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## Research on Heat Exchange in Biomedical Tubes for Thermoelectric Temperature Control of Irrigation Fluid Flow

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*The work investigates the problem of steady-state heat exchange in a cylindrical tube along which irrigation fluid moves under conditions of laminar hydraulically stabilized flow. An analytical solution is obtained for the temperature distribution inside the moving fluid and in the tube material. Numerical simulation of the temperature field of the fluid temperature inside the tube and in the tube body is carried out. The influence of fluid flow rate on the intensity of heat exchange in the radial direction and on mass transfer along the tube axis was investigated. The dependences of the average fluid temperature at the tube outlet on the change in fluid flow rate were established. The results of the study can be used for the design and optimization of operating modes of fluid transportation systems, in particular for the control and monitoring of the safe temperature of solutions during ophthalmic operations. The results obtained have applied significance for the operation of medical thermoelectric heating and cooling systems.*

**Keywords:** heat exchange, thermal conductivity, laminar flow, irrigation fluid, silicone tube, temperature profile, heat flow, heat transfer, heat emission.

### Introduction

Modern ophthalmological practice widely uses surgical treatment methods, including cataract surgery, vitreoretinal interventions for retinal detachment, penetrating eye injuries, and diabetic retinopathy. During such procedures, surgical instruments are inserted into the eye

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cavity, and the circulation of irrigation fluid ensures washing of the surgical field and protection of intraocular tissues.

During neither cataract nor vitreoretinal surgery, as a rule, the intraocular temperature or the temperature of the irrigation solutions is not controlled. The surgeon also has no possibility to intraoperatively regulate the temperature of the irrigation fluid and influence the thermal regime of the intraocular structures. In such conditions, the most effective means of thermostating the irrigation fluid in the operating room are thermoelectric devices.

The papers [1–3] examine the potential for using thermoelectric cooling and heating of irrigation fluid during ophthalmological procedures. The advantages of using thermoelectric devices in medical practice are demonstrated, and the need to determine optimal energy and temperature conditions for their operation is emphasized.

Heat exchange in cylindrical tubes is one of the fundamental problems of applied thermodynamics and hydrodynamics, which has numerous engineering applications - from heat exchange devices in industry to systems for transporting biological and medical irrigation fluids [4-6]. Analytical models of heat exchange in tubes were laid down in the classical works of Nusselt, where laminar and turbulent flow conditions were considered.

The study of heat exchange in thin-walled silicone tubes [7] is of particular relevance in biomedical technologies, where temperature control of medicinal irrigation solutions transported to the patient's body is important.

**The purpose of the study** is to establish the patterns of influence of the intensity of convective heat exchange on the change in the temperature profile of the flow of irrigation fluid in a restricted channel – a biomedical tube. The study is aimed at identifying the influence of the design parameters of the system under convective heat exchange conditions and the parameters of the coolant on the outlet fluid temperature  $T_{out}$ , as well as establishing the possibility of operational regulation of the outlet fluid temperature  $T_{out}$  at given values of fluid flow rate  $Q$  and inlet temperature  $T_{in}$  through the implementation of a temperature monitoring system on the tube surface and the corresponding feedback with the inlet temperature control microcontroller.

## 1. Formulation of the steady-state heat exchange problem

The paper investigates laminar hydraulically steady fluid motion in a thin tube and steady-state processes of heat exchange between the fluid, tube, and the surrounding environment.

The physical model describing the problem is shown in Fig. 1.

