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Computer Simulation of the Non-Stationary Operating Mode of Thermoelectric Cooling Chamber for Medical Purposes

The paper proposes a model of a thermoelectric cooling chamber for medical purposes, which takes into account the thermal resistance and heat capacity of all the main elements of its design, ensuring that the simulation of the chamber cooling process is close to the actual conditions of its operation. A mathematical method of simulating the characteristics of the non-stationary cooling process of such a chamber is described, based on the solution of quasi-stationary heat balance equations at the boundaries between the main elements of the refrigerator model in combination with the solution of a stationary boundary value problem for finding the distribution of temperature and heat flow in thermoelectric legs. An algorithm and a computer tool have been developed to calculate the characteristics and parameters of the chamber cooling in the non-stationary mode of its operation. The computer program allows analyzing the influence of the design of thermoelectric modules and their power supply mode on the efficiency of the chamber cooling process, and using the obtained results to improve the design of TE modules and optimize their operating modes.

Keywords: thermoelectric cooling chamber, non-stationary mode, computer simulation, thermoelectric module.

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Introduction

Medical cooling chambers are widely used for storage and transportation of biological materials, drugs, vaccines, donor blood and transplant organs, for which the stability of the temperature regime is a critical condition for ensuring quality and safety. A temperature deviation of even a few degrees or its short-term fluctuation can lead to the degradation of the biological properties of the samples in the chamber, which causes increased requirements for the accuracy and reliability of the cooling systems of medical chambers for various purposes.

For modern medical chambers, thermoelectric (TE) coolers are increasingly used [1-12], which differ from other cooling systems in compactness, absence of moving parts, high reliability and the ability to precisely regulate temperature. In particular, in [1], small-volume medical thermoelectric refrigerators (from 5 to 20 l) are considered which are used for storing pharmaceuticals and biological reagents. The chambers are characterized by compact dimensions and low energy consumption. The authors note the significant influence of non-stationary thermal processes on the stability of the temperature field inside the chamber.

In [5], an example of a medical chamber for storing pharmaceuticals is given. In the chamber, the dimensions of which are 400 × 300 × 300 mm, active air heat exchange is implemented, and heat removal from the heat-emitting surface of thermoelectric modules is carried out by aluminum radiators with forced ventilation. The authors emphasize that the efficiency of the system depends significantly on the dynamics of heat exchange between the chamber's interior and its cooling elements.

A separate group consists of specialized medical cooled chambers and devices for local use, in particular systems for cooling biological fluids or surgical instruments [8-12]. Such devices have a small volume (up to 1–2 liters), but operate in a mode of rapid temperature change, which requires accurate consideration of non-stationary thermal processes in the chamber and in thermoelectric elements.

Article [13] examines the dynamic behavior of two-stage thermoelectric coolers, which are among the most common designs for efficient cooling in practical medical and technical applications. The authors focus on analyzing the temporal characteristics of the thermal regime under the influence of pulsed currents that alter heat flows in the system, and demonstrate how these dynamic processes affect temperature stability in the cooled volume. The study compares temperature behavior under traditional and modified controlled power supply modes for a thermoelectric cooler, allowing for the identification of optimal conditions for quickly achieving a set temperature and reducing temperature fluctuations. This approach highlights the importance of considering non-stationary thermal processes in the simulation and design of thermoelectric cooling chambers, particularly for medical and laboratory devices where high temperature accuracy is required.

A significant portion of scientific research is devoted to the analysis of steady-state operating modes of thermoelectric coolers, optimization of thermoelement geometry, selection of materials, and improvement of heat exchange systems. In real-world operating conditions of medical cooling chambers, non-stationary processes predominate [14–15], associated with system startup, chamber opening, changes in thermal load, placement of new objects, or fluctuations in ambient temperature.

This problem is of particular relevance for medical applications, where it is necessary to ensure rapid achievement of the set temperature and minimal temperature fluctuations under conditions of variable thermal load. In this regard, the application of mathematical and computer simulation of non-stationary thermal processes in medical cooling chambers with thermoelectric coolers is relevant.

The purpose of the work is focused on developing a method for computer simulation of non-stationary operating modes of a thermoelectric cooling chamber, in which an object with active heat release is placed, to study the time dependence of the temperature in the chamber and to assess the influence of heat transfer conditions, radiator parameters and thermoelectric module design on the efficiency of the cooling process. The results obtained can be used to optimize the design of medical cooling chambers and increase their energy efficiency and temperature stability.

