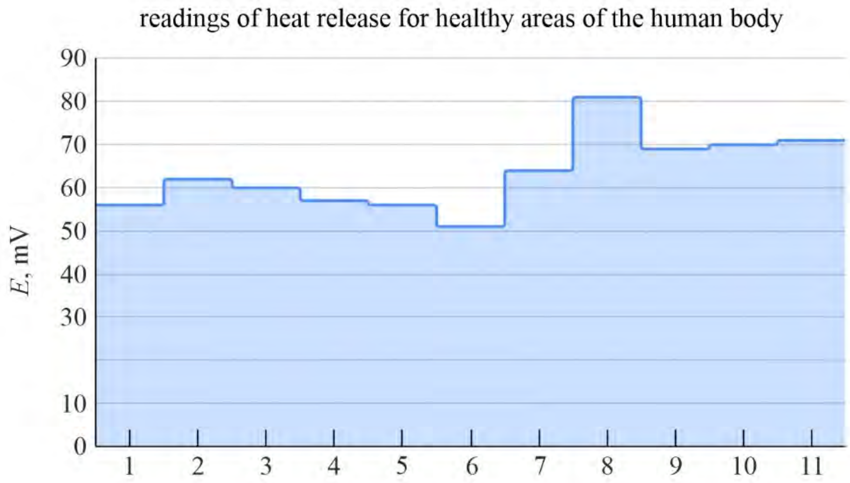

Fig. 6. Average readings of a thermoelectric heat meter for healthy areas of the human body: 1 – liver, 2 – pancreas, 3 – kidneys, 4 – intestines, 5 – spleen, 6 – knee joint, 7 – right shin, 8 – temples, 9 – heart, 10 – mammary gland, 11 – large intestine.

Fig. 7 shows a diagram of average readings of a thermoelectric heat flow sensor for diseased areas of the human body with different patient diagnoses.

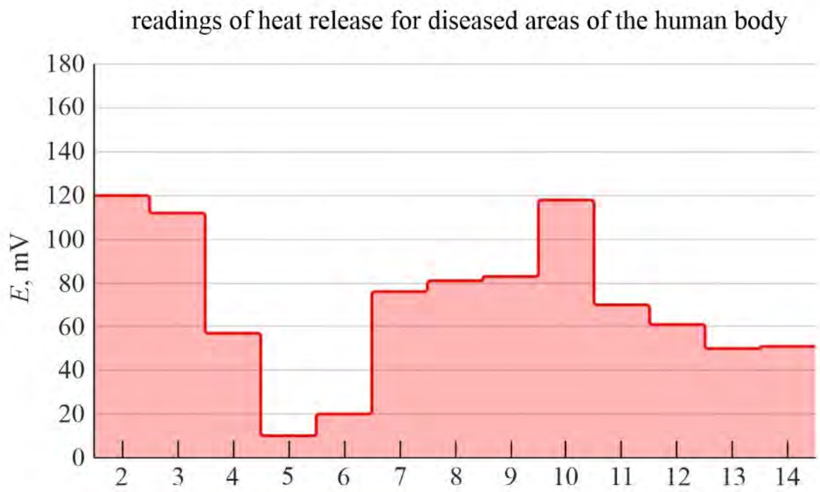

Fig. 7. Average readings of the thermoelectric heat meter for various patient diagnoses: 1 – liver cirrhosis (ascid); 2 – inflammation of the pancreas (pancreatonecrosis); 3 – inflammation of the kidneys (nephritis); 4 – atrophic cirrhosis of the liver (liver readings); 5 – atrophic cirrhosis of the liver (intestine readings); (spleen readings), 7 – rheumatoid arthritis (inflammation of the knee joint), 8 – trauma to the right shin, 9 – post-traumatic phlebothrombosis (concomitant diagnosis – suppurative hematoma on the right leg), 10 – stroke, 1, 12 – heart attack, 13 – benign breast tumor, 14 – tumor of ileocecal angle (readings in the colon area).

Let us consider in more detail the possible reasons for changes in heat release in diseased areas of the human body in various diseases.

In liver cirrhosis (at the ascites stage), the patient's liver enlarges and fluid accumulates in the abdominal cavity. During this, inflammatory reactions occur, resulting in an increase in the heat flow of this area. In nephritis (inflammation of the kidneys) and pancreatic necrosis (inflammation of the pancreas), the interstitial tissue of the kidneys and pancreas is acutely affected, which is also accompanied by a significant increase in the heat release of this area.

A characteristic feature of atrophic liver cirrhosis is that the liver size decreases, and blood stagnation occurs around it in the portal vein system. At the same time, the heat flow of the intestine and spleen decreases several times compared to heat release in a healthy state.

Rheumatoid arthritis (inflammation of the knee joint) is characterized by a chronic inflammatory process of autoimmune nature, the final result of which is ankylosis (i.e. a person loses the ability to move). Naturally, such an inflammatory process is also accompanied by increased values of heat flow density, which has been experimentally confirmed using a thermoelectric medical heat meter.

Posttraumatic phlebothrombosis is a condition of a person after thrombosis. Due to limited accumulation of blood in tissues and formation of a cavity that contains liquid or coagulated blood and accumulation of microbes, such patients develop a suppurating hematoma. During this, inflammatory processes occur, accompanied by increased heat release. It is important to determine the presence of such inflammatory processes in the early stages in order to take priority measures to improve the patient's health.

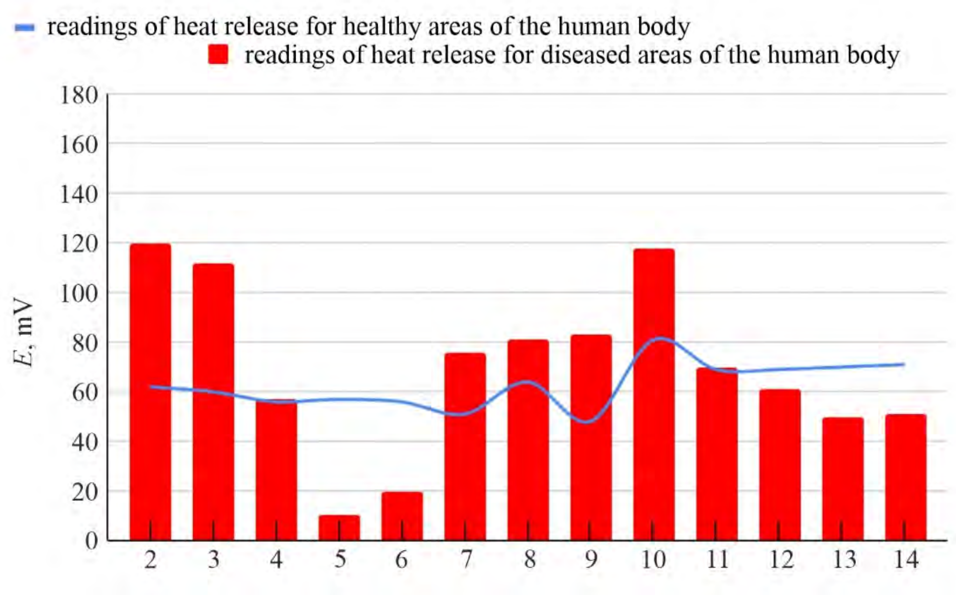

Fig. 8. Average readings of the thermoelectric heat meter for various patient diagnoses: 1 – liver cirrhosis (ascites), 2 – inflammation of the pancreas (pancreatonecrosis), 3 – inflammation of the kidneys (nephritis), 4 – atrophic cirrhosis of the liver (liver readings); 5 – atrophic cirrhosis of the liver (intestine readings), 6 – atrophic cirrhosis of the liver (spleen readings), 7 – rheumatoid arthritis (inflammation of the knee joint), 8 – right leg injury, 9 – post-traumatic phlebothrombosis (concomitant diagnosis – suppurative hematoma on the right leg), 10 – stroke, 11 – angina pectoris (readings in the heart area), 12 – heart attack, 13 – benign breast tumor; 14 – tumor of ileocecal angle (readings in the colon area).

It is known that myocardial infarction is accompanied by a sudden disruption of local cardiac blood circulation. However, it has been experimentally established that during a heart attack, there is no increase in heat release in the heart area. There are also no significant changes in heat generation in the heart area during angina, the symptoms of which are attacks of sudden pain behind the sternum due to acute insufficiency of blood supply to the myocardium. However, during a stroke (cerebral hemorrhage), heat release in the area of a person's temples increases significantly, since cerebral blood circulation is acutely disrupted, which leads to damage to brain tissue and disorders of its functions.

It is interesting that the areas of the human body affected by cancer are characterized by reduced heat release compared to similar healthy areas. For example, an area with a breast tumor (which has the form of a connective tissue tumor of a solid consistency) can have half the heat release. This indicates that, unlike inflammatory processes, cancer diseases are characterized by reduced heat release in the corresponding damaged areas of the human body.

After averaging the readings of the thermoelectric heat meter within each diagnosis, the results of experimental measurements can be presented in the following form (Fig. 8).

When analyzing the diagram shown in Fig. 8, we can conclude that in the presence of inflammatory processes, heat release in diseased areas increases, and in the presence of thrombotic processes and oncological diseases, heat release in the corresponding areas decreases significantly. This is due to a change in the metabolic activity of the affected areas of the human body.