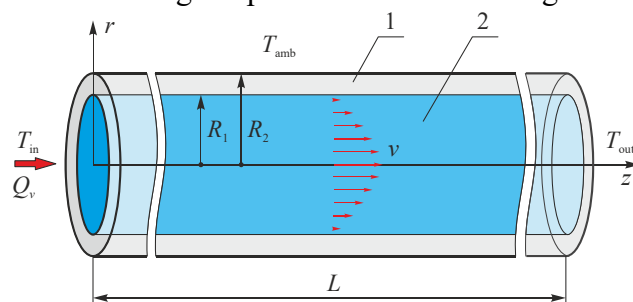


Fig. 1. Physical model of heat exchange in a thin-walled tube

Consider a cylindrical tube 1 through which fluid 2 flows. The length of the tube  $L$  is much greater than the values of its inner  $R_1$  and outer  $R_2$  radii ( $L \gg R_1, R_2$ ); the thickness of the cylindrical wall  $\delta = R_2 - R_1$ . The coordinate system is cylindrical  $(r, \phi, z)$ , the axis  $z$  coincides with the axis of the tube, where  $r \in [0, R]$ ,  $z \in [0, L]$ .

At the inlet of the tube, the fluid has a temperature  $T_{in}$  and a mass flow rate  $Q_v$ . At the outlet of the tube, the fluid acquires an average temperature  $T_{out}$ . The ambient temperature is  $T_{amb}$ .

The physical model assumes that the fluid is incompressible, its physical properties are constant; there are no internal heat sources and heat losses due to friction; axial heat conduction is neglected compared to convective heat conduction.

## 2. Analytical solution of the problem

The formulation of the described problem corresponds to the classical Nusselt solution.

In cylindrical coordinates for a steady process, the general energy balance equation (thermal conductivity + convection) for a fluid can be written as:

$$\rho_L \cdot c_p \left( v_z \frac{\partial T}{\partial z} + v_r \frac{\partial T}{\partial r} \right) = \lambda_L \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right). \quad (1)$$

where  $T = T(r, z)$  is fluid temperature,  $\rho_L$  is fluid density,  $c_p$  is fluid heat capacity,  $\lambda_L$  is fluid thermal conductivity,  $v_z$  and  $v_r$  are the axial and radial components of the fluid velocity.

With hydraulically stabilized flow:  $v_r = 0$ ,  $v_z = v_z(r)$ . Due to neglecting thermal conductivity in the axial direction  $\left( \frac{\partial^2 T}{\partial z^2} \ll v_z \frac{\partial T}{\partial z} \right)$ , the final energy balance equation will take on the form:

$$\rho_L \cdot c_p v_z(r) \frac{\partial T}{\partial z} = \lambda_L \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \right). \quad (2)$$

In the steady-state mode ( $\partial/\partial t = 0$ ), with laminar hydraulically stabilized (Reynolds number  $Re < 2300$ ) and fully steady motion, the fluid velocity has a Poiseuille profile

$$v_z(r) = 2v_{avg} \left( 1 - \frac{r^2}{R^2} \right), \quad (3)$$

where  $v_{avg}$  is maximum fluid velocity.

### **Boundary conditions:**

1. At the inlet of the tube ( $z = 0$ ):  $T(r, 0) = T_{in}$ . (4)

2. On the tube axis ( $r = 0$ ) (symmetry):  $\frac{\partial T}{\partial r} \Big|_{r=0} = 0$ . (5)

3. On the inner surface of the tube ( $r = R_1$ ), the thermal condition of the third kind is heat transfer through the tube wall at the “fluid-wall” interface:

$$-\lambda \frac{\partial T}{\partial r} \Big|_{r=R_1} = \alpha_1 (T(R_1, z) - T_{\text{tube}}(z)). \quad (6)$$

where  $\alpha_1$  is heat transfer coefficient from fluid to wall.

4. On the outer surface of the tube ( $r = R_2$ ):

$$-\lambda_{\text{tube}} \frac{\partial T_{\text{tube}}}{\partial r} \Big|_{r=R_2} = \alpha_2 [T_{\text{tube}}(R_2) - T_{\text{amb}}], \quad (7)$$

where  $\lambda_{\text{tube}}$  is the thermal conductivity of the tube,  $\alpha_2$  is the heat transfer coefficient from the outer surface of the tube to the environment.

