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Thermal control of parallelly connected thermoelectric coolers in a uniform temperature field

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ABSTRACT

The possibility of using a set of thermoelectric devices to control the thermal regime of a number of thermo-dependent and heat-loaded elements of radio-electronic equipment, which are subject to increased requirements for reliability indicators and dynamic characteristics, is considered. A mathematical model of a thermoelectric device has been developed for a uniform temperature field, a typical range of power dissipation of the products used, a range of standard values of the supply voltage, and a fixed geometry of thermoelement legs. A relation is obtained for determining the relative operating current depending on the relative temperature difference at a given supply voltage, the geometry of the thermoelement branches, and the magnitude of the thermal load. The region of real values of the relative operating current in the zone of relative temperature differences is determined for a given geometry of branches and thermal load. An analysis is made of the relationship between the relative operating current of a single-stage thermoelectric cooler and the coefficient of performance, the amount of energy expended, the heat-removing capacity of the radiator, the time to reach a stationary mode, and the probability of failure-free operation. The dependence of the relative failure rate and the probability of failure-free operation, the amount of energy expended, the heat-removing capacity of the radiator, and the number of thermoelements on the supply voltage of the thermoelectric cooler has been studied. This made it possible to evaluate the control features and identify the effectiveness of the control actions when the coolers are connected in parallel in a uniform temperature field. The possibility of choosing the optimal supply voltage is shown, taking into account a number of restrictive factors in terms of weight, size, energy, dynamic and reliability characteristics of a complex of thermoelectric coolers as part of systems for ensuring thermal regimes of heat-loaded radio-electronic equipment.

Keywords: Mathematical model; thermoelectric cooler; thermal regime; temperature difference; operating current; reliability indicators; dynamic characteristics

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INTRODUCTION

One of the most promising ways to ensure the thermal regime of elements and components of radio-electronic systems is thermoelectric, as the most effective in a wide range of operating temperatures. Thermoelectric cooling devices (TEC) allow you to control the amount of heat flow by simply changing the amount of operating current. The main advantages of the thermoelectric cooling method over others are high reliability and small overall dimensions, ease of control and speed. These advantages are inherently a consequence of the solid state nature of such coolers, the absence of moving parts, pumped liquids or gases. Among the design features of the onboard equipment is the dispersal of heat-loaded elements with different dissipation power. Therefore, in order to provide a given thermal regime for a number of heat-loaded and temperature-dependent elements, it is possible to use a group layout system of thermoelectric coolers located on one heat-removing radiator and connected electrically in parallel. To power the complex, it is significant to use a number of standard voltages and ensure the same temperature of the elements. In this case, it is necessary to determine such a supply voltage that provides the minimum performance of the system for ensuring thermal conditions in terms of mass, dimensions, energy consumption and failure rate.

LITERATURE REVIEW

Systems for providing thermal regimes for heat-loaded elements are a necessary component of modern on-board radio-electronic equipment [1]. In terms of weight, size and operational characteristics for on-board systems, thermoelectric coolers are the most acceptable [2]. The main advantage of TEC in comparison with air and liquid cooling systems is the ease of control and high dynamic characteristics [3]. At the same time, the tightening of requirements for the dynamics and reliability of heat-loaded equipment [4, 5] implies their increase for systems for providing thermal regimes [6, 7]. In [8], the influence of the load on the reliability indicators of thermoelectric coolers was studied, but the influence of design parameters was not considered. In [9], studies of the influence of design parameters on TEC reliability indicators are presented. In [10], the relationship between the reliability indicators and the current operating modes of the cooler was analyzed, which made it possible to choose the optimal operating conditions for this criterion. However, for the control of thermoelectric systems, in addition to reliability indicators, dynamic characteristics are also important, the relationship of which was not considered in the cited sources [11]. It is known that the dynamics unambiguously negatively affects the reliability indicators, which is a fundamental problem [12], in particular, linear thermal expansion of the materials of thermoelements and the substrate leads to cracking of the junctions [13]. In [14], the connection of dynamic indicators with the TEC design is shown, in [15] with the number of thermoelements, in [16] with the current modes of operation of the product, but only for one single-stage cooler. In addition, in subsequent works [17, 18], the possibilities of optimizing the control of thermoelectric plants were analyzed according to complex criteria, including indicators of reliability and dynamics. The actual development of this direction is the control of thermoelectric coolers when they are connected in parallel, which is aimed at solving the problem of harmonizing the reliability indicators and the dynamics of operation, in relation to the control of systems for ensuring the thermal regimes of radio-electronic equipment.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the work is to develop a model for controlling the thermal regime of parallel-connected thermoelectric coolers that operate in a uniform temperature field.

