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INVESTIGATION OF A THERMOELECTRIC SYSTEM FOR LOCAL FREEZING OF LARYNX TISSUES

The paper is concerned with a thermoelectric system for local freezing of larynx tissues. The results of its mathematical simulation and full-scale test of a prototype are presented. Two-dimensional and one-dimensional theoretical and experimental plots of temperature variation at different system points are given.

Key words: larynx, thermoelectric system, thermopile, thermal exposure, temperature field, mathematical model, prototype, experiment.

Introduction

One of the priority areas in medicine is safety and the use of natural treatment methods capable of stimulating biological response of human organism. In this connection, drug-free modalities are of considerable current use. One of the most widespread and efficient natural physical factors in medicine is low-temperature exposure that serves the basis for methods of local hypothermia of individual human organs and tissues. Among them, one should emphasize local cooling and freezing of larynx tissues which is actively used not only for treatment of throat diseases, such as chronic tonsillitis, pharyngitis, but also as an all-purpose immunostimulating drug, recommended for mass adoption in medical institutions of various level.

Current facilities for local cooling of larynx tissues suppose the use of liquid coolant and have the form of metal rods pre-cooled in liquid nitrogen or oxygen, the so-called passive cryoprobes, as well as systems with open and closed circulation of liquid coolant [1-3]. To the above facilities one can refer devices described in [4-6]. The equipment includes a reservoir with liquid nitrogen, heat-insulated pipes for coolant feed and rejection equipped with corresponding valves, operating tip of various shape and gas evacuation system. To improve the efficiency of cryotip defrosting, as well as to expand the potential of cryodestruction method, in [7] use is made of optical fibers attached to laser radiation source and brought with their operating tips to cryotip cold conductor. In [8], replaceable tips are used as a working source of cold which are filled with coolant and arranged in a case fixed in the holder which allows improving the ergonomics of the device and assures the possibility of its operational application in the field. To improve the operating efficiency of the device for local freezing of larynx tissues due to acceleration of coolant circulation and improvement of heat transfer, [9] involves pressure rise unit and additional heat-exchange unit.

The above facilities do not always meet safety requirements due to possible depressurization of compression systems, biological aggressivity of coolants used, delayed operating processes and low accuracy of cooling effect dosing. The use of liquid coolants in such devices complicates to a large extent their design and maintenance, reduces the operating time due to a restricted coolant volume, prevents from reaching the necessary level of thermal exposure control, does not solve the problem of adhesive effect which calls for the presence of additional heating devices. Said disadvantages interfere with a wide adoption of efficient methods of cryotherapeutic effect on larynx tissues in medical practice.

Under these conditions it is advisable to use thermopiles as a function element in a device for cooling larynx tissues. Their use offers a number of definite advantages, namely eliminates liquid coolants owing to which the device becomes independent from centres of production and delivery of cryogenic fluids, provides for unlimited service life, environmental friendliness, noise-free operation; improves the accuracy of dosing and exposure control, supposes arrangement of reverse mode by switching supply current direction.

In so doing, design of thermopile-based cooling system should conform to a number of specific features including mandatory provision of device temperature parameters in conformity with medical procedures corresponding to the existing hygienic standards, high reliability of exposure, precise localization of cold focus, safety, etc.

In this connection, the purpose of the paper is to investigate a thermoelectric system for local cooling and freezing of larynx tissues, to study the processes occurring in it with regard to the influence of target object parameters and thermopile characteristics.

Mathematical simulation of a thermoelectric system for local freezing of larynx tissues

A quasi-steady-state mathematical model of a system for local freezing of larynx tissues has been developed. This mathematical model considers a device as a totality of components, namely heat-exchange devices (heat exchanger, thermal bridge, thermopile, heat insulation, and operating tip), assuring temperature reduction of a biological object within the required time to the necessary value.

Fig. 1 shows a design circuit of the system. Here, the first junctions of additional thermopile 1 through operating tip of heat capacity c_{p1} and thermal conduction σ_{p1} are connected to biological tissue of heat capacity c_m and thermal conductivity σ_m, respectively.

