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Parametric approach to improving significant indicators of thermoelectric systems for maintaining thermal conditions

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ABSTRACT

The problem of improving the reliability of complex systems is fundamental, since it is impossible to achieve complete failure-free operation in real systems that interact with the external environment. In modern information systems, increasing the probability of failure-free operation by stabilizing the temperature of critical heat-loaded elements using a thermal control system remains a pressing issue. To solve this problem, a mathematical model of a thermoelectric cooler of a given design has been developed. The model is intended for comparative analysis and assessment of the influence of various combinations of parameters of the initial thermoelectric material of equal efficiency on the main performance indicators of the product under variable current load. The results of calculations of reliability indicators, dynamic and energy characteristics of single-stage thermoelectric coolers, and the geometry of thermoelectric element chains are presented for various combinations of parameters of the initial thermoelectric materials. It is shown that with a rational design of a single-stage thermoelectric cooler, it is possible to select a combination of parameters of the initial material with the same efficiency to reduce the operating current and increase the supply voltage at different thermal loads. Additional means of controlling the parameters of a thermoelectric cooler are the geometry of the thermocouple branches, the physical parameters of the initial thermocouple materials, the operating current, the supply voltage, and the failure rate. Analysis of the research results showed that it is possible to select a combination of raw material parameters that reduces the operating current by an average of 20% and reduces the relative failure rate by up to 40% under otherwise equal conditions.

Keywords: reliability indicators, dynamic characteristics, thermoelectric material, efficiency, current mode

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INTRODUCTION

A distinctive feature of onboard information systems is the spatial heterogeneity of heat load distribution, which is associated with the presence of laser, ultrasonic and microwave emitters, processor and conversion elements, and external heating. Thermoelectric systems for maintaining the thermal conditions of electronic equipment are most suitable for onboard systems, since the executive body – a thermoelectric cooler – is small in size and weight and is invariant to spatial location. Dynamic characteristics and reliability are also important indicators for thermal management systems.

Control approaches can be divided into:

– independent control of each thermoelectric cooler connected to a dedicated heat-loaded element, i.e. an independent distributed control system;

– grouping of heat-loaded elements by proximity to the heat load, in which case the number of control channels is reduced to the number of groups;

– control with electrical parallel and serial connection of coolers, which potentially provides the possibility of reducing the control channels to one or two;

– taking into account the inertia of the coolers, it is possible to sequentially control all independent executive coolers from a single decision-making channel;

– taking into account the cross-connections of heat flows, a device is needed to account for this circumstance when forming the model.

Common to all control approaches are strict requirements for the dynamics and reliability of the thermoelectric cooler, which is located in heat-loaded conditions close to the cooled element.

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LITERATURE REVIEW

Thermal management systems for electronic equipment are an integral part of information systems [1]. Sensory and processing onboard electronic equipment is distributed according to the functional purpose of the object [2]. The use of thermoelectric coolers as actuators significantly reduces the weight and dimensions of the product [3], since the heat dissipation of the elements varies [4]. The requirements for coolers are constantly becoming more stringent [5], therefore research aimed at reducing the failure rate and increasing dynamics and energy efficiency is justified [6]. Product models have been developed to study the relationship between these indicators and design and energy characteristics [7], [8]. However, the proposed models do not show the relationship between reliability indicators and the design and energy characteristics of the cooler [9]. The influence of the design parameters of thermocouples on the reliability indicators of thermoelectric coolers has been studied in [10], and on energy indicators in [11], but these dependencies were considered only for static modes [12]. The antagonism between reliability indicators and cooler dynamics is studied in [13], [14]. Issues related to finding a compromise between dynamics and reliability remains unexplored; their analysis is presented in [15]. Given that the main disadvantage of thermoelectric coolers is their low efficiency, considerable attention has been paid to the creation of new thermoelectric materials [16], [17], [18]. Despite significant efforts, no significant progress has been made in new thermoelectric materials. In addition to thermoelectric efficiency, operational characteristics such as mechanical, climatic, and radiation characteristics are also important [19]. Attempts have been made to improve reliability and energy characteristics based on existing thermoelectric materials [20]. However, questions regarding the influence of thermoelectric materials on the dynamics of thermoelectric coolers remain relevant.

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of this work is to improve the reliability and dynamics of the cooler by taking into account the physical characteristics of the thermocouple material.

To achieve this goal, the following tasks must be solved:

1. Develop a model linking the physical parameters of the thermocouple material with the reliability, dynamics, and energy performance of the thermoelectric cooler.

2. Conduct a comparative analysis of significant parameters and indicators when the thermal load varies from zero to maximum.

COOLER MODEL DEVELOPMENT

When designing highly reliable thermoelectric coolers, the following goals are pursued:

– maximum cooling capacity per thermocouple

– maximum cooling and minimum number of thermocouples in the product;

– reduction of operating current (affects the weight and dimensions of the cooler's power supply);

– increasing the cooling coefficient (reduces power consumption);

– increasing the voltage drop (affects the weight and dimensions of the power supply);

– reducing the time to reach operating mode (improves the dynamic characteristics of the coolers);

– reduction in energy consumption (reduction in energy costs);

– improvement in cooler reliability (reduction in failure rate, and therefore an increase in the probability of trouble-free operation);

– reduction in the heat dissipation capacity of the radiator (affects the weight and dimensions of the product).

