DOI: 10.15276/hait.04.2020.5
UDC 004.621.39

THERMAL CONTROL OF THERMOELECTRIC COOLING DEVICES OF TRANSMISSION AND RECEIVING ELEMENTS OF ON-BOARD INFORMATION SYSTEMS

Vladimir P. Zaykov[1)]
ORCID: http://orcid.org/0000-0002-4078-3519, gradan@i.ua
Vladimir I. Mescheryakov[2)]
ORCID: http://orcid.org/0000-0003-0499-827X, gradan@ua.fm
Yurii I. Zhuravlov[3)]
ORCID: http://orcid.org/0000-0001-7342-1031, ivanovich1zh@gmail.com

[1)] Institute "STORM", 27, Geroev Krut St., Odessa, 65076, Ukraine
[2)] Odessa State Environmental University, 15, Lvivska St, Odessa, 65016, Ukraine
[3)] National University "Odessa Maritime Academy", 8, Didrikhsona St., Odessa, 65029, Ukraine

ABSTRACT

The work is a continuation of studies of the dynamic characteristics of thermoelectric coolers aimed at analyzing the influence of temperature differences, current operating modes, design parameters of the device and physical parameters of the material of thermoelements for a time constant. The article analyzes the effect of the heat sink capacity of the radiator on the dynamic characteristics, energy and reliability indicators of a single-stage thermoelectric cooler. A dynamic model of a thermoelectric cooler has been developed taking into account the weight and size parameters of the radiator, which relate the main energy indicators of the cooler with the heat removal capacity of the radiator, operating currents, the value of the heat load and the relative temperature difference. The analysis of the dynamic model shows that with an increase in the heat-removing capacity of the radiator at a given thermal load and various current modes, the main parameters of the cooler change. The required number of thermoelements, power consumption, time to reach a stationary mode, and relative failure rate are reduced. With an increase in the relative operating current, the time to reach the stationary mode of operation decreases for different values of the heat sink capacity of the radiator. It is shown that the minimum time to reach the stationary operating mode is provided in the maximum refrigerating capacity mode. The studies were carried out at different values of the heat sink capacity of the radiator in the operating range of temperature drops and the geometry of thermoelements. The possibility of minimizing the heat-dissipating surface of the radiator at various current operating modes and the relationship with the main parameters, reliability indicators and the time to reach the stationary operating mode are shown. Comparative analysis of weight and size characteristics, main parameters, reliability indicators and dynamics of functioning with rational design makes it possible to choose compromise solutions, taking into account the weight of each of the limiting factors.

Keywords: thermoelectric cooler; dynamic characteristics; heat dissipation capacity; reliability indicators

***For citation*: Zaykov V. P., Mescheryakov V. I., Zhuravlov Yu. I. Thermal Control of Thermoelectric Cooling Devices of Transmission and Receiving Elements of On-Board Information Systems. *Herald of Advanced Information Technology.* 2020;Vol.3, No.4: 263–278.**
DOI: 10.15276/hait.04.2020.5

INTRODUCTION

The defining requirements for the systems for ensuring the thermal modes of the transmitting and receiving elements of onboard information systems are reliability indicators and dynamic characteristics.The presence of a heat sink radiator significantly affects the mass and dimensional characteristics of the thermoelectric cooling device (TEC). With natural convective heat exchange of the radiator with the environment, the mass and dimensions of the this radiator often significantly prevail over the mass and dimensions of the TEC. In addition, with a decrease in the heat dissipation capacity of the radiator (αF), the cooling coefficient E decreases. At the same time the following parameters increase: the value of the operating current I, the time to reach the stationary operating mode τ, the relative value of the failure rate λ/λ_0, and, consequently, the probability of failure-free operation P of the entire device decreases. Due to the improvement of the technology for the manufacture of TEC, it was possible to reduce their size and mass per unit of cooling capacity. This has led to an increase in the density of heat flows on the heat-generating surface of the TEC and the question of minimizing the heat-removing surface of the radiator, especially in the case of natural convection, arises more acutely [1]. The working range of variation of the heat sink capacity is within $\infty > \alpha F \geq \alpha F_{\min}$. Therefore, during the rational design of the TEC one should inextricably connect it with the characteristics of the heat sink radiator.

1. ANALYSIS OF LITERARY DATA AND PROBLEM SETTING

Systems for ensuring thermal modes of radio electronic equipment are their integral part, since the functioning of heat-loaded elements is impossible without removing excess heat [2].

The variety of design versions of the equipment, the released density of thermal energy, the dynamic characteristics of heat flows and requirements for reliability exclude the creation of universal means of ensuring thermal modes [3]. Thermoelectric coolers are most commonly used for heat-loaded elements with impulse heat generation or absorption. Their main advantages are small dimensions, high reliability and speed performance in comparison with compression devices [4-11]. From the point of view of reliability theory, the heat-loaded element and thermoelectric cooler are connected in series. Therefore, the requirements for coolant reliability indicators should not be lower than the parameters of the element [12-17]. The tightening of operational requirements for electronic equipment has led to the need of study not only static, but also dynamic characteristics of thermoelectric coolers and their impact on reliability indicators [18-20]. Two design parameters influence the reliability indicators of thermoelectric modules. These parameters include the geometry of thermoelectric modules and the structure, which is the subject of the studies presented in [21-23]. It is known that the cyclic test mode of thermoelectric coolers is used for reliability tests, since the time between failures (MTBF) is reduced by one order of magnitude [24-26]. The inclusion of the cooler in the feedback loop of the temperature maintenance circuit of the impulse heat-loaded elements makes it relevant to increase the dynamic characteristics of the cooler, which are directly related to its reliability indicators. The work [27] is devoted to the analysis of the connection between the reliability indicators and the dynamic characteristics of thermoelectric coolers. In this work the issues of reducing the time to reach the stationary mode depending on temperature drops and current operating modes are considered, since the reliability indicators and dynamic characteristics are in direct contradiction. The work [28] presents further studies in the direction of improving the dynamic characteristics of thermoelectric coolers and related reliability. This work analyzes the dependencies of the influence of structural parameters of thermoelements. The influence of the thermoelement material on the dynamic characteristics and reliability indicators are presented in [29, 30], where the possibility of the effective influence of the physical parameters of the thermoelectric material on the reliability and dynamics of the thermoelectric cooler is shown. At the same time, the influence on the reliability indicators and dynamic characteristics of such a mandatory component as a heat sink radiator remained unexplored. Its mass and overall dimensions directly affect the system for providing thermal modes of on-board equipment.

2. PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the work is to study the effect of heat sink radiator parameters on the dynamics and reliability indicators of single-stage cooling devices.

In order to achieve the goal, it is necessary to solve the following tasks:

– to develop a dynamic model of the combination of a thermoelectric cooling device with a heat sink radiator;

– to analyze the dynamic characteristics and reliability indicators for the main current modes of thermoelectric coolers, taking into account the influence of the heat-removing radiator.

3. DYNAMIC MODEL OF A THERMOELECTRIC COOLER CONSIDERING A HEAT SINK RADIATOR

The ratio for determining the heat dissipation capacity of a radiator (αF) can be recorded as:

$$\alpha F = Q/(T - T_c) \qquad (1)$$

where: α – is the heat transfer coefficient, W/m^2·K;

F – radiator surface area, m^2;

$Q = Q_0(1+1/E)$ – the heat output of the TEC;

Q_0 is the amount of heat load, W;

Refrigerating coefficient, relative units:

$$E = \frac{2B - B^2 - \Theta}{2B\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right)}$$

where: $B = I/I_{\max}$ – relative operating current;

I – is the value of the operating current, A;

$I_{\max} = eT_0/R$ – maximum operating current, A;

T_0 – is the temperature of the heat-absorbing junction of the TEC, K;

T – the temperature of the heat-generating joint of the TEC, K;

T_c – the temperature of the medium, K;

$\Theta = T/\Delta T_{\max}$ – relative temperature drop, rel. units;

$\Delta T_{\max} = 0,5\,\bar{z}\,T_0^2$ – maximum temperature drop, K;

$\bar{z}$ – is the efficiency of the thermoelectric material in the module, 1/K;

$R = l/(\sigma S)$ – electrical resistance of the thermoelectric branch, Ohm;

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

$\overline{e}$, $\overline{\sigma}$ – respectively, thermoelectric coefficient, V/K and electrical conductivity, S/cm of thermoelectric branch.

Expression (1) can be represented as:

$$\alpha F = \frac{Q_0\left[B^2 + 2B\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right) - \Theta\right]}{\left(2B - B^2 - \Theta\right)\Delta T_{\max}\left(\Theta - \Theta_c\right)}, \quad (2)$$

or

$$K = \frac{\alpha F \Delta T_{\max}}{Q_0} = \frac{B^2 + 2B\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right) - \Theta}{\left(2B - B^2 - \Theta\right)\Delta T_{\max}\left(\Theta - \Theta_c\right)}, \quad (3)$$

since, as $\alpha F \to \infty$ $K \to \infty$ $\alpha F \to \infty$ $K \to \infty$, it is expedient to consider in next studies the value $a = 1/K = Q_0/(\alpha F \Delta T_{\max})$;

$$a = \frac{1}{K} = \frac{Q_0}{\alpha F \Delta T_{\max}} = \frac{\left(2B - B^2 - \Theta\right)\Delta T_{\max}\left(\Theta - \Theta_c\right)}{B^2 + 2B\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right) - \Theta} \quad (4)$$

where: $\Theta_c = (T_c - T_0)/\Delta T_{\max}$; $T - T_c = \Delta T_{\max}(\Theta - \Theta_c)$.

In some cases of the design of the system "object–TEC–heat sink", there are unified series of TEC and heat sinks (αF) at the disposal of the developer. In this case, it is necessary for a given values of αF of heat-dissipating radiators, as well as heat load Q_0 and thermoelectric efficiency of modules $\overline{z}$ ($\Delta T_{\max}$) to choose a TEC design that provides the specified conditions for the system operation. For this case, one can use the relation (4)

$$\Theta^2 B(2 - B) - \Theta[2B(1 - a\Delta T_{\max}/T_0) - B^2 + \Theta_c + a] + aB(2 + B) + B\Theta_c(2 - B) = 0. \quad (5)$$

Analysis of expression (3), (4) shows that if the temperature of the heat-generating junctions T is close to the ambient temperature T_c, a large finning surface is required to remove thermal power. $\alpha F \to \infty$ $a \to 0$. If the temperature difference ($T - T_c$) is sufficiently large, then the cooling coefficient E will noticeably decrease. This will result in the increase of the heat flow at the heat-generating joints, which requires an increase in the surface of the radiator. Determination of the maximum of the function $a = f(\Theta)$ at the optimal relative temperature difference Θ_{opt} allows us to find the minimum heat-removing surface of the radiator $\alpha F_{\min}$.

