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Analysis of dynamic and reliability indicators of a thermoelectric cooler at minimization of a complex of three basic parameters

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ABSTRACT

The inclusion of a thermoelectric cooler in the thermal mode control circuit of a heat-loaded element operating in a pulsed mode makes the requirements for dynamic characteristics and reliability indicators more stringent. The main parameters of thermoelectric devices that provide a given thermal mode of operation include: the number of thermoelements, the magnitude of the operating current and the heat dissipation capacity of the radiator. With the optimal design of a thermoelectric cooler, one should strive to reduce the number of thermoelements, the magnitude of the operating current and the heat sink surface of the radiator. With a given geometry of thermoelement legs, a decrease in the number of thermoelements leads to a decrease in the specified cooling capacity or heat load. This can be compensated by an increase in the operating current, and, conversely, a decrease in the operating current leads to the need to increase the number of thermoelements, which affects the reliability indicators. The possibility of controlling the thermal regime of single-stage thermoelectric cooling devices while minimizing this complex is considered. The number of thermoelements, the magnitude of the operating current and the heat dissipation capacity of the radiator were investigated in the range of temperature drops from 10K to 60K at a thermal load of 0.5 W for different geometry of thermoelement legs. A relationship is obtained to determine the optimal relative operating current corresponding to the minimum of the complex of the number of thermoelements, the value of the operating current and the heat sink surface of the radiator. The analysis of the model revealed that with an increase in the relative operating current for different geometry of thermoelement legs, the required number of thermo-elements decreases, the time to reach a stationary mode, the relative value of the failure rate increases, and the probability of failure-free operation decreases. The functional dependence of the coefficient of performance has a maximum; the heat sink capacity of the radiator has a minimum, and does not depend on the geometry of thermoelements and the amount of energy expended. It is shown that the use of the current mode of operation at the minimum value of the complex provides optimal control of the thermal mode of the thermoelectric cooler with a minimum amount of consumed energy.

Keywords: thermoelectric cooler; thermoelements; operating current; heat dissipation capacity of the radiator; failure rate; time to reach the mode

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INTRODUCTION. FORMULATION OF THE PROBLEM

Modeling is a necessary stage in the creation of thermoelectric systems for providing thermal conditions for electronic components operating in heat-loaded conditions. At the same time, it is important to highlight the most significant parameters and features that affect the integral characteristics of coolers, such as reliability indicators and dynamics that determine the potential capabilities of products. These include: the number of thermocouples, the operating current and the cooling capacity of the radiator. Since thermoelements are connected in series, their increase leads to an increase in the failure rate, however, it allows to reduce the operating current, the growth of which, in turn, worsens the reliability indicators. The cooling capacity of the radiator affects the weight and size characteristics and load capacity, i.e. all indicators are linked. The use of a complex of three parameters is proposed, a relationship is obtained to determine the optimal relative operating current, a solution corresponding to the minimum of the complex. The cooling capacity of the radiator affects the weight and size characteristics and load capacities, i.e. all indicators are linked. The use of a complex of three parameters is proposed, a relationship is obtained to determine

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the optimal relative operating current, a solution corresponding to the minimum of the complex.

In work [1] it is shown that the functioning of heat-loaded equipment is impossible without systems for ensuring thermal conditions. Taking into account the difference in heat release and the dynamics of heat sources, such as semiconductor lasers, ultrasonic emitters, receivers of intense radiation, put forward new requirements for systems for ensuring thermal conditions [2]. The need to maintain thermal conditions puts heat flux removal systems in conditions similar to heat-loaded elements in terms of dynamics and reliability [3]. From the point of view of the theory of reliability, the heat-loaded element and the heat removal system are connected in series; the resulting probability of failure-free operation is equal to the product of the indicators of the components [4]. If we take into account the requirements for the weight and size parameters of onboard systems, then there is practically no alternative to thermoelectric coolers at present [5-6]. The coordination of the energy relationship of the heat-loaded element with the heat extraction system is considered in [7], where, on the basis of the thermodynamic balance, interaction surfaces and thermophysical parameters of materials are taken into account [8]. Since the research was carried out only for static modes, more severe operating conditions required additional research aimed at increasing the reliability indicators over the entire life cycle of thermoelectric devices [9]. Particular attention is paid to the operation phase, during which the influence of mechanical and climatic conditions of operation, which have a negative impact on the reliability indicators of the cooler, was analyzed [10–11]. Further studies are aimed at the influence of the design parameters of thermoelectric coolers and the structural integrity of the modules on the reliability indicators, which made it possible to optimize the indicators by choosing the geometric parameters [12]. Dynamic characteristics are extremely important when thermoelectric coolers are included in the feedback loop [13]. This is due to the fact that in the switching mode the reliability indices fall by an order of magnitude and the cyclic mode of transition from cooling to heating of the thermoelectric device is used as a test for reliability [14–15]. The control mode for a thermoelectric cooler assumes taking into account both dynamic and reliability characteristics of coolers [16]. An increase in the temperature gradient leads to an increase in the linear expansion of the junctions of inhomogeneous materials, therefore, to a decrease in reliability indicators, which is a significant problem. The work [17] is devoted to the study of the relationship between the reliability indicators of thermoelectric coolers with dynamic characteristics. The questions of influence on the reliability indicators and dynamic characteristics of the design parameters of coolers remained unsolved. Further research is aimed at studying the effect of design parameters in the operating range of current modes and temperature drops [18]. In [19], the influence of the physical parameters of the material of thermoelements on the reliability indices was investigated and the possibility of the effective influence of these parameters on the operational indices of the cooler was shown. The problem is to identify the most significant indicators for control that affect the reliability and dynamic characteristics in the range of energy modes of operation of thermoelectric coolers.

