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R.R. Kobylianskyi, *Cand.Sc.(Phys-Math)* [1,2]
O.S. Zadorozhnyi, [3]
M.M. Umanets, [3]
N.V. Pasyechnikova, [3]
Yu.Yu. Rozver, [2]
A.O. Babich [1,2]

[1] Institute of Thermoelectricity of the NAS and MES of Ukraine,
1 Nauky str., Chernivtsi, 58029, Ukraine;
[2] Yuriy Fedkovych Chernivtsi National University,
2 Kotsiubynskyi str., Chernivtsi, 58012, Ukraine;
e-mail: anatych@gmail.com
[3] State Institution "The Filatov Institute of Eye Diseases and Tissue Therapy
of the National Academy of Medical Sciences of Ukraine",
Odesa, 49/51, French Boulevard, Ukraine

COMPUTER SIMULATION OF A THERMOELECTRIC DEVICE FOR CONTROLLING THE TEMPERATURE OF IRRIGATION FLUID DURING OPHTHALMOLOGICAL OPERATIONS

A physical, mathematical and computer model of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmic operations has been created. Using computer simulation, the temperature distributions of the therapeutic fluid and inside the cooling unit have been obtained depending on the cooling capacity of the thermoelectric module, the flow rate of the therapeutic fluid and the length of the medical tube in which the cooled fluid circulates. The results of calculations and computer simulation are presented.

Key words: thermoelectric cooling, irrigation fluid, surgery, ophthalmology.

Introduction

In ophthalmology, restoring or preserving vision often requires intraocular surgery. Surgery is widely used for cataracts, retinal detachments, penetrating eye injuries, diabetic retinopathy, and other pathologies. During surgical interventions, an irrigation fluid is injected into the eye, usually at room temperature, i.e. much lower than the temperature of the intraocular media [1 – 3]. In doing so, during standard surgery, monitoring of intraocular temperature and temperature of irrigation solutions is not performed [1, 2]. Therefore, ophthalmic surgery is accompanied by artificial uncontrolled (often prolonged) deep hypothermia of intraocular structures with their subsequent rapid uncontrolled warming after the cooling stage. Rapid, uncontrolled changes in intraocular temperatures pose a risk of damage to the structures of the eye, as well as the occurrence of undesirable vascular reactions during surgery, which can also be accompanied by complications [4]. The surgeon has no ability to intraoperatively control the temperature of the irrigation fluid entering the eye and influence the temperature of the intraocular media.

Advisability of performing ophthalmological surgical interventions under hypothermia conditions is confirmed by various authors. However, today there is no consensus regarding the optimal temperature of the irrigation fluid and the level of intraocular hypothermia during surgery. For example, Mauro et al. proposed a device that allows for retinal surgery under temperature control and is capable of heating the infusion fluid and air during surgery, maintaining their temperature in the range of mild or moderate hypothermia [5, 6]. Other authors prefer to perform surgery under conditions of deep hypothermia, citing evidence of the beneficial effects [7 – 10].

In our opinion, it is advisable to use a mild level of hypothermia in the middle of the eye during vitreoretinal surgeries, since such conditions are safer for intraocular structures, especially during long interventions. The level of mild hypothermia can be achieved by heating the irrigation fluid above room temperature before it enters the middle of the eye [4, 6]. On the other hand, short-term cooling of irrigation solutions will allow using the beneficial effects of deep hypothermia during certain types of operations [7 – 10]. To solve this problem, it is necessary to solve the issue of effective intraoperative cooling of the liquid. The use of thermoelectric devices in the mode of both heating and cooling of the irrigation liquid during surgery looks the most promising.

Thus, the development of effective and safe methods for regulating the temperature of irrigation solutions with the subsequent implementation of a controlled hypothermia system in the practice of ophthalmic surgery is an urgent task.

The *purpose of the work* is to develop a design and computer simulation of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmological operations.

1. Physical model

The thermoelectric device for controlling the temperature of the irrigation fluid contains two main functional units – a metal cooling unit and a control and power supply unit. The physical model of the cooling unit is shown in Fig. 1.