From the condition $da/(d\Theta) = 0$, we obtain the ratio for determining the optimal relative temperature drop Θ_{opt} corresponding to the minimum heat-removing capacity of the radiator $\alpha F_{\min}$ for various current operating modes.

$$\Theta^2_{опт}\left(1 - 2B\frac{\Delta T_{\max}}{T_0}\right) - 2\Theta_{опт}\left(B^2 + 2B\right) + \left(2B + B^2 + \Theta_c\right)\left(B^2 + 2B\right) - \left(1 - 2B\frac{\Delta T_{\max}}{T_0}\right)\left(2B - B^2\right)\Theta_c = 0; \quad (6)$$

In this case, the relative value of the failure rate λ/λ_0 can be determined in accordance with [2] from the relation

$$\lambda/\lambda_0 = nB^2(\Theta + C)\frac{\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2} K_{T_1}; \quad (7)$$

where: $\lambda_0 = 3 \cdot 10^{-8}$ 1 / h is the nominal failure rate;
n – number of thermoelements, pcs;
$C = \frac{Q_0}{nI^2_{\max} R}$ – relative heat load;
K_{T1} – is a significant coefficient of reduced temperature [2].

The probability of failure-free operation P of the TEC can be determined from the expression

$$P = \exp(-\lambda t), \quad (8)$$

where t is the assigned resource, h.

The time to reach the stationary operating mode τ can be determined from the expression in accordance with [3]

$$\tau = \frac{\sum_i m_i C_i}{K_К\left(1 + 2B_К\frac{\Delta T_{\max}}{T_0}\right)} \ln\frac{\gamma B_Н(2 - B_Н)}{2B_К - B^2_К - \Theta} \quad (9)$$

where: $\sum_i m_i C_i = 175 \cdot 10^{-4}$ J/K – is the total value of the product of heat capacity and mass of constituent structural and technological elements (STE) for a given geometry of thermoelectric branches l/S = 10cm^{-1};

$$\gamma = \frac{I^2_{\max Н} R_Н}{I^2_{\max К} R_К},$$

where: $I_{\max К}$, $R_К$ – respectively, the maximum operating current, A and the electrical resistance of the thermoelectric branch, Ohm, at the end of the cooling process τ;
$B_Н = I/I_{\max Н}$ – relative operating current at $\tau = 0$;
$B_К = I/I_{\max К}$ – relative operating current at τ;
$I_{\max Н} = e_Н T/R_Н$; $I_{\max К} = e_К T/R_К$;
$\overline{e}_н$, $\overline{e}_к$ – accordingly, the averaged thermoelectric coefficient of the thermoelectric branch at the beginning and at the end of the cooling process, V/K;
$K_К = æ_К/(l/S)$ – heat transfer coefficient, W/K;

$\bar{æ}_K$ – averaged coefficient of thermal conductivity, W/(cm·K).

The number of thermoelements n can be determined from the ratio

$$n = \frac{Q_0}{I^2_{\max K} R_K \left(2B_K - B^2_K - \Theta\right)}, \quad (10)$$

Power consumption W_K of TEC can be determined from the expression:

$$W_K = 2nI^2_{\max K} R_K B_K \left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right). \quad (11)$$

Voltage drop

$$U_K = W_K/I. \quad (12)$$

The cooling coefficient E can be calculated by the formula:

$$E = Q_0/W_K. \quad (13)$$

4. ANALYSIS OF THE DYNAMIC MODEL

4.1. Mode Q_{0max} (B=1)

Let us use relation (4) to consider the functional dependence $a = f(\Theta)$ at a given heat load Q_0 = 0,5 Вт, T_c= 300 K in the Q_{0max} mode for different values of Θ_c.

The functional dependence $a = f(\Theta)$ has a maximum for different Θ_c, corresponding to the optimal relative temperature drop Θ_{opt} (Fig. 1).

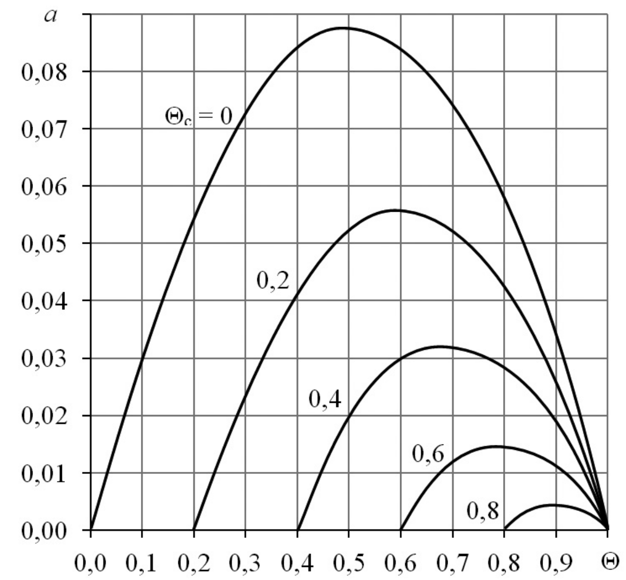

Fig. 1. **Dependence of the value $a = Q_0/(\alpha F\Delta T_{max})$ on the relative temperature difference Θ of a single-stage TEC at T = 300 K for different values of Θ_c in the Q_{0max} mode**
***Source*: compiled by the author**

For the Q_{0max} (B=1) mode, relation (6) takes the form:

$$\Theta^2\left(1-2\frac{\Delta T_{\max}}{T_0}\right) - 6\Theta + 3\left(1+\Theta_c\right) - \Theta_c\left(1-2\frac{\Delta T_{\max}}{T_0}\right) = 0$$

or .(14)

$$\Theta^2\left(1-2\frac{\Delta T_{\max}}{T_0}\right) - 6\Theta + 3 + 2\Theta_c\left(1+\frac{\Delta T_{\max}}{T_0}\right) = 0$$

With the increase of Θ_c, the optimum relative temperature difference Θ_{opt} increases (Fig. 2, Item 1) from Θ_{opt} = 0.5 at Θ_c = 0 to Θ_{opt} = 1.0 at Θ_c = 1.

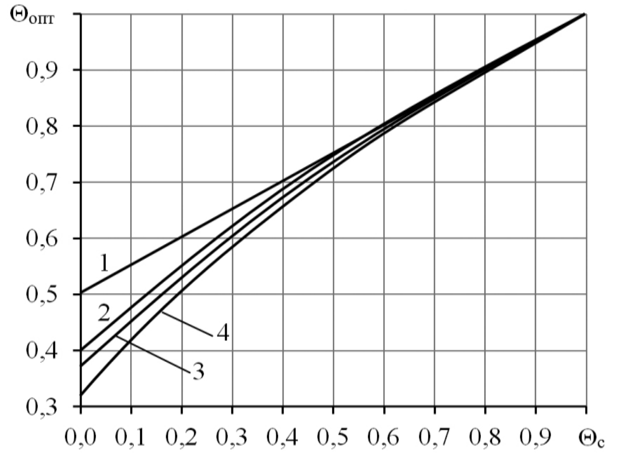

Fig. 2. **Dependence of the optimal value of the relative temperature difference Θ_{opt} of a single-stage TEC on the Θ_c value at T = 300 K, Q_0 = 0.5 W for different operating modes:**
1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}
***Source*: compiled by the author**

The results of calculations of the main parameters, reliability indicators and dynamics of functioning of a single-stage TEC in the Q_{0max} mode at T_c= 300 K, T_0= 280 K, Θ_c = 0,213, Q_0 = 0,5 W Вт; l/S = 10 cm^{-1} for different temperature T of the heat-generating junction are given in Table 1.

With an increase in the heat dissipation capacity of the radiator from αF_{min} (a = 0,055) to $\alpha F \to \infty$ ($a \to 0$) at a given heat load Q_0 = 0,5 W и $\Theta_c = (T_c - T_0)/\Delta T_{max}$ = 0,213 in the mode Q_{0max} (T_c= 300 K, T_0= 280 K) ΔT_{max} = 94,1 K:

– the optimal relative temperature difference Θ_{opt} (Fig. 1) decreases from Θ_{opt} = 0.573 at αF_{min} (a = 0,055) to Θ_{opt} = 0.213 at $\alpha F \to \infty$ (a = 0);
– the operating current I_{max} (Fig. 3, item 1) increases from I_{max} = 5.02 A at αF_{min} (a = 0,055) to I_{max} = 5.32 A at $\alpha F \to \infty$ (a = 0);
– the number of thermoelements n (Fig. 4, item 1) decreases from n = 4 at αF_{min} (a = 0,055) to n = 2.2 at $\alpha F \to \infty$ (a = 0);
– power consumption W decreases from W = 2.8 W at αF_{min} (a = 0,055) up to W = 1.36 W at $\alpha F \to \infty$ (a = 0);

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

Table 1. **The main parameters, reliability indicators and dynamics of functioning of a single-stage TEC**

Mode Q_{0max} (B=1); T_c= 300 K; Q_0 = 0,5 W Вт; T_0= 280 K; Θ_c = 0,213; ΔT_{max} = 94,1 K

αF, W/K	T, K	Θ, rel . units.	$R\cdot10^3$, Ohm	I_{max}, A	n, pcs.	W, W	U, V	E	I, A	a	τ, s	λ / λ_0	$\lambda\cdot10^8$, 1/h	P
∞	300	0,213	10,64	5,26	2,15	1,36	0,26	0,37	5,26	0.0	2,51	2.17	6,5	0,99935
0,4	305	0,266	10,75	5,24	2.30	1,48	0,28	0,34	5,24	0,0133	2,93	2,33	7,0	0,99930
0,21	310	0,319	11,0	5,17	2,50	1,63	0,32	0,31	5,17	0,025	3,46	2,53	7,6	0,99924
0,125	320	0,425	11,1	5,14	3,0	2,0	0,39	0,25	5,14	0,043	4,61	3,0	9,0	0,99910
0,10	330	0,53	11,36	5,08	3,6	2,52	0.50	0,20	5,08	0,053	6,0	3,7	11,0	0,9989
min/0,097	337,3	opt/0,61	11,50	5,02	4,0	2.80	0,56	0.18	5,02	0,055	6,77	4,1	12,3	0,99877

