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THERMOELECTRIC SYSTEM OF CONTRAST THERMAL EFFECT ON THE REFLEXOGENIC ZONES OF HUMAN FOOT

The paper deals with a thermoelectric system for contrast thermal effect on the reflexogenic zones of human organism, in particular, for local effect on the lower surface of human foot. The results of its mathematical simulation and prototype full-scale test are presented. Experimental plots of temperature variation at different system points are given.

Key words: reflexogenic zone, thermoelectric system, thermopile, thermal effect, temperature field, mathematical model, prototype, experiment.

Introduction

In modern medical practice increasing acceptance is gained by the methods based on the use of various physical factors (heat, electromagnetic radiation, low-potential electric effect, etc). The advantage of these methods over pharmacotherapy in medical rehabilitation, treatment and health improvement lies in the fact that they stimulate own resources of the organism, that is, sanogenesis processes, actually have no contraindications and do not result in any considerable complications when administered.

The methods using physical factors also include local thermal effect on the biological tissues that has certain specific features. Unique therapeutic properties of heat and cold are physiologically and immunologically substantiated when affecting human organism and its individual organs and areas, in particular, low-conductivity reflexogenic zones. One of the areas of medicine where exposure to heat is efficient is physiotherapy, especially with regard to locomotor apparatus treatment.

Currently known methods of exposure to heat (contrast baths, whirlpool baths, paraffin and ozokeritotherapy, etc.) have various shortcomings [1], such as low efficiency, procedure discomfort, impossibility of contrast combined exposure to several physical factors. Under these conditions, it is efficient to use as a source of cold and heat the thermoelectric power converters offering high reliability, environmental friendliness, and noise-free operation, possibility of quick transition from cooling to heating mode and vice versa.

At the Research Institute of Semiconductor Thermoelectric Instruments and Devices of Federal State Budgetary Educational Institution of Higher Professional Education "Dagestan State Technical University" a semiconductor thermoelectric (TE) device has been developed for carrying out physiotherapeutic thermal procedures related to effect on the reflexogenic zones of human foot [3, 4]. The device design is shown in Fig. 1, and its appearance – in Fig. 2. the device comprises a thermopile 1 the first junctions of which are in thermal contact with the lower surface of human foot 2 through bath 3 made of highly thermally conductive material having on its bottom metal balls 4, also made of high thermal conductivity materials. Heat removal from the second junctions of thermopile 1 is done by liquid heat exchanger 5. The operating modes of thermopile 1 are controlled by programmable supply unit.

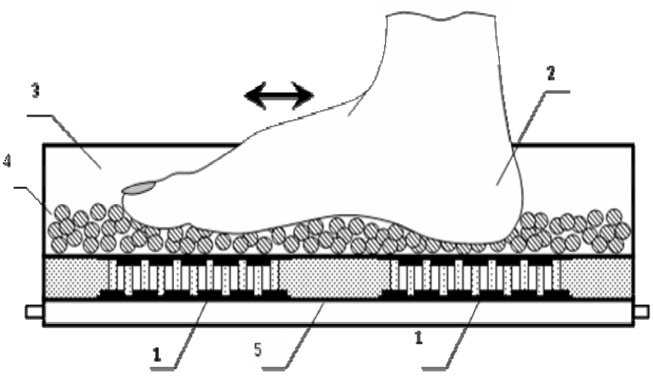

Fig. 1. Design of thermoelectric device for carrying out physiotherapeutic procedures.

Fig. 2. Appearance of thermoelectric device for carrying out physiotherapeutic procedures.

The purpose of this work is theoretical and experimental investigation of the above described design with a view to optimize its characteristics.

Mathematical simulation of thermoelectric system for contrast thermal effect on the reflexogenic zones of human foot

In the analysis of operation of thermoelectric systems used for cryothermoapplication, i.e. the use of local thermal effect, it is very important to know not only the steady-state characteristics of device, but also the peculiarities of transient processes of device-target object system. It is due to the necessity of evaluation of such parameter of thermoelectric device operation as the time to reach given operating mode, as well as determination of the dynamic characteristics of device.

To evaluate said parameters, a quasi-stationary model of transient process of device for thermal effect on human foot was created which considers a thermoelectric device as a single combination of elements – heat exchangers, thermopile, and thermal insulation assuring temperature reduction of biological object within required time to required value.

We now consider a thermal model of system under study which is shown in Fig. 3.

