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DESIGN OF A MULTI-STAGE THERMOELECTRIC COOLER FOR A HUMAN HEART ABLATION DEVICE

The paper presents an analysis of the requirements for a human heart ablation device. Optimal control theory methods were used to design cascade thermoelectric coolers (TEC) and calculate their characteristics. A special iterative algorithm was developed to design and calculate the characteristics of a cascade TEC. The design of the structure and calculation of the parameters of a multi-stage thermoelectric cooler for a human heart ablation device were performed. Bibl. 13, Figs. 1, Tables 2.

Key words: cryoablation, multi-stage thermoelectric cooler, thermoelectric cooling.

Introduction

Cardiac arrhythmia is a common pathology of the human cardiovascular system, which significantly affects the quality of life and can cause serious complications, including heart failure and even stroke [1]. An effective method of treating arrhythmia is cryoablation, which destroys pathological electrical pathways in the myocardium using low temperatures [2].

The effectiveness and safety of cryoablation procedures depend largely on the efficiency of the cooler, which requires the development of highly efficient thermoelectric systems to maintain optimal temperature regimes [3, 4].

Single-stage thermoelectric coolers are an optimal solution for use in cryoablation devices due to their compactness, absence of moving parts, and ability to quickly regulate temperature [5]. However, single-stage thermoelectric modules often do not provide the necessary temperature difference and cooling power required to achieve the consistently low temperatures typical for cryoablation procedures [6].

Therefore, *the purpose of this work* is to design a multi-stage thermoelectric cooler for a human heart ablation device.

1. Requirements for human heart ablation device

The effectiveness of cardiac cryoablation largely depends on the ability of the device to provide stable temperature conditions and quickly achieve the required temperatures [1].

To effectively destroy pathological foci in cardiac tissue, the device must provide a temperature in the contact zone in the range of –50 to –70°C [7]. The accuracy of temperature regulation must be within ±2°C to ensure the stability of the procedure and minimize the risk of damage to nearby biological tissues [3].

The device must have sufficient cooling capacity to compensate for the heat input from the circulation and metabolic processes in the cardiac tissue. It is estimated that the minimum cooling power is 5–10 W in the working area, depending on the size of the device and the duration of the procedure [8].

To adapt to dynamic conditions in the heart, such as changes in blood flow or contact with biological tissue, the device must reach the required temperature within 5–10 seconds after activation. This requires high heat transfer efficiency in a multi-stage system [9].

2. Methodology for designing the structure and calculating the parameters of a thermoelectric cooler

Optimal control theory methods are used to design cascade thermoelectric coolers (TECs) and calculate their characteristics [10–12]. These methods allow for the most accurate optimization of the thermoelectric module design, taking into account the temperature dependence of the parameters of thermoelectric materials and the influence of electrical and thermal losses in the module.

The main initial data for designing a TEC are the cooling temperature T_c of the medical instrument for ablation, the rational number of cascades N of the module, the temperature of the cooler base T_h and the cooling capacity of the TEC Q_0, equal to the power of the thermal load on the working surface of the medical instrument. The temperature dependences of the properties of thermoelectric materials of the n- and p-legs of thermoelements must also be specified, namely the Seebeck coefficient $\alpha_{n,p}(T)$, electrical conductivity $\sigma_{n,p}(T)$, thermal conductivity $\kappa_{n,p}(T)$, specific values of contact resistance r_c, electrical and thermal resistance of connecting and isolating plates and their thickness. The length of thermoelement legs L and the electric current I for TEC supply are also fixed. The main requirement is that the TEC design meets the condition of the maximum coefficient of performance:

$$\varepsilon = Q_0 / W , \qquad (1)$$

where W is the power consumed by the cooler in operating mode. This will ensure cooling of the working tool for ablation with minimal electricity consumption.