***Source*: compiled by the author**

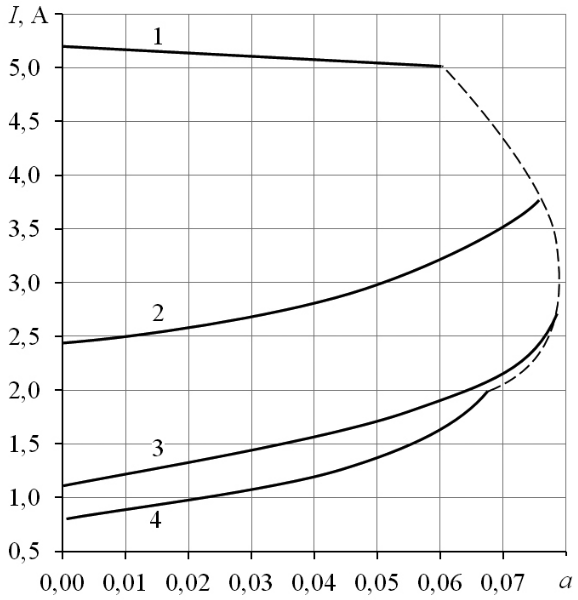

Fig. 3. **Dependence of the relative operating current B_K on the transient time τ of a single-stage TEC at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, ΔT = 40K for different operating modes: 1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min} (the dotted line indicates the time of reaching the stationary mode)**

***Source*: compiled by the author**

– the voltage drop U decreases from U = 0.56 V at αF_{min} (a = 0,055) up to U = 0.26 V at $\alpha F \to \infty$ (a = 0);

– the refrigerating coefficient E (Fig. 5, item 1) increases from E = 0.18 at αF_{min} (a = 0,055) to E = 0.37 at $\alpha F \to \infty$ (a = 0);

– the time of reaching the stationary mode τ (Fig. 6, item 1) decreases from τ = 6.7 at αF_{min} (a = 0,055) to τ = 2.45 at $\alpha F \to \infty$ (a = 0);

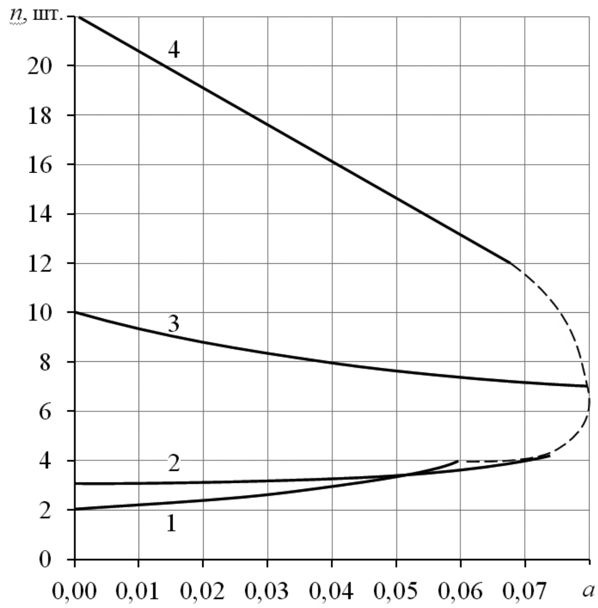

Fig. 4. **The dependence of the number of thermoelements n on a single-stage TEC on the value of a at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, Θ_c = 0,213 for different operating modes: 1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode$(Q_0/I^2)_{max}$; 4 – mode λ_{min} (dotted line indicates points corresponding to αF_{min})**

***Source*: compiled by the author**

– the relative failure rate λ/λ0 (Fig. 7, item 1) decreases from λ/λ0 = 4.1 at αF_{min} (a = 0.055) to λ/λ0 = 2.2 at $\alpha F \to \infty$ (a = 0);

– the probability of failure-free operation P increases (Fig. 8, item 1) from P = 0.99877 at αF_{min} (a = 0.055) to P = 0.99935 at $\alpha F \to \infty$ (a = 0).

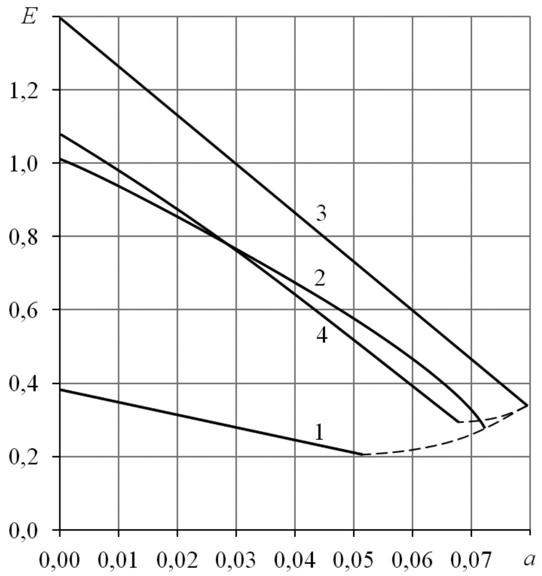

Fig. 5. **Dependence of the cooling coefficient E of a single-stage TEC on the value of a at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, Θ_c = 0,213 for various operating modes:**
1 –Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$;
3 – mode$(Q_0/I^2)_{max}$; 4 – mode λ_{min} (dotted line indicates points corresponding to αF_{min})
***Source*: compiled by the author**

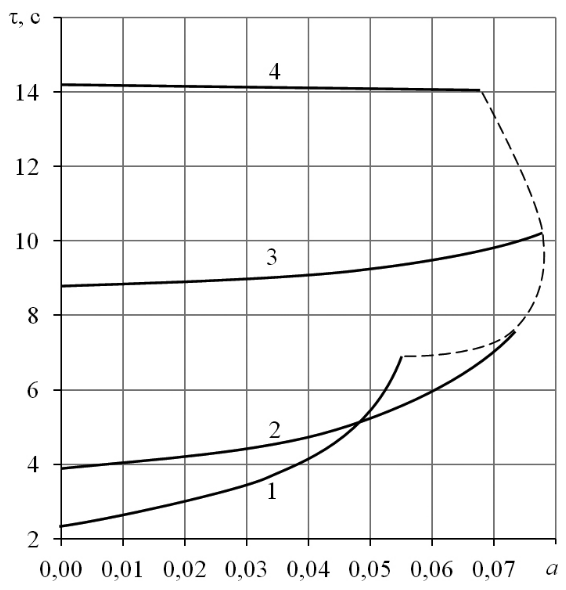

Fig. 6. **Dependence of the time of reaching the stationary mode τ of a single-stage TEC on the value of a at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, Θ_c = 0,213 for various operating modes:**
1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$;
3 – mode$(Q_0/I^2)_{max}$; 4 – λ_{min} mode (dotted line indicat es points corresponding to αF_{min})
***Source*: compiled by the author**

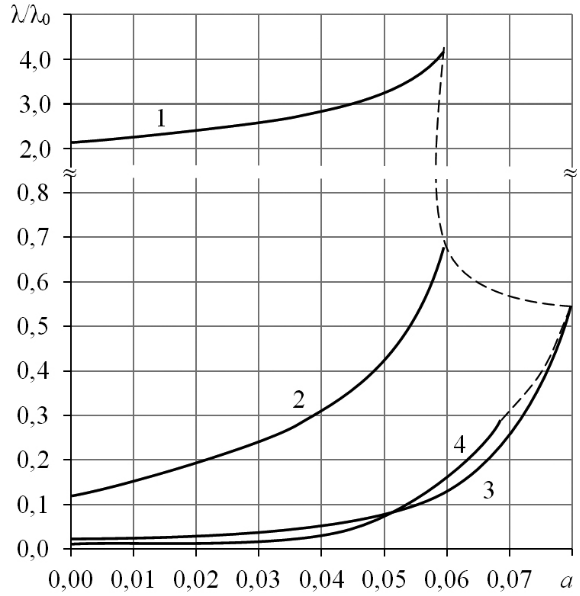

Fig. 7. **Dependence of the relative value of the failure rate λ/λ0 of a single-stage TEC on the value of a at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, Θ_c = 0,213 for various operating modes:**
1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$;
3 – mode$(Q_0/I^2)_{max}$; 4 – λ_{min} mode (dotted line indicates points corresponding to αF_{min})
***Source*: compiled by the author**

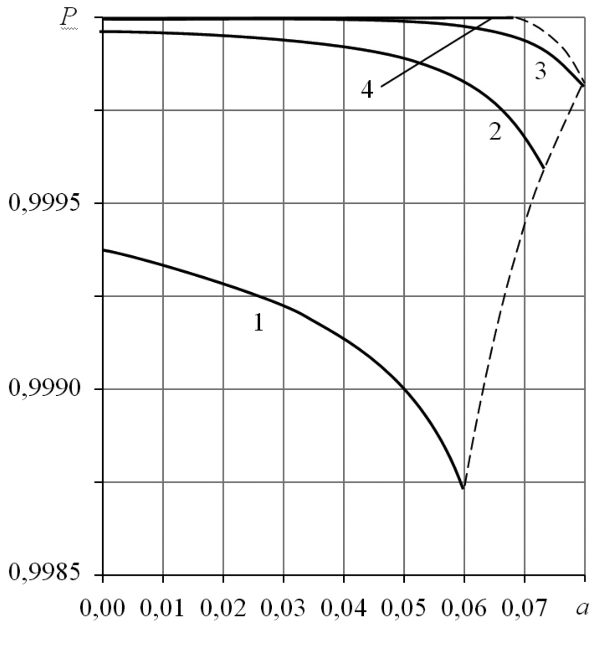

Fig. 8. **Dependence of the probability of failure-free operation P of single-stage TEC on the value of a at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0,5 W, Θ_c = 0,213 for different operating modes:**
1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$;
3 – mode$(Q_0/I^2)_{max}$; 4 – λ_{min} mode (dotted line indicates points corresponding to αF_{min})
***Source*: compiled by the author**

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

4.2. Mode $(Q_0 / I)_{max}$ $(B = \sqrt{\Theta})$

Let us use relation (4) to consider the functional dependence $a = f(\Theta)$ at a given heat load $Q_0 = 0.5$ W, $T_c = 300$ K in the mode (Q_0/I) max for different values of Θ_c.

The functional dependence $a = f(\Theta)$ has a maximum for different Θ_c, corresponding to the optimal relative temperature drop Θ_{opt} (Fig. 9).