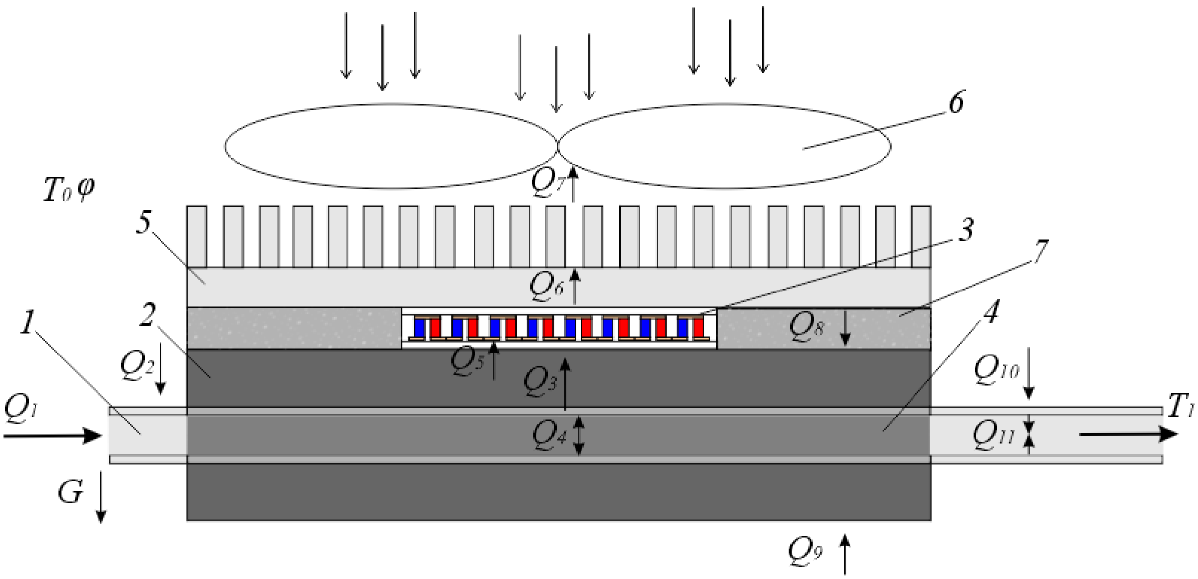

Fig. 1. Physical model of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmic operations: 1 – medical tube, 2 – metal cooling unit, 3 – thermoelectric module, 4 – steel tube, 5 – heat sink, 6 – fan, 7 – thermal insulation.

In Fig.1: T_0, φ is temperature and relative air humidity; G is force of gravity; Q_1 is heat flow entering the cooling unit together with treatment fluid; Q_2 is heat inleak to the inlet of the cooling unit from the environment; Q_3 is heat flow removed from the steel tube to the plates of the cooling unit; Q_4 is heat flow removed from the treatment fluid to the steel tube; Q_5 is cooling capacity of the thermoelectric module; Q_6 is heat removed from the hot side of the thermoelectric module; Q_7 is heat removed from the heat sink to the environment; Q_8 is heat inleak from the hot side of the heat sink to the cooling unit; Q_9 is heat inleak from the environment to the cooling unit; Q_{10} is heat inleak from the environment to the medical tube; Q_{11} is heat inleak from the medical tube to the cooled fluid; T_1 is the temperature of the cooled fluid.

2. Mathematical description and computer model

[11 – 12], the theory of optimal control of the time dependence of cooling temperature in thermoelectric devices was developed, and in [13], computer simulation of thermal processes of the human eye was carried out. Based on the results obtained, thermoelectric devices for hypothermia of the human eye were developed [14 – 17].

A computer model of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmic operations was built using the Comsol Multiphysics program [18, 19]. The following sections of this program were used:

1. Heat Transfer in Solids and Fluids. It allows solving heat transfer equations with additional terms that describe the thermal interaction between a fluid and a solid. It also allows calculating changes in material parameters that occur depending on changes in temperature or other factors.