Thus, when rationally designing thermoelectric coolers taking into account the above requirements, the developer faces a multifactorial task, the solution to which requires selecting a combination of parameters for the source material, current operating mode, and reliability level.

One of the main methods for ensuring the above requirements and improving the reliability of coolers is the parametric method [19]. The essence of parametric method is to improve the quality of the initial thermoelectric materials, primarily by increasing their efficiency and researching materials with different combinations of parameters such as the thermoelectric coefficient and electrical conductivity.

As global practice has shown, it is currently not possible to significantly increase the efficiency of thermoelectric materials. At the same time, with the same efficiency of the initial thermoelectric materials, it is possible to increase reliability indicators by selecting combinations of parameters such as the thermoelectric coefficient $\bar{e}$ and electrical conductivity $\bar{\sigma}$. It should be noted that using these parameters as the main ones provides fairly complete information about the cooling capabilities of modules assembled on their basis.

The nominal spread of the average values of the specified parameters of the raw materials used in the manufacture of standardized thermoelectric modules lies within the following limits: $\bar{e}$=250-165 μ V/K, $\bar{\sigma}$=550-1500 *Sm/sm* with an efficiency of $\bar{z}$=2.4 10-3 1/K at $\bar{T}$=300 K [20].

The use of $\bar{e}$ and $\bar{\sigma}$ as the main significant parameters of thermoelectric materials provides sufficiently complete information about the cooling capabilities of modules assembled on their basis.

Table 1 shows the possible (experimentally obtained) combinations of parameters of the source materials in the module. These materials will be further distinguished by the number of the combination of parameters *№*. Note that option *№ 3* is a traditional combination of parameters of the initial materials used in the manufacture of thermoelectric modules in mass production.

To calculate the main parameters, reliability indicators, and operating dynamics of a single-stage thermoelectric cooler, we use the following equations [19]:

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

where n is the number of thermocouples; Q_0 is the heat load or heat dissipation power of the cooling object, *W*; I_{maxK} is the maximum operating current; R_K is the electrical resistance of the branch; B is the relative operating current; Θ is the relative temperature difference.

Given the number of thermocouples in the thermoelectric cooler, the relative operating current B_K can be determined from (1):

$$B_K = 1 - \sqrt{1 - \left(\Theta + \frac{Q_0}{nI_{\max}^2 R}\right)} . \qquad (2)$$

Provided that

$$1 - \left(\Theta + \frac{Q_0}{nI_{\max}^2 R}\right) = 0 \qquad (3)$$

it is possible to determine the maximum cooling capacity $Q_{0\max}$ for a given n .

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

$$W_K = 2nI_{\max K}^2 R_K B_K (B_K + \frac{\Delta T_{\max}}{T_0}\Theta) . \qquad (4)$$

Voltage drop U_K

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

Coefficient of performance E

$$E = \frac{Q_0}{W_K} . \qquad (6)$$

The relative value of the failure rate λ/λ_0 can be determined from [19]

$$\frac{\lambda}{\lambda_0} = nB^2(\Theta + c)\frac{\left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2} K_T , \qquad (7)$$

where $c = \frac{Q_0}{nI_{\max}^2 R}$ is the relative heat load; λ_0 =3 10^{-8}1/h is the nominal failure rate; K_T is the significant coefficient of reduced temperatures.

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

$$P = \exp[-\lambda t] , \qquad (8)$$

where t =10^4h is the designated resource.

Table 1. **Combinations of parameters for initial thermoelectric materials**

No.	$\bar{e}$, $\mu V/K$	$\bar{\sigma}$, Sm/sm	$\bar{\chi}$, $W/sm \cdot K$	$\bar{e}^2 \bar{\sigma} \cdot 10^3$, $W/sm \cdot K^2$	$\gamma = \bar{e}^2 \bar{\sigma} T_o^2 \, s/l$, W
1	250	550	14.3	0.344	0.310
2	210	800	14.7	0.353	0.318
3	200	900	15.0	0.360	0.325
4	180	1200	16.0	0.390	0.351
5	165	1500	17.0	0.410	0.370

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The formula for determining the time required to reach steady-state operation τ can be expressed as [15]:

$$\tau = \frac{m_0 c_0 + n \sum_i m_i c_i}{nK(1 + 2B_K \frac{\Delta T_{\max}}{T_0})} \ln \frac{\gamma B_H (2 - B_H)}{eB_K - B_K^2 - \Theta}, \quad (9)$$

where $\gamma = \frac{I_{\max H}^2 R_H}{I_{\max K}^2 R_K}$; $m_0 c_0$ – product of mass and heat capacity of the cooling object. In our case, $m_0 c_0 \rightarrow 0$ (object is absent); $\sum_i m_i c_i$ – total value of the product of heat capacity and mass of the structural and technological elements on the heat-absorbing layer of the module at a given l/S. The index H denotes the initial time moment. The index K denotes the final moment.