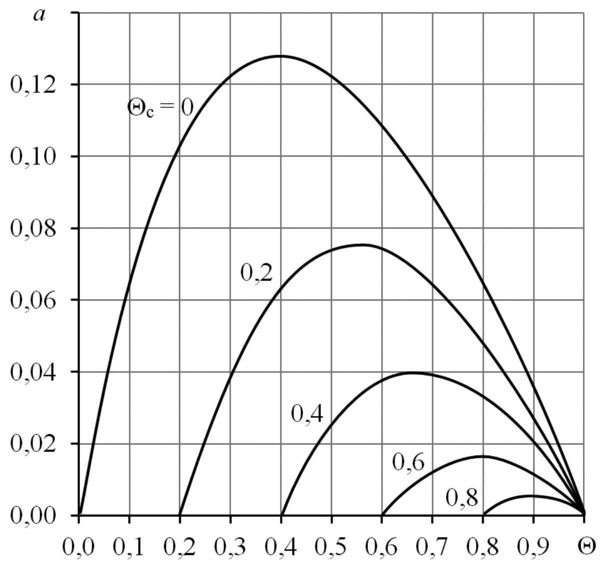

Fig. 9. **Dependence of the value $a = Q_0/(\alpha F \Delta T_{max})$ on the relative temperature drop Θ of a single-stage TEC at T = 300 K for different values of Θ_c in the mode $(Q_0/I)_{max}$**

***Source*: compiled by the author**

For the mode $(Q_0/I)_{max}$, relation (6) takes the form:

$$\Theta^2 \frac{\Delta T_{max}}{T_0} + \Theta\left(3 + \frac{\Delta T_{max}}{T_0}\Theta_c\right) - 2\sqrt{\Theta}\left(1 + \frac{\Delta T_{max}}{T_0}\Theta_c\right) - \Theta_c = 0 \quad (15)$$

With an increase in Θ_c, the optimal relative temperature drop Θ_{opt} increases (Fig. 2, item 2) from $\Theta_{opt} = 0.4$ at $\Theta_c = 0$ to $\Theta_{opt} = 1.0$ at $\Theta_c = 1$.

The results of calculations of the main parameters, reliability indicators and dynamics of functioning of a single-stage TEC in the mode $(Q_0/I)_{max}$ at $T_c = 300$ K, $T_0 = 280$ K, $\Theta_c = 0.213$, $Q_0 = 0.5$ W; $l/S = 10$ cm^{-1} for different heat-generating junction temperature T are shown in Table 2.

With an increase in the heat dissipation capacity of the radiator from αF_{min} ($a = 0.073$) to $\alpha F \to \infty$ ($a = 0$) at a given heat load $Q_0 = 0.5$ W and $\Theta_c = 0.213$ in the mode (Q_0/I) max ($T_c = 300$ K, $T_0 = 280$ K) $\Delta T_{max} = 94.1$ K:
– the optimal relative temperature difference Θ_{opt} (Fig. 9) decreases from $\Theta_{opt} = 0.55$ at αF_{min} ($a = 0.073$) to $\Theta_{opt} = 0.213$ at $\alpha F \to \infty$ ($a = 0$);
– the operating current I decreases (Fig. 3, item 2) from $I = 3.8$ A at αF_{min} ($a = 0.073$) up to $I = 2.4$ A at $\alpha F \to \infty$ ($a = 0$);
– the number of thermoelements n (Fig. 4, item 2) decreases from $n = 4.4$ at αF_{min} ($a = 0.073$) to $n = 3.4$ at $\alpha F \to \infty$ ($a = 0$);
– power consumption W decreases from W = 1.79 W at αF_{min} ($a = 0.073$) to W = 0.5 W at $\alpha F \to \infty$ ($a = 0$);
– the voltage drop U decreases from U = 0.47 V at αF_{min} ($a = 0.073$) up to U = 0.2 V at $\alpha F \to \infty$ ($a = 0$);
– the refrigerating coefficient E (Fig. 5, item 2) increases from $E = 0.28$ at αF_{min} ($a = 0.073$) up to E = 1.0 at $\alpha F \to \infty$ ($a = 0$);
– the time of reaching the stationary mode τ (Fig. 6, item 2) decreases from τ = 7.5 at αF_{min} ($a = 0.073$) to τ = 3.9 at $\alpha F \to \infty$ ($a = 0$);
– the failure rate λ/λ_0 decreases (Fig. 7, item 2) from $\lambda/\lambda_0 = 1.41$ at αF_{min} ($a = 0.073$) to $\lambda/\lambda0 = 0.129$ at $\alpha F \to \infty$ ($a = 0$);
– the probability of failure-free operation P increases (Fig. 8, item 2) from $P = 0.99958$ αF_{min} ($a = 0.073$) to $P = 0.999961$ at $\alpha F \to \infty$ ($a = 0$).

Table 2. The **main parameters, reliability indicators and dynamics of functioning of a single-stage TEC**
Mode $(Q_0/I)_{max}$; $T_c = 300$ K; $Q_0 = 0.5$ W; $T_0 = 280$ K; $\Theta_c = 0.213$; $\Delta T_{max} = 94.1$ K

αF, W/K	T, K	Θ, rel. units	$R \cdot 10^3$, Ohm	I_{max}, A	n, pcs	W, W	U, V	E	I, A	a	τ, s	λ / λ_0	$\lambda \cdot 10^8$, 1/h	P
∞	300	0,213	10,64	5,26	3,4	0,5	0,20	1,01	2,43	0,0	3,9	0,129	0,388	0,999961
0,225	305	0,266	10,75	5,24	3,4	0,625	0,23	0,80	2,70	0,024	4,3	0,216	0,647	0,999935
0,127	310	0,319	11,0	5,17	3,46	0,773	0,26	0,65	2,92	0,042	4,85	0,333	1,0	0,99990
0082	320	0,425	11,1	5,14	3,76	1,143	0,34	0,44	3,35	0,065	6,0	0,687	2,06	0,99980
min/0,073	331,8	opt/0,55	11,2	5,12	4,43	1,79	0,47	0,28	3,8	max/0,073	7,5	1,41	4,24	0,99958

***Source*: compiled by the author**

4.3. Mode $(Q_0/I^2)_{max}$ $(B = \Theta)$

Let us use relation (4) to consider the functional dependence $a = f(\Theta)$ at a given heat load Q_0 = 0,5 W , T_c= 300 K in the mode $(Q_0/I^2)_{max}$ for different values of Θ_c.

The functional dependence $a = f(\Theta)$ has a maximum for different Θ_c , corresponding to the optimal relative temperature drop Θ_{opt} (Fig. 10).

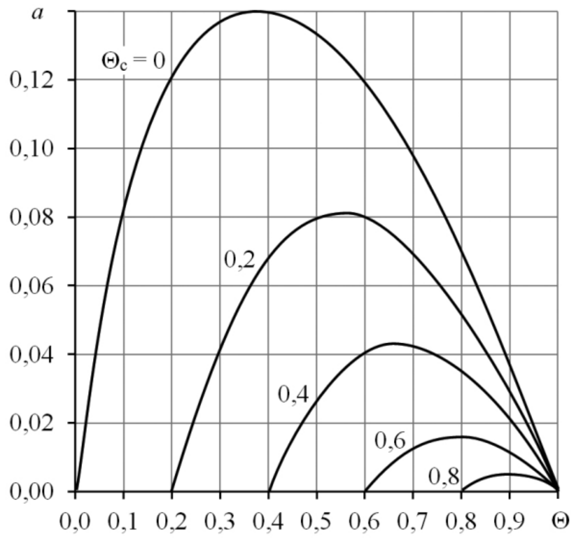

Fig. 10. **Dependence of the value $a = Q_0/(\alpha F \Delta T_{max})$ on the relative temperature difference Θ of a single-stage TEC at T = 300 K for different values of Θ_c in the mode $(Q_0/I^2)_{max}$**
***Source*: compiled by the author**

For the mode $(Q_0/I^2)_{max}$(B = Θ), relation (6) takes the form:

$$\Theta^2_{опт}\left(1+2\frac{\Delta T_{max}}{T_0}\right)+2\Theta_{опт}-\left[1+2\Theta_c\left(1+\frac{\Delta T_{max}}{T_0}\right)\right]=0. \quad (16)$$

With an increase in Θ_c , the optimal relative temperature drop Θopt increases (Fig. 2, item 3) from Θ_{opt} = 0.38 at Θ_c = 0 to Θ_{opt} = 1.0 at Θ_c = 1.

The results of calculations of the main parameters, reliability indicators and dynamics of functioning of a single-stage TEC in the mode $(Q_0/I^2)_{max}$ at T_c = 300 K, T_0 = 280 K, Θ_c = 0.213, Q_0 = 0.5 W; l/S = 10 cm^{-1} for different temperature T of the heat-generating junction are given in Table. 3.

With an increase in the heat sink capacity of the radiator from αF_{min} (a = 0.079) to $\alpha F \to \infty$ ($a \to 0$) at a given heat load Q_0 = 0.5 W and $\Theta_c = (T_c–T_0)/\Delta T_{max}$ = 0.213 in the mode $(Q_0/I^2)_{max}$ (T_c = 300 K, T_0 = 280 K) ΔT_{max} = 94.1 K:
– the optimal relative temperature difference Θopt (Fig. 10) decreases from Θ_{opt} = 0.531 at αF_{min} (a = 0.079) to Θ_{opt} = 0,213 при $\alpha F \to \infty$ ($a \to 0$) ;
– the operating current I (Fig. 3, item 3) decreases from I = 2.72 A at αF_{min} (a = 0.079) to I = 1.12 A at $\alpha F \to \infty$ (a = 0);
– the number of thermoelements n increases (Fig. 4, item 3) from n = 6.9 at αF_{min} (a = 0.079) to n = 10.1 at $\alpha F \to \infty$ (a = 0);
– power consumption W decreases from W = 1.51 W at αF_{min} (a = 0.079) to W = 0.36 W at $\alpha F \to \infty$ (a = 0);
– the voltage drop U decreases from U = 0.56 V at αF_{min} (a = 0.079) up to U = 0.32 V at $\alpha F \to \infty$ (a = 0);
– the refrigerating coefficient E (Fig. 5, item 3) increases from E = 0.33 at αF_{min} (a = 0.079) to E = 1.39 at $\alpha F \to \infty$ (a = 0);
– the time of reaching the stationary mode τ decreases (Fig. 6, item 3) from τ = 10.3 s at αF_{min} (a = 0.079) to τ = 8.9 at $\alpha F \to \infty$ (a = 0);
– the relative failure rate λ/λ_0 decreases (Fig. 7, item 3) from λ/λ_0 = 0.55 at αF_{min} (a = 0.079) to λ/λ_0 = 0.0124 at $\alpha F \to \infty$ (a = 0);
– the probability of failure-free operation P (Fig. 8, item 3) increases from P = 0.99983 at αF_{min} (a = 0.079) to P = 0.9999963 at $\alpha F \to \infty$ (a = 0).