Conclusions

1. Experimental studies and medical tests of the thermoelectric heat flow sensor were carried out in the intensive care and surgical departments of the Vizhnitsa Central District Hospital. It was found that inflammatory processes in the human body are accompanied by increased heat release in the corresponding areas even at normal human body temperature, while the presence of oncological diseases and thrombotic processes are characterized by reduced heat release values.
2. It has been established that thermoelectric heat flow sensors are promising for diagnosis in the early stages of cancer and inflammatory processes in the human body. The implementation of such sensors in medical practice will provide a simple and effective method of diagnosing various human diseases.

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РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ ТЕРМОЕЛЕКТРИЧНИХ МЕДИЧНИХ СЕНСОРІВ ТЕПЛОВОГО ПОТОКУ

У роботі представлено результати експериментальних досліджень та медичних випробувань локального тепловиділення людського тіла за допомогою термоелектричного медичного сенсора теплового потоку. Дослідження проведено в реанімаційному та

хірургічному відділеннях Вижницької центральної районної лікарні. Пристрій використовує багатоелементний термоелектричний сенсор з високою чутливістю та точністю в широкому діапазоні температур. Медичні випробування підтвердили, що запальні процеси супроводжуються збільшеним тепловиділенням у певних зонах, навіть якщо загальна температура тіла залишається в нормі. Водночас, при онкологічних захворюваннях та тромбозах спостерігається знижене тепловиділення у відповідних ділянках тіла. Отримані результати демонструють перспективність застосування термоелектричних сенсорів теплового потоку для ранньої діагностики різних патологічних станів, включаючи запалення та онкопроцеси. Впровадження термоелектричних тепломірів у медичну практику забезпечить доступний та ефективний інструмент для виявлення захворювань на ранніх стадіях, що значно спростить діагностичні процедури та підвищить їхню ефективність.
Ключові слова: сенсор теплового потоку, термоелектричний тепломір, локальне тепловиділення, діагностика захворювань, термоелектричний датчик, тепловиділення тіла, рання діагностика, запальні процеси, онкологічні захворювання.

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ENERGY CHARACTERISTICS OF THERMOELECTRIC CONVERTERS POWERED BY HUMAN BODY HEAT

The paper presents a three-dimensional physical model, analytical description and results of computer simulation of thermoelectric converters placed on the surface of the human body. Optimal properties of thermoelectric converters are determined, whereby maximum values of electric power W_{max} and efficiency are achieved in a state of rest and during physical exertion on the human body.
Key words: thermoelectric microgenerator, human body, energy characteristics, state of rest, physical exertion, computer simulation.

Introduction

In [1 – 10], simple one-dimensional physical models of a thermoelectric microgenerator and the process of temperature distribution and heat flows in the "human body – thermoelectric microgenerator" system are used. Such models do not take into consideration thermophysical processes in human biological tissue, namely blood circulation and metabolic processes

Therefore, *the purpose of the work* is to develop a three-dimensional physical model of thermal and electrical processes in the "human body – thermoelectric microgenerator" system, its mathematical description and determination by computer methods of the optimal properties of thermoelectric converters, which achieve the maximum values of electrical power and efficiency in a state of rest and during physical exertion on the human body.

1. Physical model

Consider a three-dimensional physical model of human skin (Fig. 1), on the surface of which a thermoelectric converter 1 is placed. Human skin consists of four layers (epidermis 2, dermis 3, subcutaneous layer 4, internal biological tissue 5) and is characterized by the following parameters: thermal conductivity κ_i, specific heat capacity C_i, density ρ_i, blood perfusion rate ω_{bi}, blood density ρ_b, blood heat capacity C_b and specific heat release q_{meti} due to metabolic processes (Table 1). The geometric dimensions of each skin layer are a_i, b_i, L_i. The temperatures at the boundaries of the corresponding skin layers are $T(z_i)$.

A thermoelectric converter 1 is a monolithic homogeneous bar of thickness L_1 with equivalent thermal conductivity κ_1. The temperature on the contact surface of the human skin and the thermoelectric converter is $T(z_1)$, and the temperature on the surface of the thermoelectric converter is $T(0)$. The temperature difference across the thermoelectric converter is ΔT.

The surface of the skin and the thermoelectric converter are in a state of heat exchange with the environment with heat exchange coefficients α_1 and α_2. The ambient temperature is T_{amb}. The density of the heat flow passing through the thermoelectric converter is Q. The lateral surfaces of the human skin and the thermoelectric converter are adiabatically insulated.

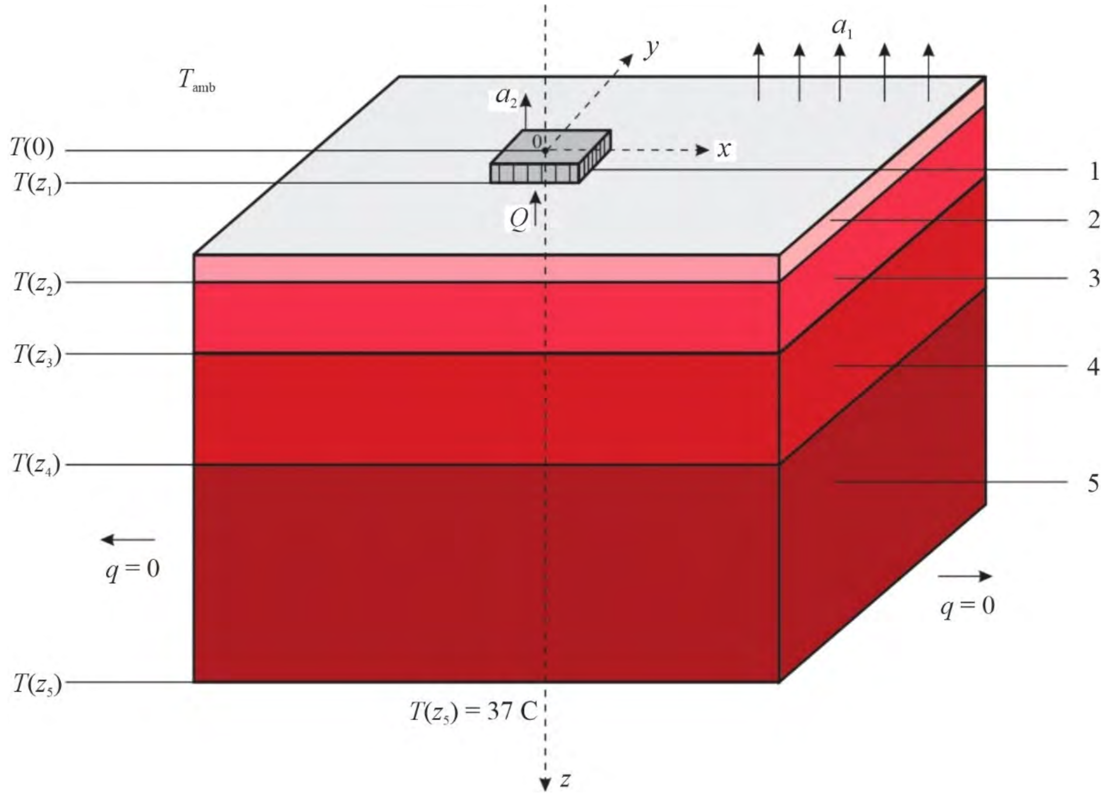

Fig. 1. Physical model of human skin, on the surface of which a thermoelectric converter is located: 1 – thermoelectric converter, 2 – epidermis, 3 – dermis, 4 – subcutaneous layer, 5 – internal tissue.

Table 1

Thermophysical properties of human skin layers [12 – 16]

Layers of biological tissue	*Epidermis*	*Dermis*	*Subcutaneous layer*	*Internal tissue*
Thickness, L (mm)	0.08	2	10	30
Specific heat, C ($W \cdot c \cdot kg^{-1} \cdot K^{-1}$)	3590	3300	2500	4000
Thermal conductivity, κ ($W \cdot m^{-1} \cdot K^{-1}$)	0.24	0.45	0.19	0.5
Density, ρ ($kg \cdot m^{-3}$)	1200	1200	1000	1000
Metabolic heat density, q_{met} ($W \cdot m^{-3}$)	368.1	368.1	368.3	368.3
Blood tissue perfusion rate, ω_b ($m^3 \cdot s^{-1} \cdot m^{-3}$)	0	0.00125	0.00125	0.00125
Blood temperature, T_b, (K)	310	310	310	310
Blood density, ρ_b ($kg \cdot m^{-3}$)	1060	1060	1060	1060
Blood heat capacity, C_b ($W \cdot c \cdot kg^{-1} \cdot K^{-1}$)	3770	3770	3770	3770

2. Analytical description

In general, the equation of heat exchange in biological tissue has the following form [12-16]:

$$\rho c \frac{\partial T}{\partial t} = \nabla\left(\kappa \nabla T\right) + \rho_b c_b w_b \left(T_b - T\right) + q_{met}\,, \tag{1}$$

where ρ is the density of biological tissue, *c* is the specific heat of biological tissue, κ is the thermal conductivity of biological tissue, ρ_b is the density of blood, c_b is the specific heat of blood, ω_b is blood perfusion rate, T_b is blood temperature, q_{met} is the density of heat release due to metabolism.