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

$$I = B_K I_{\max K} = B_H I_{\max H}. \quad (10)$$

The voltage drop U across the cooler can be written as

$$U = 2nI_{\max K} R_k (B + \frac{\Delta T_{\max}}{T_o} \Theta). \quad (11)$$

The amount of energy expended N can be written as a ratio:

$$N = W\tau. \quad (12)$$

The heat dissipation capacity of a radiator αF can be represented as

$$\alpha F = \frac{Q}{T - T_c}, \quad (13)$$

where $Q = Q_0 + W$ is heat output of the cooler, W; T_c is medium temperature, K.

The results of calculations of the main parameters, reliability indicators, dynamic and energy characteristics using various combinations of parameters of the initial materials in single-stage thermoelectric coolers at a cooling temperature level T_o =260K, environment temperature T_c =290K, heat-generating junction temperature T =300K, thermocouple branch geometry l/s for different heat loads Q_0, are given in Table 2.

It is possible to select combinations of source material parameters with the same efficiency, namely, the thermoelectric power coefficient $\bar{e}$ and electrical conductivity $\bar{\sigma}$, which allow reducing the operating current I, relative failure rate λ/λ_0, increasing the supply voltage U, of a single-stage cooler of the selected design with a fixed geometry of the thermocouple branches l/s at practically unchanged values: cooling coefficient E, time to reach steady-state operation τ, amount of energy consumed N, for different thermal loads Q_0 and current operating modes.

ANALYSIS OF THE MODEL

We will not consider option 2 further, since the main parameters and reliability indicators of a single-stage TEC based on the source material for this option are practically identical to those for option 3 (differing by no more than 1-5 %).

With an increase in the thermal load Q_0 on a single-stage thermoelectric cooler of a given design (n =27, thermocouple branch geometry l/s =10), at a cooling temperature level T_0 =260K, heat-generating junction temperature T =300K, ambient temperature T_c =290K, and using various combinations of source material parameters with the same efficiency:

– relative operating current B (Fig. 1) for various combinations of source material parameters (№ 1, 3, 4, 5);

The maximum cooling capacity $Q_{0\max}$ (B =1.0) (Fig. 1) is at ΔT =40K:

for option № 1 $Q_{0\max}$ =3.2W

for option № 3 $Q_{0\max}$ =3.3W

for option № 4 $Q_{0\max}$ =3.5W

for option № 5 $Q_{0\max}$ =3.7W.

The relative operating current B is the same for different combinations of parameters of source materials № 1, 3, 4, 5 when the thermal load Q_0 changes from Q_0 =0 to $Q_{0\max}$;

– the operating current I increases (Fig. 2) for different combinations of raw material parameters (№ 1, 3, 4, 5).