Table 3. **The main parameters, reliability indicators and dynamics of functioning of a single-stage TEC**

Mode $(Q_0/I^2)_{max}$; T_c = 300 K; Q_0 = 0.5 W; T_0 = 280 K; Θ_c = 0.213; ΔT_{max} = 94,1 K

αF, W/K	T, K	Θ, rel. units	R·10^3, Ohm	I_{max}, A	n, pcs	W, W	U, V	E	I, A	a	τ, s	λ / λ$_0$	λ·10^8, 1/h	P
∞	300	0,213	10,64	5,26	10,1	0,36	0,32	1,39	1,12	0,0	8,94	0,0124	0,037	0,9999963
0,20	305	0,266	10,75	5,24	8,7	0,49	0,35	1,03	1,39	0,027	8,98	0,03	0,091	0,9999909
0,113	310	0,319	11,0	5,17	7,8	0,63	0,38	0,80	1,65	0,047	9,16	0,064	0,193	0,999981
0,0745	320	0,425	11,1	5,14	7,0	0,989	0,45	0,51	2,18	0,071	9,6	0,225	0,68	0,999932
min/0,067	330	опт/0,531	11,2	5,12	6,85	1,51	0,56	0,33	2,72	0,079	10,3	0,55	1,66	0,99983

***Source*: compiled by the author**

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

4.4. Mode λ_{min} ($B = \eta\Theta$)

Let us use relation (4) to consider the functional dependence $a = f(\Theta)$ at a given heat load $Q_0 = 0.5$ W, $T_c = 300$ K in the λ_{min} mode for different values of Θ_c.

The functional dependence $a = f(\Theta)$ has a maximum for different Θ_c, corresponding to the optimal relative temperature drop Θ_{opt} (Fig. 11).

For the λ_{min} mode, relation (6) takes the form:

$$\Theta_{opt}^2\eta^3\left(\eta+2\frac{\Delta T_{max}}{T_0}\right)+2\Theta_{opt}\eta^2(2\eta-1)-\\ -(2\eta-1)\left[2\eta-1+\eta^2\Theta_c+\eta\left(\eta+2\frac{\Delta T_{max}}{T_0}\right)\Theta_c\right]=0. \quad (17)$$

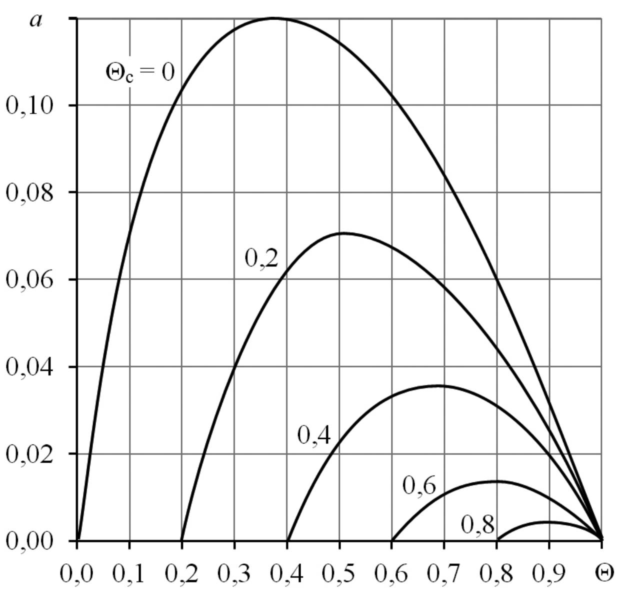

Fig. 11. **Dependence of the value $a = Q_0/(\alpha F\Delta T_{max})$ on the relative temperature difference Θ of a single-stage TEC at $T = 300$ K for different values of Θ_c in the mode λ_{min}**

***Source*: compiled by the author**

With an increase in Θ_c, the optimal relative temperature difference Θ_{opt} increases (Fig. 2, item 4) from $\Theta_{opt} = 0.33$ at $\Theta_c = 0$ to $\Theta opt = 1.0$ at $\Theta_c = 1.0$.

The results of calculations of the main parameters, reliability indicators and dynamics of functioning of a single-stage TEC in the λ_{min} mode at $T_c = 300$ K, $T_0 = 280$ K, $\Theta_c = 0.213$, $Q_0 = 0.5$ W; $l/S = 10 cm^{-1}$ for different temperature T of the heat-generating junction are given in Table. 4.

With an increase in the heat dissipation capacity of the radiator from αF_{min} ($a = 0.068$) to $\alpha F \to \infty$ ($a \to 0$) at a given heat load $Q_0 = 0.5$ W and $\Theta_c = (T_c–T_0)/\Delta T_{max} = 0.213$ in the λ_{min} mode ($T_c = 300$ K, $T_0 = 280$ K) $\Delta T_{max} = 94.1$ K:

– the optimal relative temperature difference Θ_{opt} (Fig. 11) decreases from $\Theta_{opt} = 0.50$ at αF_{min} ($a = 0.068$) to $\Theta_{opt} = 0.213$ at $\alpha F \to \infty$ ($a = 0$);
– the operating current I (Fig. 3, item 4) decreases from $I = 2.05$ A at αF_{min} ($a = 0.068$) to $I = 0.83$ A at $\alpha F \to \infty$ ($a = 0$);
– the number of thermoelements n increases (Fig. 4, item 4) from $n = 12.2$ at αF_{min} ($a = 0.068$) to $n = 22.2$ at $\alpha F \to \infty$ ($a = 0$);
– power consumption W decreases from $W = 1.63$ W at αF_{min} ($a = 0.068$) to $W = 0.47$ W at $\alpha F \to \infty$ ($a = 0$);
– the voltage drop U decreases from $U = 0.8$ V at αF_{min} ($a = 0.068$) up to $U = 0.56$ V at $\alpha F \to \infty$ ($a = 0$);
– the refrigerating coefficient E (Fig. 5, item 4) increases from $E = 0.31$ at αF_{min} ($a = 0.068$) to $E = 1.07$ at $\alpha F \to \infty$ ($a = 0$);
– the relative failure rate λ/λ_0 decreases (Fig. 7, item 4) from $\lambda/\lambda_0 = 0.3$ at αF_{min} ($a = 0.068$) to $\lambda/\lambda_0 = 0.0073$ at $\alpha F \to \infty$ ($a = 0$);
– the probability of failure-free operation P (Fig. 8, item 4) increases from $P = 0.999910$ at αF_{min} ($a = 0.068$) to $P = 0.9999980$ at $\alpha F \to \infty$ ($a = 0$).

Table 4. **The main parameters, reliability indicators and dynamics of functioning of a single-stage TEC**
Mode $\lambda_{min;}$ $T_c = 300$ K; $Q_0 = 0.5$ W; $T_0 = 280$ K; $\Theta_c = 0.213$; $\Delta T_{max} = 94.1$ K

αF, W/K	T, K	Θ, rel. units	$R\cdot10^3$, Ohm	I_{max}, A	n, pcs	W, W	U, V	E	I, A	a	τ, s	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
∞	300	0,21	10,64	5,26	22,2	0,47	0,56	1,07	0,83	0,0	14,2	0,0073	0,022	0,999998
0,223	305	0,266	10,75	5,24	18,0	0,62	0,59	0,81	1,05	0,024	14,1	0,019	0,056	0,9999944
0,129	310	0,32	11,0	5,17	16,0	0,79	0,63	0,63	1,25	0,041	14,28	0,04	0,12	0,999988
0,086	320	0,425	11,1	5,14	13,2	1,22	0,72	0,41	1,70	0,062	14,1	0,14	0,42	0,999958
min/0,078	327	опт/0,513	11,2	5,12	12,2	1,63	0,80	0,31	2,05	max/0,068	14,2	0,30	0,90	0,999910

***Source*: compiled by the author**

– the time of reaching the stationary mode τ (Fig. 6, item 4) practically does not change;

A comparative analysis of the main parameters, reliability indicators and functioning dynamics for various typical current operating modes is given below.

Fig. 12 presents functional dependence of the maximum values $a_{max} = f(B)$ pos. 1 of a single-stage TEC, corresponding to the minimum heat dissipation capacity of the radiator $\alpha F_{min} = f(B)$ pos. 2 for various characteristic current modes of operation.

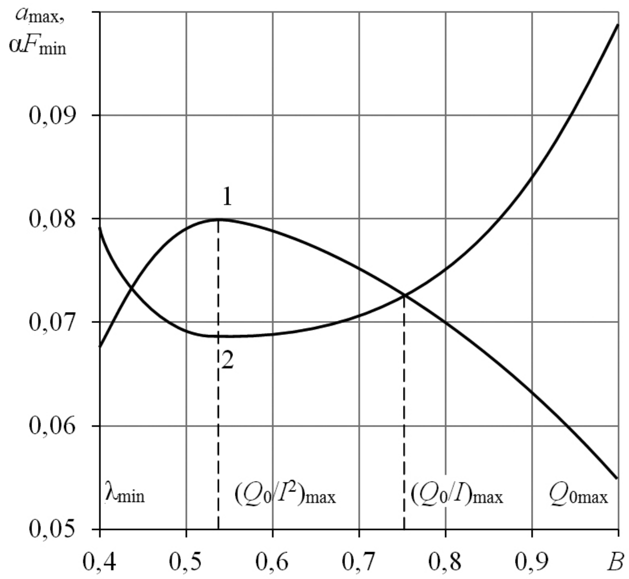

Fig. 12. **Dependence of the value of a_{max} (1) and the minimum heat-removing capacity of the radiator αF_{min} (2) of a single-stage TEC on the relative operating current B at T = 300 K, l/S = 10 cm^{-1}, Q_0 = 0.5 W, Θ_c = 0.213**
***Source*: compiled by the author**

The functional dependence $a_{max} = f(B)$ has a maximum at B = 0.53 (Fig. 12, item 2), which corresponds to the mode $(Q_0/I^2)_{max}$. The functional dependence $\alpha F_{min} = f(B)$ has a minimum at B = 0.53 (Fig. 12, item 1), which also corresponds to the mode $(Q_0/I^2)_{max}$.

The absolute minimum of the heat dissipation capacity of the radiator αF_{min} can be achieved in the mode $(Q_0/I^2)_{max}$.

Fig. 13 shows the dependence of the time of reaching the stationary mode τ on the relative operating current B for the maximum values amax $a_{max}(\alpha F_{min})$ (Fig. 13, pos. 1) and $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ (Fig. 13, pos. 2) at Θ_c = 0.213.

