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MODEL OF THERMOELECTRIC DEVICE FOR CARRYING OUT THERMAL COSMETOLOGY PROCEDURES

A model of thermoelectric system for carrying out thermal cosmetology procedures is considered which is based on solving a two-dimensional nonstationary problem for a system of complex configuration. Temporal variations of temperature at different points of target object – skin area exposed to thermal cosmetology procedures, were obtained as a function of cooling capacity and heating efficiency of thermoelectric modules.

Key words: thermoelectric system, thermal exposure, cosmetology, biological object, temperature field, model.

Introduction

At the present time, in the practice of carrying out cosmetology procedures the methods based on thermal exposure (thermal and cryotherapy) are increasingly used [1, 2]. Such fairly active use of this type of methods is due to the fact that thermal exposure has a great influence on the energy balance in the body. Under the influence of heat, the blood and lymph vessels expand, which improves blood circulation in many internal organs. This leads to activation of metabolism and qualitative saturation of the body with nutrients and oxygen. Heating stimulates fat oxidation, purifies organism, removing harmful toxins and other products of vital activity through sweat, thereby contributing to the improvement of skin condition. Cooling has a strong anti-aging effect, smooths wrinkles, eliminates the spread of acne, cellulite deposits, smooths scars, removes skin formations, papillomas and benign tumors. Cooling masks remove puffiness of the face, model its shape, smooth wrinkles and improve color. Thermal massage is used to strengthen the scalp and hair roots and effectively treats seborrhea.

The application of heat to the body as a whole or its parts is constantly improved, differentiated and at present represents a number of approved methods, each of which has its own indications [3]. Today, the use of thermal exposure in cosmetology practice follows two main directions. First, cooling or heating the entire organism or its comparatively large parts. Second, thermal effect only on certain tissue areas, including pathologically changed.

While in the former case powerful cooling and thermal machines (e.g., vapour compression, absorption, etc.) are used for cooling (heating) the entire organism, systems with lower heating efficiency and cooling capacity based on other principles of energy conversion can be used for exposure to heat of individual zones of human body.

Under these conditions, the use of thermoelectric systems (TES) [4], which are characterized by high reliability, ecological compatibility, noiselessness, functionality and a significant service life, as well as the possibility of a simple transition from cooling to heating mode and vice versa, has a good outlook for local thermal exposure for the purpose of cosmetology procedures.

The purpose of the work is development of a theoretical model to study various operating modes of TES for carrying out thermal cosmetology procedures, taking into account complex configuration of the system, as well as the possibility of a simultaneous contrast thermal effect on biological object in arbitrary zones.

Design of TES for carrying out thermal cosmetology procedures

The appearance of operating part of TES (control unit bases) is shown in Fig. 1 [5]. It comprises a base made in the form of a mask repeating the contours of human face with the holes for eyes, nose and mouth. In the frontal and cheek areas on the inside of the base there are thermal exposure zones the function elements of which are thermoelectric modules (TEM) contacting with heat-leveling plates for creation of a uniform heat flux. The TEM are connected to programmable direct current source implementing various operating conditions of modules (cooling, heating, their alternation) depending on the type of cosmetology procedure. The dose and duration of thermal exposure is determined by the doctor-cosmetologist, who is also in charge of current monitoring of the patient's condition.

Fig. 1. Appearance of operating part of the system for carrying out cosmetology procedures.

Model of TES for carrying out thermal cosmetology procedures

The model is based on solving two problems: determination of the required values of heat flux from TEM, the function element of TES, and calculation of the basic characteristics of the latter.

The first problem is solved on the basis of analysis of the temperature field of arbitrary-shaped plate which is a target object, with discrete energy sources corresponding to TEM in the system [6].

With regard to presentation of heat sources and sinks (TEM) as a step function, mathematical formulation of the problem of calculation of the temperature field of target object was obtained as follows:

$$\lambda \frac{\partial^2 T}{\partial x^2} + \lambda \frac{\partial^2 T}{\partial y^2} + q_{TEM}\left(x, y\right) + q_{amb} = c\rho \frac{\partial T}{\partial \tau}, \tag{1}$$

$$q_{TEM}(x,y)=\sum_{j=1}^{J} q_{TEM_j}(x,y); \tag{2}$$

$$q_{TEM_j}(x,y)=\begin{cases}\dfrac{Q_{TEM_j}}{S_{TEM_j}} \text{ in the area of energy source}\\ 0 \text{ outside the area of energy source}\end{cases}, \tag{3}$$