Table 2. **Estimated values for various options**

Q_0	Mode	B	I	W	E	U	Q_0/n	τ	N	αF	F	λ/λ_0	$\lambda \cdot 10^8$	P
Option № 1. $\bar{T}_0 = 300K$, $\bar{z} = 2.4 \cdot 10^{-3}\ 1/K$, $\bar{e} = 2.5 \cdot 10^{-4}\ V/K$, $\bar{\sigma} = 550\ Sm/sm$, $\bar{\chi} = 14.3 \cdot 10^{-3}\ W/smK$, $T_c = 290K$, $T_0 = 260K$, $T = 300K$, $\Delta T = 40K$, $n = 27\ pcs$, $R = 16.1 \cdot 10^{-3} Ohm$, $I = 3.84A$, $\Theta = 0.50$														
0.0	$Q_0 = 0.0$	0.29	1.12	1.68	0.0	1.50	0.0	-	-	0.17	57	0.18	0.54	0.999947
0.1	F_{max}	0.30	1.17	1.8	0.056	1.53	0.0037	39.6	71	0.19	63.0	0.21	0.62	0.999938
0.5	L_{max}	0.35	1.35	2.27	0.22	1.68	0.0185	23.1	52	0.28	92.0	0.37	1.12	0.99988
1.0	λ_{min}	0.41	1.59	3.0	0.33	1.89	0.037	16.7	50	0.40	133	0.75	2.24	0.99978
2.0	$(nI \lambda/\lambda_0 \tau)_{min}$	0.56	2.18	5.2	0.38	2.40	0.074	11.0	58	0.72	241	2.8	8.4	0.99916
3.0	$(nI)_{min}$	0.82	3.15	10.3	0.29	3.3	0.111	8.1	84	1.33	443	12.85	38.6	0.9961
3.2	$Q_{0\,max}$	1.0	3.84	14.8	0.216	3.86	0.119	7. 5	111	1.8	600	27.6	82.8	0.99175
Option № 2. $\bar{T}_0 = 300K$, $\bar{z} = 2.4 \cdot 10^{-3}\ 1/K$, $\bar{e} = 2.1 \cdot 10^{-4}\ V/K$, $\bar{\sigma} = 800\ Sm/sm$, $\bar{\chi} = 14.7 \cdot 10^{-3}\ W/smK$, $T_c = 300K$, $\Delta T = 40K$, $n = 27\ pcs$, $R = 11.5 \cdot 10^{-3} Ohm$, $I = 4.57A$, $\Theta = 0.50$														
0.0	$Q_0 = 0.0$	0.29	1.34	17	0.0	1.27	0.0	-	-	0.17	57	0.18	0.54	0.999946
0.1	F_{max}	0.30	1.40	1.8	0.056	1.30	0.0037	36	66	0.19	64	0.21	0.63	0.999937
0.5	L_{max}	0.35	1.60	2.3	0.217	1.4	0.019	21	49	0.28	93	0.37	1.12	0.99988
1.0	λ_{min}	0.41	1.90	3.0	0.33	1.6	0.037	15	47	0.40	133	0.74	2.2	0.99978
2.0	$(nI \lambda/\lambda_0 \tau)_{min}$	0.56	2.6	5.2	0.38	2.0	0.074	10	54	0.72	240	2.7	8.1	0.99919
3.0	$(nI)_{min}$	0.81	3.7	10.0	0.30	2.7	0.111	7.6	76	1.3	443	121	36.2	0.9964
3.2	$Q_{0\,max}$	1.0	4.57	15.0	0.22	3.3	0.12	6. 9	104	1.8	608	27.6	82.8	0.9918
Option № 3. $\bar{T}_0 = 300K$, $\bar{z} = 2.4 \cdot 10^{-3}\ 1/K$, $\bar{e} = 2.0 \cdot 10^{-4}\ V/K$, $\sigma = \bar{900}\ Sm/sm$, $\bar{\chi} = 15.0 \cdot 10^{-3}\ W/smK$, $T_0 = 260K$, $T = 300K$, $\Delta T = 40K$, $n = 27\ pcs$, $R = 10.42 \cdot 10^{-3} Ohm$, $I = 4.84A$, $\Theta = 0.50$														
0.0	$Q_0 = 0.0$	0.29	1.42	1.73	0.0	1.22	0.0	-	-	0.17	58	0.18	0.54	0.999947
0.10	F_{max}	0.30	1.47	1.84	0.054	1.25	0.0037	38	70	0.19	65	0.21	0.63	0.999938
0.50	L_{max}	0.35	1.69	2.32	0.216	1.37	0.0185	19.0	44	0.28	94	0.37	1.1	0.99989
1.0	λ_{min}	0.41	1.98	3.05	0.33	1.54	0.037	16.0	49	0.405	135	0.72	2.17	0.99978
2.0	$(nI \lambda/\lambda_0 \tau)_{min}$	0.557	2.69	5.23	0.38	1.94	0.074	10.7	56	0.72	241	2.6	7.8	0.99922
3.0	$(nI)_{min}$	0.79	3.8	9.8	0.31	2.57	0.111	7.9	78	1.28	427	10.9	32.8	0.9967
3.3	$Q_{0\,max}$	1.0	4.8	15.2	0.216	3.15	0.122	7.2	109	1.85	617	27.6	82.8	0.99175
Option № 4. $\bar{T}_0 = 300K$, $\bar{z} = 2.4 \cdot 10^{-3}\ 1/K$, $\bar{e} = 1.8 \cdot 10^{-4}\ V/K$, $\bar{\sigma} = 1200\ Sm/sm$, $\bar{\chi} = 16.0 \cdot 10^{-3}\ W/smK$, $T_0 = 260K$, $T = 300K$, $\Delta T = 40K$, $n = 27\ pcs$, $R = 7.81 \cdot 10^{-3} Ohm$, $I = 5.79A$, $\Theta = 0.50$														
0.0	$Q_0 = 0.0$	0.29	1.70	1.86	0.0	1.09	0.0	-	-	0.186	62	0.18	0.54	0.999947
0.10	F_{max}	0.30	1.75	1.96	0.051	1.12	0.0037	36.3	71	0.21	69	0.205	0.61	0.999939
0.50	L_{max}	0.34	2.0	2.44	0.205	1.22	0.0185	21.4	52	0.29	98	0.35	1.05	0.999895
1.0	λ_{min}	0.40	2.3	3.15	0.317	1.36	0.037	15.6	49	0.42	138	0.66	2.0	0.99980
2.0	$(nI \lambda/\lambda_0 \tau)_{min}$	0.53	3.1	5.2	0.39	1.68	0.074	10.5	55	0.72	241	2.2	6.6	0.999934
3.0	$(nI)_{min}$	0.73	4.2	9.0	0.33	2.15	0.111	8.0	72	1.2	400	7.8	23.3	0.9977
3.5	$Q_{0\,max}$	1.0	5.8	16.3	0.214	2.8	0.131	6.8	112	2.0	661	27.6	82.8	0.99175