The equations look as follows [18, 19]:

$$\rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{1}$$

(Stationary problem)

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{2}$$

(Non-stationary problem)

$$q = -k \nabla T \tag{3}$$

(Fourier law for thermal conductivity)

where:

- ρ – material density (kg/m³);
- C_p – specific heat capacity at constant pressure (J/kg·K);
- t – time (s);
- u – flow velocity vector (m/s);
- T – temperature gradient (K);
- q – heat flow vector (W/m²);
- Q – volumetric heat source (W/m³);
- Q_{ted} – additional heat sources (W/m³);
- k – thermal conductivity of material (W/(m·K)).

2. Laminar flow. Makes possible simulation of laminar flow of a fluid or gas using the Navier-Stokes equations. This module is focused on the analysis of flows characterized by low Reynolds numbers ($Re \leq 2300$).

$$\rho(u \cdot \nabla)u = \nabla \cdot [-pI + K] + F + \rho g \tag{4}$$

(The Navier-Stokes equation for the stationary case)

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot [-pI + K] + F + \rho g \tag{5}$$

(The Navier-Stokes equation for the time-dependent case)

where:

- ρ – density of fluid or gas (kg/m^3);
- u – flow velocity vector (m/s);
- p – pressure in fluid or gas (N/m^2);
- I – unit tensor;
- K – viscous stress tensor;
- F – vector of external forces (kg/m^2 s^2);
- g – gravitational acceleration vector (m/s^2).

The geometry of the cooling unit with a medical tube, as well as the finite element method mesh [18, 19] used for calculations in Comsol Multiphysics, are shown in Fig. 2 *a, b.*

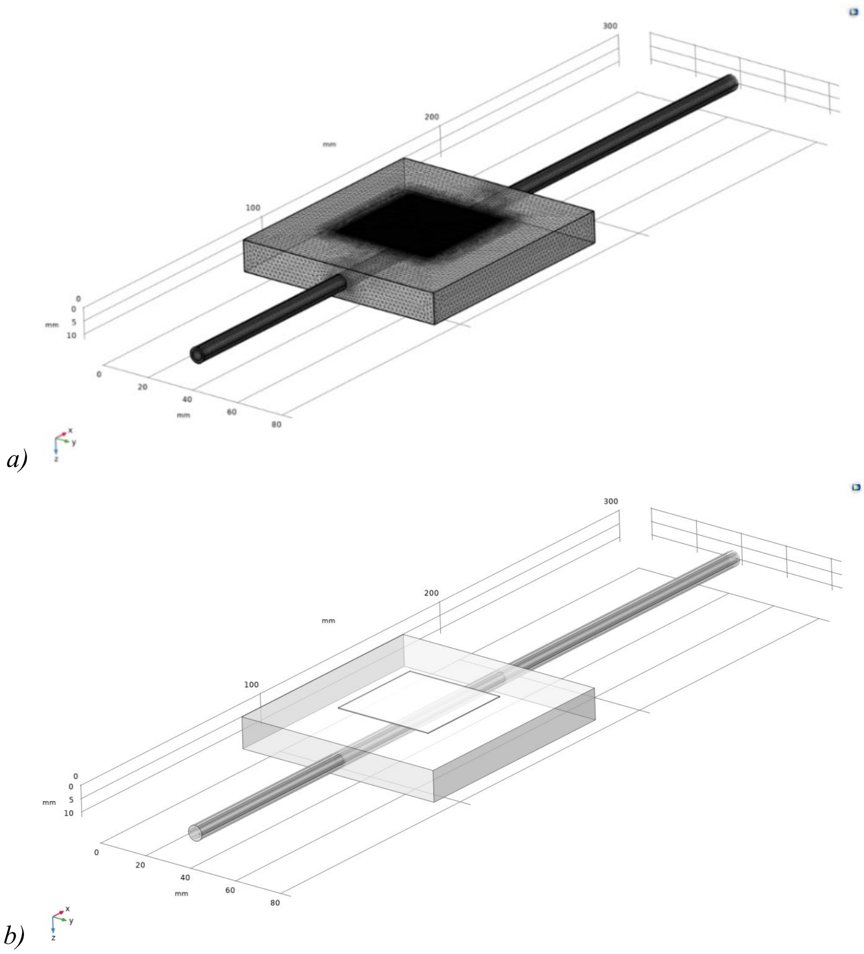

Fig. 2 a, b. Computer model of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmic surgeries.