1. Model of a thermoelectric cooling chamber and mathematical description of its non-stationary cooling process

The model of the chamber in which the cooled object is placed is shown in Fig. 1. The source of cold in chamber 1 is thermoelectric modules 2. Depending on the temperature to which the object is cooled, its heat capacity and the amount of heat it releases, one or more single-stage or multi-stage TE modules can be used. The transfer of cold from the heat-absorbing surface of the modules to the chamber is carried out using a radiator 3 due to natural or forced convection of air in the chamber, which is provided by a fan 4.

The cooling chamber is thermally insulated with a layer of insulating material 5. Between the base of radiator 3 and modules 2, a heat-equalizing metal insert 6 is usually placed. Heat from the heat-generating junctions of the TE modules is dissipated into the environment using a radiator 7, cooled by blowing fan 8.

- the total heat capacity C_o of the cooled object, the air in the chamber and its walls is concentrated inside the chamber, the temperature in which is T_1;
- the heat capacity C_{rc} of the radiator in the cooling chamber is concentrated at the interface between the radiator base and the metal insert, and the temperature at this interface is T_2;
- the heat capacity C_m of the metal insert is concentrated at the interface between the insert and the heat-absorbing surface of the TE modules, the temperature at which is T_3;
- the heat capacity C_{rh} of the external radiator is concentrated on the interface between the heat-emitting surface of the modules and the base of this radiator, and the temperature at this interface is T_4;
- the inherent heat capacity of thermoelectric modules can be neglected, since it is significantly less than the heat capacity of the cooled object, chamber, radiators and metal insert, and therefore does not actually affect the cooling time of the chamber.

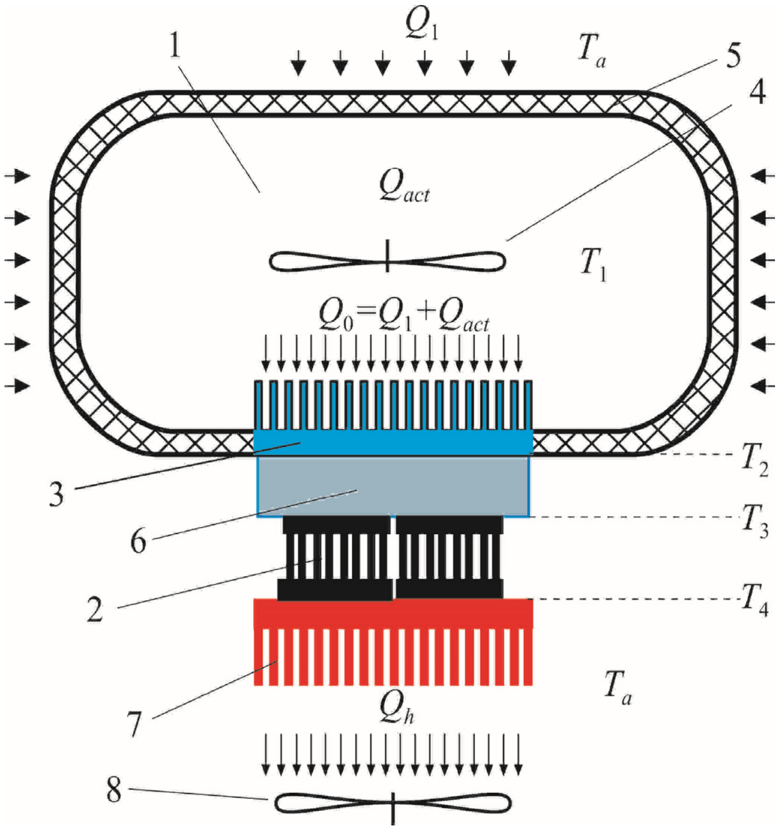

Fig. 1. Schematic of a thermoelectric cooling chamber.
1 – cooling chamber; 2 – thermoelectric modules; 3 – radiator for transferring cold to the chamber; 4 – fan in the chamber; 5 – thermal insulation of the chamber; 6 – metal insert; 7 – radiator for heat removal from the heat-emitting junctions of TE modules to the environment; 8 – fan.