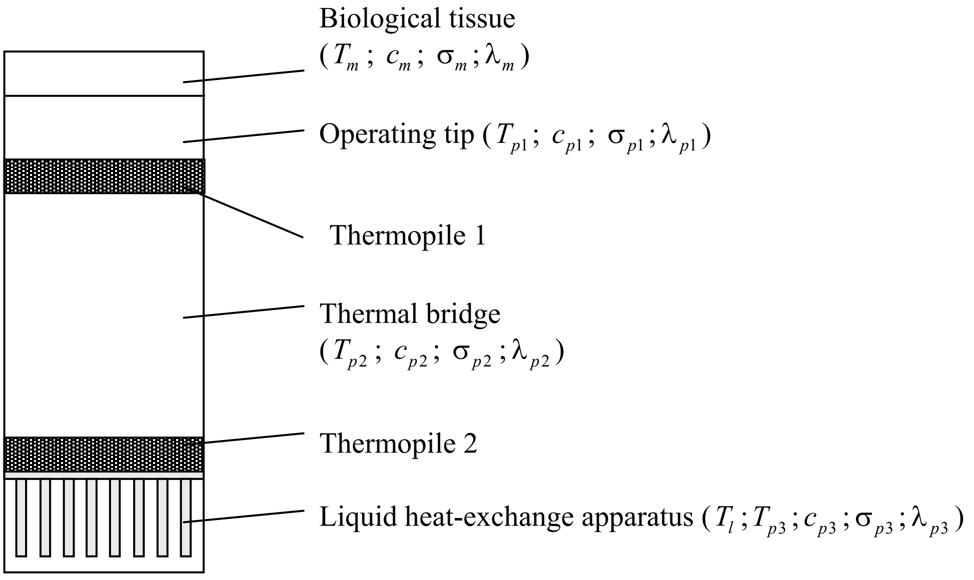

Fig. 1. Design circuit of a system for local freezing of larynx tissues.

The second junctions of thermopile 1 are brought into contact with the end face of thermal bridge of heat capacity c_{p2} and thermal conductivity σ_{p2} whose second end face is connected to the first junctions of the basic thermopile 2.

The second junctions of thermopile 2 by means of a liquid heat exchange apparatus of heat capacity c_{p3} and thermal conductivity σ_{p3} are maintained at temperature T_{p3}. The temperature of liquid flowing in the heat-exchange apparatus is maintained equal to T_l. Current of constant density, j_1 and j_2, respectively, flows through thermopile 1 and thermopile 2. Moreover, biological object under study is characterized by specific power of heat release Q_r.

Under these conditions, mathematical implementation of the model is determined by a system of differential equations:

$$\left.\begin{aligned}
&\frac{dT_m}{d\tau}=\frac{1}{m_m c_m}\left[\sigma_m\left(T_{p1}-T_m\right)+Q_r+\sigma_{amb}\left(T_{amb}-T_m\right)\right]\\
&\frac{dT_{p1}}{d\tau}=\frac{1}{m_{p1}c_{p1}}\left[n_1S_1\left[-e_1j_1T_{p1}+\frac{1}{2}j_1^2\rho_1h_1+\frac{\lambda_1}{h_1}\left(T_{p2}-T_{p1}\right)\right]-\sigma_{amb}\left(T_{amb}-T_{p1}\right)\right]\\
&\frac{dT_{p2}}{d\tau}=\frac{1}{m_{p2}c_{p2}}\left[\begin{aligned}&n_2S_2\left[-e_2j_2T_{p2}+\frac{1}{2}j_2^2\rho_2h_2+\frac{\lambda_2}{h_2}\left(T_{p3}-T_{p2}\right)\right]+\\&+n_1S_1\left[e_1j_1T_{p1}+\frac{1}{2}j_1^2\rho_1h_1+\frac{\lambda_1}{h_1}\left(T_{p2}-T_{p1}\right)\right]-\sigma_{amb}\left(T_{amb}-T_{p1}\right)\end{aligned}\right]\\
&\frac{dT_{p3}}{d\tau}=\frac{1}{m_3c_{p3}}\left[n_2S_2\left[e_2j_2T_{p2}+\frac{1}{2}j_2^2\rho_2h_2-\frac{\lambda_2}{h_2}\left(T_{p3}-T_{p2}\right)\right]-\sigma_{p3}\left(T_{p3}-T_l\right)\right]
\end{aligned}\right\}, \qquad (1)$$