The purpose of this work is an analysis of the dynamic and reliability indicators of a single-stage thermoelectric cooler, while minimizing the complex: the number of thermoelements, operating current and heat dissipation capacity of the radiator.

To achieve this goal, it is necessary to solve the following tasks:

– to develop an analytical model for the connection of the complex: the number of thermoelements, operating current, heat dissipation capacity of the radiator with the energy performance of the thermoelectric cooler;

– to analyze the relationship between the operating current and the number and geometry of thermoelements, the time to reach the stationary mode, and the failure rate.

ANALYTICAL MODEL OF THE RELATIONSHIP OF THE RELATIVE CURRENT WITH THE COMPLEX

The main parameters of thermoelectric devices (TEC) that provide a given thermal mode of operation include: the number of thermoelements, the magnitude of the operating current I and the heat dissipation capacity of the radiator αF. With the optimal design of the TEC, one should strive to reduce n, I, and αF. With a given geometry of thermoelement legs (l/S), a decrease in the number of thermoelements leads to a decrease in the specified cooling capacity Q_0 or heat load. This can be compensated for by increasing the operating current I, but an increase in the operating current I leads to an increase in the failure rate. The possibility of controlling the thermal regime of single-stage thermoelectric coolers while minimizing the complex $(nI\alpha F)_{\min}$ is considered. By varying the number n of thermoelements, the magnitude of the operating current I and the heat dissipation capacity αF of the radiator in the range of temperature drops from ΔT = 10 K to ΔT = 60 K and heat load Q_0 = 0.5 W for different geometries of thermoelement legs.

The number of thermoelements n of a single-stage TEC can be determined from [20]:

$$n = \frac{Q_0}{I^2_{\max K} R_K (2B_K - B_K^2 - \Theta)}, \qquad (1)$$

where: Q_0 is the value of the heat load, W;

$I_{\max K} = \frac{\bar{e}_K T_0}{R_K}$ is the maximum operating current at the end of the cooling process, A;

$\bar{e}_K$ – average value of thermoEMF coefficient of thermoelement leg at the end of the cooling process, V / K;

$R_K = \frac{l}{\bar{\sigma}_K S}$ – electrical resistance of the thermoelement leg at the end of the cooling process, Ohm;

l and S – respectively, the height and cross-sectional area of the thermoelement leg;

$\bar{\sigma}_K$ – average value of electrical conductivity of the thermoelement leg at the end of the cooling process, S / cm;

T_0 – heat-absorbing junction temperature, K;

$B_K = \frac{I}{I_{\max K}}$ – relative operating current at the end of the cooling process;

I – working current, A;

$\Theta = \frac{T - T_0}{\Delta T_{\max}}$ – relative temperature difference;

T – heat-generating junction temperature, K;

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

$\bar{Z}$ – average value of efficiency of initial thermoelectric materials in a module, 1 / K.

The value of the heat sink capacity of the radiator can be determined from the ratio [20]:

$$\alpha F = \frac{Q_0 + W}{T - T_c} = \frac{Q_0 (1 + 1/E)}{\Delta T_{\max} (\Theta - \Theta_c)}, \qquad (2)$$

where: α is the heat transfer coefficient, $\frac{W}{sm^2 \cdot K}$;

F – radiator surface area, sm^2;

$\Theta = \frac{T_c - T_0}{\Delta T_{\max}}$ – relative temperature difference with the environment;

T_c – medium temperature, K.

The coefficient of performance E can be written as

$$E = \frac{2B - B^2 - \Theta}{2B(B + \frac{\Delta T_{\max}}{T_0}\Theta)} = \frac{Q_0}{W_f}. \qquad (3)$$

The power consumption of the W_K TEC can be determined from the expression:

$$W_f = 2nI^2_{\max K} R_K B_K (B_K + \frac{\Delta T_{\max}}{T}\Theta). \qquad (4)$$

Voltage drop U_K

$$U_K = \frac{W_K}{I}. \qquad (5)$$

The relative magnitude of the failure rate λ / λ_0 can be determined from the expression [20]:

$$\lambda / \lambda_0 = nB_K^2 (\Theta + C) \frac{(B_K + \frac{\Delta T_{\max}}{T_0}\Theta)^2}{(1 + \frac{\Delta T_{\max}}{T_0}\Theta)^2} K_T, \qquad (6)$$

where: $C = \frac{Q_0}{nI^2_{\max K} R_K}$ – relative heat load;

K_T – significant coefficient of reduced temperatures.

The probability of failure-free operation P of the TEC can be determined from the expression [20]:

$$P = \exp[-\lambda t], \qquad (7)$$

where t – assigned resource, h.