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Table 2. **Continued**

Option № 5. $\bar{T_0} = 300K$, $\bar{z} = 2.4 \cdot 10^{-3}\ 1/K$, $\bar{e} = 1.65 \cdot 10^{-4}\ V/K$, $\bar{\sigma} = 1500\ Sm/sm$, $\bar{\chi} = 17.0 \cdot 10^{-3}\ W/smK$,

$T_0 = 260K, T = 300K, \Delta T = 40K, n = 27\,pcs, R = 6.5 \cdot 10^{-3}\,Ohm, I = 6.5, \Theta = 0.50$

0.0	$Q_0 = 0.0$	0.29	1.9	1.9	0.0	1.0	0.0	-	-	65	0.19	0.18	0.54	0.999947
0.50	F_{max}	0.34	2.2	2.5	0.20	1.14	0.0185	20.4	52	100	0.30	0.34	1.0	0.999897
1.0	λ_{min}	0.40	2.6	3.2	0.31	1.25	0.937	14.9	48	141	0.42	0.63	1.9	0.99981
2.0	$(nI\frac{\lambda}{\lambda_0}\tau)_{min}$	0.52	3.4	5.2	0.39	1.54	0.074	10.1	53	240	0.72	2.0	6.0	0.999998
3.0	$(nI)_{min}$	0.69	4.5	8.7	0.35	1.93	0.111	7.7	67	357	1.1	6.5	19.5	0.99940
3.7	$Q_{0\,max}$	1.0	6.5	17.0	0.22	2.6	0.137	6.4	110	692	2.1	27.4	82.3	0.99805

Source: **compiled by the authors**

The minimum operating current I_{min} is provided for the combination of raw material parameters № 1. The operating current I decreases from option № 5 to option № 1;

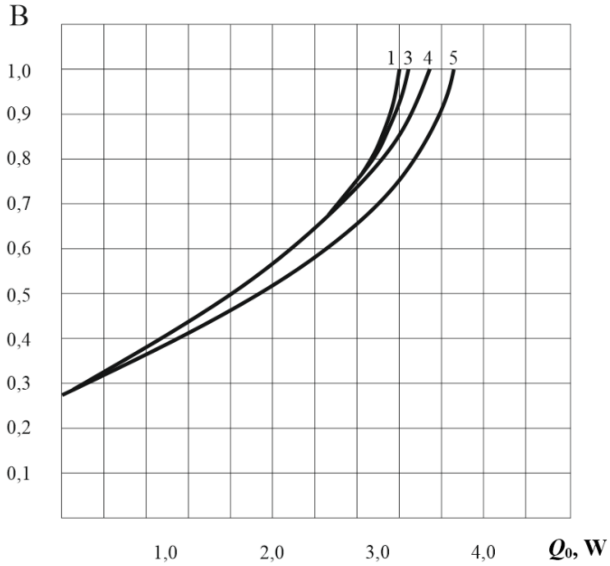

Fig. 1**. Dependence of the relative operating current B of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4 of equal efficiency at T_0=260K, T=300K, n=27, l/s=10**

Source: **compiled by the authors**

– the functional dependence of the cooling coefficient $E = f(Q_0)$ on the heat load Q_0 has a maximum E_{max}=0.38 at Q_0=2.0W (Fig. 3). The cooling coefficient E is practically the same for different combinations of parameters of the initial material № 1, 3, 4, 5 in the range of thermal load Q_0 changes from Q_0=0.04 to Q_0=2.0W when changing from Q_0=3.0W to Q_0=3.7W, the cooling capacity of the cooler increases from variant № 1 to variant № 5;

– the voltage drop U increases (Fig. 4) for various combinations of initial material № 1, 3, 4, 5. The voltage drop U increases from option № 5 to option № 1. The maximum voltage drop U_{max} is achieved when using option № 1;

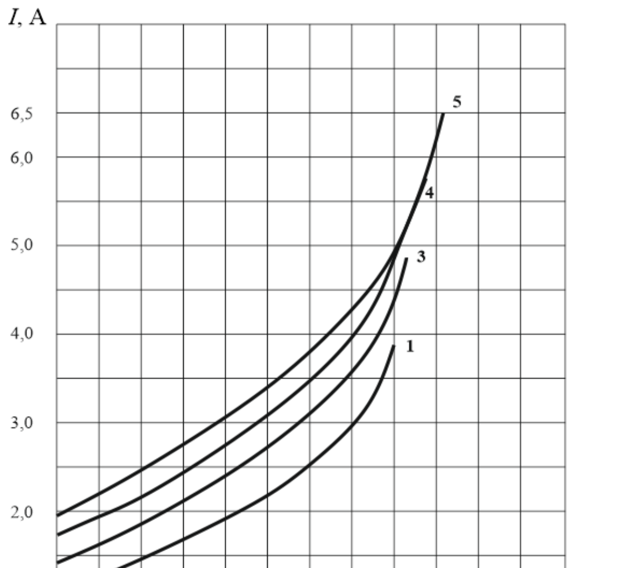

*Fig. 2***. Dependence of the operating current value I of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4 of equal efficiency at**