where T_m is the temperature of biological tissue; T_{p1} is the temperature of operating tip having thermal contact with the biological object; T_{p2} is the temperature of thermal bridge; m_m is the average mass of tissue; $m_{p1,p2,p3}$ is the mass of operating tip, thermal bridge and heat exchanger; $e_{1,2}$ is the Seebeck coefficient of thermoelements in thermopile; $\rho_{1,2}$ is the electric resistivity of thermopile; $h_{1,2}$ is the height of thermoelements in thermopile; $\lambda_{1,2}$ is the thermal conductivity of thermopile material; T_{amb} is the ambient temperature, σ_{amb} is coefficient of heat exchange with the ambient.

The initial conditions for the case of evaluation of the time to reach the operating mode by the device are given at no-load operation (no contact of device to biological object), based on the assumption that at the initial time moment the thermoelectric system is in thermodynamic equilibrium with the ambient, and the temperature of all system points is equal to ambient temperature. In so doing, the system of equations (1) is written as:

$$\left.\begin{aligned}
&\frac{dT_{p1}}{d\tau}=\frac{1}{m_{p1}c_{p1}}\left[n_1S_1\left[-e_1j_1T_{p1}+\frac{1}{2}j_1^2\rho_1h_1+\frac{\lambda_1}{h_1}\left(T_{p2}-T_{p1}\right)\right]-\sigma_{amb}\left(T_{amb}-T_{p1}\right)\right]\\
&\frac{dT_{p2}}{d\tau}=\frac{1}{m_{p2}c_{p2}}\left[\begin{aligned}&n_2S_2\left[-e_2j_2T_{p2}+\frac{1}{2}j_2^2\rho_2h_2+\frac{\lambda_2}{h_2}\left(T_{p3}-T_{p2}\right)\right]+\\&+n_1S_1\left[e_1j_1T_{p1}+\frac{1}{2}j_1^2\rho_1h_1+\frac{\lambda_1}{h_1}\left(T_{p2}-T_{p1}\right)\right]-\sigma_{amb}\left(T_{amb}-T_{p1}\right)\end{aligned}\right]\\
&\frac{dT_{p3}}{d\tau}=\frac{1}{m_3c_{p3}}\left[n_2S_2\left[e_2j_2T_{p2}+\frac{1}{2}j_2^2\rho_2h_2-\frac{\lambda_2}{h_2}\left(T_{p3}-T_{p2}\right)\right]-\sigma_{p3}\left(T_{p3}-T_l\right)\right]
\end{aligned}\right\}, \qquad (2)$$

For the case of evaluation of the time of exposure of larynx tissues, the initial conditions are taken from the previously obtained data for the evaluation of the time of reaching the operating mode, and the temperature of target object is 309 K.

It was also assumed that the temperatures of operating tip and heat exchanger are equal to the respective junction temperatures. This assumption increases the time of reaching the operating mode, and the results subsequently obtained will be overrated.