The term on the left side of equation (1) represents the rate of change of thermal energy contained in a unit volume of biological tissue. The three terms on the right side of this equation represent, respectively, the rate of change of thermal energy due to thermal conductivity, blood perfusion, and metabolic heat.

To solve the problem posed in this paper, we will consider a three-dimensional stationary case. Then equation (1) will take on the form (2):

$$\kappa \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right) + \rho_b c_b w_b \left(T_b - T\right) + q_{met} = 0\,. \tag{2}$$

The stationary heat exchange equation for a thermoelectric converter, provided that the influence of thermoelectric phenomena is neglected, which is valid for small temperature differences, will have the following form:

$$\kappa\left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right) = 0\,. \tag{3}$$

Therefore, to find the stationary temperature distribution in the "thermoelectric converter – human body surface" system, it is necessary to solve the boundary value problem for a three-dimensional system of equations (4), each equation of which corresponds to the corresponding layer of skin according to the physical model (Fig. 1):

$$\begin{cases}
\kappa_1 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=0\div z_1}} = 0 \\
\kappa_2 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + q_{met_1} = 0 \\
\kappa_3 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_2} = 0 \\
\kappa_4 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_3} = 0 \\
\kappa_5 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_4} = 0
\end{cases} \tag{4}$$

with the following boundary conditions (5 – 9) in the form:

$$\alpha_1 \cdot (T(x,y,z) - T_{пов})\Big|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=0}} = \kappa_1 \cdot \frac{\partial T(x,y,z)}{\partial z}\Big|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=0}}$$

$$\kappa_1 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^- \Bigg|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=z_1}} = \kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^+ \Bigg|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=z_1}} \tag{5}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0 \\ y=0\div y_1 \\ z=0\div z_1}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_1 \\ y=0 \\ z=0\div z_1}} = 0$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=x_1 \\ y=0\div y_1 \\ z=0\div z_1}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_1 \\ y=y_1 \\ z=0\div z_1}} = 0$$

$$T^-(x,y,z)\Big|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=z_1}} = T^+(x,y,z)\Big|_{\substack{x=0\div x_1 \\ y=0\div y_1 \\ z=z_1}};$$

$$\kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^+ \Bigg|_{\substack{x=x_1\div x_2 \\ y=y_1\div y_2 \\ z=z_1}} = \alpha_2 \cdot \left(T^+(x,y,z) - T_{пов}\right)\Big|_{\substack{x=x_1\div x_2 \\ y=y_1\div y_2 \\ z=z_1}}$$

$$\kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^- \Bigg|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_2}} = \kappa_3 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^+ \Bigg|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_2}} \tag{6}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0 \\ y=0\div y_2 \\ z=z_1\div z_2}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2 \\ y=0 \\ z=z_1\div z_2}} = 0$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=x_2 \\ y=0\div y_2 \\ z=z_1\div z_2}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2 \\ y=y_2 \\ z=z_1\div z_2}} = 0$$

$$T^-(x,y,z)\Big|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_2}} = T^+(x,y,z)\Big|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_2}}$$

$$\kappa_3 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^- \Bigg|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_3}} = \kappa_4 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^+ \Bigg|_{\substack{x=0\div x_2 \\ y=0\div y_2 \\ z=z_3}} \tag{7}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0 \\ y=0\div y_2 \\ z=z_2\div z_3}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2 \\ y=0 \\ z=z_2\div z_3}} = 0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_2\div z_3}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_2\div z_3}}=0$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}}=\left.T^{+}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}}$$

$$\left.\kappa_4\cdot\left(\frac{\partial T(x,y,z)}{\partial z}\right)^{-}\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}=\left.\kappa_5\cdot\left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}} \tag{8}$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=0\\ y=0\div y_2\\ z=z_3\div z_4}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=0\\ z=z_3\div z_4}}=0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_3\div z_4}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_3\div z_4}}=0$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}=\left.T^{+}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_5}}=37+273 \tag{9}$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=0\\ y=0\div y_2\\ z=z_4\div z_5}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=0\\ z=z_4\div z_5}}=0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_4\div z_5}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_4\div z_5}}=0$$

where α_1 is the heat exchange coefficient of the skin surface with the environment, α_2 is the heat exchange coefficient of the thermoelectric converter with the environment, $T(x,y,z)$ is the absolute temperature, T_{amb} is the ambient temperature (air).

The solution to this boundary value problem gives the distribution of temperature and heat flow in the "thermoelectric converter – human body surface" system.

To determine the maximum value of the generated electric power W_{max} of the thermoelectric converter, we determine the EMF according to formula (10):

$$E=\lambda\cdot N\cdot\Delta T\,, \tag{10}$$

where

$$\Delta T=T(0,0,z_1)-T(0,0,0)\,. \tag{11}$$

Then the maximum generated electric power W_{max} of the thermoelectric converter is determined by the formula (12):

$$W_{\max} = \frac{E^2}{4 \cdot R_L}, \tag{12}$$

where the load resistance R_L in the W_{max} mode is equal to the resistance of the thermoelectric converter, i.e

$$R_L = R = \frac{1}{\sigma} \cdot \frac{l}{S} \cdot N. \tag{13}$$

The efficiency of the thermoelectric converter is determined by formula (14):

$$\eta = \frac{W}{Q} \cdot 100\%, \tag{14}$$

where the amount of heat passing through the thermoelectric converter is determined as follows:

$$Q = \kappa_1 \cdot S_1 \cdot \int_0^{x_1}\int_0^{y_1} \frac{\partial T(x,y,z)}{\partial z}\bigg|_{z=z_1} dxdy. \tag{15}$$

3. Computer model

In order to determine the optimal properties of thermoelectric converters, whereby the maximum values of electric power and efficiency are achieved, a three-dimensional computer model of human skin, on the surface of which a thermoelectric converter is placed, was created. For this, the Comsol Multiphysics package of application programs was used [17], which makes it possible to simulate thermophysical processes in biological tissue, taking into account blood circulation and metabolism [18 – 39].

The calculation of temperature distributions and heat flux density in human skin and a thermoelectric converter was carried out using the finite element method (Fig. 2), the essence of which is that the object under study is divided into a large number of finite elements and in each of them the value of the function is sought that satisfies the specified second-order differential equations with the corresponding boundary conditions. The accuracy of the solution to the problem depends on the level of division and is ensured by using a large number of finite elements [17].

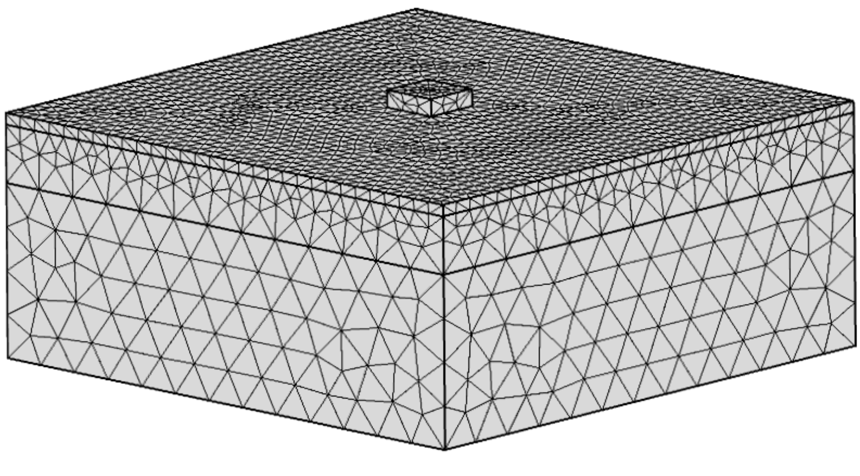

Fig. 2. Finite element method mesh.

Using object-oriented computer simulation, temperature distributions (Fig. 3) and heat flux density lines in the skin and thermoelectric converter were obtained.

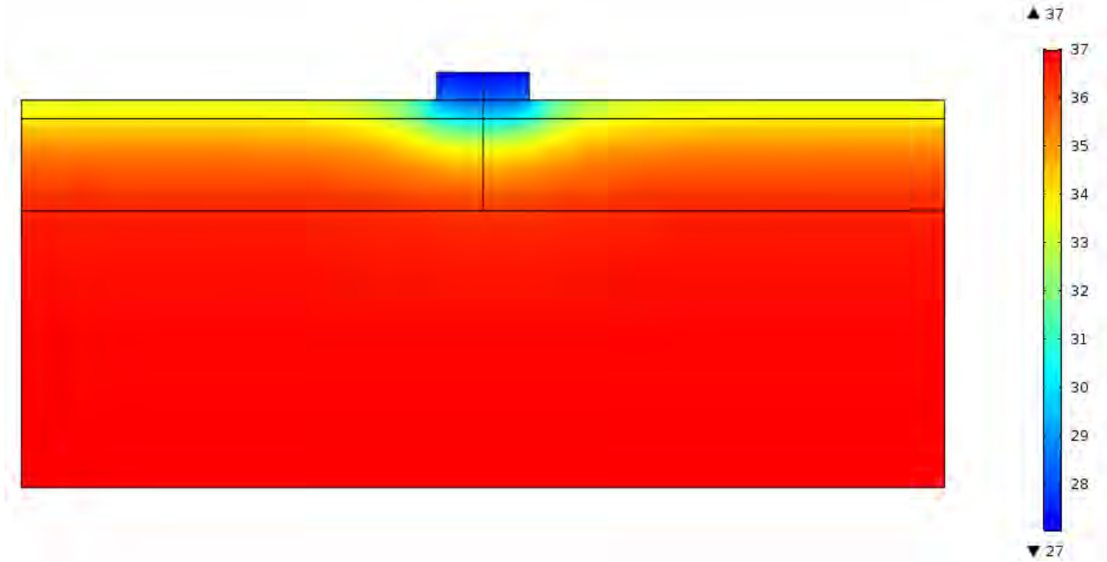

Fig. 3. Temperature distribution in a cross-section of human skin, on the surface of which a thermoelectric converter is located (at an ambient temperature of T = 20 °C).