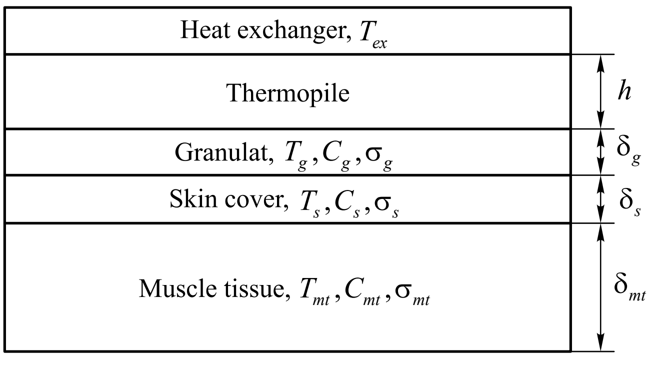

Fig. 3. Thermal model of thermoelectric system.

In this system, a thermopile through heat exchanger of heat capacity C_g and thermal conductivity σ_g with its first (internal) junction is connected to target object more simply represented as a two-layer structure consisting of skin cover and muscle tissue of heat capacity C_g, C_{mt} and thermal conductivity σ_s, σ_{mt}, respectively. The temperature of external thermopile junction via air or liquid heat exchanger is maintained at certain time-invariant value T_{ex}. Current of constant density *j* flows through the thermopile. Moreover, it is supposed that heat exchange between tissue and blood occurs at any point of biological object under study and is characterized by specific power of volumetric heat sources P_s and P_{mt} for skin cover and muscle tissue, respectively.

Mathematical realization of the model is determined by a system of the following differential equations [2]:

$$\left.\begin{aligned} \frac{\mathrm{d}T_g}{\mathrm{d}\tau} &= \frac{1}{C_g}\left[\sigma_g\left(T_s - T_g\right) + \left[qejT_g + \frac{1}{2}j^2\rho h + \frac{\lambda}{h}\left(T_{ex} - T_g\right)\right] + \sigma_g\left(T_{amb} - T_g\right)\right] \\ \frac{\mathrm{d}T_s}{\mathrm{d}\tau} &= \frac{1}{C_s}\left[\sigma_g\left(T_g - T_s\right) + \sigma_s\left(T_{mt} - T_s\right) + P_s\right] \\ \frac{\mathrm{d}T_{mt}}{\mathrm{d}\tau} &= \frac{1}{C_{mt}}\left[\sigma_s\left(T_s - T_{mt}\right) + P_{mt}\right] \end{aligned}\right\} \tag{1}$$

where T_g is temperature of heat exchanger which is in thermal contact with the biological object; T_s is skin cover temperature; $q = -1$ at thermopile operation in target object cooling mode, $q = 1$ at thermopile operation in target object heating mode; *e* is the Seebeck coefficient of thermoelements in a thermopile; ρ is thermopile electric resistivity; *h* is the height of thermoelements in a thermopile; λ is thermal conductivity of thermopile material; T_{amb} is ambient temperature; T_{mt} is temperature of muscle tissue.

The initial conditions are assigned on the assumption that at initial time instant a TE device is in thermodynamic equilibrium with the environment and the temperature of all system points is equal to ambient temperature, and the temperature of target object is 309 K.

The solution of system (1) was done numerically in MATHCAD applied program package with the use of the Runge-Kutta fourth-order method. Calculation was done with the following input data: $e = 350\cdot10^{-6}$ V/K; $h = 0.002$ m; $\lambda = 3$ W/m·K; $\rho = 0.0001$ Ohm·m; $C_g = 380$ J/kg·K; $C_s = 3600$ J/kg·K; $C_{mt} = 3458$ J/kg·K. In so doing, thermal conductivities were determined by the formulae:

$$\sigma_g = \frac{\lambda_g \cdot S}{\delta_g}, \tag{2a}$$

$$\sigma_s = \frac{\lambda_s \cdot S}{\delta_s}, \tag{2b}$$

$$\sigma_{mt} = \frac{\lambda_{mt} \cdot S}{\delta_{mt}}, \tag{2c}$$

where λ_g, λ_s, λ_{mt} is thermal conductivity of heat exchanger, skin cover and muscle tissue, respectively; *S* is the area of contact surface between TE device for cryothermoapplication and biological target object; σ_g, σ_s, σ_{mt} is the thickness of heat exchanger, skin cover and muscle tissue layer, respectively. The numerical values of original quantities in expressions (2) were assumed to be as follows: $\lambda_g = 200$ W/m·K; $\lambda_s = 0.389$ W/m·K; $\lambda_{mt} = 0.2$ W/m·K; $S = 0.015$ m^2; $\delta_g = 0.02$ m; $\delta_s = 0.002$ m; $\delta_{mt} = 0.03$ m.