We will use the relation to determine the time of reaching the stationary operating mode τ [18]:

$$\tau = \frac{\sum_i m_i C_i}{K_K \left(1 + 2B_K \frac{\Delta T_{\max}}{T_0}\right)} \ln \frac{\gamma B_H (2 - B_s)}{2B_K - B_K^2 - \Theta}, \qquad (8)$$

where: $\gamma = \frac{I^2_{\max H} R_H}{I^2_{\max K} R_K}$,

$\sum_i m_i C_i$ – the total value of the product of the heat capacity and the mass of the constituent structural technological elements on the heat-absorbing junction of the module at a given l / S;

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R_H – electrical resistance of the thermoelement branch at the beginning of the cooling process, Ohm;

$B_H = \dfrac{I}{I_{\max H}}$ – relative operating current at the beginning $\tau = 0$ of the cooling process;

$I_{\max H} = \dfrac{e_H \bar{T}}{R_H}$ – maximum operating current at the beginning of the cooling process, $\tau = 0$.

Provided that the currents are equal at the beginning and at the end of the cooling process:

$I = B_K I_{\max K} = B_H I_{\max H}$,

Then the expression $(nI\alpha F)$ for the complex can be written in the form using (1) and (2):

$$K = (nI\alpha F) = \frac{\dfrac{Q_0^2 B_K [2B_K(1+\dfrac{\Delta T_{\max}}{T_0}\Theta) + B_K^2 - \Theta]}{T_0}}{I_{\max K} R_K \Delta T_{\max} (2B_K - B_K^2 - \Theta)^2 (\Theta - \Theta_c)} \quad (10)$$

From the condition $\dfrac{dK}{dB_f} = 0$, we obtain the relations for determining the optimal value of the relative operating current B_{opt} corresponding to the minimum value of the complex $(nI\alpha F)_{\min}$:

$$B_{opt}^4 + 2B_{opt}^3(3 + 2\frac{\Delta T_{\max}}{T_0}\Theta) - 6B_{opt}^2\Theta - 2B_{opt}\Theta(1 + 2\frac{\Delta T_{\max}}{T_0}\Theta) + \Theta^2 = 0 . \quad (11)$$

MODEL ANALYSIS

Calculation results of the main parameters, reliability indicators, time to reach the stationary operating mode of a single-stage TEC at ΔT = 40K, Q_0 = 0.5W of various geometry of thermoelement legs l/S = 4,5; 10; 20; 40; ($l = 4mm = Const$; $S = 3\times 3\ mm^2$; $S = 2\times 2\ mm^2$; $S = 1{,}4\times 1{,}4\ mm^2$; $S = 1\times 1\ mm^2$) given in the *Table 1*.

Table 1

The results of calculating the main parameters and reliability indicators for

$T = 300\,K$; $\Delta T = 40\,K$; $\Delta T_{\max} = 79{,}8\,K$; $\Theta = 0{,}5$; $Q_0 = 0{,}5\,W$; $T - T_0 = 5\,K$

l/S	Режим работы	B	$R\cdot 10^3$	$I_{\max}$	N	n	W	U	E	I	αF	$nI\alpha F$	τ	λ/λ_0	$\lambda\cdot 10^8$	P
	$Q_{0\max}$	1,0			17,9	1,8	2,30	0,21	0,216	11,1	0,56	11,2	7,8	1,6	4,8	0,99955
	$(Q_0/I)_{\max}$	0,707			13,4	2,30	1,46	0,19	0,34	8,0	0,39	7,18	9,2	0,44	1,53	0,99985
4,5	$(nI\alpha F)_{\min}$	0,62	4,55	11,1	13,8	2,51	1,35	0,20		6,9	0,37	6,4	10,2	0,38	1,14	0,99988
	$(Q_0/I^2)_{\max}$	0,50			17,5	4,2	1,36	0,24	0,37	5,6	0,37	8,7	12,9	0,19	0,57	0,999944
	$\lambda_{\min}$	0,40			25,9	6,6	1,62	0,34	0,31	4,8	0,41	13,0	16,0	0,154	0,46	0,999954
	$Q_{0\max}$	1,0			14,7	3,9	2,30	0,46	0,216	5,02	0,56	11,0	6,4	4,0	12,0	0,99880
	$(Q_0/I)_{\max}$	0,707			11,2	4,70	1,46	0,41	0,34	3,6	0,39	6,6	7,7	1,23	3,7	0,99963
10	$(nI\alpha F)_{\min}$	0,62	10,1	5,0	12,0	5,5	1,36	0,44	0,36	3,11	0,37	6,3	8,8	0,83	2,5	0,99975
	$(Q_0/I^2)_{\max}$	0,50			15,0	7,9	1,36	0,54	0,37	2,51	0,362	7,1	11,0	0,48	1,44	0,999861
	$\lambda_{\min}$	0,40			22,7	12,0	1,62	0,81	0,31	2,0	0,414	9,8	14,0	0,36	1,1	0,99990
	$Q_{0\max}$	1,0			13,8	7,9	2,30	0,92	0,216	2,51	0,56	11,1	6,0	6,2	18,5	0,9982
	$(Q_0/I)_{\max}$	0,707			10,8	10,3	1,46	0,81	0,34	1,80	0,39	7,2	7,4	2,0	6,0	0,99941
20	$(nI\alpha F)_{\min}$	0,62	20,2	2,51	12,1	11,0	1,36	0,88	0,365	1,56	0,37	6,4	8,9	1,7	5,1	0,99949
	$(Q_0/I^2)_{\max}$	0,50			14,4	18,3	1,36	1,04	0,37	1,30	0,36	8,6	10,6	0,83	2,5	0,99975
	$\lambda_{\min}$	0,40			21,5	29,3	1,62	1,61	0,31	1,0	0,41	12,0	13,3	0,68	2,04	0,99980
	$Q_{0\max}$	1,0			12,0	16,0	2,3	1,84	0,216	1,25	0,56	11,2	5,2	12,2	36,7	0,9963
	$(Q_0/I)_{\max}$	0,707			9,2	20,8	1,46	1,62	0,34	0,90	0,39	7,3	6,3	4,0	12,0	0,9988
40	$(nI\alpha F)_{\min}$	0,62	40,4	1,25	10,4	22,3	1,37	1,76	0,365	0,78	0,37	5,1	7,6	3,4	10,2	0,99898
	$(Q_0/I^2)_{\max}$	0,50			12,1	37,4	1,36	2,16	0,37	0,63	0,36	8,5	8,9	1,4	4,8	0,99958
	$\lambda_{\min}$	0,40			18,1	59,6	1,62	3,1	0,31	0,53	0,41	13,0	11,2	1,36	4,08	0,99959