For a laminar stabilized regime (fully developed temperature profile), we proceed to establish the mass-average flow temperature  $T_L(z)$ , which is determined by the energy balance equation

$$\rho_L \cdot c_p Q_v \frac{dT_L}{dz} = -U_l (T_L - T_{\text{amb}}), \quad (8)$$

where  $U_l$  is the linear heat transfer coefficient:

$$U_l = \frac{1}{R'_{\text{tot}}} = \frac{1}{R'_{\text{conv},1} + R'_{\text{tube}} + R'_{\text{conv},2}}, \quad (9)$$

thermal resistances:

$$R'_{\text{conv},1} = \frac{1}{2\pi R_1 \alpha_1}, \quad R'_{\text{tube}} = \frac{\ln(R_2/R_1)}{2\pi \lambda_{\text{tube}}}, \quad R'_{\text{conv},2} = \frac{1}{2\pi R_2 \alpha_2}. \quad (10)$$

Then

$$T_L(z) = T_{\text{amb}} + (T_{\text{in}} - T_{\text{amb}}) \exp\left(-\frac{U_l}{\rho_L \cdot c_p Q_v} z\right). \quad (11)$$

### **Temperature profile in the tube**

After deriving the average mass temperature of the flow, we calculate the heat flux per unit length of the tube

$$q'(z) = U_L (T_L - T_{\text{amb}}). \quad (12)$$

Then the temperature of the inner surface of the wall

$$T_{R1}(z) = T_L(z) - q'(z) R'_{\text{conv},1},$$

temperature of the outer wall surface

$$T_{R2}(z) = T_{R1}(z) - q'(z) \cdot R'_{\text{tube}}. \quad (13)$$

The temperature profile in the wall remains logarithmic:

$$T_{\text{tube}}(r, z) = T_{R1}(z) - \frac{q'(z)}{2\pi\lambda} \ln \frac{r}{R_1}. \quad (14)$$

The temperature profile in the fluid will be as follows:

$$T_L(r, z) = T_{R1}(z) + [T_{R2}(z) - T_{R1}(z)] \cdot \left(1 - \frac{r^2}{R_1^2}\right). \quad (15)$$

### 3. Calculation results

The calculations were performed according to the analytical solution (15) for the temperature profile of the fluid inside the tube, with account for the calculation of the temperature distribution in the tube wall (14). The radial distribution of the temperature of the fluid flow in the selected cross-sections of the tube and the dependence of its temperature on the coordinate  $z$  along the tube axis at different fluid flow rates  $Q_v$  were established.

The algorithm for solving the problem is implemented in **Python 3.11** using the **NumPy**, **SciPy**, and **Matplotlib** libraries.

The tube material is medical silicone, the flow of irrigation fluid is considered, and the following values of the input parameters of the problem are used:

- Tube length  $L = 2.0$  m.
- Inner tube radius  $d_1 = 0.0015$  m.
- Outer tube radius  $d_2 = 0.0025$  m.
- Silicone thermal conductivity  $\lambda_{\text{tube}} = 0.24$  W/(m·K).
- Silicone density  $\rho_{\text{tube}} = 1500$  kg/m<sup>3</sup>.
- Specific heat of silicone  $c_p = 1200$  J/(kg·K).
- Specific heat of liquid  $\lambda_L = 0.63$  W/(m·K).
- Specific heat of irrigational liquid  $c_p = 4000$  J/(kg·K).
- Inlet fluid temperature:  $T_{\text{in}} = 35^\circ\text{C}$ .
- Ambient temperature  $T_{\text{amb}} = 20^\circ\text{C}$ .
- Coefficient of heat transfer  $\alpha_1$  from fluid to wall  $\alpha_1 = 768.6$  W/(m<sup>2</sup>·K).
- Coefficient of heat transfer to environment  $\alpha_2 = 10$  W/(m<sup>2</sup>·K).

The fluid flow rates  $Q_v$  and the corresponding values of the average fluid velocities  $v_{\text{avg}}$  and Reynolds numbers for calculations are given in Table 1.