According to optimal control methods [10], the efficiency of a cascade thermoelectric module is estimated by the functional:

$$J = \sum_{k=1}^{N} (\ln q_1^k - \ln q_0^k) \ , \qquad (2)$$

the minimum of which corresponds to the maximum value of the coefficient of performance (1). In this expression, the specific densities of heat flows, which are respectively absorbed and released on the surfaces of the k-th cascade, are determined as follows:

$$q_0^k = \frac{Q_0^k}{n_k I}, \quad q_1^k = \frac{Q_1^k}{n_k I}, \qquad (3)$$

where Q_0^k, Q_1^k are thermal powers on the heat-absorbing and heat-releasing surfaces of the k-th cascade, which contains n_k thermocouple elements. To calculate flows q_0^k, q_1^k in a one-dimensional approximation, a system of equations of non-equilibrium thermodynamics [10] is used, which for n- and p-legs of thermocouples of the k-th cascade has the form:

$$\left.\begin{aligned} \frac{dT}{dx} &= -\frac{\alpha j_k}{\kappa} T - \frac{j_k}{\kappa} q, \\ \frac{dq}{dx} &= \frac{\alpha^2 j_k}{\kappa} T + \frac{\alpha j_k}{\kappa} q + \frac{j_k}{\sigma}, \end{aligned}\right\}_{n,p} \quad k = 1,\dots,N , \qquad (4)$$

where $x = x/L$, $0 \le x \le L$ is a dimensionless coordinate directed in each cascade from the hot junctions of the thermocouples to the cold ones, $\left(j_k\right)_{n,p} = IL/\left(s_k\right)_{n,p}$ is a specific current density vector, s is cross-section of thermoelectric legs, N is the number of cascades, which are numbered starting from the hot cascade to the cold one. System (4) is solved under the boundary conditions:

$$\begin{gathered} T_{nk}(0) = T_{pk}(0) \equiv T_k(0), \quad T_{nk}(1) = T_{pk}(1) \equiv T_k(1), \quad k = 1,...,N \\ T_1(0) = T_h + \delta T_0, \; T_N(1) = T_c - \delta T_N, \; T_k(0) = T_{k-1}(1) + \delta T_{k-1}, \quad k = 2,...,N, \end{gathered} \tag{5}$$

where temperature differences δT take into account heat losses in the connecting and insulating plates and are calculated in a one-dimensional approximation as follows:

$$\begin{gathered} \delta T_0 = -\frac{q_1^1}{\left(L/(j_1)_n + L/(j_1)_p\right)}\left(\frac{R_{ins} l_{ins}}{K_{ins}} + \frac{R_{con} l_{con}}{K_{con}}\right), \\ \delta T_k = -\frac{q_0^k}{\left(L/(j_k)_n + L/(j_k)_p\right)}\left(\frac{R_{ins} l_{ins}}{K_{ins}} + \frac{R_{con} l_{con}}{K_{con}}\right), \; k = 1,....N, \end{gathered} \tag{6}$$

where R_{ins}, R_{con}, l_{ins}, l_{con}, $K_{ins\,k} = s_{ins\,k}/n_k(s_n + s_p)$, $K_{con} = s_{con}/(s_n + s_p)$, are the specific thermal resistance, thickness and fill factor of the insulating and connecting plates, respectively.

The solution of the boundary value problem (4)-(5) makes it possible to calculate the specific heat flows q_0^k, q_1^k according to the following relations:

$$q_{0\,k} = \sum_{n,p}\left[q_k(1) + j_k \frac{r_c}{L}\right]_{n,p} + q_{con}, \quad q_{1k} = \sum_{n,p}\left[q_k(0) - j_k \frac{r_c}{L}\right]_{n,p} - q_{con}, \tag{7}$$

де $q_{con} = \dfrac{2 r_{con} I}{l_{con}}\left(K_{con} - \dfrac{2}{3}\right)$ [10]. Formulae (7) take into account the release of the Joule heat as a result of the resistances of contacts r_c and connecting plates r_{com}.