4. Results of computer simulation

Using computer simulation, the optimal parameters of thermoelectric converters were determined, whereby maximum values of electrical power and efficiency are achieved in a state of rest and during physical exertion on the human body (Fig. 4 – 9).

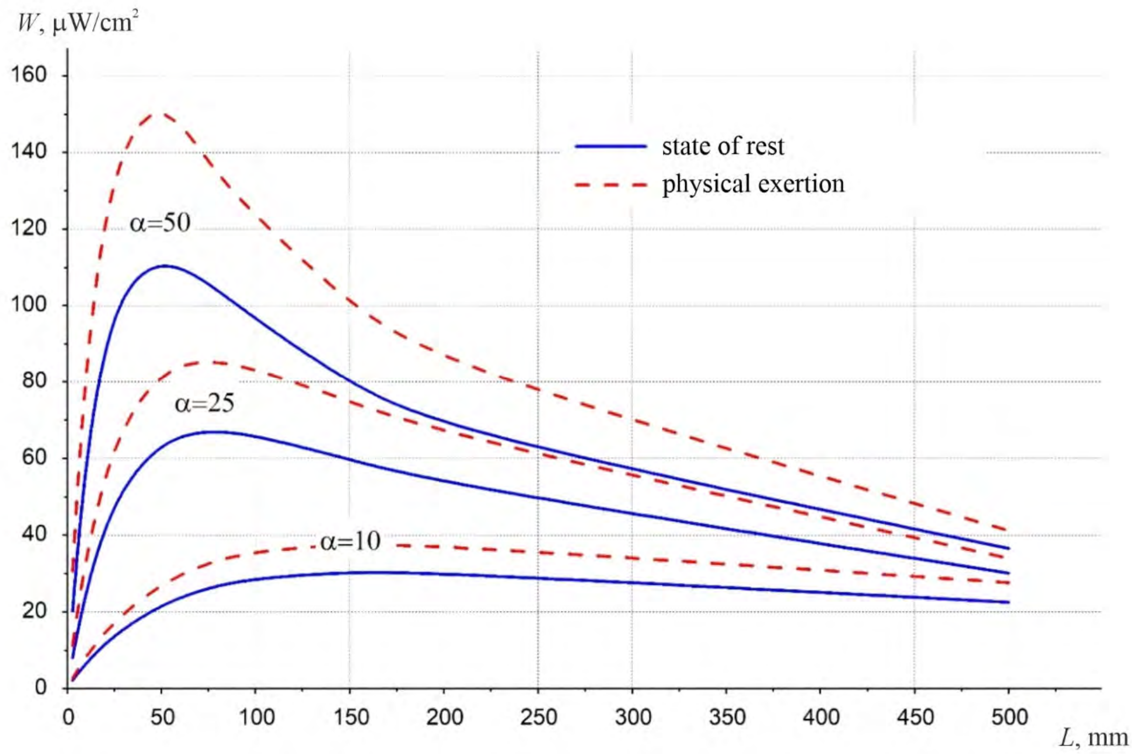

Fig. 4. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 20 °C and a coefficient of heat exchange with the environment of α = 10, 25, 50 W/m² K.

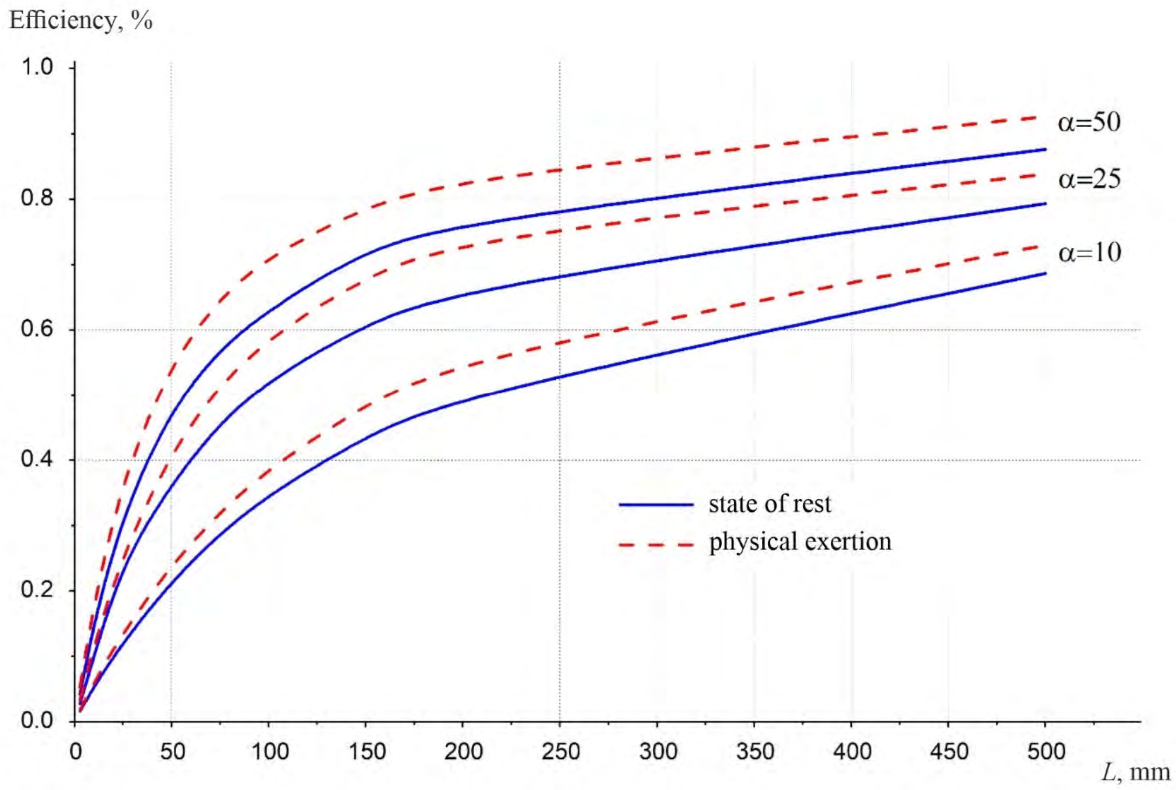

Fig. 5. Dependence of the efficiency on the height of the thermoelectric converter at an ambient temperature of T = 20 °C and a coefficient of heat exchange with the environment α=10, 25, 50 W/m²·K.

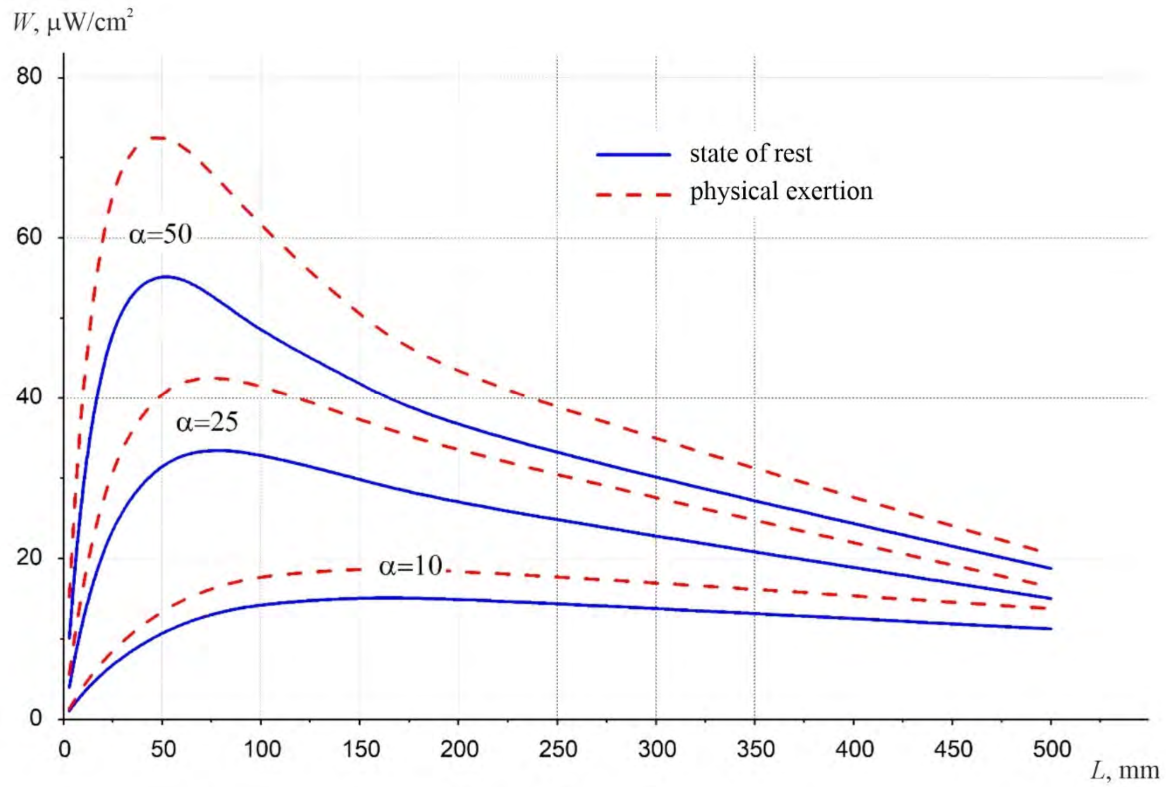

Fig. 6. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 25 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m² K.