The solution of system (1) and (2) was done numerically in the MATHCAD application program package. In so doing, thermal conductivities were found from the formulae:

$$\sigma_{p1}=\frac{\lambda_{p1}\cdot S_{p1}}{\delta_{p1}},\ \sigma_{p2}=\frac{\lambda_{p2}\cdot S_{p2}}{\delta_{p2}},\ \sigma_{p3}=\frac{\lambda_{p3}\cdot S_{p3}}{\delta_{p3}},\quad \sigma_{m}=\frac{\lambda_{m}\cdot S_{m}}{\delta_{m}}.$$

where λ_{p1}, λ_{p2}, λ_{p3}, λ_m is thermal conductivity of operating tip, thermal bridge, heat exchanger and biological tissue, respectively; $S_{p1,2,3,m}$ is the area of contact surfaces of TE device for freezing of larynx tissues and biological tissue, operating tip and thermopile 1, thermal bridge and thermopile 2, and heat exchanger, respectively; δ_{p1},$_{p2}$,$_{p3}$, δ_m is the thickness of operating tip, thermal bridge, heat exchanger, and biological tissue, respectively. The numerical values of the initial quantities in expressions (3) were assumed as follows [4]: λ_{p1} = 389 W/m·K; λ_{p2} = 389 W/m·K; λ_{p3} = 389 W/m·K; λ_m = 0.2 W/m·K; $S_{p1} = 25\cdot10^{-6}$ m^2; $S_{p2} = 10^{-4}$ m^2; $S_{p3} = 36\cdot10^{-4}$ m^2; δ_{p1} = 0.01 m; δ_{p2} = 0.13 m; δ_{p3} = 0.02 m; δ_m = 0.01 m.

In order to evaluate the time of reaching the operation mode by the device, as well the time of exposure, the purpose of calculation was to obtain the temperature field of device-target object system as a function of time at ambient temperature T_{amb} = 298 K for the case of no-load system operation (Fig. 2 and Fig. 3) and in the case of influence on larynx tissue (Fig. 4). The time dependences of larynx tissue temperature, operating tip, thermal bridge and liquid heat exchange apparatus at different thermopile supply currents, as well as for different T_l values were obtained.

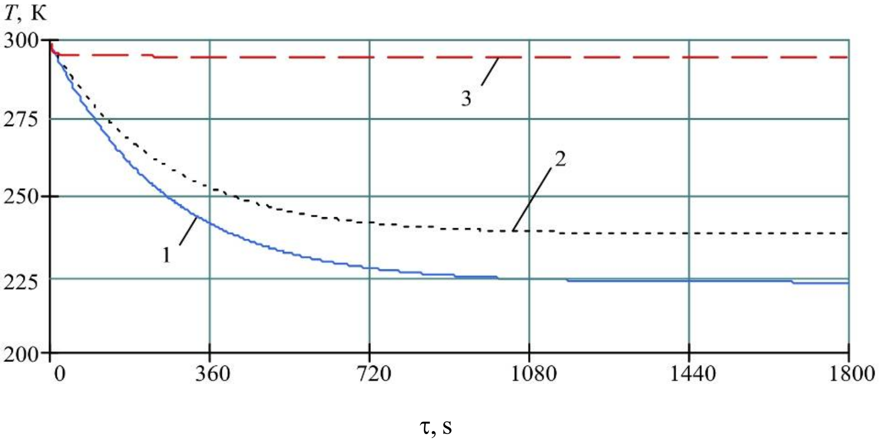

Fig. 2. Temperature field of TE device as a function of time without thermal load.
1 – temperature of operating tip, 2 – temperature of thermal bridge,
3 – temperature of liquid heat exchange apparatus.

As it follows from the represented data, the dependences are of a monotonous decreasing nature. According to the above plots, without thermal load the temperature of operating tip is stabilized in about 18-20 minutes (Fig. 2), which corresponds to time necessary to reach its operating mode. Increase in current strength of additional thermopile (Fig. 3) from 0.5 to 1A at supply current of basic thermopile 5 A reduces the temperature of operating tip T_{p1} from 235 K to 220 K.