With an increase in the relative operating current B, the time to reach the stationary mode τ decreases and reaches its minimum values. It varies from τ = 6.8s for $a_{max} = f$ (B), and reaches τ = 2.5s for $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ in the Q_{0max} mode, which corresponds to the absolute minimum.

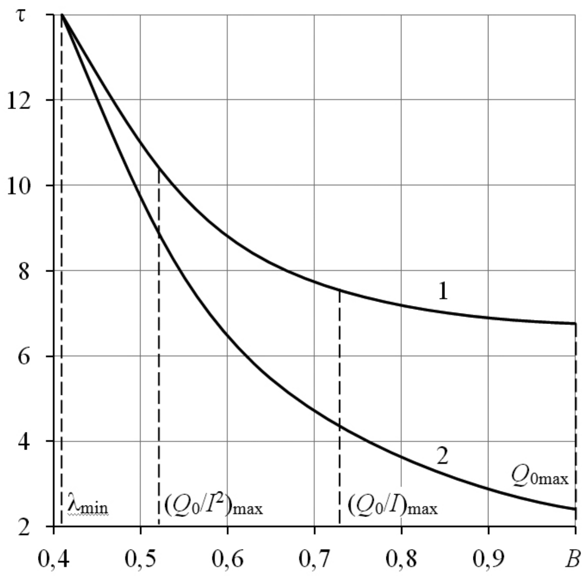

Fig. 13. **Dependence of the time of reaching the stationary mode τ of a single-stage TEC on the relative operating current B for different current modes at T = 300 K,l/S = 10 cm^{-1}; Q_0 = 0.5 W; Θ_c = 0.213; 1 – a_{max} (αF_{min}); 2 – $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$**
***Source*: compiled by the author**

The range of values of τ, enclosed between curves 1 and 2, corresponds to values of τ in the range from αF_{min} to $\alpha F \rightarrow \infty$.

Fig. 14 shows the dependence of the refrigerating coefficient E on the relative operating current B for $a_{max}(\alpha F_{min})$ (Fig. 14, pos. 1) and $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ (Fig. 13, pos. 2).

The functional dependence $E = f(B)$ has a maximum at B = 0.53 for $a_{max}(\alpha F_{min})$ (Fig. 14, pos. 1) and B = 0.21 for and $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ (Fig. 12, pos. 2), which corresponds to the mode $(Q_0/I^2)_{max}$ at Θ_c = 0.213.

The range of values of E, enclosed between curves 1 and 2, corresponds to the values of αF in the range from αF_{min} to $\alpha F \rightarrow \infty$.

Fig. 15 presents the dependence of the relative value of the failure rate λ/λ_0 of a single-stage TEC on the relative operating current B for the maximum values $a_{max}(\alpha F_{min})$ (Fig. 15, item 1) and $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ (Fig. 15, item 2).

With an increase in the relative operating current B, the relative value of the failure rate λ/λ_0 increases and reaches its minimum values for $a_{max} = f(B)\lambda/\lambda_0$ = 4.1, and for $a \rightarrow 0$ $(\alpha F \rightarrow \infty)$ λ/λ_0 = 2.17 in Q_{0max} mode.

The range of λ/λ_0 values, enclosed between curves 1 and 2, corresponds to λ/λ_0 values in the range from αF_{min} to $\alpha F \rightarrow \infty$.

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

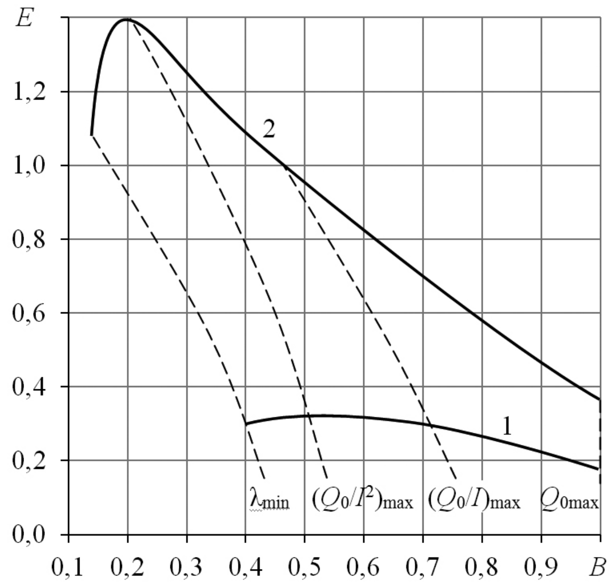

Fig. 14. **Dependence of the refrigerating coefficient *E* of a single-stage TEC on the relative operating current *B* for different current modes at T = 300 K; ΔT = 94.1 K; l/S = 10 cm^{-1}; Q_0 = 0.5 W; Θ_c = 0.213: 1 – $a_{max}(\alpha F_{min})$; 2 – $a \to 0$ ($\alpha F \to \infty$)**

***Source*: compiled by the author**

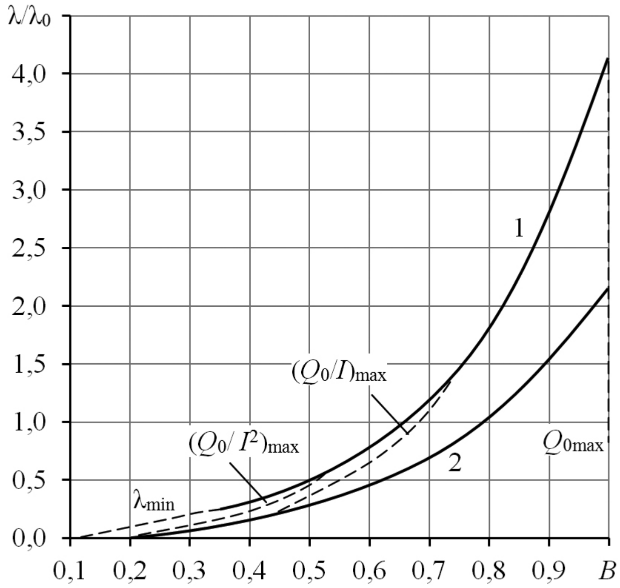

Fig. 15. **Dependence of the relative value of the failure rate λ/λ_0 of a single-stage TEC on the relative operating current *B* for various current modes at T = 300 K, ΔT = 94.1 K, l/S = 10 cm^{-1}, Q_0 = 0.5 W, Θ_c = 0.213, $\lambda_0 = 3\cdot10^{-8}$1/h: $a_{max}(\alpha F_{min})$; 2 – $a \to 0$ ($\alpha F \to \infty$)**

***Source*: compiled by the author**

Fig. 16 shows the dependence of the optimal values of the relative temperature difference Θ_{opt} corresponding to a_{max} (αF_{min}) on the relative operating current B for different Θ_c.

With an increase in the relative operating current *B*, the value of the optimal relative temperature drop Θ_{opt} increases for different Θ_c. The maximum value of Θ_{opt} corresponds to the Q_{0max} mode, the minimum – to the λ_{min} mode at a given Θ_c.

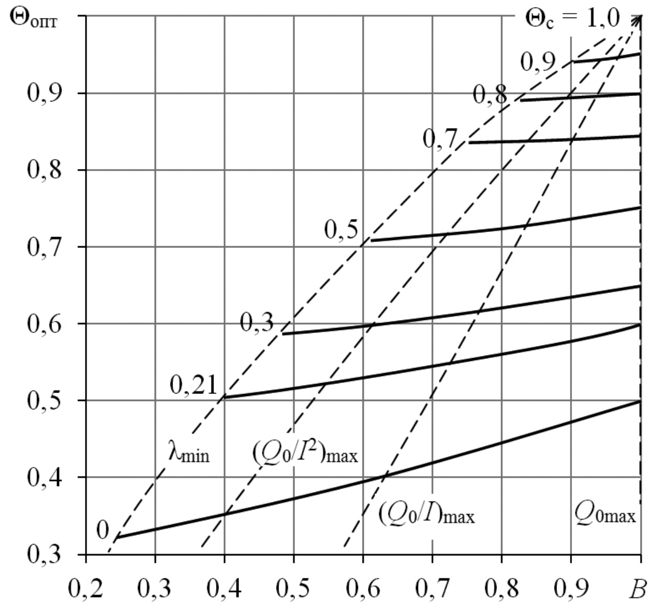

Fig. 16. **Dependence of the optimal relative temperature difference Θ_{opt} of a single-stage TEC on the relative operating current *B* at T = 300 K; ΔT = 94.1 K; l/S = 10 cm^{-1}; Q_0 = 0.5 W and different values of Θ_c for different operating modes: 1 - Q_{0max} mode; 2 - mode $(Q_0/I)_{max}$; 3 - mode $(Q_0/I^2)_{max}$; 4 - mode λ_{min}**

***Source*: compiled by the author**

5. DISCUSSION OF THE RESULTS OF THE ANALYSIS OF HEAT SINK EFFECT ON THE DYNAMICS AND RELIABILITY OF SINGLE-STAGE COOLING DEVICES OPERATION

A comparative analysis of the main parameters, reliability indicators and functioning dynamics for various typical current operating modes is given below.

Fig. 12 shows the functional dependence of the maximum values $a_{max} = f(B)$ pos. 1 of a single-stage TEC, corresponding to the minimum heat dissipation capacity of the radiator $\alpha F_{min} = f(B)$ pos. 2 for various characteristic current modes of operation.

The functional dependence $a_{max} = f(B)$ has a maximum at B = 0.53 (Fig. 12, item 2), which corresponds to the mode $(Q_0/I^2)_{max}$. The functional dependence $\alpha F_{min} = f(B)$ has a minimum at B = 0.53 (Fig. 12, item 1), which also corresponds to the mode $(Q_0/I^2)_{max}$.

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

The absolute minimum of the heat dissipation capacity of the radiator αF_{min} can be achieved in the mode $(Q_0/I^2)_{max}$.

In Fig. 13 shows the dependence of the time of reaching the stationary mode τ on the relative operating current *B* for the maximum values amax (αF_{min}) (Fig. 13, pos. 1) and $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) (Fig. 13, pos. 2) at $\Theta_c = 0.213$.

With an increase in the relative operating current *B*, the time to reach the stationary mode τ decreases and reaches its minimum values. It drops from τ = 6.8 s for $a_{max} = f(B)$ to τ = 2.5 s for $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) in the Q_{0max} mode, which corresponds to the absolute minimum.

The range of values of τ, enclosed between curves 1 and 2, corresponds to values of τ in the range from αF_{min} to $\alpha F \rightarrow \infty$.

Fig. 14 shows the dependence of the refrigerating coefficient *E* on the relative operating current *B* for a_{max} (αF_{min}) (Fig. 14, pos. 1) and $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) (Fig. 13, pos. 2).