Figure 1, curve 2 shows the dependence of the optimal relative operating current B_{opt} corresponding to the minimum of the complex $(nI\alpha F)_{\min}$ on the relative temperature difference Θ.

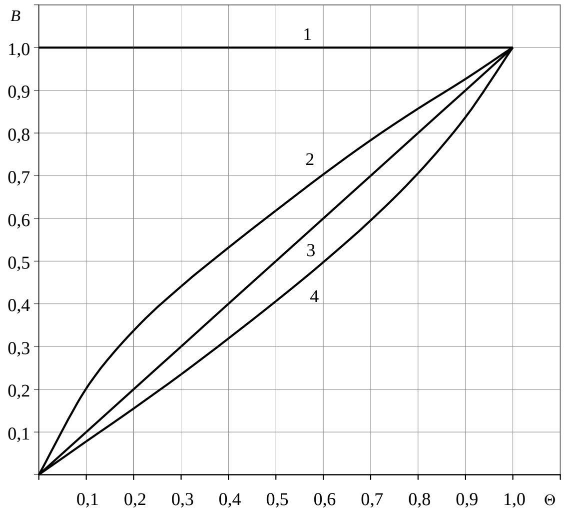

Fig. 1. **Dependence of the relative operating current** B **of the cooling thermoelement on the relative temperature drop** Θ **at for** $T = 300\,K$. **different current operating modes:**

1 – mode $Q_{0\max}$ **; 2 – mode** $(nI\alpha F)_{\min}$ **;**

3 – mode $(Q_0/I^2)_{\max}$ **; 4 – mode** $\lambda_{\min}$

With an increase in the relative operating current B for different geometry of thermoelement legs l/S at ΔT = 40K, T = 300K, Q_0 = 0.5W:

– the number of thermoelements n decreases (*Fig. 2*). With an increase l/S in the ratio, the number n of thermoelements increases at a fixed value B;

– the time to reach the stationary mode τ decreases (*Fig. 3*). With an increase l/S, the time τ to reach the stationary mode of operation decreases at a fixed value of the relative operating current B;

– the functional dependence of the coefficient $E = f(B)$ of performance has a maximum in the mode $(Q_0/I^2)_{\max}$ at B = 0.5 (*Fig. 4*) and does not depend on the geometry of the thermoelement legs;

– the functional dependence of the heat sinking capacity of the radiator $\alpha F = f(B)$ has a minimum in the mode $(Q_0/I^2)_{\max}$ at B = 0.5 (*Fig. 4*) and does not depend on the geometry of the thermoelement legs;

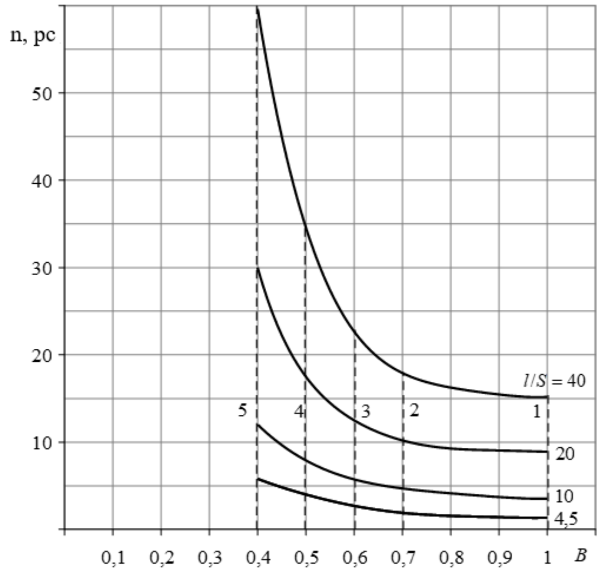

Fig.2. **Dependence of the number of thermoelements** n **of a single-stage TEC on the relative operating current** B **for different geometry of thermoelement legs** l/S **= 4.5; 10; 20; 40 at** $T = 300\,K$ **;** $\Delta T = 40\,K$ **;** $Q_0 = 0{,}5\,W$.