$$S_{TEM_j}=\iint\limits_{S_{TEM_j}} S_{TEM_j}(x,y)\,dxdy, \tag{4}$$

$$q_{cp}=\alpha(T-T_{amb}), \tag{5}$$

$$\lambda\frac{\partial T}{\partial n}=\alpha(T-T_{amb}) \text{ at } x,y\in L, \tag{6}$$

$$T = 309.6 \text{ K at } \tau = 0. \tag{7}$$

where T is temperature at any point of target object; T_{amb} is ambient temperature; τ is time; δ is plate thickness; λ is effective thermal conductivity coefficient of target object; α is coefficient of heat transfer to the environment (α = const); c is heat capacity of target object, ρ is density of target object, $q_{TEM}(x, y)$ is total surface density of heat flux from the local heat sources and sinks, $q_{TEMj}(x, y)$ is surface density of heat flux from j-th local heat source (TEM); Q_{TEMj} is power dissipated by j-th local source of heat; q_{amb} is surface density of heat flux to target object from the environment; L is curve restricting the area of biological object exposed to thermal effect, n is normal to curve $\boldsymbol{n} = (x\boldsymbol{h} + y\boldsymbol{g})$; $\boldsymbol{h}$, $\boldsymbol{g}$ are unit vectors.

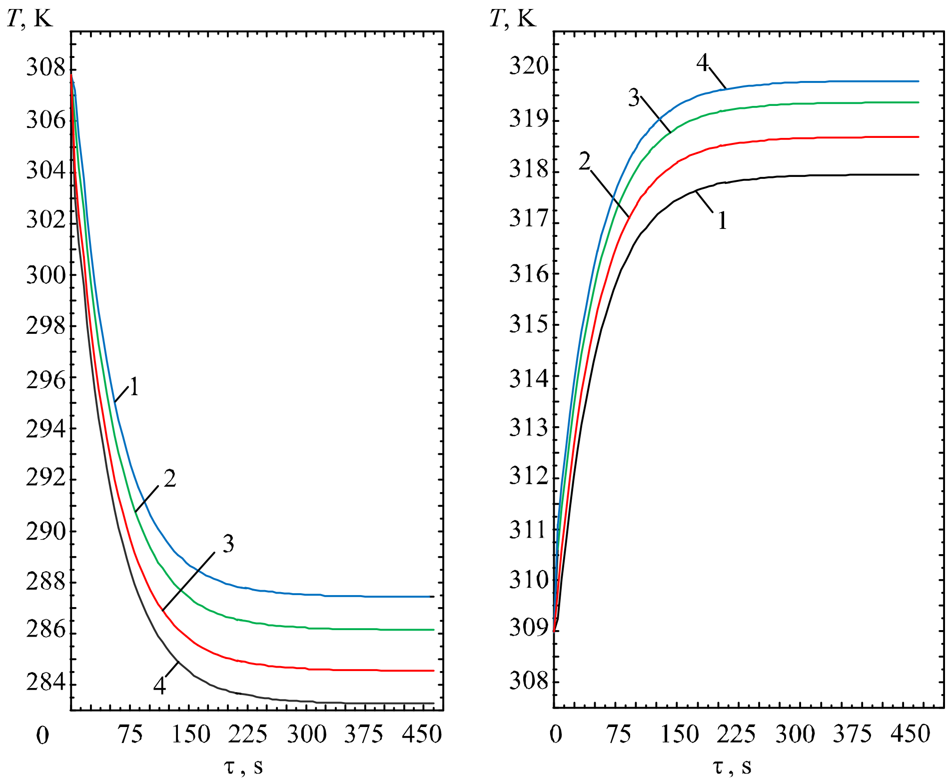
Solving of equations by finite element numerical method (1) – (7) allowed temperature determination at different points of target object – skin area exposed to thermal cosmetology procedures, as well as tracing its variation depending on the value of heat flux from TES (cooling capacity and heating efficiency of TEM), ambient conditions.

Calculation was performed in conformity with the necessary conditions of carrying out cosmetology procedures: target object temperature – 283 ÷ 313 K, exposure duration – 3 ÷ 12 min., possibility of alternation of heating and cooling modes. In the system model it was supposed to use 6 standard TEM, 2 of which are arranged in the frontal part, and 2 in each cheek zone. TEM dimensions: length - 40 mm, width - 40 mm. The input data were as follows: λ = 0.6 W/(m·K), C =3458 J/(kg·K), ρ = 1041 kg/m^3, T_{amb} = 295 K, α = 5 W/(m^2·K).