The functional dependence $E = f(B)$ has a maximum at $B = 0.53$ for a_{max} (αF_{min}) (Fig. 14, pos. 1) and $B = 0.21$ for $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) (Fig. 12, pos. 2), which corresponds to the mode $(Q_0/I^2)_{max}$ at $\Theta_c = 0.213$.

The range of values of *E*, enclosed between curves 1 and 2, corresponds to the values of αF in the range from αF_{min} to $\alpha F \rightarrow \infty$.

Fig. 15 shows the dependence of the relative value of the failure rate λ/λ_0 of a single-stage TEC on the relative operating current *B* for the maximum values a_{max} (αF_{min}) (Fig. 15, pos. 1) and $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) (Fig. 15, pos. 2).

With an increase in the relative operating current *B*, the relative value of the failure rate λ/λ_0 increases and reaches its minimum values for $a_{max} = f(B)$ $\lambda/\lambda_0 = 4.1$, and for $a \rightarrow 0$ ($\alpha F \rightarrow \infty$) $\lambda/\lambda_0 = 2.17$ in Q_{0max} mode.

The range of λ/λ_0 values, enclosed between curves 1 and 2, corresponds to λ/λ_0 values in the range from αF_{min} to $\alpha F \rightarrow \infty$.

Fig. 16 shows the dependence of the optimal values of the relative temperature difference Θ_{opt}, and the corresponding a_{max} (αF_{min}) on the relative operating current *B* for different Θ_c. With an increase in the relative operating current *B*, the value of the optimal relative temperature drop Θ_{opt} increases for different Θ_c. The maximum value of Θ_{opt} corresponds to the Q_{0max} mode, the minimum – to the λ_{min} mode at a given Θ_c.

CONCLUSIONS

A physical model of the relationship between the main parameters, reliability indicators and the dynamics of functioning of a single-stage TEC has been developed. We take into account the effect of the heat-removing capacity of the radiator in the range from $\alpha F \rightarrow \infty$ to αF_{min}, temperature drops ΔT from 10 to 60 K at a given heat load $Q_0 = 0.5$ W.

Relationships are obtained to determine the optimal relative temperature difference Θ_{opt} corresponding to the maximum value a_{max} or the minimum heat dissipation capacity of the radiator αF_{min} . These relationships were made in the range of different current operating modes and relative temperature drops with the environment Θ_c at a given value of the heat load Q_0 and the efficiency of the initial thermoelectric materials in the module $\bar{z}$ (ΔT_{max}).

With an increase in the relative operating current *B*, the time to reach the stationary operating mode τ decreases for different values of the heat sink capacity αF. The minimum time for reaching the stationary operating mode is provided in the Q_{0max} mode for different values of the heat sink capacity of the radiator.

The possibility of reducing the weight and size characteristics of the cooling device in 2-3 times by minimizing the heat sink in relation with the main parameters, indicators of reliability and the dynamics of the TEC operation is shown, which is especially important when creating or modernizing on-board information systems with heat-loaded elements.

Comparative analysis of weight and size characteristics, main parameters, reliability indicators and dynamics of functioning with rational design makes it possible to choose compromise solutions, taking into account the weight of each of the limiting factors.

REFERENCES

1. Zaikov, V. P., Kinshova, L. A., Moiseev, V. F. “Prediction of reliability on thermoelectric cooling devices”. [KN.1]. *Single-stage devices*. *Publ. Politehperiodika.* Odessa. Ukraine: 2009. 120 p. (in Russian).

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

2. Huu Luong Quach, Ji Hyung Kim & Yoon Seok Chae. "Analysis on Electrical and Thermal Characteristics of a No-Insulation HTS Coil Considering Heat Generation in Steady and Transient States". *IEEE Transactions on Applied Superconductivity*. 2019; Vol.29 Issue 5. DOI: 10.1109/TASC.2019.2898543.

3. Huu Luong Quach, Ji Hyung Kim & Yoon Seok Chae. "Analysis on Electrical and Thermal Characteristics of a No–Insulation HTS Coil Considering Heat Generation in Steady and Transient States". *IEEE Transactions on Applied Superconductivity*. Aug. 2019; Vol. 29 Issue 5. DOI: 10.1109/TASC.2019.2898543.

4. Hyoung-Seuk Choi, Won-SeonSeo & Duck-Kyun Choi. "Prediction of Reliability on Thermoelectric Module through Accelerated Life Test and Physics-of-Failure". *Electronic Materials Letters,* 2011; 7. Article number: 271. DOI: 10.1007/s13391–011–0917–x.

5. Leila Bakhtiaryfard & YeongShu Chen. "Design and Analysis of a Thermoelectric Module to Improve the Operational Life. Advances in Mechanical Engineering". 2014. 7(1). DOI: 10.1155/2014/152419.

6. Manikandan S., Kaushik, S.C. & Ronggui Yang. "Modified pulse operation of thermoelectric coolers for building cooling applications". *Energy Conversion and Management,* 2017; 140: 145 –156. DOI: 10.1016/j.enconman. 2017.03.003.

7. Zebarjadi, M., Esfarjani, K., Dresselhaus, M. S., Ren, Z. F. & Chen, G. "Perspectives on thermoelectrics: from fundamentals to device Applications". *Energy & Environmental Science.* 2012. 5. 5147–5162. DOI: https://doi.org/10.1039/C1EE02497C.

8. Ping, Yang. "Approach on thermoelectricity reliability of board–level backplane based on the orthogonal experiment design". *International Journal of Materials and Structural Integrity.* 2010; 4 (2-4): 170–185. DOI: 10.1504/IJMSI.2010.035205.

9. En Fang, Xiaojie Wu, Yuesen Yu & Junrui Xiu. "Numerical modeling of the thermoelectric cooler with a complementary equation for heat circulation in air gaps". *Open Physics.* 2017; Vol. 15: 27–34. DOI: 10.1515/phys-2017-0004.

10. Leila Bakhtiaryfard & Yeong Shu Chen. "Design and Analysis of a Thermoelectric Module to Improve the Operational Life". *Advances in Mechanical Engineering.* 2014; 7(1). DOI: 10.1155/2014/152419.

11. Hee Seok Kim, Tianbao Wang, Weishu Liu & Zhifeng Ren. "Engineering Thermal Conductivity for Balancing Between Reliability and Performance of Bulk Thermoelectric Generators". *Advanced Functional Materials.* 2016; Vol. 26: 3678–3686. DOI: org/10.1002/adfm.201600128.

12. Hyoung-Seuk Choi, Won-Seon Seo & Duck-Kyun Choi. "Prediction of Reliability on Thermoelectric Module through Accelerated Life Test and Physics-of-Failure". *Electronic_Materials_Letters* 7. 2011. p. 271–275. DOI: 10.1007/s13391–011–0917 –x.

13. Sootsman, J. R., Chung, D. Y. & Kanatzidis, M. G. „New and Old Concepts in Thermoelectric Materials". *Angewandte Chemie International Edition.* 2009; 48: 8616–8639. DOI: https://doi.org/10.1002/anie.200900598.

14. Farshad Tajeddini, Mohammad Eslami & Nazanin Etaati. "Thermodynamic analysis and optimization of water harvesting from air using thermoelectric coolers". *Journal Energy conversion and management.* 2018; Vol.174: 417–429. DOI: org/10.1016/j.enconman.2018.08,045.

15. Changki, Mo. "Structural Reliability Evaluation of Thermoelectric Generator Modules: Influence of End Conditions, Leg Geometry, Metallization, and Processing Tempera-tures". *Journal of Electronic Materials*. 2018; Vol. 47 Issue 10: 6101–6120. DOI: 10.1007/s11664-018-6505-1.

16. Haopeng Song, Kun Song & Cunfa Gao. "Temperature and thermal stress around an elliptic functional defect in a thermoelectric material". *Mechanics of Materials*. 2019; Vol. 130: 58–64. DOI: 10.1016/j.mechmat.2019.01.008.

17. Jurgensmeyer, A. L. "High Efficiency Thermoelectric Devices Fabricated Using Quantum Well Confinement Techniques". *Colorado State University.* 2011. 54 p. – Access mode: https://mountainscholar.org/bitstream/handle/10217/51877/Jurgensmeyer_colostate_0053N_10583.pdf?sequence=1. – (Active link: 07.11.20200).

18. Rowe, D. M. "Thermoelectrics and its Energy Harvesting". Materials, Preparation and Characterization in Thermoelectrics. *Boca Raton: CRC Press.* 2012. 544 p.

19. Farshad Tajeddini, Mohammad Eslami & NazaninEtaati. "Thermodynamic analysis and optimization of water harvesting from air using thermoelectric coolers". *Journal Energy conversion and management*. 2018; Vol.174:417–429. DOI: 10.1016/j.enconman. 2018.08.045.

20. Zaykov, V., Mescheryakov, V. & Zhuravlov, Yu. “Analysis of the possibility to control of the inertia of the thermoelectric cooler”. *Eastern–European Journal of Enterprise Technologies*. 2017. 6/8 (90): 17–24. DOI: 10.15587/1729-4061.2017.116005.

21. Mani Ranjan & Tanmoy Maiti. “Device modeling and performance optimization of thermoelectric generators under isothermal and isoflux heat source condition”. J*ournal of Power Sources*. December 2020; Vol. 480, 31. DOI: https://doi.org/10.1016/j.jpowsour.2020.228867.

22. Ugur Erturun, Karla Mossi. “A Feasibility Investigation on Improving Structural Integrity of Thermoelectric Modules with Varying Geometry”. *Smart Materials*, *Adaptive Structures and Intelligent Systems*. 2012. p.939–945. DOI: 10.1115/SMASIS2012–8247.

23. Zaykov, V., Mescheryakov, V., Zhuravlov, Yu. & Mescheryakov, D. “Analysis of dynamics and prediction of reliability indicators of a cooling thermoelement with the predefined geometry of branches”, *Eastern–European Journal of Enterprise Technologies*, 2018; No. 5/8(95): 41–51. DOI: https://doi.org/10.15587/1729-4061.2018.123890.

24. Corson, L., Cramer, Hsin Wang & Kaka Ma. “Performance of Functionally Graded Thermoelectric Materials and Devices: A Review”. *Journal of Electronic Materials*. 2018; No.9: 5122–5132. DOI: org/10.1007/s11664-018-6402-7.

25. Corson, L. Cramer, Wenjie Li, Zhi-He Jin, Jue Wang, Kaka Ma & Troy B. Holland. “Techniques for Mitigating Thermal Fatigue Degradation, Controlling Efficiency, and Extending Lifetime in a ZnO Thermoelectric Using Grain Size Gradient FGMs”. *Journal of Electronic Materials.* 2017; No.1: 866–872. DOI: https://doi.org/10.1007/s11664-017-5879-9.