Temperatures $T_1,\ldots,T_4$ change with time. Under the above assumptions, to calculate the time dependence of these temperatures, a system of quasi-stationary heat balance equations at the boundaries between the main elements of the refrigerator model is used, which is written in the form

$$\begin{aligned}
&C_o\frac{(T_1^{i+1}-T_1^i)}{\tau}=\frac{1}{R_{rc}}(T_1^i-T_2^i)-Q_0\\
&C_{rc}\frac{(T_2^{i+1}-T_2^i)}{\tau}=\frac{\kappa_m s_m}{h_m}(T_2^i-T_3^i)-\frac{1}{R_{rc}}(T_1^i-T_2^i)\\
&C_m\frac{(T_3^{i+1}-T_3^i)}{\tau}=Q_c(I,T_3^i,T_4^i)-\frac{\kappa_m s_m}{h_m}(T_2^i-T_3^i)\\
&C_{rh}\frac{(T_4^{i+1}-T_4^i)}{\tau}=Q_h(I,T_3^i,T_4^i)-\frac{1}{R_{rh}}(T_4^i-T_a)
\end{aligned}, \qquad (1)$$

where τ is the time step, and the superscript i denotes time instant. System (1) must be satisfied at every time instant $t_i = i\tau$. In this system, $Q_0 = Q_1 + Q_{act}$ is the thermal power that needs to be removed from the chamber for its cooling, Q_{act} is active heat release of the object in the chamber, $Q_1 = (\kappa_{in} s_{in} / h_{in})(T_a - T_1)$ is the heat capacity that enters the chamber through the insulation, R_{rc} and R_{rh} are thermal resistances of the radiator in the chamber and the external radiator, respectively, under conditions of natural or forced convection, κ_{in}, s_{in}, h_{in} and κ_m, s_m, h_m are thermal conductivity, area and thickness of the insulating material and metal insert, respectively. $Q_c(I, T_3^i, T_4^i)$ is cooling capacity of TE modules at the i-th time instant, which depends on the supply current of modules I and temperatures T_3^i, T_4^i, $Q_h(I, T_3^i, T_4^i) = Q_c(I, T_3^i, T_4^i) + W(I, T_3^i, T_4^i)$ is their heat output, $W(I, T_3^i, T_4^i)$ is power consumed by the modules.

To solve the quasi-stationary system (1), initial conditions are required, which have the form

$$T_1 = T_2 = T_3 = T_4 = T_a, \tag{2}$$

where T_a is ambient temperature. Also, at each time step, it is necessary to calculate the cooling capacity Q_0 and the electrical power W of the TE modules for a given design and supply current.

2. Method for calculating the cooling capacity and power of thermoelectric modules

The method for calculating the cooling capacity Q_c and electric power W of N-stage TE modules is based on solving a system of differential equations for finding the temperature distributions $T(x)$ and specific heat flux $q(x) = Q(x)/I$ in thermoelectric legs of n- and p-type conductivity, which is given by [16]

$$\left.\begin{aligned} \frac{dT^{(k)}}{dx} &= -\frac{\alpha j}{\kappa} T^{(k)} - \frac{j}{\kappa} q^{(k)}, \\ \frac{dq^{(k)}}{dx} &= \frac{\alpha^2 j}{\kappa} T^{(k)} + \frac{\alpha j}{\kappa} q^{(k)} + \frac{j}{\sigma}, \end{aligned}\right\}_{n,p} \quad k = 1, \dots, N, \tag{3}$$

where $x = x/L$, $0 \le x \le 1$ is dimensionless coordinate, $j = I\,L/s_0$ is specific current density, s_0 is cross-sectional area of a thermoelectric leg, L is its height. In these equations, the Seebeck coefficient $\alpha_{n,p} = \alpha_{n,p}(T)$, electrical conductivity $\sigma_{n,p} = \sigma_{n,p}(T)$ and thermal conductivity $\kappa_{n,p} = \kappa_{n,p}(T)$ of the materials of n- and p-type legs are functions of temperature.