T_0=260K; T=300K; n=27; l/s=10

Source: **compiled by the authors**

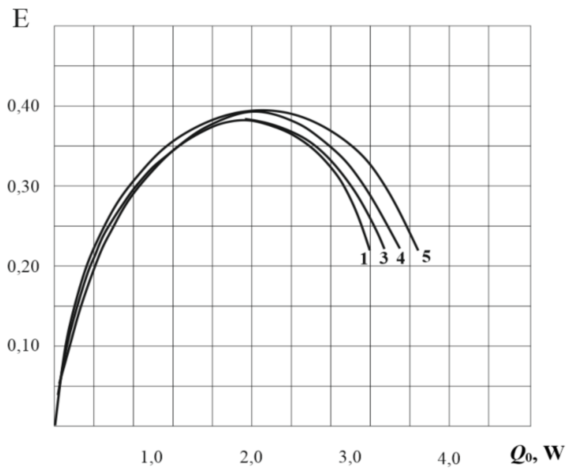

Fig. 3. **Dependence of the refrigeration coefficient E of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at T_0=260K; T=300K; n=27; l/s=10**

***Source:* compiled by the authors**

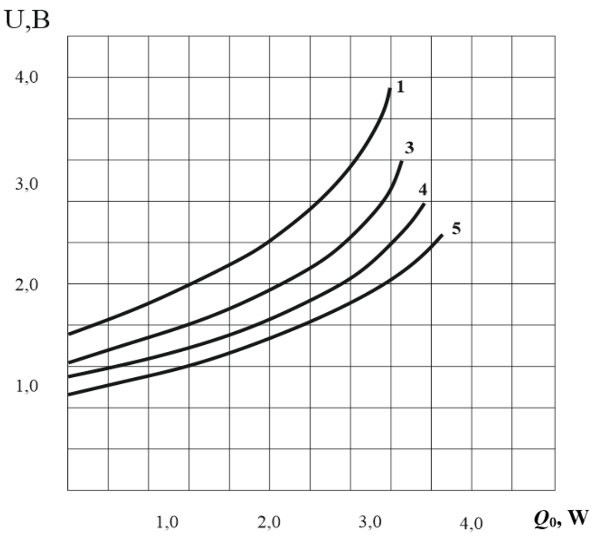

Fig. 4. **Voltage drop dependence U of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at T_0=260K; T=300K; n=27; l/s=10**

***Source:* compiled by the authors**

– the time required to reach steady-state operation τ is reduced (Fig. 5) for various combinations of raw material parameters. The time required to reach steady-state operation is practically independent of the combination of parameters of the initial material № 1, 3, 4, 5. The minimum time required to reach steady-state operation $\tau_{\min}$ is ensured in the mode $Q_{0\max}$ for various combinations of parameters of the initial material;

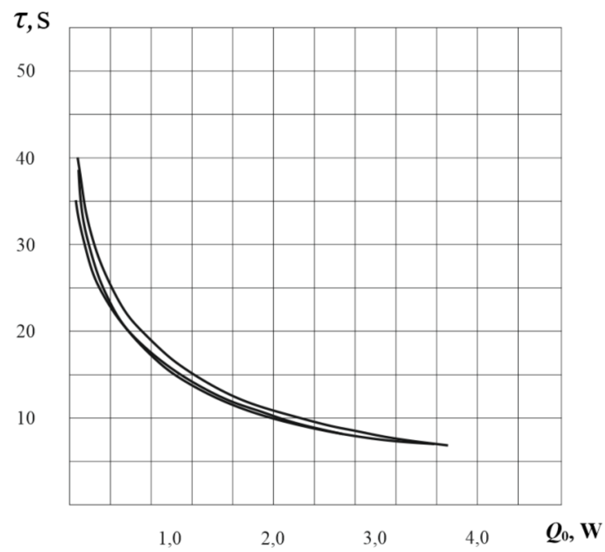

Fig. 5. **Dependence of the time required to reach steady-state operation τ of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at T_0=260K; T=300K; n=27; l/s=10**

***Source:* compiled by the authors**

– the functional dependence $N = f(Q_0)$ of the amount of energy consumed Q_0 on the heat load (Fig. 6) has a minimum $N_{\min}$=50Ws at Q_0=1.0W for various combinations of parameters of the initial material № 1, 3, 4, 5. The amount of energy consumed N practically does not depend on the combination of parameters of the initial material № 1, 3, 4 in the range Q_0 from Q_0=0 to Q_0=W, and in the range of values Q_0 from Q_0=2.0W to the amount of energy consumed N decreases from option № 1 to option № 5. The minimum value is achieved when using option № 5.