The created computer model allows you to calculate temperature distributions in the flow of therapeutic fluid and inside the cooling unit at different parameters of fluid velocity, cooling capacity of the thermoelectric module, etc.

The boundary conditions of the computer model used correspond to the physical model shown in Fig. 1. Based on the data obtained from ophthalmologists, it is known that the fluid flow rate during surgery varies from 4 to 20 ml/min, and the length of the medical tube from the cooling unit does not exceed 0.5 m. The therapeutic fluid is a balanced salt solution BSS with almost identical rheological parameters to distilled water. With such parameters, the task was set to cool the therapeutic fluid to 15 °C.

3. Computer simulation results

The above input data were used for calculations. Fig. 3 shows a typical temperature distribution along the liquid flow and in the cooling unit. For the given case, the following input parameters were used: air temperature and incoming therapeutic liquid temperature – 25 °C, air humidity – 40 %, liquid flow rate – 4 ml/min, cooling capacity of the thermoelectric module – 8.2 W.

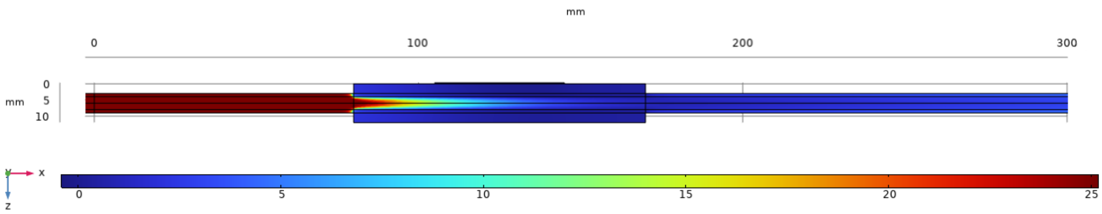

Fig. 3. Temperature distribution along the flow of the therapeutic fluid, obtained by computer simulation using the Comsol Multyphysics program.

Fig. 3 shows the results of computer simulation, including the temperature distribution in the cooling unit and the medical tube.

The computer model allows to calculate similar distributions of other values of input parameters and, if necessary, to change the geometric parameters of the device. In this way, it is possible to determine the requirements for thermoelectric modules and improve the design of the device.

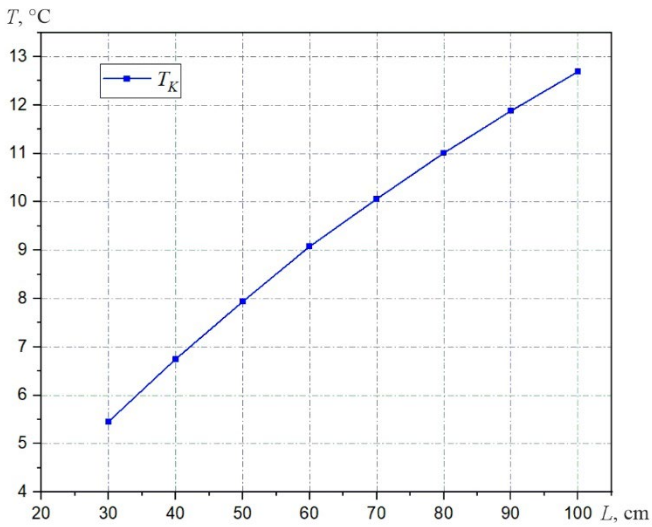

Fig. 4. Dependence of temperature on the cannula (T_K) on the length of the medical tube after the cooling unit.