Figs. 4 – 5 show the results of calculation of thermal field of device-target object system as a function of time at $T_{amb} = T_{ex} = 293$ K for the case of thermopile operation in cooling mode (Fig. 4) and heating mode (Fig. 5) of biological object. Time variation of heat exchanger temperature on thermopile internal junction, skin cover and muscle tissue temperature has been analyzed. As it follows from the represented data, the dependences are of monotonous nature – decreasing at thermopile operation in cooling mode and increasing when using thermopile in biological object heating mode.

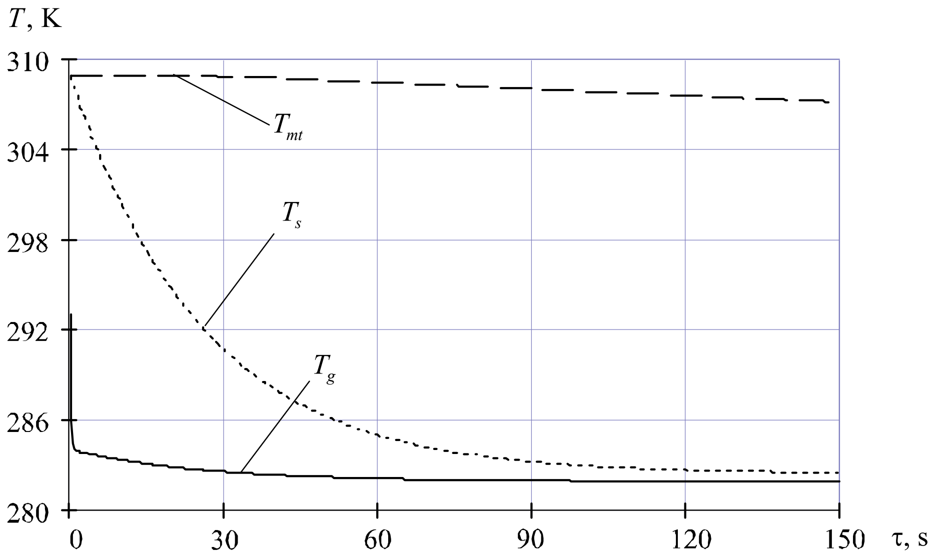

Fig. 4. Time history of granulate temperature on the internal junction of thermopile, skin cover and muscle tissue in cooling mode.

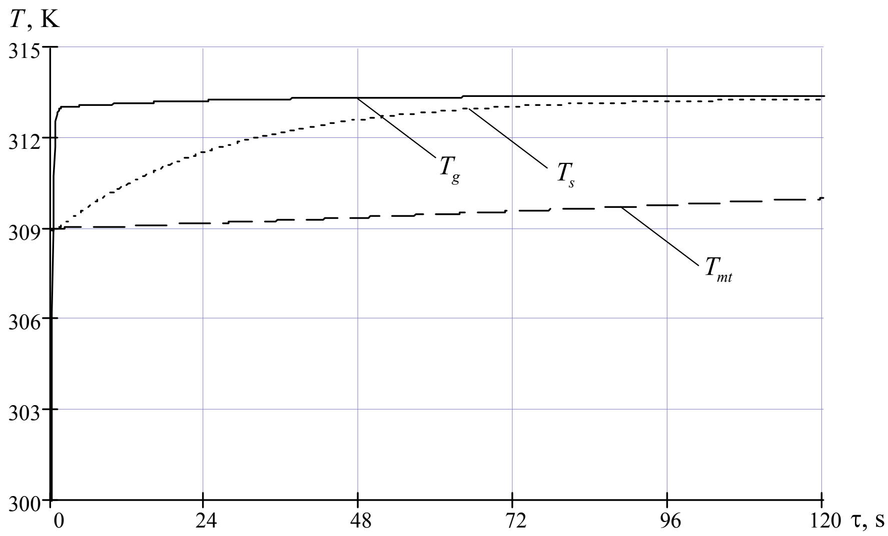

Fig. 5. Time history of granulate temperature on the internal junction of thermopile, skin cover and muscle tissue in heating mode.