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

1. Develop a mathematical model that links energy performance with dynamic, reliability performance and design parameters of TEC.

2. Analyze the developed model to identify the optimal operating modes of the thermoelectric cooler.

DISTRIBUTED THERMOELECTRIC COOLER MODEL

To calculate the main parameters, reliability indicators and dynamic characteristics of the TEC, we will use the following relationships:

The voltage drop across the TEC can be determined from the relationship [19]:

$$U = 2nI_{\max} R(B + \frac{\Delta T}{T_0}\Theta), \tag{1}$$

where n is the number of thermoelements, pcs;

$I_{\max} = \frac{\bar{e}T_0}{R}$ – maximum operating current, A;

$\bar{e}$ is the average value of the thermoelectric coefficient of the thermoelement branch, V/K;

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

$R = \frac{l}{\bar{\sigma} S}$ is the electrical resistance of thermoelement branch, Ohm;

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

$\bar{\sigma}$ is the average value of the electrical conductivity of the thermoelement branch, Sm/cm;

$B = \frac{I}{I_{\max}}$ – relative operating current;

I is the value of the operating current, A;

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

T is the temperature of the heat-releasing junction, K;

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

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

The value of the operating current I can be determined from the expression:

$$I = BI_{\max}. \tag{2}$$

The number of thermoelements n of a single-stage TEC can be determined from the relation:

$$n = \frac{Q_0}{I_{\max}^2 R\left(2B - B^2 - \Theta\right)}, \tag{3}$$

where Q_0 is the value of the heat load, W.

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The coefficient of performance E can be calculated using the formula:

$$E = \frac{Q_0}{W}. \qquad (4)$$

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

$$\lambda/\lambda_0 = nB^2(\Theta + C)\frac{(B + \frac{\Delta T_{\max}}{T_0}\Theta)^2}{(1 + \frac{\Delta T_{\max}}{T_0}\Theta)^2}K_T, \qquad (5)$$

where $C = \frac{Q_0}{nI_{\max}^2 R}$ is the relative thermal load;

K_T is the low temperature coefficient [19].

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

$$P = \exp[-\lambda t], \qquad (6)$$

where $t = 10^4$ is the assigned resource, hour.

The expression for determining the time to reach the stationary mode of operation τ can be represented as [20]:

$$\tau = \frac{m_0 C_0 + \sum_i m_i C_i}{A\left(1 + 2B_K\frac{\Delta T_{\max}}{T_0}\right)} \ln\frac{\gamma B_H(2 - B_H)}{2B_K - B_K^2 - \Theta}, \qquad (7)$$

where – $\gamma = \frac{I_{\max H}^2 R_H}{I_{\max K}^2 R_K}$;

A is the heat transfer coefficient, W/K;

$m_0 C_0$ is the product of the mass and heat capacity of the cooling object. In our case $m_0 C_0 \to 0$ (the object is missing);

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

index H means the initial moment of time;

index K is the final moment of time [19];

R_H – is the electrical resistance of the thermoelement leg at the beginning of the cooling process, Ohm.

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

$I_{\max H} = \frac{\bar{e}_H T}{R_H}$ is the maximum operating current at the beginning of the cooling process, A, provided that the currents at the beginning and at the end of the cooling process are equal:

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

Substituting expression (3) into (1), we obtain the relation

$$B^2 K - B(2K - 1) + \Theta(K + \frac{\Delta T_{\max}}{T_0}) = 0, \qquad (8)$$

where $K = \frac{UI_{\max}}{2Q_0}$,

for the functional dependence of the relative operating current B on the voltage drop – U, the magnitude of the thermal load Q_0 and the relative temperature drop Θ for a given geometry of the thermoelement legs (ratio *l/S*):

$$B = \frac{2K - 1}{2K}\left[1 \pm \sqrt{1 - \frac{4\Theta K(K + \frac{\Delta T_{\max}}{T_0})}{(2K - 1)^2}}\right]. \qquad (9)$$

Analysis of relation (9) shows that the range of real values of B can be determined from the condition:

$$1 - \frac{4\Theta K(K + \frac{\Delta T_{\max}}{T_0})}{(2K - 1)} \geq 0. \qquad (10)$$

The functional dependence $K_{min} = f(\Theta)$ can be represented as:

$$K_{\min} = \frac{1 + \Theta\frac{\Delta T_{\max}}{T_0}}{2(1 - \Theta)}\left[1 + \sqrt{\frac{(1 - \Theta)}{(1 + \Theta\frac{\Delta T_{\max}}{T_0})^2}}\right]. \qquad (11)$$

Fig. 1 shows the dependence of the K_{min} value on the relative temperature difference Θ. At $\Theta \to 0$, $K_{min}=0.5$; as $\Theta \to 1$, $K_{min} \to \infty$.