Heat flows q_0^k, q_1^k depend on the specific electric current density $\left(j_k\right)_{n,p}$ and on the inter-cascade temperatures T_k. According to the theory of optimal control, the following conditions must be met for the minimum of the functional J:

- the specific electric current density in the thermoelectric legs of each cascade must satisfy the equation:

$$-\frac{\partial J}{\partial (j_k)_{n,p}} + \int_0^1 \frac{\partial H^k(\psi, T, q, (j_k)_{n,p})}{\partial (j_k)_{n,p}} dx = 0, \tag{8}$$

where $H^k = \sum_{n,p}(\psi_1 f_1^k + \psi_2 f_2^k)_{n,p}$ is the Hamiltonian function, $(f_1^k, f_2^k)_{n,p}$ are right-hand parts of equations (4), $(\psi_1, \psi_2)_{(k)n,p}$ is an auxiliary vector-function;

- inter-cascade temperatures T_k must satisfy the system of equations:

$$\sum_{n,p}\psi_{1(k+1)_{n,p}}(0) = \sum_{n,p}\psi_{1(k)_{n,p}}(1), \quad k = 1, ..., N-1, \tag{9}$$

According to optimal control theory, the auxiliary vector function $(\psi_1, \psi_2)_{(k)n,p}$ is determined by solving the auxiliary system of differential equations in the form

$$\left.\begin{aligned} \frac{d\psi_{1k}}{dx} &= \frac{\alpha j_k}{\kappa} R_{1k}\psi_{1k} - \frac{\alpha^2 j_k}{\kappa} R_{2k}\psi_{2k}, \\ \frac{d\psi_{2k}}{dx} &= \frac{j_k}{\kappa}\psi_{1k} - \frac{\alpha j_k}{\kappa}\psi_{2k}, \end{aligned}\right\}_{n,p} \quad k = 1,...,N, \tag{10}$$

where $R_{1k}=1+\frac{d\ln\alpha}{dT}T-\frac{d\ln\kappa}{dT}\left(T+\frac{q}{\alpha}\right)$, $R_{2k}=R_{1k}-\frac{1}{Z}\frac{d\ln\sigma}{dT}+\frac{d\ln\kappa}{dT}\left(T+\frac{q}{\alpha}\right)$, $Z=\frac{\alpha^2\sigma}{\kappa}$, with the following boundary conditions:

$$\psi_{2(k)_{n,p}}(0)=\frac{1}{q_{1k}},\ \psi_{2(k)_{n,p}}(1)=\frac{1}{q_{0k}}. \quad (11)$$

The results of solving such an optimization problem are the optimal values of the specific electric current density in the thermoelectric legs $(j_k)_{n,p}$ and the inter-cascade temperatures T_k, which provide the maximum coefficient of performance $\varepsilon_{\max}=1/(\exp(J)-1)$. After solving the optimization problem, the optimal design parameters of the TEC are calculated as follows:

- the cross-sectional area of the thermoelement legs in the *k*-th cascade is determined by the formula $(s_k)_{n,p}=I/(j_k)_{n,p}$;
- the number of thermocouples in the stages is calculated using the expressions $n_N=-Q_0/q_0^N I$, $n_k=n_{k+1}q_1^{k+1}/q_0^k$, $k=1,...,N-1$.

It should be noted that usually the calculated optimal cross-sections of the n- and p-legs in each cascade do not differ significantly from each other, therefore, for the actual design of the TEC, the average value of the cross-section of the legs *s* is selected.

The optimal electric power $W=Q_0/\varepsilon_{\max}$ consumed by the module in the operating mode and the operating voltage $U=W/I$ on the module are also determined. Often, for designing a module, instead of the electric current *I* through the module, the operating voltage U_z s specified. Then, first, the maximum coefficient of performance $\varepsilon_{\max}$ and power *W* are calculated for an arbitrary rational value of the electric current I_d. Considering that $\varepsilon_{\max}$ and *W* are practically independent of the electric current in the legs, the current that provides the required specified operating voltage U_z on the module is determined, and the optimal design of the module is calculated for this current.

It is obvious that the formulated optimization problem of designing a cascade module can be solved only by numerical methods using computer tools.

3. Algorithm for computer-aided design of a thermoelectric cooler

For the design and calculation of the characteristics of a cascade TEC, a special iterative algorithm has been developed, which is as follows.

1. First, the initial distribution of inter-cascade temperatures $T_k^{(0)}$, temperature differences $\delta T^{(0)}$ and some initial approximations of the electric current density in the legs of thermoelements $(j_k)_{n,p}^{(0)}$ are specified.