26. Vladimir Zaykov, Vladimir Mescheryakov & Yurii Zhuravlov. “Designing a singlecascade thermoelectric cooler with the predefined time to enter a stationary mode of operation*”*. *Eastern-European Journal of Enterprise Technologies*, 2019; No. 8(102): 38–46. DOI: https://doi.org/10.15587/1729-4061.2019.184400.

27. Zaykov, V. P., Mescheryakov, V. I. & Zhuravlov, Yu. I. “Analysis of dynamic and reliability indicators of a thermoelectric cooler at minimization of a complex of three basic parameters”. *Herald of Advanced Information Technology.* 2020; Vol.3 No.3: 174–184. DOI: 10.15276/hait.03.2020.6.

28. Zaykov, V., Mescheryakov, V. & Zhuravlov, Yu. “Developing a model to control the thermal mode of thermoelectric devices by minimizing the set of three basic parameters”. *Eastern–European Journal of Enterprise Technologies*. 2020; No. 5/8(107): 63–73. DOI: 10.15587/1729-4061.2020.214154.

29. Zaykov, V., Mescheryakov, V., Gnatovskya, A. & Zhuravlov, Yu. “Influence of efficiency of pre-product on reliability of thermo-electric cooling devices indexes”. [Part of I]: One factorable TEC. *Technology and constructing in an electronic apparatus.* 2015; No.1: 44–48 (in Russian). DOI: 10.15222/TKEA2015.1.44.

30. Vladimir Zaykov, Vladimir Mescheryakov & Yurii Zhuravlov. “Studying the influence of the thermoelectric materials parameters on the dynamics of singlecascade cooling devices”. *Eastern-European Journal of Enterprise Technologies* 2020; No. 8(103): 6–18. DOI: org/10.15587/1729-4061.2020.195730.

Conflicts of Interest: the authors declare no conflict of interest.

Received 28.09.2020
Received after revision 04.11.2020
Accepted 20.11.2020

DOI: 10.15276/hait.04.2020.5
УДК 004.621.39

УПРАВЛІННЯ ТЕПЛОВИМ РЕЖИМОМ ТЕРМОЕЛЕКТРИЧНОГО ОХОЛОДЖУЮЧОГО ПРИСТРОЮ ПРИЙМАЛЬНО-ПЕРЕДАЮЧИХ ЕЛЕМЕНТІВ БОРТОВИХ ІНФОРМАЦІЙНИХ СИСТЕМ

Володимир Петрович Зайков[1)]
ORCID: http://orcid.org/0000-0002-4078-3519, gradan@i.ua
Володимир Іванович Мещеряков[2)]
ORCID: http://orcid.org/0000-0003-0499-827X, gradan@ua.fm

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)

Юрій Іванович Журавльов[3)]
ORCID: http://orcid.org/0000-0001-7342-1031, ivanovich1zh@gmail.com
[1)] Інститут «ШТОРМ», вул. Героїв Крут, 21, Одеса, Україна
[2)] Одеський державний екологічний університет, вул. Львівська, 15, Одеса, Україна
[3)] Національний університет «Одеська морська академія», вул. Дідріхсона, 8, Одеса, Україна

АНОТАЦІЯ

Визначальними вимогами до систем забезпечення теплових режимів приймально-передаючих елементів бортових інформаційних систем являються показники надійності і динамічні характеристики. Робота представляє собою продовження досліджень динамічних характеристик термоелектричних охолоджувачів, направлених на аналіз впливу перепадів температури, струмових режимів, конструктивних параметрів пристрою і фізичних параметрів матеріалу термоелементів на сталу часу. В статті проаналізовано вплив тепловідвідної спроможності радіатору на динамічні характеристики, енергетичні і показники надійності однокаскадного термоелектричного охолоджувача. Розроблена динамічна модель термоелектричного охолоджувача з урахуванням масогабаритних параметрів радіатору, які зв'язують основні енергетичні показники охолоджувача з тепловідвідною спроможністю радіатору, робочими струмами, величиною теплового навантаження і відносним перепадом температур. Аналіз динамічної моделі показав, що з ростом тепловідвідної спроможності радіатору при заданому тепловому навантаженні і різних струмових режимах змінюються основні показники охолоджувача. Зменшується необхідна кількість термоелементів, споживана потужність, час виходу на стаціонарний режим, відносна інтенсивність відмов. З ростом відносного робочого струму час виходу на стаціонарний режим роботи зменшується для різних значень тепловідвідної спроможності радіатору. Показано, що мінімальний час виходу на стаціонарний режим роботи забезпечується в режимі максимальної холодопродуктивності. Дослідження проведені при різних значеннях тепловідвідної спроможності радіатору в робочому діапазоні перепадів температур і геометрії термоелементів. Показана можливість мінімізації тепловідвідної поверхні радіатору при різних струмових режимах роботи і зв'язок з основними параметрами, показниками надійності і часом виходу на стаціонарний режим роботи. Порівняльний аналіз масогабаритних характеристик, основних параметрів, показників надійності і динаміки функціонування при раціональному проектування дає можливість вибору компромісних рішень з урахуванням значущості кожного з обмежувальних факторів.

Ключові слова: термоелектричний охолоджувач; динамічні характеристики; тепловідвідна спроможність радіатору; показники надійності

DOI: 10.15276/hait.04.2020.5
УДК 004.621.39

УПРАВЛЕНИЕ ТЕПЛОВЫМ РЕЖИМОМ ТЕРМОЭЛЕКТРИЧЕСКИХ ОХЛАЖДАЮЩИХ УСТРОЙСТВ ПРИЕМО-ПЕРЕДАЮЩИХ ЭЛЕМЕНТОВ БОРТОВЫХ ИНФОРМАЦИОННЫХ СИСТЕМ

Владимир Петрович Зайков[1)]
ORCID: http://orcid.org/0000-0002-4078-3519, gradan@i.ua
Владимир Иванович Мещеряков[2)]
ORCID: http://orcid.org/0000-0003-0499-827X, gradan@ua.fm
Юрий Иванович Журавлев[3)]
ORCID: http://orcid.org/0000-0001-7342-1031, ivanovich1zh@gmail.com
[1)]Институт «ШТОРМ», ул. Героев Крут, 21, Одесса, Украина
[2)]Одесский государственный экологический университет, ул. Львовская, 15, Одесса, Украина
[3)]Национальный университет «Одесская морская академия», ул. Дидрихсона, 8, Одесса, Украина

АННОТАЦИЯ

Определяющими требованиями к системам обеспечения тепловых режимов приемо-передающих элементов бортовых информационных систем являются показатели надежности и динамические характеристики. Работа представляет собой продолжение исследований динамических характеристик термоэлектрических охладителей, направленных на анализ влияния перепадов температуры, токовых режимов работы, конструктивных параметров устройства и физических параметров материала термоэлементов на постоянную времени. В статье проанализировано влияние теплоотводящей способности радиатора на динамические характеристики, энергетические и надежностные показатели однокаскадного термоэлектрического охладителя. Разработана динамическая модель термоэлектрического охладителя с учетом массогабаритных параметров радиатора, которые связывают основные энергетические показатели охладителя с теплоотводящей способностью радиатора, рабочими токами, величиной тепловой нагрузкой и относительным перепадом температур. Анализ динамической модели показывает, что с ростом теплоотводящей способности радиатора при заданной тепловой нагрузке и различных токовых режимах изменяются основные показатели охладителя. Уменьшается необходимое количество термоэлементов, потребляемая мощность, время выхода на стационарный режим, относительная интенсивность отказов. С ростом относительного рабочего тока время выхода на стационарный режим работы уменьшается для различных значений теплоотводящей способности радиатора. Показано, что минимальное время выхода на стационарный режим работы обеспечивается в режиме максимальной холодопроизводительности. Исследования проведены при различных значениях теплоотводящей способности радиатора в рабочем диапазоне перепадов температур и геометрии термоэлементов. Показана возможность минимизации теплоотводящей поверхности радиатора при различных токовых режимах работы и связь с основными параметрами, показателями надежности и временем выхода на стационарный режим работы. Сравнительный анализ массогабаритных характеристик, основных параметров, показателей надежности и динамики функционирования при рациональном проектировании дает возможность выбора компромиссных решений с учетом весомости каждого из ограничительных факторов.

Ключевые слова: термоэлектрический охладитель; динамические характеристики; теплоотводящая способность радиатора; показатели надежности

ABOUT THE AUTHORS

Vladimir Petrovich Zaykov – Candidate of Technical Sciences (1990), Head of Sector Research Institute “STORM”. Odessa. Ukraine
***Research field*:** Reliability and Dynamic Descriptions of Thermo-Electric Cooling Devices; Design; Planning of the Systems of Providing of the Thermal Modes of Electronic Apparatus

Володимир Петрович Зайков – кандидат технічних наук (1990), начальник сектору науково – дослідного інституту «ШТОРМ». Одеса. Україна

Владимир Петрович Зайков – кандидат технических наук (1990), начальник сектора научно-исследовательского института «ШТОРМ». Одесса. Украина

Vladimir Ivanovich Mescheryakov – Doctor of Technical Sciences (2004), Professor, Head of Department, Department of Informatics Odessa State Environmental University. Odessa. Ukraine
***Research field*:** **R**eliability and Dynamic Descriptions of Thermo-Electric Cooling Devices; Design of Power Processes; Biotechnical Informative Systems

Володимир Іванович Мещеряков – доктор технічних наук (2004), зав. кафедри Інформатики Одеського державного екологічного університету. Одеса. Україна

Владимир Иванович Мещеряков – доктор технических наук (2004), зав. кафедрой Информатики Одесского государственного экологического университета. Одесса. Украина

Yurii Ivanovich Zhuravlov – Candidate of Technical Sciences (2016), Associate Professor Department of Technology of Materials and Ship Repair National University “Odessa Maritime Academy”. Odessa. Ukraine
***Research field*:** **R**eliability and Dynamic Descriptions of Thermo-Electric Cooling Devices; Reliability and Reparability of Ship Equipment

Юрій Іванович Журавльов – кандидат технічних наук (2016), доцент кафедри Технології матеріалів і судноремонту Національного університету «Одеська морська академія». Одеса. Україна

Юрий Иванович Журавлев – кандидат технических наук (2016), доцент кафедры Технологии материалов и судоремонта Национального университета «Одесская морская академия». Одесса. Украина

ISSN 2663-0176 (Print)
ISSN 2663-7731 (Online)