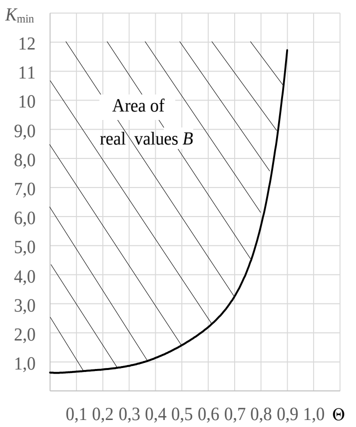

Fig.1. **Dependence of the value** $K_{\min} = \dfrac{U_{\min} I_{\min}}{2Q_0}$ **on the relative temperature difference** Θ **at a given supply voltage** U**, geometry of the thermoelement legs (ratio** l/S**) and thermal load** Q_0 **at** T**=300K**

Source: **compiled by the authors**

It should be noted that for a cooling system consisting of *M* independent elements, the probability of failure-free operation of the *i*-th element is equal to $P_i(t)$, then the total probability of failure-free operation of the system is [19]:

$$P_{\Sigma}\ (t) = P_1(t) \cdot P_2(t) \ldots P_i(t) \ldots P_M(t) = \prod_{i=1}^{M} P_i(t)\ .$$

The results of calculations of the main parameters, reliability indicators and the time to reach the stationary mode of operation τ with a parallel electrical connection of the TEC at a uniform temperature level of cooling are given in Table 1, Table 2, Table 3, Table 4, Table 5, Table 6, Table 7. Conditions: T_0=260K, heat load Q_0=0.5W; 1.0W; 3.0W; 5.0W; 10W; 15W specified standard values of voltage drop U = 5.6V; 6.0V; 7.0V; 9.0V; 12.0V; 18.0V; 24.0V) is given in Tables.

Table.1. **U_{min}=5.6V; l/S=4.5; T=300K; ΔT=40K; Θ=0.5; R=4.55·10-3Ohm; I_{max}=11.1A; T-Tc=5K**

Q_0, W	B	K	n	I, A	W, W	E	τ,s	N	αF, W/K	$B_н$	λ/λ_0	$\lambda \cdot 10^8$ 1/h	P
0.5	0.298	62.20	123	3.3	18.5	0.027	48.6	89.6	3.90	0.27	0.95	2.84	0.99972
1.0	0.303	31.10	121	3.36	18.8	0.053	40.4	744	3.96	0.28	0.97	2.9	0.99971
3.0	0.326	10.40	117	3.62	20.3	0.148	28.3	575	4.66	0.3	1.17	3.5	0.99965
5.0	0.353	6.22	109	3.92	22.0	0.23	22.6	497	5.40	0.32	1.60	4.73	0.99953
10.0	0.447	3.10	92.9	5.00	28.0	0.357	14.8	414	7.60	0.4	3.50	10.6	0.9989
15.0	0.757	2.07	62.50	8.40	47	0.32	8.6	404	12.40	0.69	21.00	62.6	0.9938
34.5			625	27.60	154.6	0.22	48.6	3530	37.90		29.20	87.6	0.9913

Source: **compiled by the authors**

Table.2. **U_{min}=6,0V; l/S=4.5; T=300K; ΔT=40K; Θ=0.5; R=4.55·10^{-3}Ω; I_{max}=11.1A; T-Tc=5K**