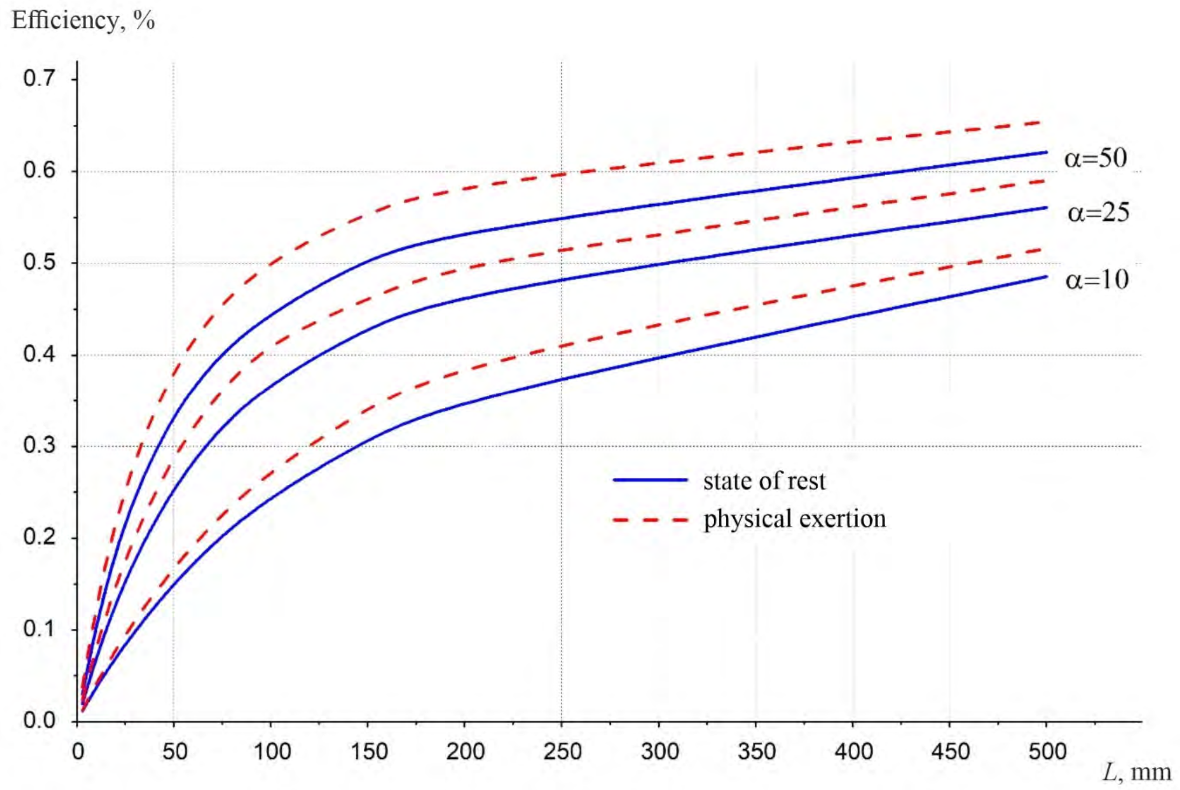

Fig. 7. Dependence of the efficiency on the height of the thermoelectric converter at an ambient temperature of T = 25 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m² K.

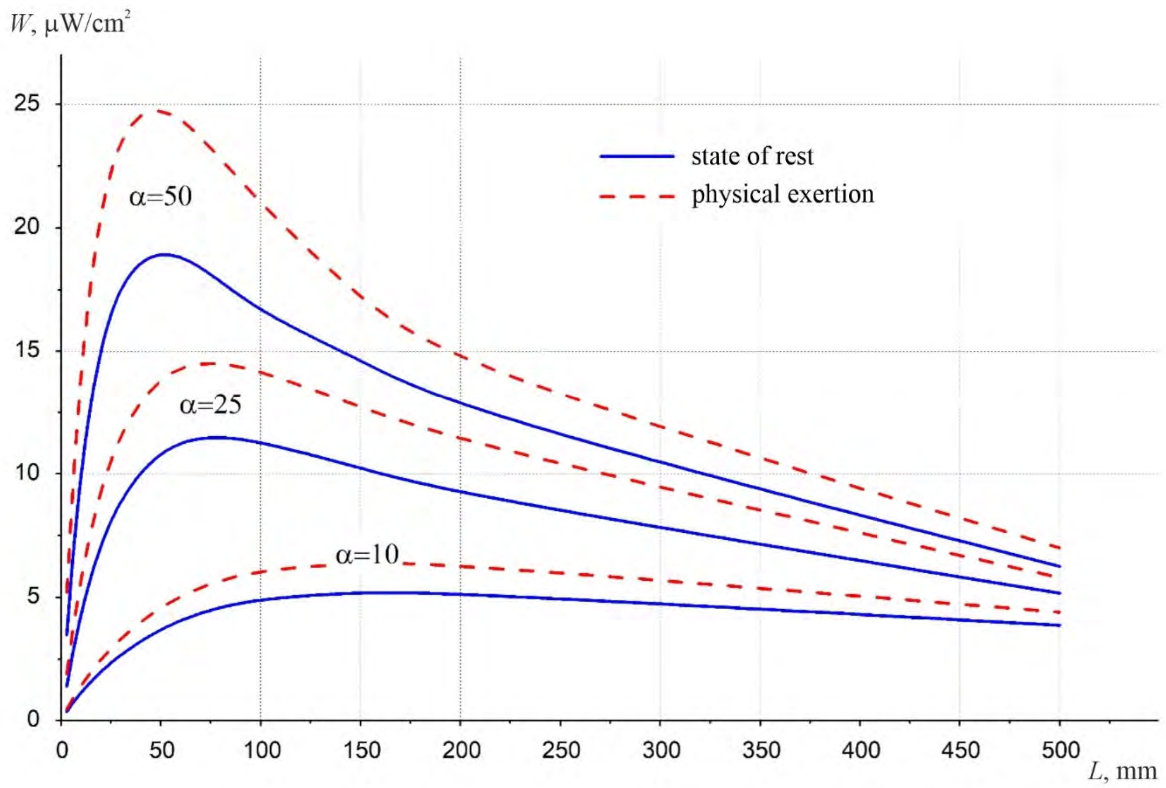

Fig. 8. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 30 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m2 K.

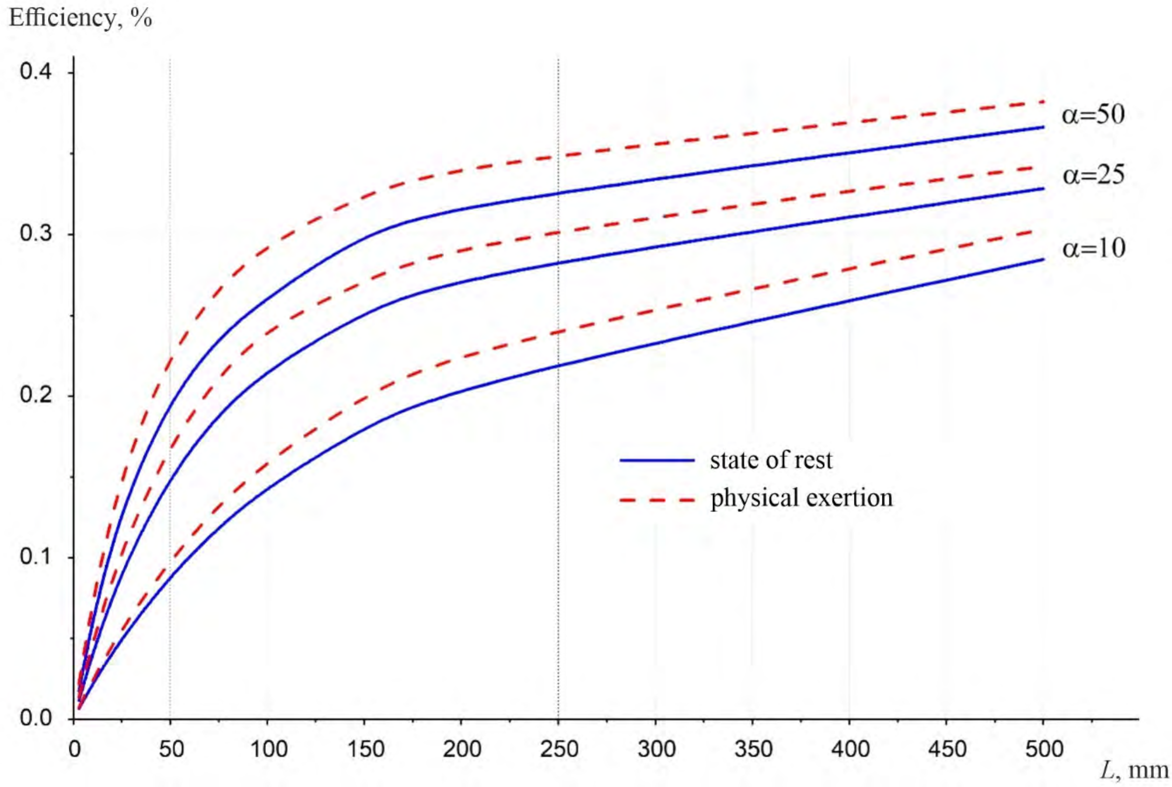

Fig. 9. Dependence of efficiency on the height of the thermoelectric converter at an ambient temperature of T = 30 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m² K.