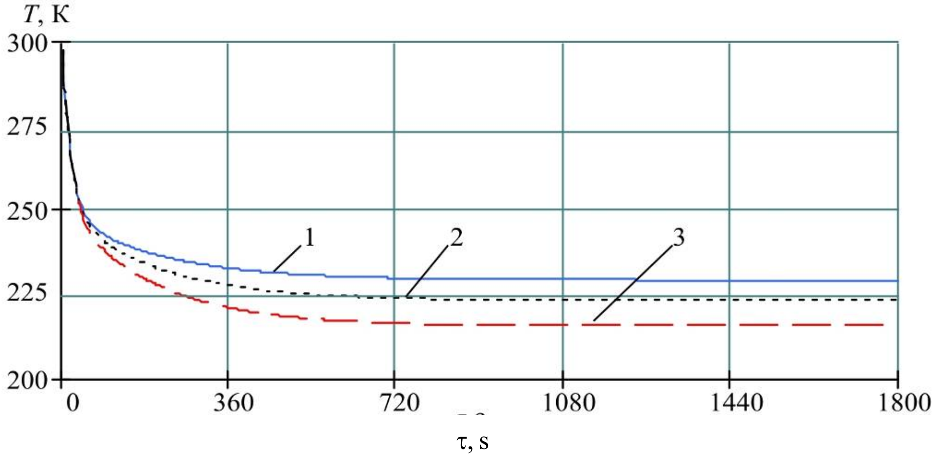

Fig. 3. Temperature variation of operating tip in time under no-load conditions at supply current for basic thermopile 5A and different supply currents for additional thermopile. 1 – 0.5 A, 2 – 0.75 A, 3 – 1 A.

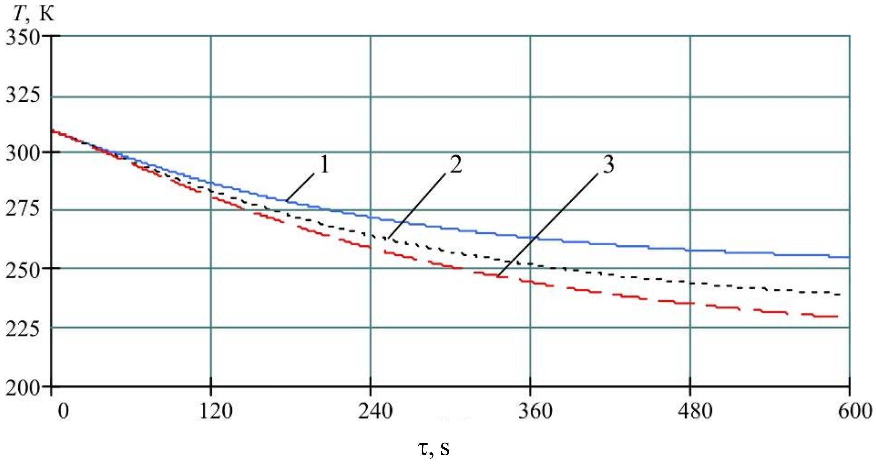

Fig. 4. Temperature variation of larynx tissue in time at different supply currents for basic thermopile. 1 – 2 A, 2 – 3.5 A, 3 – 5 A.

Further increase in current strength results in the Joule heat growth. Therefore, at fixed temperature T_l the ultimate decrease of operating tip temperature is restricted by the value of supply current optimal for this thermopile type. A deeper temperature decrease of operating tip can be obtained by reducing the temperature of liquid T_l, flowing across the heat exchange liquid apparatus. Thus, to reduce tissue temperature, for instance, to 250 K at liquid temperature T_l = 288 K requires 3 minutes less than in the case when T_l = 298 K.

The time to reach the required tissue temperature can be reduced, for instance, to 273 K, by increasing the strength of supply current for additional thermopile. Thus, for the case under study, according to the plots given in Fig. 4, the increase of current strength from 2 to 5 A allows reducing this time from 4 to 2.5 minutes.

Experimental studies of a thermoelectric system for local freezing of larynx tissues

With a view to confirm the results of mathematical simulation, full-scale test of a prototype of thermoelectric system for local freezing of larynx tissues was performed. The object of experimental studies was a prototype of TE device for local freezing of larynx tissues with two and, for comparison, with one TEM. The external view of the system prototype is given in Fig. 5.

Fig. 5. External view of a system for local freezing of larynx tissues.