Fig. 4 illustrates the dependence of the temperature of the medicinal fluid on the cannula on the distance to the cooling unit.

Fig. 5 shows how the cooling capacity of the thermoelectric module affects the depth of cooling. In this case, the cooling capacity is 8.2 W and brings the temperature of the liquid at the outlet of the cooling unit closer to the freezing point. Further increase in the cooling capacity can lead to negative consequences. It is known that the distance from the cooling unit to the cannula is 0.5 m. In this case, the minimum temperature on the cannula is achieved at 8 W of cooling capacity and is 7.6 °C. This temperature level corresponds to the conditions for surgical interventions in ophthalmology. The flow rate of the therapeutic fluid is 4 ml/min (0.067 ml/s).

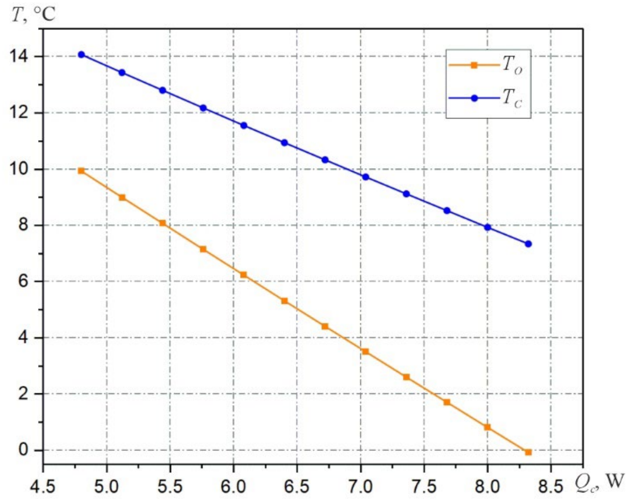

Fig. 5. Dependence of the temperature of the therapeutic fluid at the outlet of the cooling unit (T_O) and the cannula (T_C) on the cooling capacity of the thermoelectric module.

Fig. 6 illustrates the inertia of cooling the therapeutic fluid at the maximum permissible cooling capacity of the thermoelectric module. In certain cases of urgent surgical intervention, it is desirable to minimize the time for preparing the therapeutic fluid. With a given cooling capacity of the thermoelectric module, the required temperature of the medical liquid is reached in 12 minutes. To speed up the cooling process, it is possible to use a higher cooling capacity of the thermoelectric module, by equipping it with a thermostat to block possible freezing of the liquid.

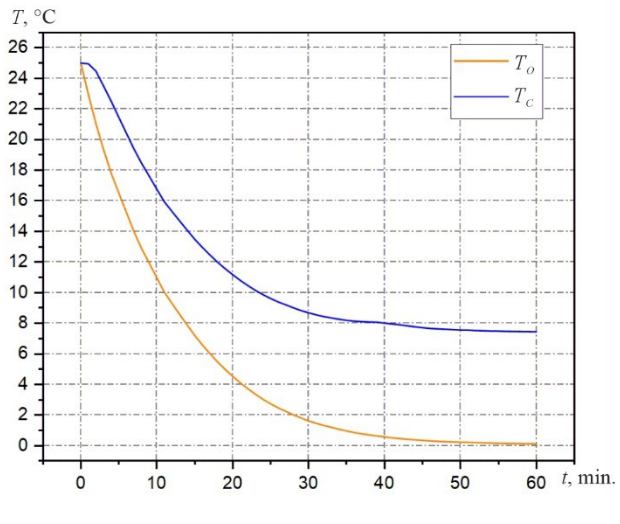

Fig. 6. Time dependence of the liquid temperature at the outlet of the unit and cannula at a cooling capacity of the thermoelectric module of 8.2 W.

Fig. 7 shows the dependence of the temperature of the therapeutic fluid on its circulation speed. From the practical needs of ophthalmologists, it follows that the therapeutic fluid can circulate at a speed in the range from 0.005 to 0.025 m/s (in flow rate this is from 4 to 20 ml/min). An increase in the circulation speed or flow rate of the therapeutic fluid leads to a decrease in the temperature difference at the outlet of the cooling unit and the cannula due to a decrease in the influence of the ambient temperature.