The obtained results show that the optimal height of the thermoelectric microgenerator is $L = 30 \div 50$ mm, regardless of the heat exchange coefficient of the thermoelectric microgenerator surface with the environment. Improving the heat exchange conditions from $\alpha = 10$ W/m^{2}K to $\alpha = 50$ W/m^{2}K leads to an increase in the generated electric power by 4 – 5 times. In this case, the efficiency of the thermoelectric microgenerator increases significantly in the range of $L = 0 \div 100$ mm, and a further increase in the height of the thermoelectric microgenerator does not lead to a sharp increase in efficiency due to a sharp decrease in the generated electric power. Improvement of heat exchange conditions on the surface of the thermoelectric microgenerator provides efficiency increase by approximately 3 times.

As the calculation results showed (Fig. 4 – 9), the generated electric power and efficiency depend significantly on the ambient temperature. It is obvious that at elevated ambient temperatures the value of the working temperature difference on the thermoelectric microgenerator decreases, which leads to a decrease in the value of the generated power and efficiency. Thus, for instance, when the ambient temperature changes from 20 to 30 °C, the optimal value of the generated electric power of the thermoelectric microgenerator decreases several times from 25 μW/cm^2 to 5 μW/cm^2 for a coefficient of heat exchange $\alpha = 10$ W/m^{2}K and, accordingly, from 110 μW/cm^2 to 18 μW/cm^2 for a coefficient of heat exchange $\alpha = 50$ W/m^{2}K. Therefore, in order to preserve the energy performance of the thermoelectric microgenerator under elevated ambient temperatures, it is necessary to improve the heat exchange conditions. In practice, this can be ensured by an electronic heat exchange control system on the surface of the thermoelectric microgenerator. For example, for low-power electronic medical equipment, for the power supply of which 20 μW/cm^2 generated by a thermoelectric microgenerator under normal ambient conditions ($T = 20$ °C, $\alpha = 10$ W/m^2 K) is sufficient, when the temperature increases to T = 30 °C, it is necessary to improve the heat exchange of the surface of the thermoelectric microgenerator under conditions in which the coefficient of heat exchange will be α = 50 W/m^2 K. In practice, this can be achieved by switching to forced convection from the surface of the thermoelectric microgenerator by controlling the electronic power supply system of the fans that cool the surface of the thermoelectric microgenerator.

Thus, according to estimates and calculations carried out in the work, it was established that in a state of rest, from 1 cm^2 of the surface of the human body can be obtained from 25 μW to 100 μW of electrical energy, and during physical exertion – from 40 μW to 150 μW of electrical energy, depending on the conditions of heat exchange of the surface of the thermoelectric microgenerator with the environment. If we take into account that the average human body surface is 2 m^2, then due to heat emission from the entire surface of the human body, it is possible to obtain from 0.5 W to 2 W of electrical energy in a state of rest, and from 0.8 W to 3 W of electrical energy during physical exertion. Such indicators are sufficient to power many low-power electronic medical devices.

Conclusions

1. A three-dimensional physical model of thermal and electrical processes in the “human body – thermoelectric microgenerator” system has been developed, taking into account thermophysical processes in biological tissue, namely blood circulation and metabolism, and its mathematical description has been performed.
2. Using computer simulation methods, the optimal properties of thermoelectric converters were determined, whereby maximum values of electrical power and efficiency are achieved in a state of rest and during physical exertion on the human body.
3. It has been established that from 1 cm^2 of the human body surface in a state of rest it is possible to obtain a maximum of about 100 μW of electrical energy and during physical exertion – about 150 μW, and, accordingly, from the entire surface of the human body in a state of rest and during physical exertion it is possible to obtain about 2 W and 3 W of electrical energy, which is quite sufficient to power a variety of low-power electronic medical equipment. At the same time, the efficiency of thermoelectric microgenerators powered by the heat of the human body reaches 0.5 – 0.6 %.

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ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ТЕРМОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ, ЩО ЖИВЛЯТЬСЯ ВІД ТЕПЛА ТІЛА ЛЮДИНИ

У роботі наведено трьохвимірну фізичну модель, аналітичний опис та результати комп'ютерного моделювання термоелектричних перетворювачів, розміщених на поверхні тіла людини. Визначено оптимальні властивості термоелектричних перетворювачів, при яких досягаються максимальні значення електричної потужності W_{max} та ККД у стані спокою та при фізичному навантаженні організму людини.

Ключові слова: термоелектричний мікрогенератор, тіло людини, енергетичні характеристики, стан спокою, фізичне навантаження, комп'ютерне моделювання.

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DEVICE FOR DETERMINING ANTIFREEZE FREEZING POINT

The results of the development of the device for experimental measurement of antifreeze freezing point are provided. The device applies a direct measurement of antifreeze temperature upon its cooling to the freezing point using a thermoelectric module. An optimized heat exchange system, which has contributed to the development of a compact inexpensive device, available both to ordinary car enthusiasts and entrepreneurs dealing with car maintenance services, is used in the device design.
Key words: antifreeze, tosol, tester, freezing temperature.

Introduction

Urgency of an issue. Antifreeze is a coolant, and along with engine oil, brake fluid and fuel it is one of the main functional fluids of the car. The cooling system malfunctions during severe frosts usually occur if there has been a need to add water into an expansion tank during the year. This leads to the change in water proportion in ethylene glycol mixture and to the increase of the freezing point, respectively. Although, antifreeze diluted with water does not freeze, like water, however, if turned into a gel or a dense mixture with ice particles, it may cause problems with cooling system circulation and accelerated wear of a water pump.

Today the market of antifreezes (tosol cooling fluids) is rather diverse. Fakes, having nothing to do with original cooling fluid, flooded shop shelves and markets.

The question arises how to distinguish the true tosol from its fake, or how to check the quality of used antifreeze. The use of thermoelectric cooling in the development of special equipment for antifreeze quality control will promote to answer this question in full.

Literature analysis. Unlike water, antifreeze, being a water-ethylene glycol solution is freezing in several stages. Water freezes «instantaneously» and antifreeze freezes gradually; the liquid crystals begin to form at a certain negative temperature during cooling. Then, upon further cooling of the fluid, the amount of crystals increases therein - something similar to slurry is formed, and finally at some lower final temperature this slurry solidifies. The initial temperature of the first crystal formation is called «crystallization point». The final temperature of transition from liquid to solid state is called the «pour point».

There are different methods for determining antifreeze freezing point. Usually, «crystallization point» is used. In the CIS countries, this index is described in the regulations, developed on the basis of GOST 28084-89. However, in Europe, the term «freeze-proofing temperature» is oftener used. It is defined as an arithmetic average of the «crystallization point» and the «pour point». It is described in ASTM D1177.

There are many laboratory-household appliances for measuring crystallization point under «field» conditions. When using such devices, antifreeze does not freeze until the crystals appear, and other characteristics – density or refraction index, are measured, which are related to ethylene glycol concentration in the solution, and to the freezing point, respectively. The first type of such «laboratory-household» appliances includes a submerged density hydrometer («float»). It is immerged into the liquid, and base on its depth of submersion value one can estimate the density, and hence, the freezing point of the fluid. Sometimes, the measuring scale of such aerometers/ density hydrometers (also referred to as «aerometer - hydrometer») is not normally calibrated in grams per cubic centimetre, but in degrees Celsius, or in the percentage of ethylene glycol content in the solution. A typical representative of this class of devices is «hydrometer АЕГ / tosol cooling fluid, antifreeze /» Fig. 1.

Fig.1. Hydrometer АЕГ / tosol cooling fluid, antifreeze.

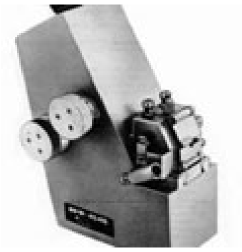
It should be noted that each hydrometer of this kind is calibrated for a certain liquid, such as "Tosol cooling fluid AM" or water-ethylene glycol solution, and when measuring other antifreeze it will cause an error of up to five degrees. When using an aerometer - hydrometer, the following three factors should be taken into account.

Firstly, this device measures the actual liquid density, rather than the freezing point. Therefore, the measurement made with hydrometer, can serve only as the indicator, the estimate of the freezing point, but not the qualification test.

Secondly, all antifreezes (and Tosol cooling liquids) include additive packages in their composition along with water and ethylene glycol, which differ in quantity and density. Therefore, various antifreezes have different densities when diluted with water depending on the freezing point, although they are similar to each other.