Temporal variations of biological object temperature on exposure to uniform and contrast thermal effect were obtained. The results of calculations are given in Figs. 2 – 3.

Fig. 2 represents temporal variations of base surface temperature brought into contact with human face on exposure to cooling and heating for the values of $q_{TEMj}(x, y)$, equal to 7000 W/m^2; 9000 W/m^2; 11000 W/m^2; 13000 W/m^2, respectively.

As follows from the above dependences, the duration of onset of steady-state regime is 5 minutes for device operation in cooling mode and 4 minutes for device operation in heating mode. In so doing, the increase in surface density of heat flux from TEM leads to decreasing temperature of biological object for TES operation in cooling mode and to increasing its temperature for TES operation in heating mode, respectively, which corresponds to increase in cooling capacity and heating efficiency of modules. Thus, the increase in q_{TEMj} (x, y) from 7000 W/m^2 to 13000 W/m^2 on cooling biological object reduces its temperature from 287.5 K to 283 K, and the increase in q_{TEMj} (x, y) by the same value on heating increases the temperature of target object from 317.7 K to 320 K.



a) *b)*

Fig. 2. Temporal variation of biological simulator temperature on exposure to cooling (a), to heating (b) for different values of q_{TEMj} (x, y): 1 – q_{TEMj} = 7000 W/m^2; 2 – q_{TEMj} = 9000 W/m^2; 3 – q_{TEMj} = 11000 W/m^2; 4 – q_{TEMj} = 13000 W/m^2.

Here it should be noted that it seems expedient to bring TES to operating mode prior to carrying out cosmetology procedures with a view to increase their comfort. The above can be implemented by preliminary cooling (heating) of the base, and then, on achievement of required temperatures, its application on the face of a person.

With the use of the proposed TES design, a dynamic thermal operating mode of the device can be implemented, which is characterized by alternation of cooling and heating modes in conformity with the specified program.

To study the possibilities of TES with implementation of this operating mode, the dependences of temporal change of biological simulator temperature with alternation of device operating conditions were obtained, which are shown in Fig. 3. The results are represented for q_{TEMj} (x, y) equal to 6000 W/m^2; 5000 W/m^2; 4000 W/m^2. In both cases, the duration of transition from cooling to heating mode and vice versa is of the order of 5 minutes, which calls for further optimization in terms of reducing the duration of this transition from one mode to the other.

This optimization seems possible by selecting the appropriate type of TEM characterized by high-speed performance; transition when switching TES from cooling to heating from the mode of maximum coefficient of performance (heating coefficient) to the mode of maximum cooling capacity (heating efficiency); reduction of total heat capacity of design by selecting the appropriate base material; reduction of total thermal inertia of design due to elimination of certain zones of human face from the cosmetology procedure and, accordingly, the base area (exposure of only certain areas of human face, as needed), arrangement of TEM directly in the affected area, instead of using the entire base for cooling (heating).