According to the plots, the temperature of heat exchanger and skin cover is rather quickly stabilized (in case of cooling, the time to reach the steady-state of heat exchanger and skin cover temperature is 93 and 120 s, respectively, and in case of heating – 72 and 96 s), which is due to low heat capacity and high thermal conductivity of heat exchanger, as well as small thickness of skin cover. Assuming that exactly skin cover is rich in thermal receptors and is a direct object of cryothermoapplication, this fact indicates to apparent advantages of TE device use which are primarily due to fast response of thermal effect.

Fig. 6 shows the plots of time variation of skin cover temperature for different values of thermopile supply current I ($j = \frac{I}{S}$). The data are given for the case of local cooling and heating of target object. According to these dependences, the duration of temperature stabilization of skin cover in the considered current range is constant and makes about 120 s. In Fig. 6, a dependence of skin cover cooling on supply current value can be traced. From the plots describing time variation of skin cover temperature it follows that with a change of current force from 0 to optimal value whereby there is maximum temperature reduction on thermopile cold junction (in the present case 2 A), the ratio of temperature variation to current force variation is reduced.

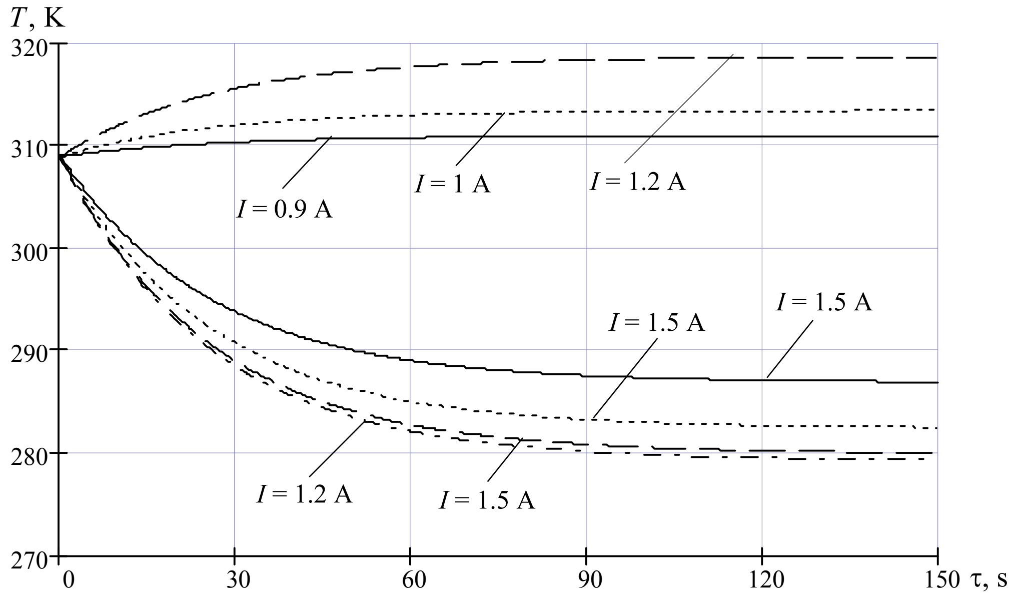

Fig. 6. Time history of skin cover temperature at different supply currents of thermopile operated in cooling mode.