Q_0, W	B	K	n	I, A	W, W	E	τ,s	N	αF, W/K	$B_н$	λ/λ_0	$\lambda \cdot 10^8$ 1/h	P
0.5	0.298	66.60	130.8	3.30	19.8	0.025	48.0	950	4.06	0.27	0.81	2.73	0.99973
1.0	0.302	33.30	129.3	3.35	20.1	0.05	41.5	834	4.2	0.27	1.04	3.13	0.99969
3.0	0.325	11.10	123.9	3.61	21.7	0.138	28.5	617	4.94	0.295	1.22	3.67	0.99963
5.0	0.349	6.66	117.8	3.87	23.2	0.216	23.3	541	5.6	0.316	1.62	4.85	0.99952
10.0	0.431	3.33	101.5	4.80	28.8	0.347	15.5	446	7.8	0.392	3.36	10.1	0.9990
15.0	0.60	2.22	78.7	6.66	40	0.375	10.5	420	11.0	0.544	10.4	31.2	0.9969
34.5			682	25.60	153.6	0.225	48.0	3808	37.6	–	18.6	55.6	0.99445

Source: **compiled by the authors**

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Table 3. **U=7.0V; *T*=300K; Δ*T*=40K; Θ=0.5; *l/S*=4.5; *R*=4.55·10^{-3}Ohm; *I*$_{max}$=11.1A**

Q_0, W	*B*	*K*	*n*	*I*, A	*W*, W	*E*	*τ*,s	*N*, *W*·s	*αF*, W/K	B_H	*λ/λ*$_0$	*λ*·10^8 1/h	*P*
0.5	0.297	77.70	153.8	3.30	23.1	0.0216	49.9	1153	4.72	0.269	1.07	3.22	9.99968
1.0	0.301	38.85	156.5	3.34	23.4	0.0427	42.7	998.3	4.88	0.273	1.156	3.47	0.99965
3.0	0.319	12.95	147.8	3.54	24.8	0.121	30.7	761	5.56	0.289	1.39	4.2	0.99958
5.0	0.340	7.77	138.5	3.77	26.4	0.189	24.8	654	6.3	0.308	1.7	5.1	9.99949
10.0	0.402	3.89	125.3	4.46	31.2	0.32	17.4	543	8.2	0.364	3.1	9.27	0.99907
15.0	0.505	2.59	104.9	5.60	39.2	0.385	12.6	494	10.8	0.458	6.74	20.2	0.99800
34.5	–	–	827	24.0	168	0.205	49.9	4603	40.5	–	15.16	45.5	0.99550

Source: **compiled by the authors**

Table 4. **U=9.0V; *T*=300K; Δ*T*=40K; Θ=0.5; *l/S*=4.5; *R*=4.55·10^{-3}Ohm; *I*$_{max}$=11.1A**

Q_0, W	*B*	*K*	*n*	*I*, A	*W*, W	*E*		*N*, *W*·s	*αF*, W/K	B_H	*λ/λ*$_0$	*λ*·10^8 1/h	*P*
0.5	0.296	100.00	137.3	3.30	29.60	0.017	51.9	1541	6.0	0.269	1.29	3.88	0.99961
1.0	0.300	50.00	196.0	3.33	30	0.033	44.1	1323	6.2	0.27	1.30	3.90	0.99961
3.0	0.313	16.70	1845.0	3.47	31.20	0.096	32.9	1027	6.8	0.28	1.60	4.80	0.99950
5.0	0.328	10.00	185.0	3.64	32.8	0.152	27.8	908	7.5	0.297	1.94	5.80	0.99942
10.0	0.372	5.00	168.0	4.13	37.2	0.269	20.0	743	9.4	0.34	3.00	9.00	0.99910
15.0	0.430	3.33	152.0	4.79	43.2	0.347	15.5	670	11.6	0.39	5.00	15.00	0.99850
34.5	–	–	1084	22.70	203.9	0.169	51.9	6215	47.5	–	14.20	42.60	0.99580

Source: **compiled by the authors**

Table 5. ***U*=12V; Δ*T*=40K; Θ=0.5; *l/S*=4.5; *R*=4.55·10^{-3}Ohm; *I*$_{max}$=11.1A**

Q_0, W	*B*	*K*	*n*	*I*, A	*W*, W	*E*	*τ*,s	*N W*·s	*αF*, W/K	B_H	*λ/λ*$_0$	*λ*·10^8 1/h	*P*
0.5	0.295	133.2	262.7	3.27	39.2	0.0128	57.0	2237	7.94	0.267	0.90	2.71	0.99973
1.0	0.2977	66.6	262.3	3.31	39.7	0.0253	47.6	1891	8.14	0.270	1.75	5.26	0.99947
3.0	0.3078	22.2	258	3.42	41	0.073	36.2	1486	8.8	0.280	2.05	6.20	0.99938
5.0	0.319	13.3	250.5	3.54	42.5	0.118	30.4	1291	9.5	0.290	2.27	6.80	0.99932
10.0	0.349	6.66	236	3.87	46.4	0.216	23.3	1082	11.3	0.316	3.2	9.60	0.99904
15.0	0.385	4.44	219	4.27	51.2	0.293	18.8	963	13.2	0.350	4.53	13.60	0.99865
34.5			1495	21.7	260	0.133	57.0	8950	58.9		14.7	44.10	0.9956