Table 1

Input fluid flow values

Fluid flow rate, ml/min	Average fluid velocity, m/s	Reynolds number
$Q_v = 0.10$	$v_{avg} = 0.0002$	$Re = 1.0$
$Q_v = 0.50$	$v_{avg} = 0.0012$	$Re = 4.9$
$Q_v = 1.00$	$v_{avg} = 0.0024$	$Re = 9.8$
$Q_v = 2.00$	$v_{avg} = 0.0047$	$Re = 19.6$
$Q_v = 5.00$	$v_{avg} = 0.0118$	$Re = 48.9$

### Radial distribution of temperature $T(r)$ in the tube

For the flow rates given in Table 1, a calculation of temperature  $T(r)$  was performed.

Fig. 2 shows the radial temperature distribution in the liquid and the body of the silicone tube for different distances  $z$  from the beginning of the tube. The calculation was performed for the fluid flow rate  $Q_v = 1.00$  ml/min Fig. 3 shows a similar temperature distribution for  $Q_v = 5.00$  ml/min.

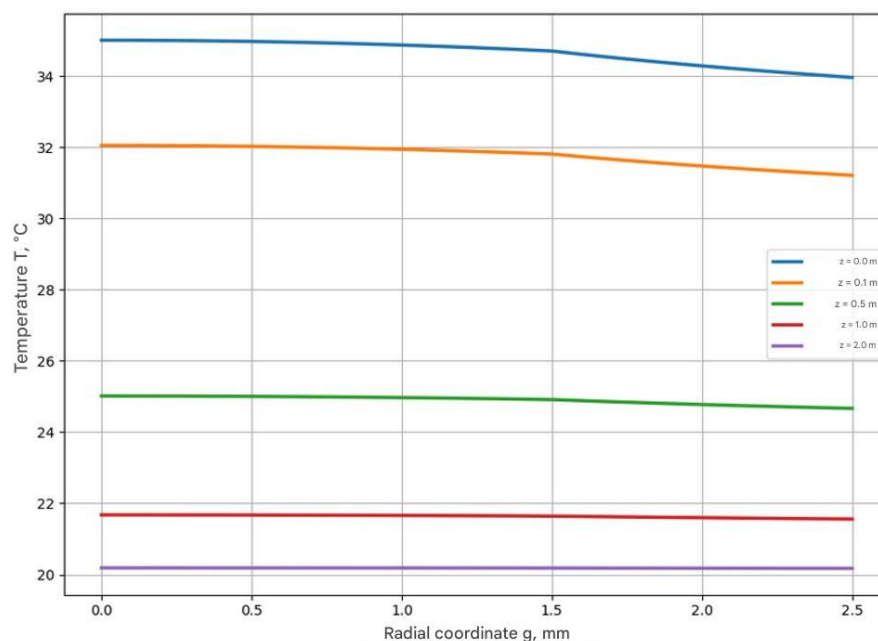


Fig. 2. Radial temperature profile  $T(r)$  in cross-sections of the tube at different  $z$  (for the flow rate  $Q_v = 1.00$  ml/min)