In the course of the experiment, the prototype was placed into a thermally isolated climatic chamber. The thermopile was powered from electric energy sources Instek PSH – 3630 and GW Laboratory DC Power Supply GPR-1850HD. The load on the operating tip was simulated by a nichrome wire wound on cylinder end. In the course of the experiment, temperature was measured by means of copper-constantan thermocouples whose reference junctions were placed in Dewar flask, and the signal was taken by a multi-channel temperature meter IRTM 2402/M3. Voltage and current on the thermopile were recorded by means of ammeters and voltmeters built into electric energy sources.

During the experiment, voltage and current on the thermopile, ambient temperature and temperatures at different points of the prototype were determined.

In conformity with the value of maximum supply current for the basic thermopile used (5.8 A) and additional thermopile (1.7 A), the work of device was tested for the four values of supply current (3 A; 4 A; 4.5 A and 5.0 A) for the basic thermopile and three values of supply current for additional thermopile (0.5 A; 1 A; 1.5 A).

The main task when performing experimental investigations of the prototype was to determine the time dependence of temperature at check points with fixed values of thermopile supply currents (Fig. 6 and 7).

In conformity with the data in Fig.6, maximum level of temperature decrease when using one basic thermopile is 243 K (–30°C) for maximum current 5 A and is increased by 2 K , 4 K and 10 K for supply currents 4.5 A, 4 A and 3 A, respectively. Based on the resulting data, one can select optimal supply current for given thermopile.

Fig. 7 represents time dependences of tip temperature for different supply currents with the use in the device of the basic and additional thermopiles. The above dependences show that with the use of additional thermopile whose supply current is increased from 0.5 A to 1.5 A, when optimal supply current of the basic thermopile is 5 A, the temperature of the tip is reduced from 233 K to 228 K.

To evaluate temperature variation along the thermal bridge of length 13 cm, the dependences of time variation along the length of the bridge were obtained for different time moments under no-load conditions. According to the results of measurements, maximum temperature difference along the length of the bridge with supply currents for the basic and additional thermopiles 5 A and 1 A, respectively, is 287 K and falls on the initial moment of device switching. When the device reaches the steady-state mode, this difference does not exceed 3 K and points to a relative uniformity of temperature distribution along the length of the thermal bridge. Owing to this fact, in the construction of a mathematical model one can use the averaged temperature of the thermal bridge. In so doing, this simplification will not have a considerable impact on the accuracy of mathematical calculations.

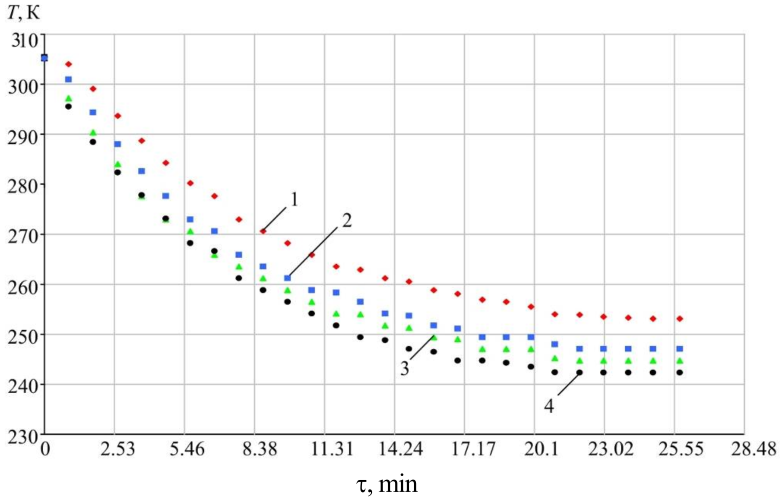

Fig. 6. Time dependence of tip temperature with different supply currents for the basic thermopile, under no-load conditions.