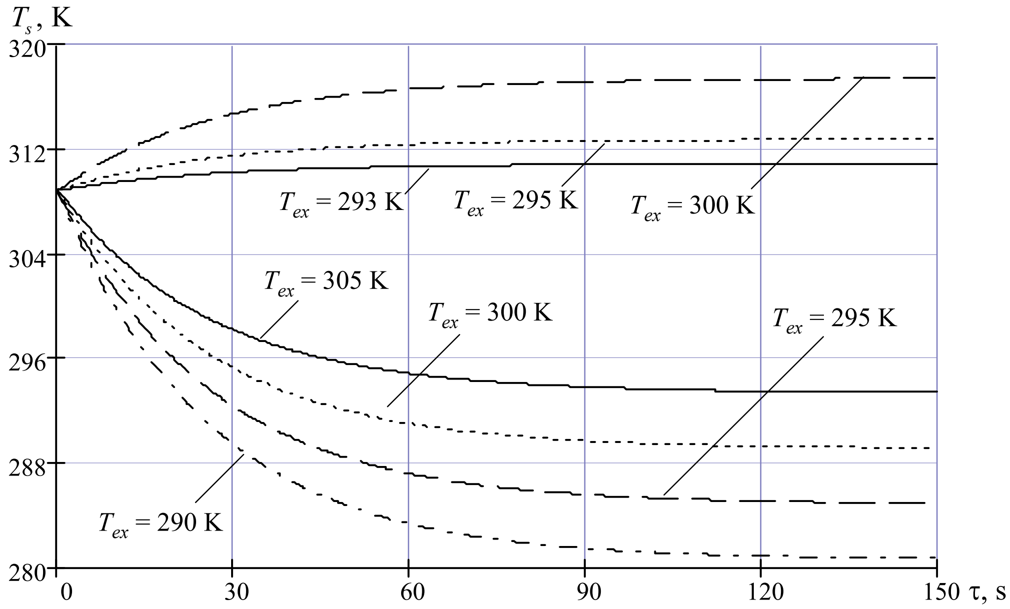

Fig. 7. Time history of skin cover temperature at different values of T_{ex}.

Thus, for the above case (upon reaching of steady-state) with increasing supply current from 0.5 A to 1 A, the temperature of skin cover is reduced from 286.5 K to 282.5 K, increase of current strength from 1 A to 1.5 A reduces the temperature from 282.5 K to 280 K, and increase of supply current from 1.5 A to 2 A reduces the temperature to 279.5 K. Further increase in current strength leads to prevailing of the Joule heat over the Peltier heat, increasing the temperature of target object. Thus, at fixed temperature T_{ex} of TE device the ultimate temperature reduction of biological object is limited by the value of thermopile supply current optimal for this thermopile type. A deeper temperature reduction of target object can be obtained by reducing the value of T_{ex}. This is illustrated in Fig. 6, showing time variation of skin cover temperature for different values of T_{ex} in cooling and heating modes of TE device (supply current – 0.9 A). From the analysis of data shown in Fig. 6 and Fig. 7 it follows that for the reduction of skin cover temperature, for instance, to 280 K at a temperature T_{ex} = 290 K, one needs 0.6 A less than at stabilization of T_{ex} on the level of 293 K. At the same tine, reduction of temperature of external junction (T_{ex}) requires increase in thermopile supply current with operation of the latter in the mode of biological object heating to obtain the same temperature of skin cover. However, it should be noted here that the required increase of thermopile supply current is insignificant. In so doing, a gain in electric energy consumption at TE device operation in cooling mode is vastly superior to its loss at TE device operation on biological object heating mode.

Experimental investigations of thermoelectric system for local freezing of larynx tissues.

In order to verify the results of mathematical simulation, a prototype of this thermoelectric system was subject to full-scale test. The object of experimental investigations was a prototype for effect on human foot in the form of a case comprising a thermopile made of standard unified thermoelectric modules (TEM), brought by the junctions into a thermal contact with the case base in the form of a copper plate that can be filled with copper granulate. The opposite thermopile junctions were in a thermal contact with liquid heat exchanger intended for heat pick-up.

In the course of the experiment, the prototype was placed into thermally insulated climatic chamber that has a thermostated work volume 120 l. The chamber provides for temperature upkeep from 283 to 343 K to accuracy of 1°C and with a relative humidity from 30% to 98%. Given temperature and relative humidity in the chamber is regulated by control unit connected with temperature and humidity sensor whose readings are registered on a digital display.

As thermopiles, standard unified TEM of ICE-71 type were used, produced by Engineering and Production Firm "Kryotherm" and connected in parallel. The TEM were powered from electric energy source. The flow rate of liquid in a heat exchanger was regulated by a controller. The measurements were conducted with the use of ammeter and voltmeter built into electric energy source, liquid flow rate sensor in liquid flow rate controller and a multi-channel meter IRTM 2402/M3 connected to PC.

During the experiment, the thermopile voltage and current, ambient temperature and the temperatures at different points of the prototype were determined. Temperature measurements were performed by copper-constantan thermocouples the reference junctions of which were arranged in a Dewar vessel, and the signal was read by IRTM 2402/M3 meter.

Thermocouples were located on the reference and operating junctions of TEM, at heat exchanger inlet-outlet, on the surface of plate (edge and centre), in the ambient, on granulate layers (using the latter in the process of experiment), as well directly on the biological object (in this case human foot).