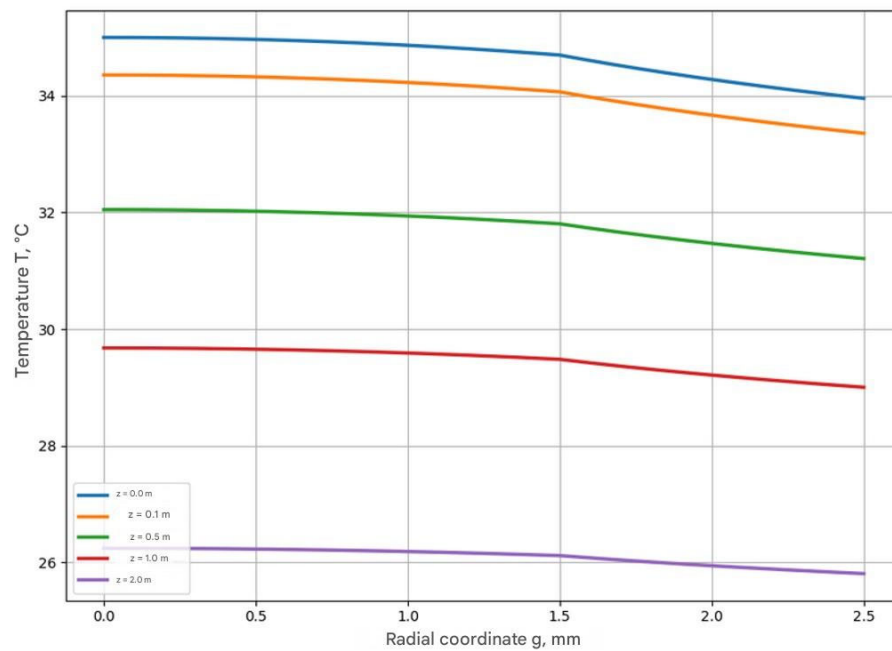


Fig. 3. Radial temperature profile  $T(r)$  in cross-sections of the tube and tube wall at different  $z$  (for the flow rate  $Q_v = 5.00$  ml/min)

At low fluid flow rates (Fig. 2), cooling occurs much more intensively, as the fluid remains inside the tube longer. For higher flow rates (Fig. 3), the temperature profile becomes more uniform, and the fluid temperature along the tube axis decreases more slowly.

As the coordinate  $z$  increases, there is a general shift of the temperature curves to lower temperature values. This confirms the gradual cooling of the fluid and the tube wall along the direction of flow.

The obtained temperature profiles demonstrate the classic logarithmic nature of the temperature distribution in the cylindrical wall. The maximum temperature is observed on the inner surface of the tube, which is in direct contact with the irrigation fluid. Towards the outer surface, the temperature decreases due to heat transfer to the environment.

#### **Temperature distribution $T_L(z)$ along the tube axis inside the fluid**

For different fluid flow rates, the dependences (11) of the mass-average temperature of the fluid flow along the tube axis were obtained.

Fig. 4 shows temperature distribution  $T_L(z)$  inside the fluid at  $r = 0$  for the flow rates given in Table 1. According to (11), temperature changes by the exponential law  $T_L(z) \sim \exp\left(-\frac{z}{Q_v}\right)$ . This is demonstrated in Fig. 4. At low fluid flow rates, we have rapid cooling along the  $z$ -axis due to significant heat exchange, and vice versa – at high fluid flow rates, heat exchange decreases, due to which the temperature decreases slowly.