Modes: 1 – $Q_{0\max}$ **; 2 –** $(Q_0/I)_{\max}$ **; 3 –** $(nI\alpha F)_{\min}$ **;**

4 – $(Q_0/I^2)_{\max}$ **; 5 –** $\lambda_{\min}$

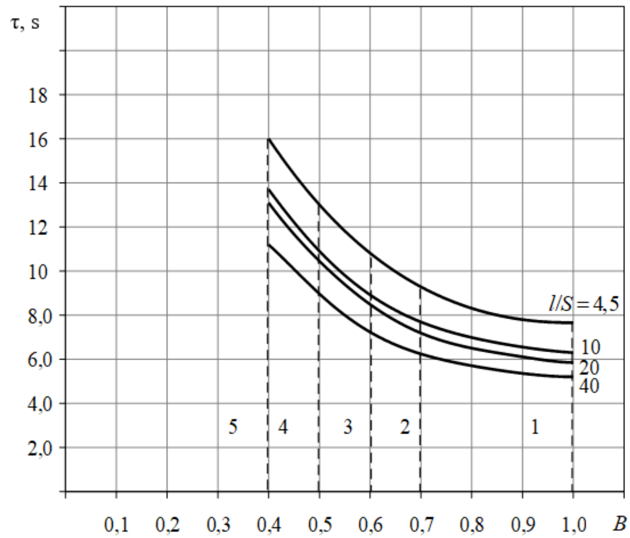

Fig. 3. **Dependence of the time of reaching the stationary operating mode of a single-stage TEC on the relative operating current** B **for different geometry of thermoelement legs** l/S **= 4.5; 10; 20; 40 at** $T = 300\,K$ **;** $\Delta T = 40\,K$ **;** $Q_0 = 0{,}5\,W$.

Operating modes: 1 – $Q_{0\max}$ **; 2 –** $(Q_0/I)_{\max}$ **; 3 –** $(nI\alpha F)_{\min}$ **; 4 –** $(Q_0/I^2)_{\max}$ **; 5 –** $\lambda_{\min}$

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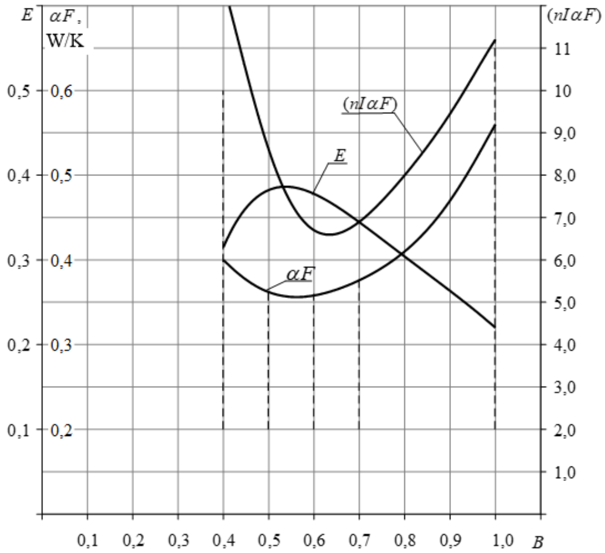

Fig. 4. **Dependence of the coefficient of performance E, heat dissipation capacity of the radiator αF and the value $(nI\alpha F)_{\min}$ of a single-stage TEC on the relative value of the operating current B at $T = 300K$; $\Delta T = 40K$; $Q_0 = 0{,}5W$.**

– the functional dependence of the complex $(nI\alpha F) = f(B)$ has a minimum in the mode $(nI\alpha F)_{\min}$ at $B = 0.62$ (*Fig. 4*) and does not depend on the geometry of the thermoelement legs;

– the relative magnitude of the failure rate λ/λ_0 increases (*Fig. 5*); with an increase in the ratio l/S, the relative failure rate λ/λ_0 increases at a fixed operating current B;

– the probability of failure-free operation P decreases (*Fig. 5*). As the ratio l/S increases, the probability of failure-free operation P decreases at a fixed relative operating current B;

– the functional dependence of the amount of consumed energy $N = f(B)$ has a minimum at $B = 0{,}71$ in the mode $(nI\alpha F)_{\min}$ (*Fig. 6*).

As the ratio l/S increases, the amount of consumed energy N decreases at a fixed relative operating current B. The results of calculating the main parameters, reliability indicators and the time to reach the stationary operating mode $(nI\alpha F)$ in the mode for various temperature drops from ΔT = 10K to ΔT = 60K at l/S = 4.5 cm-1 are shown in *Table 2.*

From the analysis of *Table 2*, it follows that with an increase in the temperature ΔT difference in the mode $(nI\alpha F)_{\min}$ with a given geometry of thermoelements l/S = 4.5 cm^{-1} and Q_0 = 0.5W:

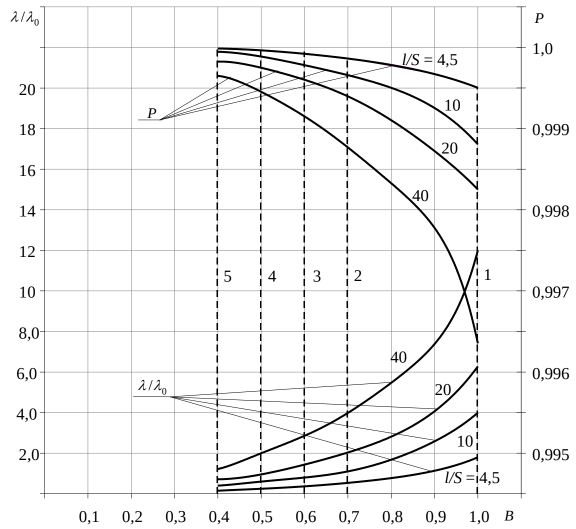

Fig. 5. **Dependence of the relative magnitude of the failure rate λ/λ_0 and the probability of failure-free operation P of a TEC on the relative operating current B for different geometry of thermoelement legs l/S at $(nI\alpha F)_{\min}$; 4 – $(Q_0/I^2)_{\max}$; 5 – $\lambda_{\min}$; $T = 300K$; $\Delta T = 40K$; $Q_0 = 0{,}5W$; $\lambda = 3 \cdot 10^{-8}$ 1 / h; $t = 10^4$ h**

Modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(nI\alpha F)_{\min}$; 4 – $(Q_0/I^2)_{\max}$; 5 – $\lambda_{\min}$

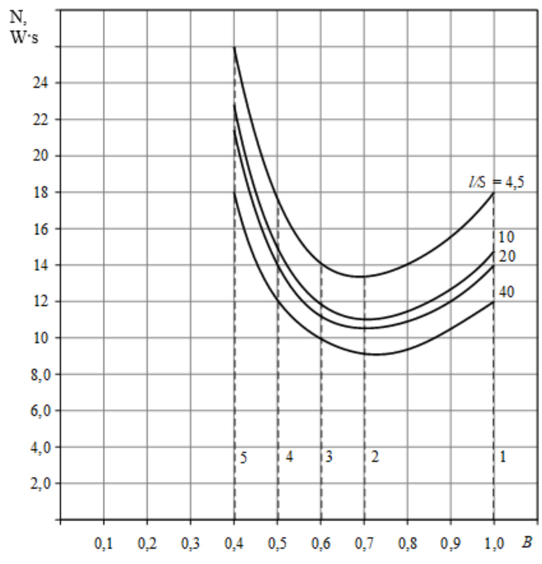

Fig. 6. **Dependence of the amount of consumed energy N of a single-stage TEC on the relative operating current B for different geometry of thermoelement legs l/S at $T = 300K$; $\Delta T = 40K$; $Q_0 = 0{,}5W$; $\lambda = 3 \cdot 10^{-8}$ 1 / h; $t = 10^4$ h.**

Operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(nI\alpha F)_{\min}$; 4 – $(Q_0/I^2)_{\max}$; 5 – $\lambda_{\min}$

Table 2

The results of calculating the main parameters and indicators in the mode $(nI\alpha F)_{\min}$ at T = 300K, Q_0 = 0.5W, l/S = 4.5 cm^{-1}

B	n	I	E	W	τ	B_s	γ	U	$K\cdot10^4$	αF	λ/λ_0	$\lambda\cdot10^8$	P
$\Delta T=10K$; $T_0=290K$; $\Delta T_{\max}=101K$; $\Theta=0{,}1$; $R=4{,}89\cdot10^{-3}Ohm$; $I_{\max}=12{,}0A$													
0,215	2,5	2,58	2,66	0,188	3,8	0,21	1,06	0,073	34,7	0,138	0,0026	0,0079	0,99999921
$\Delta T=20K$; $T_0=280K$; $\Delta T_{\max}=93{,}7K$; $\Theta=0{,}213$; $R=4{,}74\cdot10^{-3}Ohm$; $I_{\max}=11{,}8A$ $\Theta=0{,}213$; $R=4{,}74\cdot10^{-3}$ Ом; $I_{\max}=11{,}8$A													
0,35	2,1	4,1	1,24	0,40	5,7	0,335	1,135	0,10	35,1	0,18	0,023	0,070	0,9999930
$\Delta T=30K$; $T_0=270K$; $\Delta T_{\max}=86{,}8K$; $\Theta=0{,}346$; $R=4{,}69\cdot10^{-3}Ohm$; $I_{\max}=11{,}46A$													
0,48	2,14	5,5	0,68	0,74	7,9	0,45	1,23	0,135	35,1	0,25	0,104	0,31	0,999969
$\Delta T=40K$; $T_0=260K$; $\Delta T_{\max}=79{,}9K$; $\Theta=0{,}50$; $R=4{,}55\cdot10^{-3}Ohm$; $I_{\max}=11{,}1A$													
0,62	2,51	6,9	0,37	1,35	10,2	0,56	1,32	0,20	35,6	0,37	0,39	1,16	0,99988
$\Delta T=50K$; $T_0=250K$; $\Delta T_{\max}=73{,}1K$; $\Theta=0{,}684$; $R=4{,}41\cdot10^{-3}Ohm$; $I_{\max}=10{,}9A$													
0,77	3,7	8,4	0,18	2,84	14,0	0,70	1,43	0,34	35,6	0,67	1,4	4,2	0,99958
$\Delta T=60K$; $T_0=240K$; $\Delta T_{\max}=66{,}8K$; $\Theta=0{,}90$; $R=4{,}33\cdot10^{-3}Ohm$; $I_{\max}=10{,}53A$													
0,93	10,6	9,8	0,044	11,3	22,5	0,82	1,547		36,0	2,36	8,4	25,2	0,9975

– the value of the operating current I increases, the refrigerating coefficient E decreases (*Fig. 7*);

– the functional dependence $n = f(\Delta T)$ of the number of thermoelements has a minimum in the mode $(nI\alpha F)_{\min}$ at ΔT = 20K (*Fig. 7);*

– the time τ to reach the stationary operating mode increases (*Fig. 8*);

– the heat dissipation capacity of the radiator αF increases (*Fig. 8*).