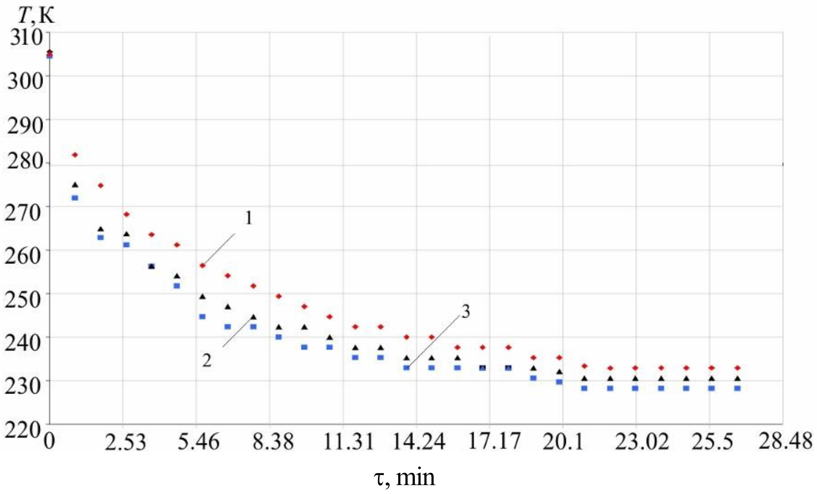

Fig. 7. Time dependence of tip temperature with different supply currents for additional thermopile, under no-load conditions with supply current for basic thermopile 5A.

To evaluate the efficiency of heat rejection system, temperature variation of the basic thermopile hot junction in time was recorded. For the case corresponding to supply currents for the basic and additional thermopiles 5 A and 1 A, respectively, the value of hot junction temperature does not exceed 302 K at cooling liquid temperature 293 K and flow rate 0.07 l/sec.

The resulting experimental data define the acceptable precision of device mathematical model. Maximum discrepancy between the calculated and experimental data does not exceed 11%. The greatest deviation of calculated data from the experiment in the case of determination of the tip temperature is mainly observed in the time interval related to reaching device regime.

Conclusions

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

1. One of the efficient methods for treatment of ORT diseases, such as chronic tonsillitis, pharyngitis, etc., is local freezing of larynx tissues. This procedure can be implemented due to the use

of thermopiles as a source of cold.

2. A thermoelectric system for local freezing of larynx tissues has been designed that consists of two thermopiles interconnected by all-metal thermal bridge equipped with operating tip and liquid heat exchanger.

3. A quasi-steady-state mathematical model of a thermoelectric system has been developed which considers a device as a totality of components, namely heat-exchange devices (heat exchanger, thermal bridge, thermopile, heat insulation, and operating tip), assuring temperature reduction of a biological object within the required time to the necessary value.

4. It has been established that under no-load conditions the operating tip temperature is stabilized in about 18-20 minutes at supply currents from 1 to 3 A, which corresponds to time necessary to reach its operating mode. In so doing, increase in current strength from 1 to 3 A reduces the operating tip temperature from 275 to 237 K.

5. When carrying out the procedures, the necessary level of larynx tissue temperature reduction (273 K) can be achieved in 4 minutes and 2.5 minutes at supply currents 2 A and 5 A.

6. With a change in current strength from 2 A to 5 A, the ratio between temperature change and current strength change is reduced. With increase in supply current from 2 A to 3 A, the temperature of tissue is reduced from 267 K to 250 K, the increase in current strength from 3 A to 4 A reduces the temperature from 250 K to 240 K, and the increase in supply current from 4 A to 5 A reduces the temperature to 233 K.

7. At fixed temperature T_l maximum reduction of operating tip temperature is restricted to the value of thermopile optimal current. A deeper cooling at this supply current value can be obtained by reduction of T_l value.

8. A test bench and measurement procedure for full-scale test of the prototype has been developed. The results of experimental investigations of the prototype have demonstrated a satisfactory repeatability of calculated and experimental data. Maximum discrepancy between the calculated and experimental data did not exceed 11% over the entire measurement range.

9. The results of theoretical and experimental investigations of the thermoelectric system fort freezing of larynx tissues have shown its definite advantages for practical application.

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