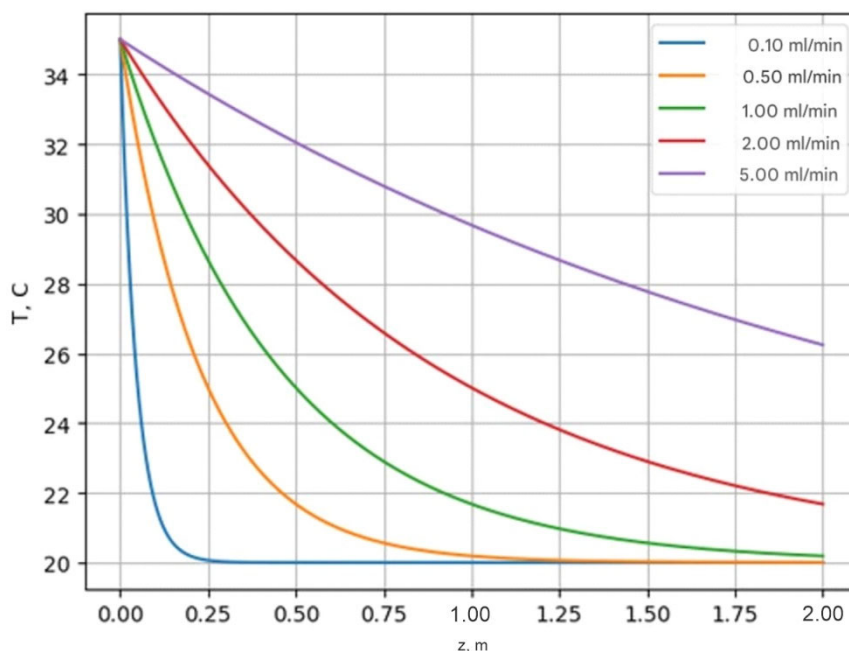


Fig. 4. Change in average fluid temperature along the tube

Based on the data of the considered regime in each specific case, we come to the physical interpretation of the obtained result. In particular, at low flow rates the liquid velocity in the tube is very low, and accordingly the liquid residence time in the tube is long. The heat has time to escape to the wall. The centre of the tube, where the velocity is maximum, cools more slowly. Near the wall, the fluid cools rapidly due to the large temperature difference. With increasing flow rate, heat transfer decreases due to the increase in the Reynolds number and mass transfer. The fluid no longer has time to cool so quickly. The temperature gradient is concentrated only in a thin near-surface layer. The relationship  $T_L(z)$  demonstrates the *competition between convection and thermal conduction*.

#### Temperature of irrigation fluid at the tube outlet

Based on the heat transfer model we adopted, the temperature of the fluid at the tube outlet ( $z = L$ ) is determined from the solution of the energy balance equation (11).

The nature of the temperature dependence at the outlet is nonlinear (exponential type). The dependence has the form:

$$T_{\text{out}} \sim \exp\left(-\frac{1}{Q_v}\right),$$

which means dramatic temperature changes at low flow rates  $Q_v$  and more stable growth at high flow rates.

The dependence of the fluid temperature at the outlet of the tube on the fluid flow rate is shown in Fig. 5.

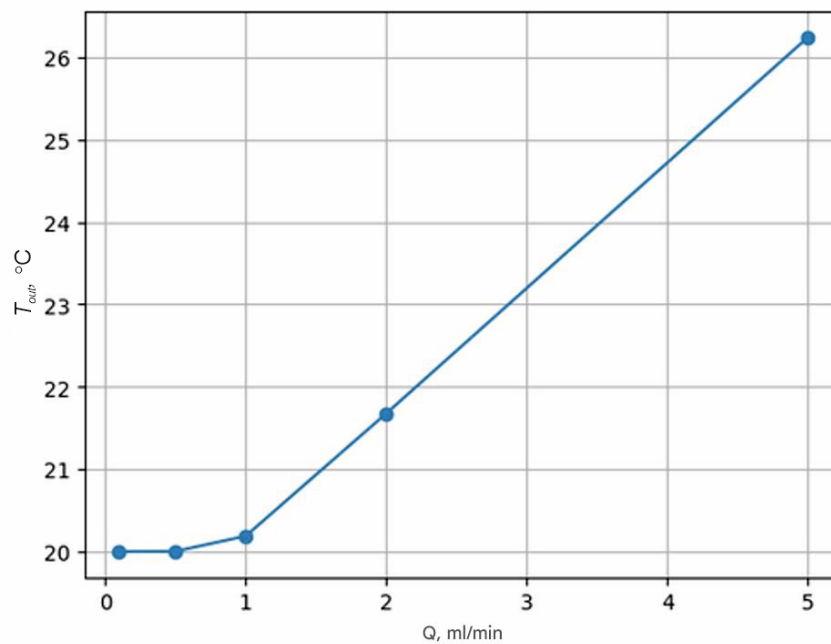


Fig. 5. The dependence of the fluid temperature at the outlet of the tube on the fluid flow rate

In the area of medium flow rates  $Q = 0.1 - 2.0$  ml/min, there is a slower decrease. For the area of high flow rates  $Q > 2$  ml/min, cooling continues to visibly decrease, but less intensively.

#### 4. Possibilities for practical implementation

The aim of the study was to substantiate the possibility of operational control of the outlet temperature  $T_{out}$  regulation through the implementation of a system for monitoring the temperature of the outer surface of the tube  $T_{R2}$ . The temperature of the tube wall at the control point can be used as an information parameter for assessing the output temperature of the fluid. A method for indirect identification of the temperature of the irrigation fluid at the outlet of the ophthalmic tube is proposed, which is based on measuring the temperature of the outer surface of the tube at a control point located at a distance  $L_0$  from the outlet edge of the tube.