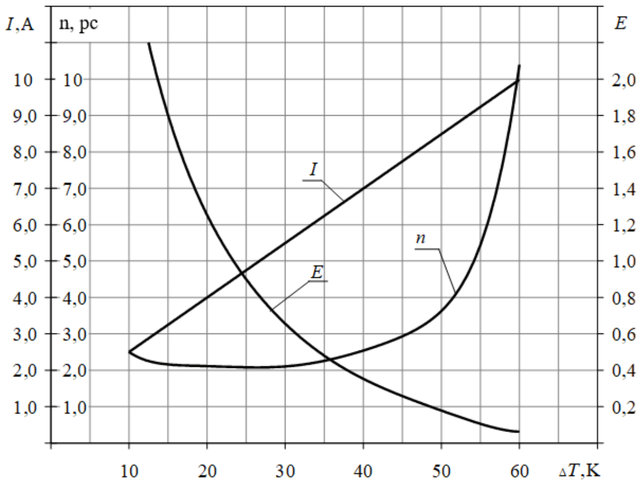

Fig. 7. **Dependence of the number of thermoelements n, the value of the operating current I and the coefficient of performance E of a single-stage TEC on the temperature difference in the mode $(nI\alpha F)_{\min}$ at T = 300K; Q_0 = 0.5W; l/S = 4.5cm^{-1}**

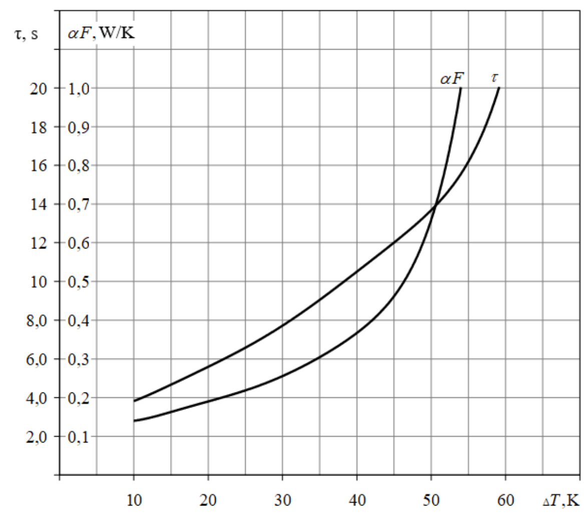

Fig. 8. **Dependence of the time τ of reaching the stationary operating mode, the heat-removing capacity of the radiator αF of a single-stage TEC on the temperature difference ΔT in the mode $(nI\alpha F)_{\min}$ at T = 300K; Q_0 = 0.5W; l/S = 4.5cm^{-1}**

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– the relative failure rate λ/λ_0 increases (*Fig. 9*);
– the relative magnitude of the failure rate increases, especially at large temperature differences (*Fig. 9*);
– the probability of failure-free operation P decreases (*Fig. 9*).

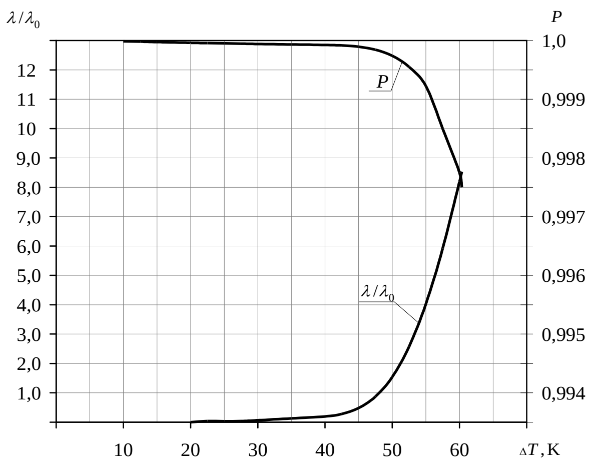

Fig. 9. **Dependence of the relative magnitude of the failure rate λ/λ_0 and the probability of failure-free operation P of a single-stage TEC on the temperature difference ΔT in the mode $(nI\alpha F)_{\min}$ at T = 300K; Q_0 = 0.5W; l/S = 4.5cm^{-1}**

Analysis of *Fig. 8* allows you to select the dynamic mode of operation when controlling the take-off of the heat load, and *Fig. 9* defines the permissible temperature differences for reliable operation.

CONCLUSIONS

1. A relation is obtained for determining the optimal relative current B_{opt} corresponding to the minimum value of the complex $(nI\alpha F)_{\min}$, which provides the possibility of optimized control of the energy characteristics of the thermoelectric cooler according to the criterion taking into account the reliability indicators expressed in terms of the number of thermoelements, the operating current and the weight and size characteristics of the radiator.