2. The main boundary value problem (4)–(5) is solved using the finite element method. The initial temperature and heat flux distributions $T_{k\,n,p}^{(0)}(x)$, $q_{k\,n,p}^{(0)}(x)$ for all cascades are found. Heat flows q_0^k, q_1^k are calculated using formulae (7) and the value of the functional $J^{(0)}$ (2) is determined.

3. The obtained data are used to integrate the linear system of auxiliary equations (10) with the boundary conditions (11). We obtain the functions $\Psi_{1(k)n,p}(x)$, $\Psi_{2(k)n,p}(x)$.

4. The nonlinear system (9) is solved using the Newton iteration method to find new values of inter-cascade temperatures $T_k^{(1)}$, and at each iteration step, equations (8) are solved and new values of the electric

current density $\left(j_k\right)_{n,p}^{(1)}$ are determined. The new values of $\delta T^{(1)}$ are calculated using formulae (6).

Steps 2–4 are repeated with new parameters $T_k^{(1)}$, $\delta T^{(1)}$, $\left(j_k\right)_{n,p}^{(1)}$, and iterations continue until the difference in the values of the functional J becomes less than the specified error.

As a result, we obtain all the optimal parameters $T_k^{(\mathrm{opt})}$, $\delta T^{(\mathrm{opt})}$, $\left(j_k\right)_{n,p}^{(\mathrm{opt})}$ and the corresponding optimal functions $T_{k\,n,p}^{(\mathrm{opt})}(x)$, $q_{k\,n,p}^{(\mathrm{opt})}(x)$ corresponding to the minimum of the functional $J_{\min}$. After that, the maximum coefficient of performance, the design of the TEC and the power consumed by it in the operating mode are calculated.

This algorithm was implemented in the MATLAB computer system.

4. Results of the design of a thermoelectric cooler for cardiac ablation and calculation of its characteristics

The proposed method was used to design a thermoelectric module structure from Bi_2Te_3-based thermoelectric materials for cooling a medical working tool used in a human heart ablation device.

Initial data for calculating TEC design are presented in Table 1.

Table 1

Initial data for calculating a cascade TEC for a medical instrument

Parameter		Units	Value
TEC base temperature	T_h	K	303
Cooling temperature	T_c	K	213
Cooling capacity	Q_0	W	0.3
Height of thermoelement legs	L	cm	0.14
Supply voltage	U	V	6
Contact resistance	r_c	Ohm·cm^2	$5\cdot10^{-6}$
Copper connection:			
thickness	l_{con}	cm	0.02
fill factor	K_{con},	–	1.25
Al_2O_3 insulating plates:			
thickness	l_{ins}	cm	0.063
fill factor	K_{ins}	–	2.25
thermal resistance	R_{ins}	cm·K/W	4

The experimental temperature dependences of thermoelectric parameters of materials based on Bi_2Te_3, given in [13], were used, which were approximated by polynomials and used for TEC calculations.

The designs of two models of cooling modules were calculated, namely a 3-stage module and a 4-stage option. The design results of these two models of thermoelectric modules are given in Table 2.

Table 2

Design and calculated parameters of two models of thermoelectric modules

Parameters	3-stage module	4-stage module
Crystal dimensions, mm	0.8×0.8×1.4	0.88×0.88×1.4
Distance between crystals, mm	0.5	0.5
Number of thermocouples in stages: lower (hot) stage middle stages upper (cold) stage	 $n_1 = 64$ $n_2 = 28$ $n_3 = 12$	 $n_1 = 70$ $n_2 = 38$, $n_3 = 21$ $n_4 = 11$
Stage dimensions, mm^2: lower (hot) stage middle stages upper (cold) stage	 $s_1 = 15×15$ $s_2 = 10×10$ $s_3 = 6×6$	 $s_1 = 17×17$ $s_2 = 12×12$, $s_3 = 9×9$ $s_4 = 7×7$
Parameters in operating mode: electric supply current I, A voltage U, V power W, W coefficient of performance ε_{max}	 1.1 6 6.6 0.046	 1.0 6 6.0 0.05
Calculated maximum module parameters at a temperature of $T_h = 303$ K: maximum temperature difference ΔT_{max}, maximum cooling capacity Q_{max}, W maximum current I_{max}, A maximum voltage U_{max}, V	 110 2.0 1.5 7.7	 114 1.92 1.5 8.4
Module resistance R, Ohm	4.9	5.4

The calculated characteristics of 3-stage and 4-stage modules are shown in Fig. 1.