Increases:

– the required heat dissipation capacity of the radiator αF (Fig. 7) for various combinations of raw material parameters (№ 1, 3, 4, 5). The required heat dissipation capacity of the radiator αF practically does not depend on the combination of parameters of the initial material №. 1, 3, 4, 5 in the range Q_0 of values from Q_0=0W to Q_0=2.0W and decreases from option № 1 to option № 5 with an increase from Q_0=2.0W to $Q_{0\max}$;

– the relative failure rate λ/λ_0 increases (Fig. 8) for different combinations of parameters of source materials № 1, 3, 4, 5. The relative failure rate λ/λ_0 decreases from option № 1 to option № 5. The

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minimum relative failure rate $(\lambda/\lambda_0)_{\min}$ is achieved when using option № 5;

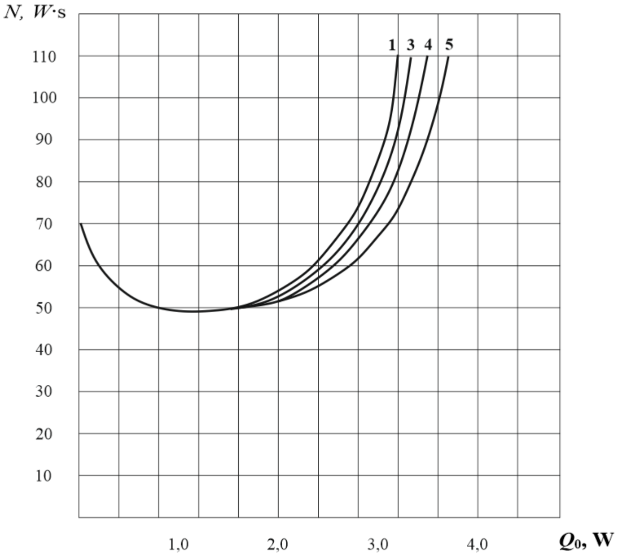

Fig. 6. **Dependence of the amount of energy consumed N of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at**
T_0=260K; T=300K; n=27; l/s=10
***Source:* compiled by the authors**

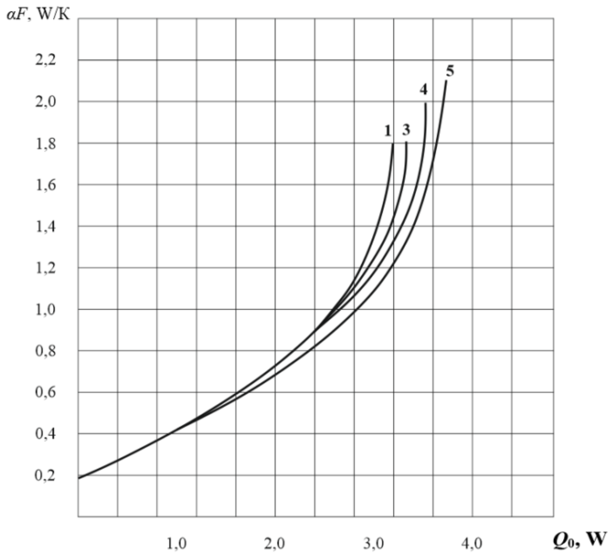

Fig. 7. **Dependence of the required heat dissipation capacity of the radiator αF of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at**
T_0=260K; T=300K; n=27; l/s=10
***Source:* compiled by the authors**

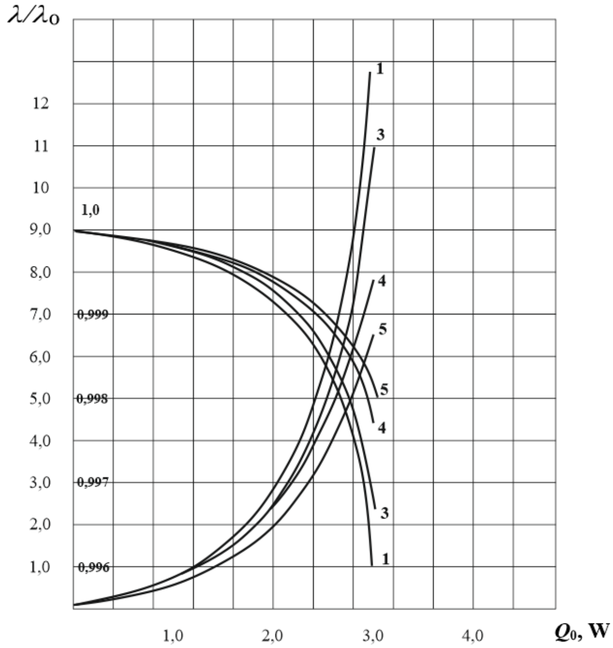

Fig. 8. **Dependence of relative failure intensity λ/λ_0 of a single-stage TEC on the thermal load Q_0 for different combinations of parameters of the initial material 1,3,4,5 of equal efficiency at**
T_0=260K; T=300K; n=27; l/s=10
***Source:* compiled by the authors**

– the probability of failure-free operation P (Fig. 8) decreases for various combinations of parameters of raw materials № 1, 3, 4 and 5. The probability of failure-free operation P increases from option № 1 to option № 5. The maximum probability of failure-free operation $P_{\max}$ is achieved when using option № 5.