Thirdly, when conducting measurements with hydrometer, one should strictly observe the set temperature of the liquid measured. It is known that all bodies expand when heated, including antifreeze. Therefore, the same antifreeze will have different density outside and in a warm room. Accordingly, the hydrometer readings will be different: outside antifreeze would be «good», and the same antifreeze would turn «bad» inside. For the large majority of such devices measurements are expected to be conducted at the exact temperature of liquid + 20 °C.

The second type of «laboratory-household» devices is refractometers. In fact, this device measures the optical characteristics of antifreeze – the refraction index, which is also associated with the degree of dilution of antifreeze concentrate with water and the crystallization point. The accuracy of determining antifreeze crystallization point using it makes up ± 1 °C. Typical representatives of refractometers are laboratory «Refractometer ИРФ 454Б2 М» or pocket «Refraktometer VBC4T», fig. 2.



a)

b)

Fig. 2. Refractometers: a) laboratory IRF 454Б2 M b) pocket VBC4T.

When using the refractometer one should follow the rules and safety measures for operating aerometers. The measurements were carried out at the exact temperature of liquid + 20 °C. The conversion table of the refraction index to the crystallization point for certain antifreeze brand should be used. If the pocket refractometer measuring scale has been set in degrees Celsius, it should be taken into consideration that the scale is adapted to a particular antifreeze type, most probable to ethylene glycol and water mixture. Such a device may be used only for indication (determination) of the crystallization point.

In addition to the devices, indirectly determining the antifreeze freezing point, there are devices for direct measurement of the freezing point, operating on the principle of actual antifreeze cooling with simultaneous monitoring the fluid state. For example, a series of automated devices for determining the crystallization point of oil products АРТЕ АТКт-01, АТК-02, АТЗ-01.

Fig. 3. ATK-02 device.

Fig. 4. "CRYSTAL" measuring device for low-temperature indicators of oil products.

The technological block of such devices has a form of a cryostat with an integrated test cell. The cryostat consists of an aluminium cup, wherein the product test tube is placed in the process of analysis. The cooling units consisting of semiconductor micro-refrigerators and radiators are placed on two opposite sides of the cup. Refrigerant continuously flows through the radiators in the course of analysis. Due to high efficiency of the semiconductor refrigerators, the temperature in the cup can be several tens of degrees lower than the temperature of the refrigerant, which, in most cases, allows the ordinary tap water with a temperature of above 20 °C to be used as the refrigerant.

Another example is "CRYSTAL" measuring device for low-temperature indicators of oil products.

The device has many functions, using it the crystallization point is automatically determined by analyzing the nature of the temperature change.

However, along with high precision of measurements, the mentioned devices are rather complicated in operation, have large dimensions and weight, and as a consequence, are rather expensive (approximately 5 – 7 thous. USD). Therefore, only large enterprises can purchase them [1-4].

Description of the development results

The device, which is easy to operate and is designed for experimental determination of antifreeze freezing point (or other non-corrosive liquids), has been developed and manufactured at ITE. The device lacks drawbacks that are inherent to aerometers and refractometers (can determine the freezing point practically of any non-corrosive fluid, falling within the operating range – from the ambient temperature to – 50 °C), has a high accuracy and low cost.

The principle of the device operation consists in a gradual cooling of an antifreeze drop placed in a cavity of an operating platform with simultaneous measurement of the temperature of this platform and visual monitoring of the aggregate state of the drop. The Peltier thermoelectric module is used as a cooling actuating element of the device. Heat dissipation from the thermoelectric module is achieved by a finned heat sink with a fan blow-off. Heat exchange system – operating platform with antifreeze drop – the Peltier module – heat sink with a fan – has been optimized by means of computer simulation. A two-stage low-power thermoelectric module was used in the device, which together with a highly efficient DC/DC voltage converter provided a possibility to manufacture sufficiently compact and fast-operating device.

The device for determining antifreeze freezing point is shown in Fig. 5 and its electrical circuit diagram – in Figure 6.

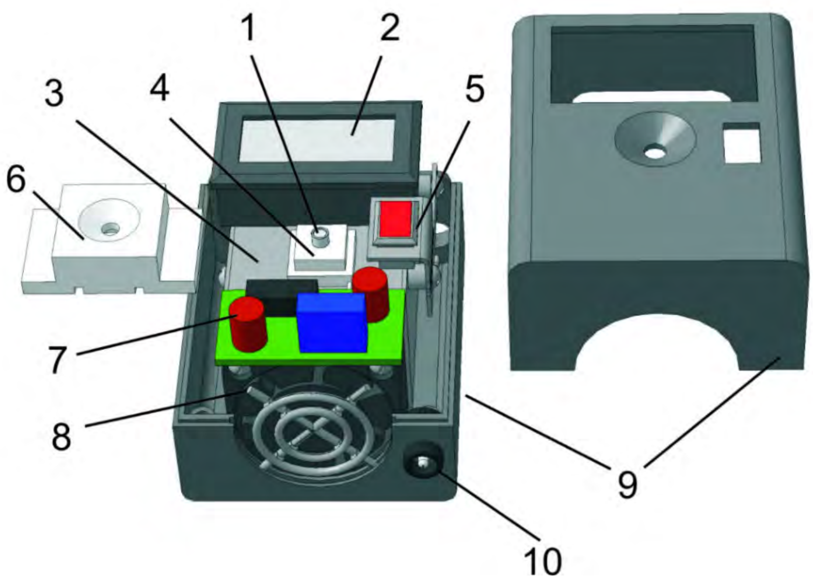


Fig. 5. Device arrangement. 1 – operating platform, 2 – digital thermometer, 3 – heat sink, 4 – thermoelectric module, 5 – switch, 6 – foam insulation, 7 – DC/DC converter, 8 – fan, 9 – housing, 10 – power input connector.

The device operating platform-1 is glued in the centre of the cooling side of the Peltier module - 4. Passive (hot) side of the module is fixed on the finned heat sink - 3. The air fan – 8 is fixed to heat sink on one side, along its fins. These elements constitute the heat exchange unit. The unit is secured with a bracket in the housing – 9, which walls additionally divide the hot and cold side of the unit. The housing incorporates a digital thermometer – 2, a switch – 5 and thermometer and module batteries. On the fan side, there is an opening in the housing for air intake, and on the opposite side – an opening for its outlet. These openings are closed with a decorative and protecting screen.

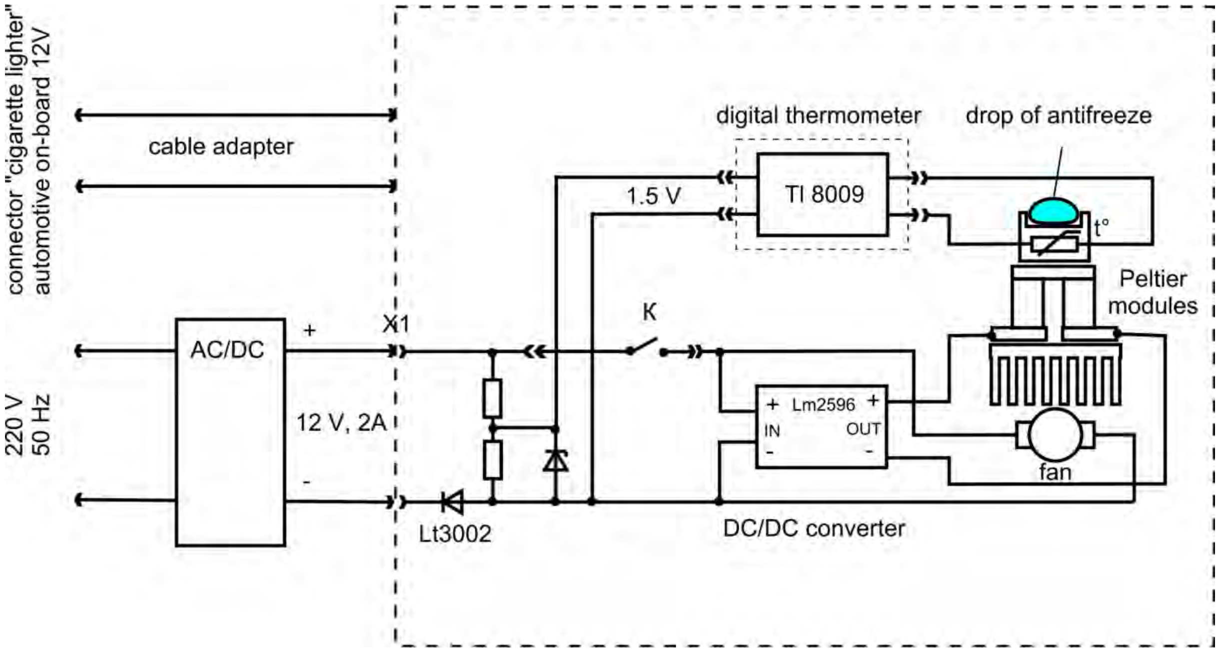


Fig. 6. Device electrical circuit.

Input voltage of X1 connector through the protective diode is supplied to the voltage divider, supplying the digital thermometer. The voltage is supplied from the same connector through the switch to the fan and DC/DC converter, which generates the stabilized voltage to supply the Peltier module.

The device uses a standard digital thermometer, temperature sensor which is located in a special hole designed for it in the operating platform.