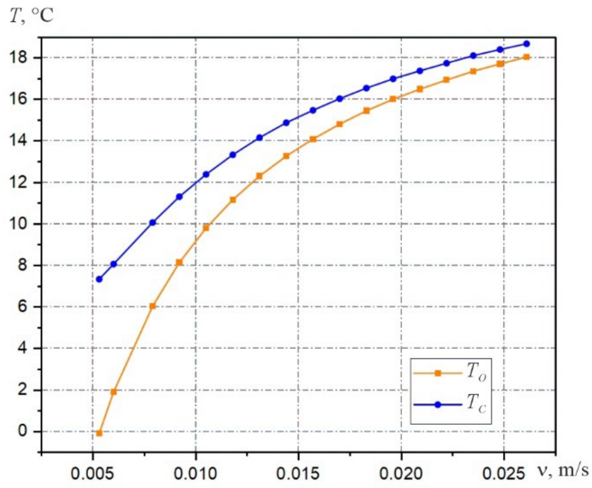

Fig. 7. Dependence of the temperature of the therapeutic fluid on its circulation speed.

The results shown show that to ensure the required cooling regimes (the temperature of the therapeutic fluid is about 15 °C at an ambient temperature of 25 °C), one thermoelectric module of the Altec-22 type is quite sufficient. With the required cooling capacity of the thermoelectric module of 8 W, about 25 W of heat is released from its hot side. The results given are the theoretical basis for further development of the optimal design of a thermoelectric device for controlling the temperature of the irrigation fluid during ophthalmic operations.

Conclusions

1. A physical, mathematical and computer model of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmological operations was constructed. Using computer simulation, the heat transfer patterns in the device and the conditions for achieving the required operating temperature conditions were determined.
2. The temperature distributions of the medical fluid and inside the cooling unit were determined depending on the cooling capacity of the thermoelectric module, the fluid circulation rate, the cooling time and the length of the medical tube.
3. It has been established that to ensure the required operating mode of the device, namely the temperature of the therapeutic fluid on the cannula is 15 °C, the required cooling capacity of the thermoelectric module should be 8 W.
4. The obtained results of computer simulation are the theoretical basis for further development of the optimal design of a thermoelectric device for controlling the temperature of irrigation fluid during ophthalmological operations.

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Кобилянський Р.Р., *канд. фіз.-мат. наук* [1,2]
Задорожний О.С., [1,3]
Уманець М.М., [3]
Пасєчнікова Н.В., [3]
Розвер Ю.Ю., [1,2]
Бабіч А.О. [1,2]

[1] Інститут термоелектрики НАН та МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2] Чернівецький національний університет імені Юрія Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна;
e-mail: anatych@gmail.com
[3] Інститут очних хвороб і тканинної терапії ім. В.П.
Філатова НАМН України, Французький бульвар 49/51,
Одеса, 65061, Україна

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ТЕРМОЕЛЕКТРИЧНОГО ПРИЛАДУ ДЛЯ КЕРУВАННЯ ТЕМПЕРАТУРОЮ ІРИГАЦІЙНОЇ РІДИНИ ПРИ ПРОВЕДЕННІ ОФТАЛЬМОЛОГІЧНИХ ОПЕРАЦІЙ

Створено фізичну, математичну та комп'ютерну моделі термоелектричного приладу для керування температурою іригаційної рідини при проведенні офтальмологічних операцій. За допомогою комп'ютерного моделювання отримано розподіли температури лікувальної рідини та всередині блоку охолодження в залежності від холодопродуктивності термоелектричного модуля, швидкості витрати лікувальної рідини та довжини медичної трубки, в якій циркулює охолоджена рідина. Наведено результати розрахунків та комп'ютерного моделювання.

Ключові слова: термоелектричне охолодження, іригаційна рідина, хірургія, офтальмологія.

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