Based on the analytical model of conjugate heat transfer, an unambiguous functional relationship between the outlet fluid temperature and the temperature of the outer surface of the tube has been established.

$$T_L(z) \leftrightarrow T_{R1}(z) \leftrightarrow T_{R2}(z),$$

therefore, there is an unambiguous functional relationship between  $T_{out} = T_L(L)$  and  $T_{R2}(L - L_0)$ .

Analytical relationship for the conjugate model

$$T_{out} = T_{amb} + \frac{T_{R2}(L - L_0) - T_{amb}}{A} e^{-\beta \cdot L_0}, \quad (16)$$

where  $\beta = \frac{U_l}{\rho \cdot c_p Q_v}$ ,  $A = 1 - U_l (R'_{conv,1} + R'_{cm})$ .

Equation (16) is the basis of the indirect monitoring method.

The obtained result confirms the fundamental feasibility of using the tube's outer surface temperature to indirectly determine the temperature of the irrigation fluid directly in the ophthalmic surgical area. This approach enables the implementation of contactless temperature monitoring and the creation of an automatic irrigation fluid temperature control system without installing sensors in the sterile surgical area.

Using a real-time mathematical model of heat transfer allows predicting the outlet fluid temperature depending on the flow rate, channel geometry, tube wall temperature, and temperature sensor operating mode.

## Conclusions

1. A conjugate mathematical model of steady-state heat exchange in the system “irrigation fluid – silicone tube wall – environment” has been developed, which provides a consistent description of the processes of convective heat transfer in a laminar fluid flow and thermal conductivity in the tube wall. Based on the model, analytical dependences were obtained for determining the radial temperature profiles of the fluid and the tube wall, which satisfy the conditions of continuity of temperature and heat flux on the border of environments.
2. The calculation of temperature fields for characteristic irrigation fluid flow rates in the range of 0.1–5.0 ml/min was performed. It was found that with increasing flow rate, the flow cooling intensity decreases, and temperature gradients are localized in the near-surface layers of the fluid. It was shown that the flow temperature along the tube changes according to an exponential law, which reflects the relationship between convective heat transfer and heat loss through the tube wall.
3. An analytical dependence of the outlet temperature of irrigation fluid on the flow rate was obtained and its behavior in a wide range of operating modes was investigated.
4. A method for indirect identification of the temperature of the irrigation fluid at the outlet of the ophthalmic tube by measuring the temperature of its outer surface at the control point and using a mathematical model of conjugate heat transfer is proposed. The existence of an unambiguous functional relationship between the outlet temperature of the liquid and the temperature of the outer surface of the tube was established, which confirms the possibility of implementing temperature monitoring of contactless and automatic control of the temperature of the irrigation fluid without installing sensors in the sterile zone of ophthalmological intervention.

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### **Дослідження теплообміну в біомедичних трубках для термоелектричного контролю температури потoku іригаційної рідини**

*У роботі досліджено задачу стаціонарного теплообміну в циліндричній трубці, вздовж якої рухається іригаційна рідина в умовах ламінарного гідравлічно стабілізованого потоку. Отримано аналітичний розв'язок для розподілу температури всередині рухомої рідини та в матеріалі трубки. Проведено чисельне моделювання температурного поля температури рідини всередині трубки та в тілі трубки. Досліджено вплив витрати рідини на інтенсивність теплообміну в радіальному напрямку та на масоперенос вздовж осі трубки. Встановлено залежності середньої температури рідини на виході з трубки від зміни витрати рідини. Результати дослідження можуть бути використані для проектування та оптимізації режимів роботи систем транспортування рідин, зокрема для керування та контролю безпечної температури розчинів при проведенні офтальмологічних операцій. Отримані результати мають прикладне значення для роботи медичних термоелектричних систем нагріву та охолодження.*

**Ключові слова:** теплообмін, теплопровідність, ламінарний потік, іригаційна рідина, силіконова трубка, температурний профіль, тепловий потік, теплоперенос, тепловіддача.