The device is equipped with power supply unit. The adapter, with an input voltage of 110 – 240 V with a frequency of 50 – 60 Hz has an output voltage of 12 V DC at 2A. The device package is also completed with the cable adapter for the automotive on-board system voltage, 12V.

The device appearance is shown in Fig. 7.

Fig. 7. The appearance of the device for determining the antifreeze freezing point.

The device operation. When connected to the power supply, the temperature of the operating platform is shown on the thermometer display (in fact – the ambient temperature). Using a drop pipette, or other available means, a small antifreeze drop (2 – 3 mm in diameter) is placed in the operating platform cavity.

Upon switching on the power supply button, the operating platform together with the drop begins to cool. While observing the aggregate state of the drop and the thermometer readings at the same time, the freezing point of the liquid is determined by the drop turbidity. Upon further cooling of the antifreeze drop, some stationary process is observed when the module power is spent on the formation of antifreeze crystals, and at their saturation the temperature of the frozen drop begins to decrease again. The dynamics of antifreeze drop cooling is shown in Fig. 8.

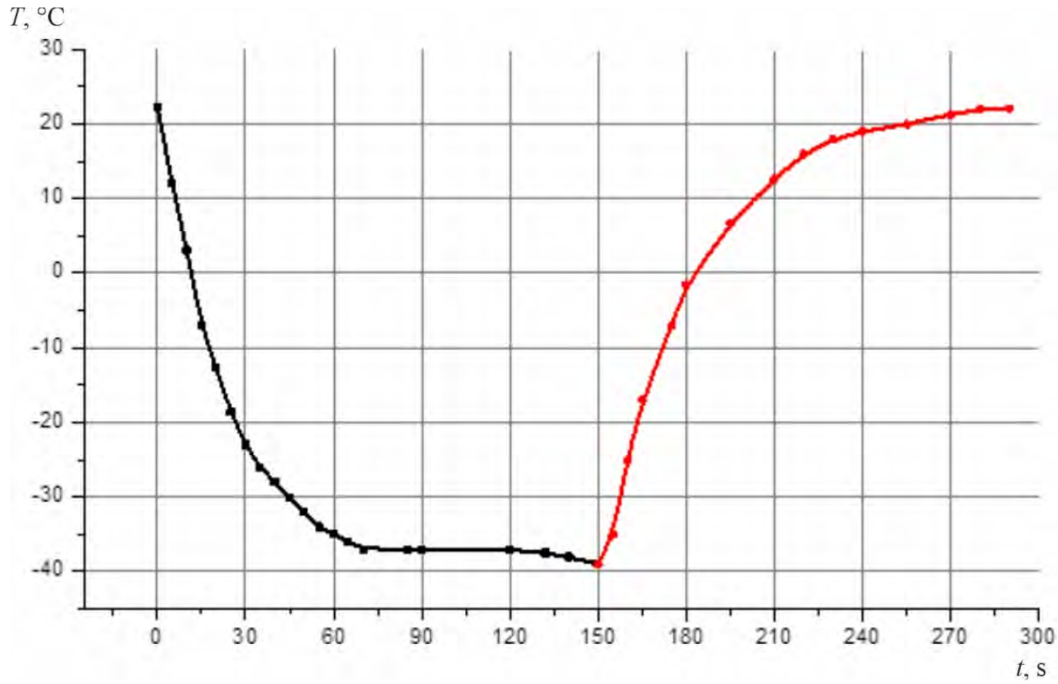


Fig. 8. Dynamics of antifreeze drop freezing-unfreezing on the device operating platform.

If the power supply to The Peltier module is switched off, the process goes in reverse direction, but an additional inflow of heat from the overheated (relative to the ambient air) heat sink, is observed.

After measurement completion, the antifreeze drop should be removed from the operating platform with a cloth or other absorbent material.

Conclusions

The considered device for determining the antifreeze freezing point due to its compact size, ease of operation and low cost will certainly gain interest among ordinary car enthusiasts and entrepreneurs selling automotive fluids and dealing with car maintenance services.

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ТЕСТЕР ДЛЯ ВИМІРЮВАННЯ ТЕМПЕРАТУРИ ЗАМЕРЗАННЯ АНТИФРИЗУ

Наведено результати розробки тестера для експериментального вимірювання температури замерзання антифризу. У тестері використовується пряме вимірювання температури антифризу при його охолоджені до температури замерзання з допомогою термоелектричного модуля. У конструкції тестера застосована оптимізована теплообмінна система, що дозволила створити компактний недорогий пристрій, доступний як рядовим автолюбителям так і підприємцям, які займаються автосервісом.
Ключові слова: антифриз, тосол, тестер, температура замерзання.

Література

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2. How to measure the freezing point of the heating medium correctly. http://netet.ru/publications/2010/09/08/publications_238.html
3. "CRYSTAL" measuring device for low-temperature indicators of oil products. http://www.shatox.ru/crystal.htm
4. Antifreeze device. Refractometer. http://www.wuerthmarket.ru/products/by_category/60/09/04/1635/

Надійшла до редакції: 18.10.2022.

ARTICLE SUBMISSION GUIDELINES

For publication in a specialized journal, scientific works are accepted that have never been printed before. The article should be written on an actual topic, contain the results of an in-depth scientific study, the novelty and justification of scientific conclusions for the purpose of the article (the task in view).

The materials published in the journal are subject to internal and external review which is carried out by members of the editorial board and international editorial board of the journal or experts of the relevant field. Reviewing is done on the basis of confidentiality. In the event of a negative review or substantial remarks, the article may be rejected or returned to the author(s) for revision. In the case when the author(s) disagrees with the opinion of the reviewer, an additional independent review may be done by the editorial board. After the author makes changes in accordance with the comments of the reviewer, the article is signed to print.

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To the manuscript is added:

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4. Medium with the text of the article, figures, tables, information about the authors in electronic form.

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Requirements for article design

The article should be structured according to the following sections:

- *Introduction*. Contains the problem statement, relevance of the chosen topic, analysis of recent research and publications, purpose and objectives.
- *Presentation of the main research material* and the results obtained.
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The first page of the article contains information:

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5) abstract to the article – not more than 1 800 characters. The abstract should reflect the consistent logic of describing the results and describe the main objectives of the study, summarize the most significant results;

6) key words – not more than 8 words.

The text of the article is printed in Times New Roman, font size 11 pt, line spacing 1.2 on A4 size paper, justified alignment. There should be no hyphenation in the article.

Page setup: “mirror margins” – top margin – 2.5 cm, bottom margin – 2.0 cm, inside – 2.0 cm, outside – 3.0 cm, from the edge to page header and page footer – 1.27 cm.

Graphic materials, pictures shall be submitted in color or, as an exception, black and white, in .opj or .cdr formats, .jpg or .tif formats being also permissible. According to author’s choice, the tables and partially the text can be also in color.

Figures are printed on separate pages. The text in the figures must be in the font size 10 pt. On the charts, the units of measure are separated by commas. Figures are numbered in the order of their arrangement in the text, parts of the figures are numbered with letters – a, b, .. On the back of the figure, the title of the article, the author (authors) and the figure number are written in pencil. Scanned images and graphs are not allowed to be inserted.

Tables are provided on separate pages and must be executed using the MSWord table editor. Using pseudo-graph characters to design tables is inadmissible.

Formulae shall be typed in Equation or MatType formula editors. Articles with formulae written by hand are not accepted for printing. It is necessary to give definitions of quantities that are first used in the text, and then use the appropriate term.

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Examples of LITERATURE CITED

Journal articles

Anatychuk L.I., Mykhailovsky V.Ya., Maksymuk M.V., Andrusiak I.S. Experimental research on thermoelectric automobile starting pre-heater operated with diesel fuel. *J.Thermoelectricity*. 2016. №4. P.84–94.

Books

Anatychuk L.I. *Thermoelements and thermoelectric devices. Handbook.* Kyiv, Naukova dumka, 1979. 768 p.

Patents

Patent of Ukraine № 85293. Anatychuk L.I., Luste O.J., Nitsovych O.V. Thermoelement.

Conference proceedings

Lysko V.V. *State of the art and expected progress in metrology of thermoelectric materials.* Proceedings of the XVII International Forum on Thermoelectricity (May 14-18, 2017, Belfast). Chernivtsi, 2017. 64 p.

Authors' abstracts

Kobylianskyi R.R. *Thermoelectric devices for treatment of skin diseases*: extended abstract of candidate's thesis. Chernivtsi, 2011. 20 p.

Examples of REFERENCES

Journal articles

Gorskiy P.V. (2015). Ob usloviakh vysokoi dobrotnosti i metodikakh poiska perspektivnykh sverhreshetochnykh termoelektricheskikh materialov [On the conditions of high figure of merit and methods of search for promising superlattice thermoelectric materials]. *Termoelektrichestvo - J.Thermoelectricity*, 3, 5 – 14 [in Russian].

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Anatychuk L.I. (2003). *Thermoelectricity. Vol.2. Thermoelectric power converters*. Kyiv, Chernivtsi: Institute of Thermoelectricity.

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Rifert V.G. Intensification of heat exchange at condensation and evaporation of liquid in 5 flowing-down films. In: *Proc. of the 9th International Conference Heat Transfer.* May 20-25, 1990, Israel.

Authors'abstracts

Mashukov A.O. *Efficiency hospital state of rehabilitation of patients with color carcer.* PhD (Med.) Odesa, 2011 [In Ukrainian].