The boundary conditions for this system are written as follows [14]:

$$\begin{aligned} &T_n^{(k)}(0) = T_p^{(k)}(0) \equiv T_{(k)}(0), \qquad T_n^{(k)}(1) = T_p^{(k)}(1) \equiv T_{(k)}(1), \quad k = 1, \dots, N, \\ &T_{(1)}(0) = T_4, \qquad T_{(N)}(1) = T_3, \qquad T_{(k)}(0) = T_{(k-1)}(1) + \delta T, \quad k = 2, \dots, N, \\ &q_1^{(k)} n_k = q_0^{(k-1)} n_{k-1}, \quad k = 2, \dots, N, \end{aligned} \tag{4}$$

where δT is the temperature difference caused by the thermal resistance of the inter-stage insulating plate, which in standard modules does not exceed 0.5 K, n_k is the number of thermocouples in the k-th stage, $q_0^{(k)}$, $q_1^{(k)}$ are specific heat flows through the heat-absorbing and heat-releasing junctions of the thermoelements of the k-th stage, respectively, which are determined as follows

$$q_0^{(k)} = \sum_{n,p} \left[q^{(k)}(1) + j\frac{r_0}{L} \right]_{n,p}, \quad q_1^{(k)} = \sum_{n,p} \left[q^{(k)}(0) - j\frac{r_0}{L} \right]_{n,p}, \tag{5}$$

where r_0 is contact resistance [16].

Applying the solution of the boundary value problem (3) – (4), the cooling capacity Q_c and the power consumption W of thermoelectric modules are calculated using the formulae:

$$Q_c = -mn_N q_0^{(N)} I, \quad W = -mI\sum_{k=1}^{N} n_k (q_1^{(k)} - q_0^{(k)}), \tag{6}$$

where m is the number of modules used to cool the chamber.

Based on the quasi-stationary heat balance equations (1) with initial conditions (2) and boundary value equations (3)–(4) for calculating the characteristics of the thermoelectric module, an algorithm and a computer program were developed to study the temporal behavior of the temperature in the thermoelectric cooling chamber and the parameters that characterize the efficiency of its operation.

It should be noted that the current I of the thermoelectric modules can be controlled, i.e., its value can be changed at certain time instants or given time functions of the current $I(t)$. can be used. Therefore, the developed algorithm can be used to study the characteristics of arbitrary dynamic modes of chamber cooling.

3. Algorithm and program for calculating the characteristics of a cooling chamber

For computer simulation of non-stationary operating modes of a thermoelectric cooling chamber, the following data must be specified: the heat capacities of the chamber, the object in the chamber, the radiators and the metal insert, the thermal resistances of the radiators, the dimensions of the chamber and the metal insert, the thickness of the chamber insulation, the specific thermal conductivity of the insulation materials and the metal insert, the ambient temperature, the temperature that must be achieved in the chamber, the thermal power of active heat release of the object being cooled in the chamber. The number of TE modules used for chamber cooling is also specified, as well as the module design parameters, namely the number of stages, the number of thermocouples in each stage, the height and cross-sectional area of their legs, and the supply current for the modules when thermocouples are connected in series. The application interface for entering this data is shown in Fig.2.

The temperature dependences of the parameters $\alpha_{n,p}(T)$, $\sigma_{n,p}(T)$ and $\kappa_{n,p}(T)$ of thermoelectric materials of n- and p-type conductivity are given in the program in the form of polynomials that approximate these characteristics for materials based on Bi_2Te_3. The program interface (Fig. 3) allows you to adjust the polynomials as needed.