The measurements were performed for the case of device idle operation (without thermal load), under thermal load, with and without granulate in device (measurements were performed with the use of granulate of various diameters, from 4 mm to 10 mm, with increment 2 mm). The experiment was carried out with direct thermal effect on human foot the temperature of which was controlled by thermocouples placed on the sole.

Figs. 8 – 9 represent time dependences of plate temperature and sole temperature at different currents in heating mode (Fig. 8) and cooling mode (Fig. 9).

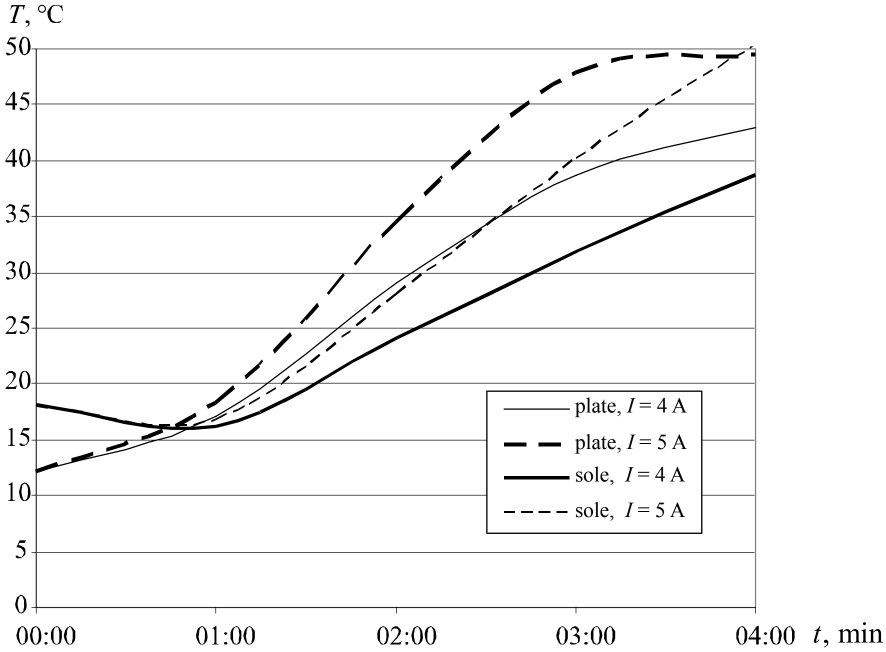

Fig. 8. Time history of temperature on the plate and foot at different supply currents of thermopile operated in heating mode.

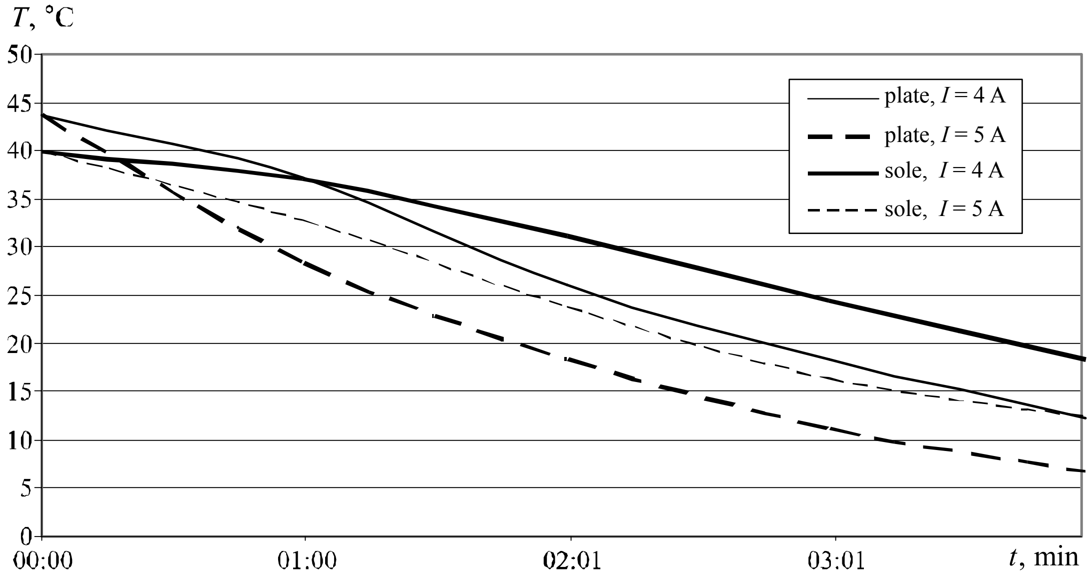

Fig. 9. Time history of temperature on the plate and foot at different supply currents of thermopile operated in cooling mode.