2. An optimized analytical model has been developed for controlling the thermal regime of a single-stage thermoelectric cooling device providing thermal regimes of heat-loaded equipment while minimizing a complex consisting of three main parameters $(nI\alpha F)$ in the range of temperature drops from ΔT = 10K to ΔT = 60K at a stationary heat load Q_0 = 0.5W.

3. The use of the current mode $(nI\alpha F)_{\min}$ of operation for controlling the thermal mode of a single-stage thermoelectric device makes it possible to provide a minimum amount of consumed energy, which is important for on-board information systems, where this indicator, along with the weight and size characteristics, is critical.

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Аналіз динамічних і надійнісних показників термоелектричного охолоджувача при мінімізації комплексу з трьох основних параметрів

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АНОТАЦІЯ

Включення термоелектричного охолоджувача в ланцюг управління тепловим режимом теплонавантаженого елементу, який працює в імпульсному режимі, посилює вимоги до динамічних характеристик і показників надійності. К числу основних параметрів термоелектричних пристроїв, що забезпечують заданий тепловий режим функціонування, належать: кількість термоелементів, величина робочого струму і тепловідвідна здатність радіатора. При оптимальному проектуванні термоелектричного охолоджувача належить прагнути до зменшення кількості термоелементів, величини робочого струму і тепловідвідної поверхні радіатора. При заданій геометрії гілок термоелементів зменшення кількості гілок термоелементів призводить до зменшення заданої холодопродуктивності або теплового навантаження. Це можливо компенсувати збільшенням робочого струму, і, навпаки, зменшення величини робочого струму призводить до необхідності збільшення кількості термоелементів, що впливає на показники надійності. Розглянута можливість управління тепловим режимом одно каскадних термоелектричних охолоджуючих пристроїв при мінімізації даного комплексу. Змінювалась кількість термоелементів, величина робочого струму від10К до 60К при тепловому навантаженні 0,5 Вт для різної геометрії гілок термоелементів. Одержано співвідношення для визначення оптимального відносно робочого струму, відповідного мінімуму комплексу кількості термоелементів, величини робочого струму і тепло відвідної поверхні радіатора. Аналіз моделі виявив, що при зростанні відносного робочого струму для різної геометрії гілок термоелементів зменшується необхідна кількість термоелементів, час виходу на стаціонарний режим, підвищується величина інтенсивності відмов, зменшується вірогідність безвідмовної роботи. Функціональна залежність холодильного коефіцієнту має максимум, тепловідвідна здатність радіатора має мінімум, і не залежать від геометрії термоелементів і кількості використаної енергії. Показано, що використання струмового режиму роботи при мінімальному значенні комплексу забезпечує оптимальне управління тепловим режимом термоелектричного охолоджувача при мінімальної кількості використаної енергії.

Ключові слова: термоелектричний охолоджувач; термоелементи; робочий струм; тепловідвідна здатність радіатору; інтенсивність відмов; час виходу на режим

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Анализ динамических и надежностных показателей термоэлектрического охладителя при минимизации комплекса из трех основных параметров

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АННОТАЦИЯ

Включение термоэлектрического охладителя в цепь управления тепловым режимом теплонагруженного элемента, работающего в импульсном режиме, ужесточает требования к динамическим характеристикам и показателям надежности. К числу основных параметров термоэлектрических устройств, обеспечивающих заданный тепловой режим функционирования, относятся: количество термоэлементов, величина рабочего тока и теплоотводящая способность радиатора. При оптимальном проектировании термоэлектрического охладителя следует стремиться к уменьшению количества термоэлементов, величины рабочего тока и теплоотводящей поверхности радиатора. При заданной геометрии ветвей термоэлементов уменьшение количества термоэлементов приводит к уменьшению заданной холодопроизводительности либо тепловой нагрузки. Это можно компенсировать увеличением рабочего тока, и, наоборот, уменьшение величины рабочего тока приводит к необходимости увеличения количества термоэлементов, что влияет на показатели надежности. Рассмотрена возможность управления тепловым режимом однокаскадных термоэлектрических охлаждающих устройств при минимизации данного комплекса. Исследовалось количество термоэлементов, величина рабочего тока и теплоотводящая способности радиатора в диапазоне перепадов температуры от 10К до 60К при тепловой нагрузке 0,5 Вт для различной геометрии ветвей термоэлементов. Получено соотношение для определения оптимального относительного рабочего тока, соответствующего минимуму комплекса количества термоэлементов, величины рабочего тока и теплоотводящей поверхности радиатора. Анализ модели выявил, что с ростом относительного рабочего тока для различной геометрии ветвей термоэлементов уменьшается необходимое количество термоэлементов, время выхода на стационарный режим, увеличивается относительная величина интенсивности отказов, уменьшается вероятность безотказной работы. Функциональная зависимость холодильного коэффициента имеет максимум, теплоотводящей способности радиатора имеет минимум, и не зависят от геометрии термоэлементов и количества затраченной энергии. Показано, что использование токового режима работы при минимальном значении комплекса обеспечивается оптимальное управление тепловым режимом термоэлектрического охладителя при минимальном количестве затраченной энергии.

Ключевые слова: термоэлектрический охладитель; термоэлементы; рабочий ток; теплоотводящая способность радиатора; интенсивность отказов; время выхода на режим

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