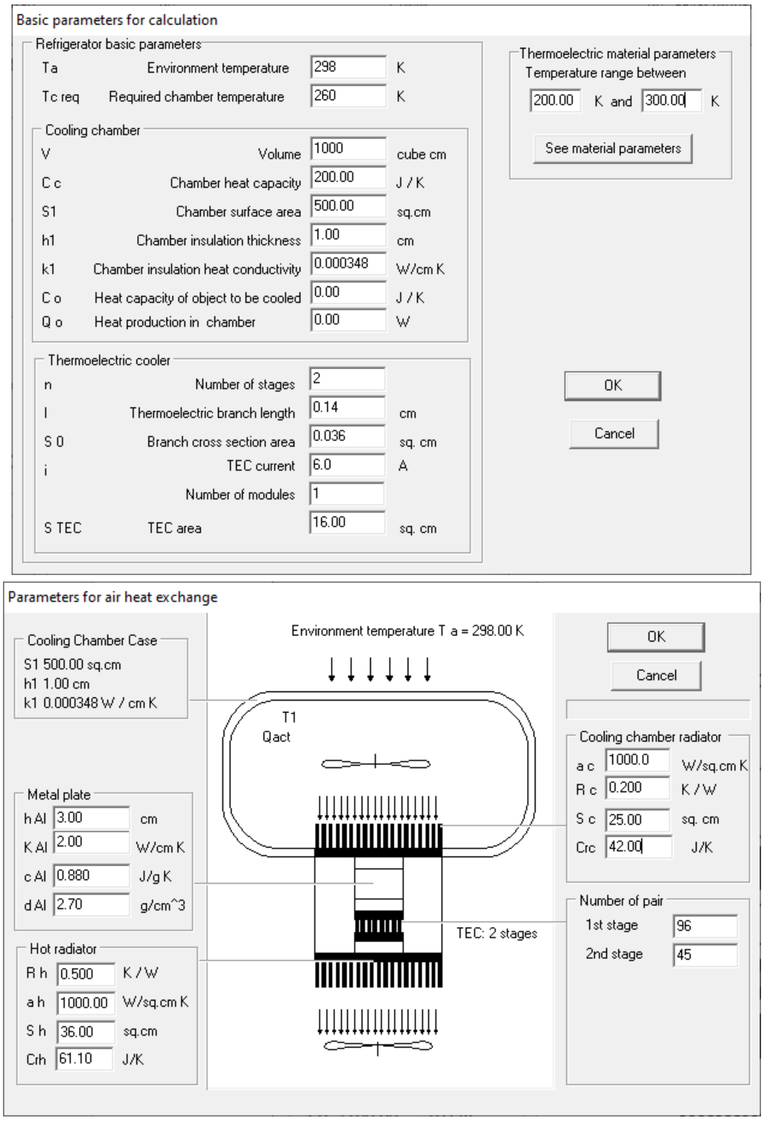

Fig. 2. Program interface for entering data for calculating a thermoelectric cooling chamber

To calculate the time dependence of the temperature in the chamber, the following algorithm of successive approximations is used.

1. Using the initial values of temperatures T_3 and T_4 (2) for boundary conditions (4), first the nonlinear boundary value problem (3)–(4) is solved by finite element methods and Newton iterations. Formulae (5) and (6) are used to calculate the values of cooling capacity $Q_c^{(1)}$ and power $W^{(1)}$ at the first time step.

2. Using the system of equations (1) of the heat balance, we calculate the temperatures $T_1^{(1)}$, $T_2^{(1)}$, $T_3^{(1)}$, $T_4^{(1)}$ at the first time step

3. We repeat steps 1–2 and find the values $Q_c^{(i)}$, $W^{(i)}$, $T_1^{(i)}$, $T_2^{(i)}$, $T_3^{(i)}$, $T_4^{(i)}$ sequentially at each time step i.

4. We perform calculations according to points 1–3 until the temperature $T_1^{(i_f)}$ at some final time instant i_f reaches a value which is close, with a given accuracy, to the cold temperature that must be achieved in the chamber.

5. We calculate the cooling time of the chamber $t_f = i_f \tau$ and the electrical energy $E_f = \tau \sum_{i=1}^{i_f} W^{(i)}$ consumed by the thermoelectric modules during this time.