Comparison of the results of calculating the operating parameters and characteristics of these two models of thermoelectric modules for cooling a medical instrument for ablation shows that the operating parameters and general characteristics of the 4-stage TEC are not significantly better compared to the 3-stage TEC. Therefore, the optimal option is the 3-stage TEC version. Note that the thermoelectric module must be placed in a hermetically sealed case evacuated or filled with a rarefied inert gas (argon, xenon).

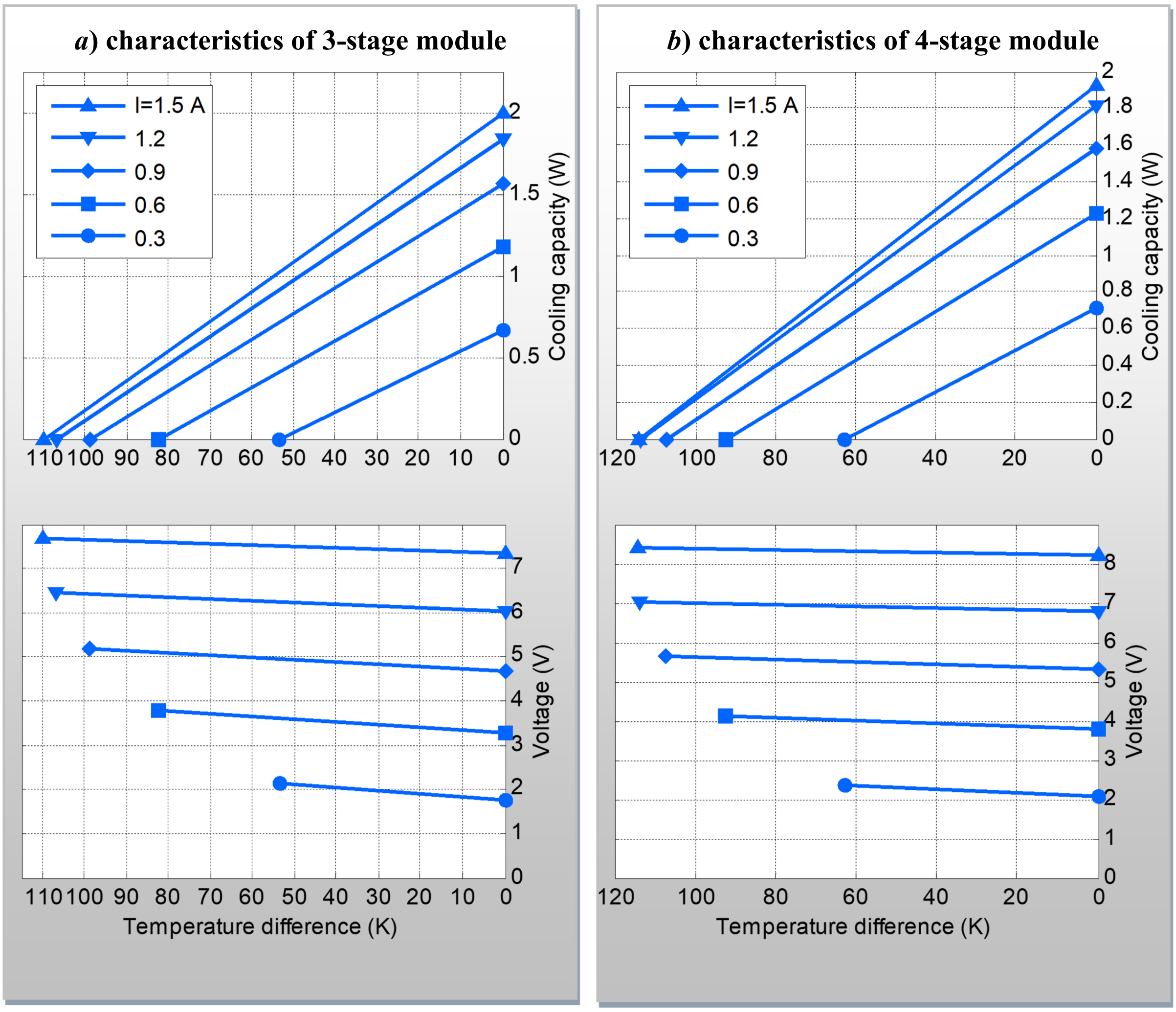

Fig.1. Characteristics of thermoelectric modules for medical working instrument of human heart ablation device: a) 3-stage module, b) 4-stage module

The main problem that will arise in the development and construction of an ablation device will be the connection of the TEC with the medical working tool. But this issue will be the subject of further research.

Conclusions

1. A methodology for designing the structure and calculating the parameters of a thermoelectric cooler has been developed based on the methods of optimal control theory.

2. A special iterative algorithm was developed for computer-aided design and calculation of the characteristics of a multi-stage thermoelectric cooler, which was implemented in the MATLAB computer system.

3. The design of two models of thermoelectric coolers for the working medical instrument of the ablation device on the human heart has been completed, in particular, a 3-stage and a 4-stage option. It has been established that the operating parameters and general characteristics of the 4-stage TEC are not significantly better compared to the 3-stage, therefore the optimal option is the 3-stage version of the TEC.

References

1. Calkins, H., Hindricks, G., Cappato, R., et al. (2017). HRS/EHRA/ECAS/APHRS/SOLAECE expert consensus statement on catheter and surgical ablation of atrial fibrillation. *Heart Rhythm*, 14(10), e275–e444.
2. Natale, A., Reddy, V.Y., Monir, G., et al. (2014). Paroxysmal AF catheter ablation with a contact force sensing catheter: results of the prospective, multicenter SMART-AF trial. *Journal of the American College of Cardiology*, 64(7), 647–656.