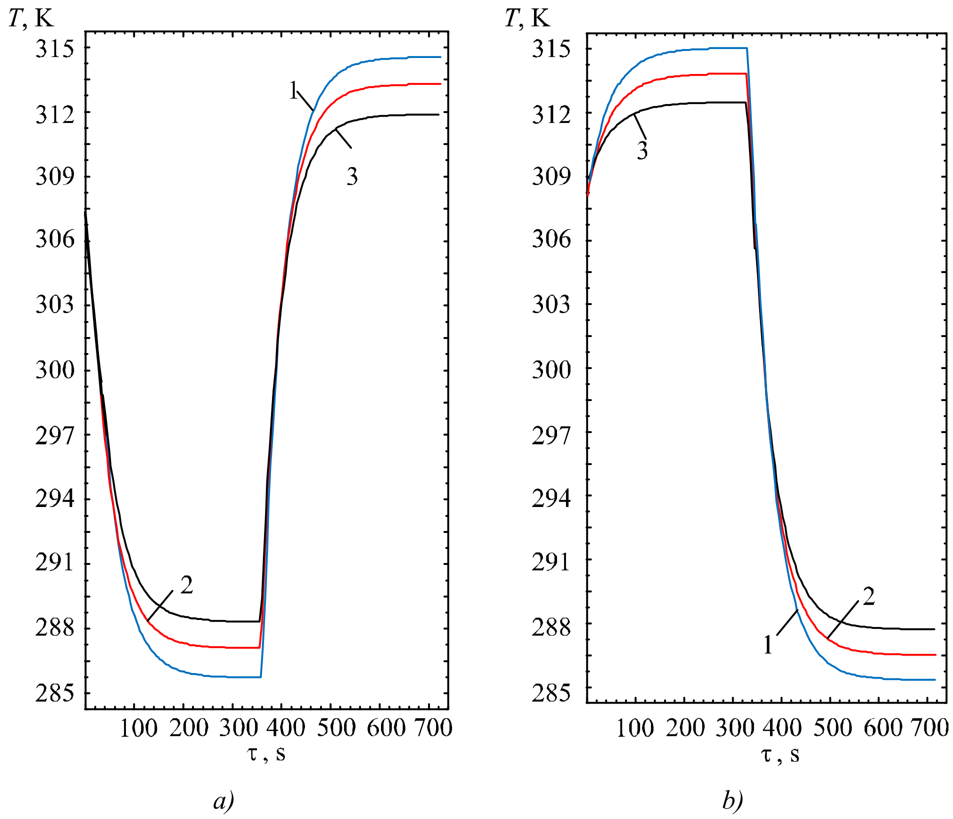


Fig. 3. Temporal variation of biological object temperature on exposure to contrast dynamic thermal effect at transition of TES from cooling to heating mode (a), from heating to cooling mode (b) for different values of q_{TEMj}.
1 – q_{TEMj} = 6000 W/m^2; 2 – q_{TEMj} = 5000 W/m^2; 3 – q_{TEMj} = 4000 W/m^2.

It should be noted that the existing analogs which implement this kind of thermal cosmetology procedures, for instance, cosmetology instruments Vivax CryoPro (company "Vivax", France) [7], OHOTA-5M (“OHOTA” Ltd., Moscow) [8], Flash 1 Jumbo (company "General Project", Italy) [9] and others, described in sufficient detail in [4], possess higher-speed performance (change of mode can be implemented within tens of seconds). However, the distinguishing feature of these systems is the use of a small-size probe as a function element, which is mechanically moved over person’s face during the procedures. In so doing, the high speed of alternation of thermal exposure modes refers only to the zone of action of this probe at given instant. If, however, we consider the cosmetology procedure with respect to the entire patient’s face, or its larger part, implementation of contrast thermal exposure will be much longer. Thus, the lack of the possibility of simultaneous coverage of large exposure areas will cancel out the advantage of high-speed performance of analogs, reduce the efficiency of procedures, and improve their duration when covering the entire face.

Based on the analysis of the obtained heat flux values formed by TES, equivalent to cooling capacity and heating efficiency of TEM, calculation of characteristics of the latter can be performed which is the second problem solved in the construction of system model. The sought-for values in this case are geometric dimensions of thermoelements that make up the module, the value of supply current, and electric power consumption. A detailed description of the method for calculating these

TEM characteristics is given in [10]. In so doing, in the majority of cases TES can employ TEM of standard type that can be selected using special software packages. For TES version under study, for instance, use can be made of standard TEM of TB-127-1.0-1.5 type, produced by Kryotherm company (Saint-Petersburg), fully implementing the required modes of carrying out therapeutic procedures. For their selection, "Thermoelectric system calculation" software package can be used [11]. This software yields the dependences of change in such TEM parameters as cooling capacity, coefficient of performance on its current characteristics.

Conclusions

1. To date, in cosmetology practice, methods of exposure based on the use of a thermal factor (cooling and heating of a biological object) are becoming increasingly widespread.
2. Among the existing methods of thermal cosmetology procedures, the use of technical means based on thermoelectric energy converters is efficient.
3. A thermoelectric system (TES) for thermal cosmetology effect on human face was developed, where the function elements are TEM enabling to combine cooling and heating modes in in a single device.
4. A model of TES was developed for carrying out thermal cosmetology procedures which is based on solving a two-dimensional nonstationary thermal conductivity problem for a complex system.
5. Temporal variations of temperature at different points of target object – skin area exposed to thermal cosmetology procedures as a function of cooling capacity and heating efficiency of TEM were obtained.
6. It was established that the onset of regime for TES is of the order of 4 – 5 minutes, so it seems advisable to reach the operating mode of TES prior to carrying out cosmetology procedures by their preliminary cooling or heating.
7. In the framework of the experiment it was established that the duration of TES switching from cooling to heating mode and vice versa is 5 minutes, which requires further design optimization due to the use of more advanced types of TEM, variation of TEM operating conditions, as well as reduction of total heat capacity of device design.

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