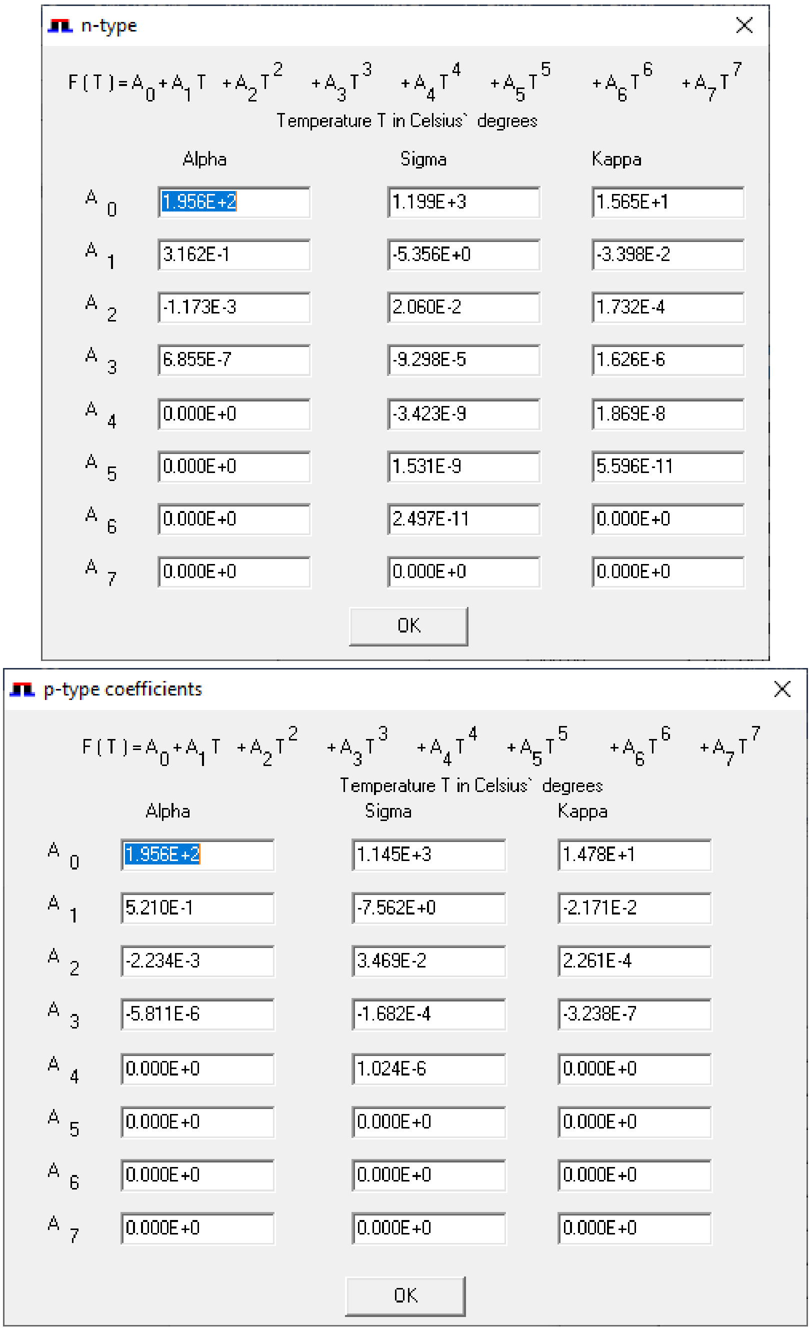

Fig. 3. Program interface for correcting the characteristics of thermoelectric materials

Note that the convergence of such an algorithm of successive approximations is ensured by a small value of time step τ.

The results of the calculation by the program are the time dependences of the temperature in the chamber $T_1(t)$, the temperature of the radiator base in the chamber $T_2(t)$, the temperature of the heat-absorbing $T_3(t)$ and heat-emitting $T_4(t)$ surfaces of the TE modules, as well as the cooling time of the chamber, the values of the temperatures T_1, T_2, T_3, T_4 at the final time instant, and the electrical energy consumed by the TE modules.

Program interface for displaying the results is shown in Fig. 4. As an example, Fig. 4 shows the results obtained for a 1 liter chamber cooled by a two-stage TE module. The module design and other input data for these results are shown in Figs. 2, 3. In this example, the chamber is cooled from 298 K to a temperature of 260 K in 28 minutes.