3. Dubuc, M., Guerra, P.G. (2018). Cryoablation for the treatment of cardiac arrhythmias: current status and future perspectives. *Canadian Journal of Cardiology*, 34(10), 1288–1295.
4. Anatychuk, L.I., Kobylianskyi, R.R., Fedoriv, R.V., Konstantynovych, I.A. (2023). On the prospects of using thermoelectric cooling for the treatment of cardiac arrhythmia. *Journal of Thermoelectricity*, 2, 5–17.
5. Rowe, D.M. (2006). *Thermoelectric Handbook: Macro to Nano*. CRC Press, 1008 p.
6. Goldsmid, H.J. (2016). *Introduction to Thermoelectricity*. Springer, 278 p.
7. Packer, D.L., Kowal, R.C., Wheelan, K.R., et al. (2013). Cryoballoon ablation of pulmonary veins for paroxysmal atrial fibrillation: first results of the North American Arctic Front (STOP AF) pivotal trial. *Journal of the American College of Cardiology*, 61(14), 1713–1723.
8. Khairy, P., Dubuc, M. (2008). Transcatheter cryoablation: biophysical principles and clinical applications. *Pacing and Clinical Electrophysiology*, 31(5), 641–652.
9. Bell, L.E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. *Science*, 321(5895), 1457–1461.
10. Anatychuk, L.I., Vikhor, L.N. (2012). *Thermoelectricity. Volume IV. Functionally graded thermoelectric materials*. Institute of Thermoelectricity, Kyiv, Chernivtsi.
11. Anatychuk, L.I., Vikhor, L.M., Kotsur, M.P., Kobylianskyi, R.R., Kadeniuk, T.Ya. (2016). Optimal control of time dependence of cooling temperature in thermoelectric devices. *Journal of Thermoelectricity*, 5, 5–11.
12. Anatychuk, L., Vikhor, L., Kotsur, M., Kobylianskyi, R., Kadeniuk, T. (2018). Optimal control of time dependence of temperature in thermoelectric devices for medical purposes. *International Journal of Thermophysics*, 39, 108. https://doi.org/10.1007/s10765-018-2430-z
13. Vikhor, L., Kotsur, M. (2003). Evaluation of efficiency for miniscale thermoelectric converter under the influence of electrical and thermal resistance of contacts. *Energies*, 16, 4082.