Analysis of the research results showed the possibility, at a given thermal load Q_0, of

– reducing: the operating current I by an average of 20 % for option № 1 compared to option № 3, traditionally used in thermoelectric instrument engineering, and by 31 % for option № 1 compared to option № 4;

– increase: voltage drop U by an average of 23 % for option № 1 compared to option № 3 and by 39 % for option № 1 compared to option № 4.

At the same time, the following values remain virtually unchanged: cooling coefficient E, time to reach steady state operation τ, amount of energy consumed N, required heat dissipation capacity of the radiator αF, relative failure rate λ/λ_0 and probability of failure-free operation P in the range of values Q_0 from Q_0=0W to $Q_{0\max}$ current mode of operation of a thermoelectric cooler (

$n = 27$, $l/s = 10$) of a given design varies from Q_0 =0 to $Q_{0\,max}$.

In addition, the use of option № 5 compared to the traditional option № 3 allows reducing the relative failure rate λ/λ_0 at a thermal load Q_0: at Q_0 =2.0W from λ/λ_0 =2.6 to λ/λ_0 =2.0, i.e. by 23 %; Q_0 =3.0W from λ/λ_0 =10.9 to λ/λ_0 =6.5, i.e. by 40% and, consequently, increase the probability of failure-free operation P.

With an increase in thermal load:

– the following increase: relative operating current B, operating current value I, power consumption W, voltage drop U, required heat dissipation capacity of the radiator αF, relative failure rate λ/λ_0;

– the following decrease: time to reach steady state operation τ, probability of failure-free operation P.

The functional dependence of the cooling coefficient $E = f(Q_0)$ on the thermal load Q_0 has a maximum E_{max} =0.38 at B =0.57 and Q_0 =2.0W in mode $(nI\,\lambda/\lambda_0\,\tau)_{min}$.

The functional dependence of the amount of energy consumed $N = f(Q_0)$ on the thermal load Q_0 has a minimum N_{min} =49Ws at Q_0 =1.0W, B =0.41 in mode λ_{min} for various combinations of parameters of source materials № 1, 3, 4, 5 of equal efficiency.

CONCLUSIONS

A mathematical model of a single-stage thermoelectric cooler of a given design has been developed for comparative analysis and assessment of the influence of various combinations of parameters of the source material of equal efficiency on the main parameters, reliability indicators, dynamic and energy characteristics when the thermal load varies from zero to maximum.

Analysis of the research results showed the possibility of choosing a combination of parameters of the initial material № 1 compared to options

№ 3 and № 4, 5, which allow reducing the operating current by an average of 20 % and increasing the voltage drop by an average of 39 % under other equal conditions.

In addition, the use of option № 5 compared to option № 3 allows the relative failure rate to be reduced by up to 40 %. The economic feasibility of options № 1, 4, and 5 lies in the reduction of the cost of thermoelectric coolers when using substandard materials.

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Параметричний підхід підвищення значущих показників термоелектричної системи забезпечення теплових режимів

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АНОТАЦІЯ

Проблема підвищення показників надійності складних систем є фундаментальною, оскільки досягти повної відсутності відмов у реальних системах, що взаємодіють із зовнішнім середовищем, неможливо. У сучасних інформаційних системах підвищення ймовірності безвідмовної роботи за рахунок температурної стабілізації режимів критичних теплонавантажених елементів системою забезпечення теплових режимів залишається актуальним. Для її вирішення розроблено математичну модель термоелектричного охолоджувача заданої конструкції, призначену для порівняльного аналізу та оцінки впливу різних об'єднань комбінацій параметрів вихідного термоелектричного матеріалу однакової ефективності на основні показники виробу при змінному струмовому навантаженні. Наведено результати розрахунків показників надійності, динамічних і енергетичних характеристик одно каскадних термоелектричних охолоджувачів, геометрії ланцюгів термоелементів при варіації варіантів поєднань параметрів вихідних термоелектричних матеріалів. Показано, що при раціональній побудові однокаскадного термоелектричного охолоджувача забезпечена можливість вибору варіанту поєднання параметрів вихідного матеріалу однакової ефективності для зменшення величини робочого струму і підвищення напруги живлення при різному тепловому навантаженні. Додатковими засобами управління параметрами термоелектричного охолоджувача є геометрія гілок термоелементів, фізичні параметри вихідних матеріалів термоелементів, величина робочого струму, напруги джерела живлення, інтенсивність відмов. Аналіз результатів досліджень показав можливість вибору варіанту поєднання параметрів вихідного матеріалу, який дозволяє зменшити величину робочого струму в середньому на двадцять відсотків і зменшити відносну інтенсивність відмов до сорока відсотків за інших рівних умов.

Ключові слова: показники надійності; динамічні характеристики; термоелектричний матеріал; ефективність; струмовий режим

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