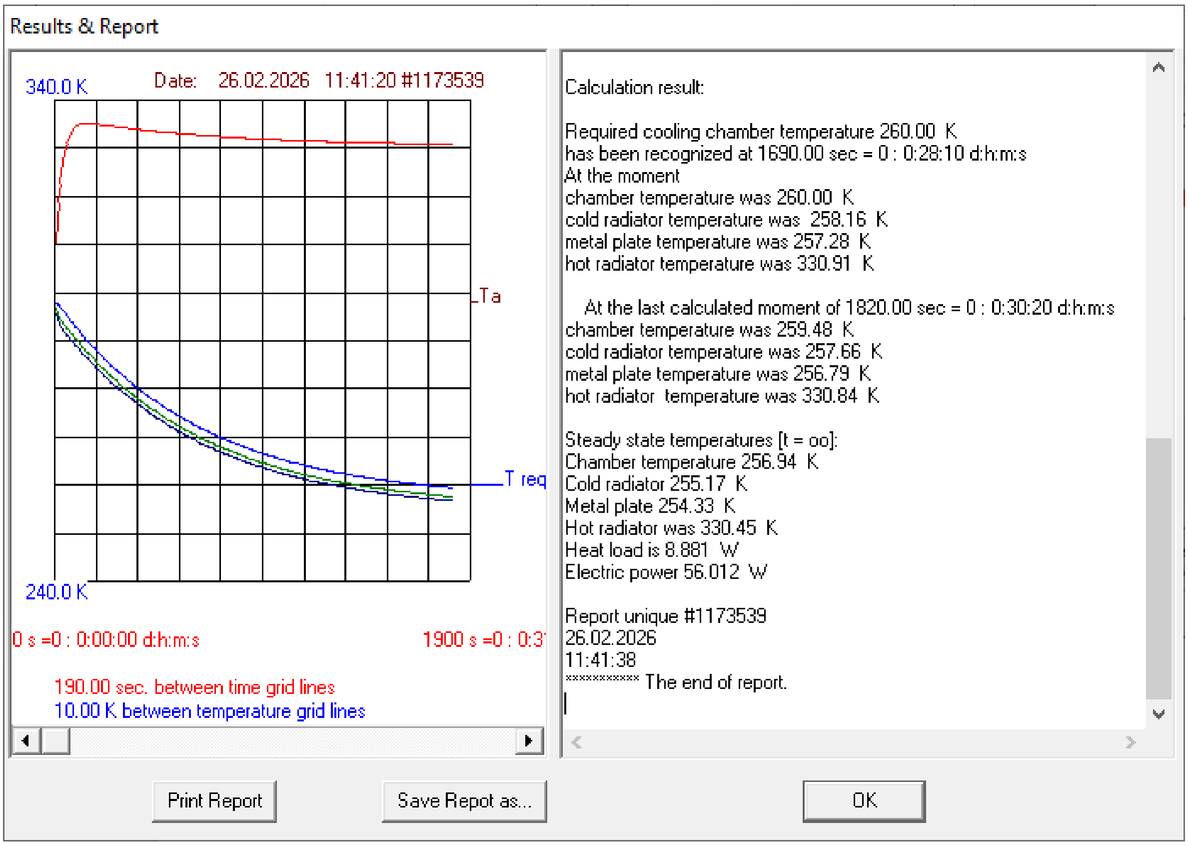

Fig. 4. Program interface for displaying the results of calculating the characteristics of a thermoelectric cooling chamber

Conclusions

The developed model of the cooling chamber takes into account the thermal resistance and heat capacity of all the main elements of its design, which ensures that the simulation of the chamber cooling process is close to the actual conditions of its operation.

The solution of quasi-stationary heat balance equations at the boundaries between the main elements of the refrigerator model, together with the solution of a stationary boundary value problem for finding the temperature distribution and heat flow in thermoelectric legs, allowed the development of an algorithm and a computer tool for simulation of non-stationary operating modes of TE cooling chamber.

The implemented computer tool allows visualization of the temporal temperature change in the chamber and analysis of the influence of the design parameters of thermoelectric modules and their operating mode on the efficiency of the cooling process. The results obtained can be used to improve the existing and develop new designs of TE modules and optimize their operating modes in order to increase the energy efficiency of chamber cooling and ensure its temperature stability.

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Комп'ютерне моделювання нестаціонарного режиму роботи термоелектричної холодильної камери медичного призначення

У роботі запропоновано модель термоелектричної холодильної камери медичного призначення, яка враховує тепловий опір та теплоємність всіх основних елементів *її конструкції, що забезпечує наближеність моделювання процесу охолодження камери до реальних умов її експлуатації. Описано математичний метод моделювання характеристик нестаціонарного процесу охолодження такої камери, який ґрунтується на розв'язуванні квазістаціонарних рівнянь теплового балансу на межах між основними елементами моделі холодильника у сукупності з розв'язуванням стаціонарної крайової задачі для знаходження розподілу температури і теплового потоку в термоелектричних вітках. Розроблено алгоритм і комп'ютерний засіб для розрахунку характеристик і параметрів охолодження камери в нестаціонарному режимі її роботи. Комп'ютерна програма дозволяє аналізувати вплив конструкції термоелектричних модулів і режиму їх живлення на ефективність процесу охолодження камери, а отримані результати використовувати для вдосконалення конструкції ТЕ модулів та оптимізації режимів їх роботи.*

Ключові слова: термоелектрична холодильна камера, нестаціонарний режим, комп'ютерне моделювання, термоелектричний модуль.