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ПРОЄКТУВАННЯ БАГАТОКАСКАДНОГО ТЕРМОЕЛЕКТРИЧНОГО ОХОЛОДЖУВАЧА ДЛЯ ПРИЛАДУ АБЛЯЦІЇ СЕРЦЯ ЛЮДИНИ

У роботі наведено аналіз вимог до приладу для абляції серця людини. Для проектування каскадних термоелектричних охолоджувачів (ТЕО) і розрахунку їх характеристик використано методи теорії оптимального керування. Для проєктування та розрахунку характеристик каскадного ТЕО розроблено спеціальний ітераційний алгоритм. Виконано проєктування конструкції та розрахунок параметрів багатокаскадного термоелектричного охолоджувача для приладу абляції серця людини. Бібл. 13, рис. 1, табл. 2.

Ключові слова: кріоабляція, багатокаскадний термоелектричний охолоджувач, термоелектричне охолодження

Література

1. Calkins, H., Hindricks, G., Cappato, R., et al. (2017). HRS/EHRA/ECAS/APHRS/SOLAECE expert consensus statement on catheter and surgical ablation of atrial fibrillation. *Heart Rhythm*, 14(10), e275–e444.
2. Natale, A., Reddy, V.Y., Monir, G., et al. (2014). Paroxysmal AF catheter ablation with a contact force sensing catheter: results of the prospective, multicenter SMART-AF trial. *Journal of the American College of Cardiology*, 64(7), 647–656.
3. Dubuc, M., Guerra, P.G. (2018). Cryoablation for the treatment of cardiac arrhythmias: current status and future perspectives. *Canadian Journal of Cardiology*, 34(10), 1288–1295.
4. Anatychuk, L.I., Kobylianskyi, R.R., Fedoriv, R.V., Konstantynovych, I.A. (2023). On the prospects of using thermoelectric cooling for the treatment of cardiac arrhythmia. *Journal of Thermoelectricity*, 2, 5–17.
5. Rowe, D.M. (2006). *Thermoelectric Handbook: Macro to Nano*. CRC Press, 1008 p.
6. Goldsmid, H.J. (2016). *Introduction to Thermoelectricity*. Springer, 278 p.
7. Packer, D.L., Kowal, R.C., Wheelan, K.R., et al. (2013). Cryoballoon ablation of pulmonary veins for paroxysmal atrial fibrillation: first results of the North American Arctic Front (STOP AF) pivotal trial. *Journal of the American College of Cardiology*, 61(14), 1713–1723.
8. Khairy, P., Dubuc, M. (2008). Transcatheter cryoablation: biophysical principles and clinical applications. *Pacing and Clinical Electrophysiology*, 31(5), 641–652.
9. Bell, L.E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. *Science*, 321(5895), 1457–1461.
10. Anatychuk, L.I., Vikhor, L.N. (2012). *Thermoelectricity. Volume IV. Functionally graded thermoelectric materials*. Institute of Thermoelectricity, Kyiv, Chernivtsi.
11. Anatychuk, L.I., Vikhor, L.M., Kotsur, M.P., Kobylianskyi, R.R., Kadeniuk, T.Ya. (2016). Optimal control of time dependence of cooling temperature in thermoelectric devices. *Journal of Thermoelectricity*, 5, 5–11.
12. Anatychuk, L., Vikhor, L., Kotsur, M., Kobylianskyi, R., Kadeniuk, T. (2018). Optimal control of time dependence of temperature in thermoelectric devices for medical purposes. *International Journal of Thermophysics*, 39, 108. https://doi.org/10.1007/s10765-018-2430-z
13. Vikhor, L., Kotsur, M. (2003). Evaluation of efficiency for miniscale thermoelectric converter under the influence of electrical and thermal resistance of contacts. *Energies*, 16, 4082.

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