Investigation of these dependences shows that plate temperature grows with increasing thermopile supply current, whereas on the sole one can observe processes of thermal regulation of living systems. At first instant of exposure to heat the sole temperature is drastically increased which is due to vasoconstriction, the second phase is accompanied by vasodilatation, afflux of blood to effecting zones and, as a result, insignificant temperature reduction. Then, thermoregulation mechanisms are involved, and temperature is gradually equalized depending on the effecting mode. It is noteworthy that plate temperature reaches the required value, namely 42 – 450°C in heating mode and 10 – 120°C in cooling mode within 3-5 minutes.

Apart from that, during our experimental investigations the following dependences were obtained: temperature variation of the operating and reference junctions of TEM versus supply current value, temperature at different plane points versus current, the curves of heating and cooling time in the range of temperatures from 10°C to 45°C versus supply current, as well as transient characteristics of device.

Fig. 10 shows transient characteristics, since this device is intended for operation in a dynamic mode, providing for alternative exposure to heat and cold.

Analysis of the dependences has shown that total time of one cycle with supply current 5 A is about 6 – 7 min, heating mode being assured in 2 – 3 min and cooling mode – in 3 – 5 min.

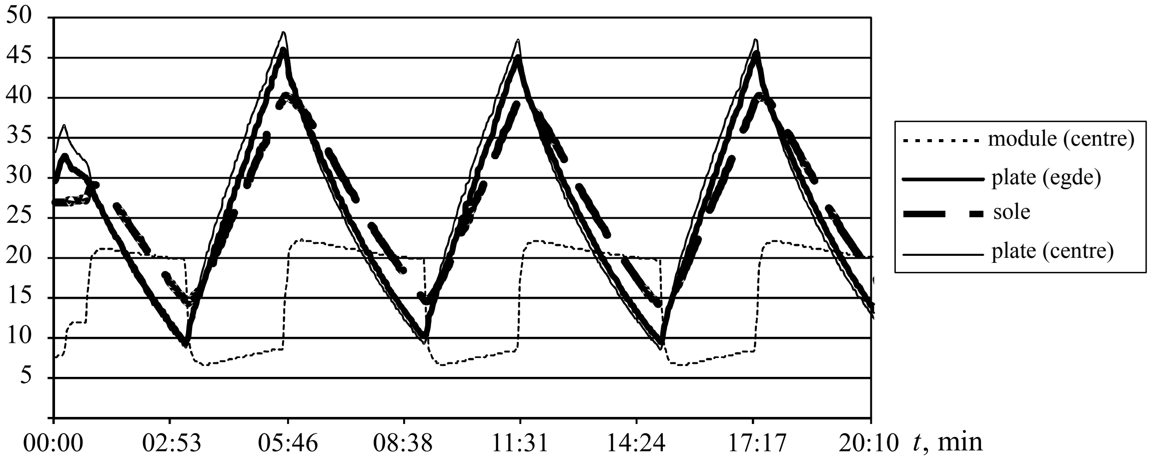

Fig. 10. Dependence of T in a dynamic mode at supply current I = 5 A.

The results obtained define the acceptable accuracy of system mathematical model. Maximum discrepancy between the calculated and experimental data does not exceed 7 – 7.5^{0}C. The greatest deviation of calculated data is mainly observed during the interval related to time necessary for device to reach the mode, which is due to environmental influence and non-perfect thermal insulation of “device-target object” system, as well as certain spread in parameters of TEM and measuring instruments.

Conclusions

On the basis of investigations performed, the following conclusions can be made:

1. A thermoelectric device for contrast thermal effect on the reflexogenic zones of human foot, composed of a thermopile, a bath filled with granules/granulate and heat exchanger, has been developed
2. A quasi-stationary mathematical model of the system under steady-state conditions has been created.
3. An experimental bench and measurement procedure for prototype full-scale test have been developed.

4. The results of experimental research on device prototype have shown satisfactory repeatability of calculated and experimental data.

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