Source: **compiled by the authors**

Table 6. **U=18V; ΔT=40K; Θ=0.5; l/S=4.5; R=4.55·10^{-3}Ohm; I_{max}=11.1A**

Q_0, W	B	K	n	I, A	W, W	E	τ,s	N, W·s	αF, W/K	B_H	λ/λ_0	$\lambda\cdot10^8$ 1/h	P
0.5	0.294	200.0	396.0	3.27	58.9	0.0085	61.8	3638	11. 9	0.267	1.34	4.00	0.99960
1.0	0.296	100.0	413.0	3.30	59.4	0.017	50.0	2970	12.1	0.270	2.45	7.35	0.99926
3.0	0.303	33.30	376.9	3.37	60.7	0.049	40.4	245	12.7	0.275	2.89	8.96	0.99910
5.0	0.309	20.00	384.0	3.43	61.7	0.081	35.6	2198	13.3	0.280	3.15	9.46	0.99905
10.0	0.328	10.00	368.6	3.64	65.5	0.153	27.7	1815	15.1	0.297	3.88	11.60	0.99884
15.0	0.350	6.66	354.0	3.87	69.7	0.215	23.3	1623	16.9	0.316	4.83	14.50	0.99855
34.5	–	–	2292	20.90	375.9	0.092	61.8	14695	82.0	–	18.6	55.90	0.99440

Source: **compiled by the authors**

Table 7. **U=24V; ΔT=40K; Θ=0.5; l/S=4.5; R=4.55·10^{-3}Ohm; I_{max}=11.1A**

Q_0, W	B	K	n	I, A	W, W	E	τ,s	N, W·s	αF, W/K	B_H	λ/λ_0	$\lambda\cdot10^8$ 1/h	P
1.0	0.295	133.2	524.6	3.278	78.7	0.0127	55.7	4382	15.9	0.268	3.56	10.70	0.99893
3.0	0.30	44.4	527.6	3.34	80.2	0.037	43.5	3487	16.6	0.273	3.80	11.47	0.99885
5.0	0.305	26.6	524.6	3.39	81.4	0.061	38.6	3140	17.3	0.277	4.09	12.30	0.99877
10.0	0.3185	13.3	501.6	3.54	85.0	0.118	30.4	2583	19.0	0.289	4.72	14.20	0.99858
15.0	0.333	8.88	482.1	3.7	88.8	0.169	26.4	2344	20.8	0.302	5.45	16.30	0.99837
34.5	–	–	3091.6	20.5	492.3	0.070	63.0	20865	105.3	–	25.20	75.60	0.99250

Source: **compiled by the authors**

ANALYSIS OF A THERMOELECTRIC COOLER MODEL

Fig. 2 shows the dependence of the minimum voltage drop U_{min} on the relative temperature difference Θ at T=300K, l/S=4.5, Q_{0max}=15W.

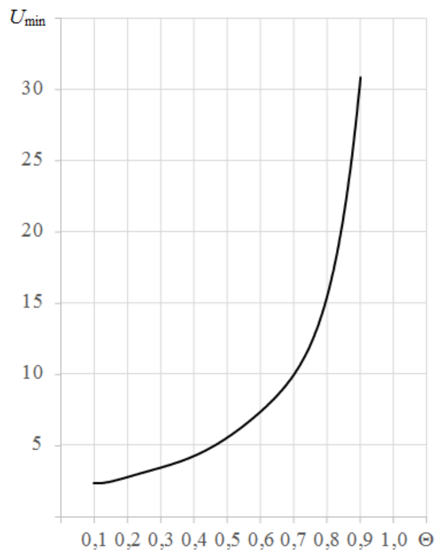

Fig.2. **Dependence of the minimum voltage drop U_{min} of a single-stage TEC on the relative temperature drop Θ at T=300K; l/S=4.5; Q_{0min}=15W**
Source: **compiled by the authors**

As the relative temperature difference Θ increases, the voltage drop U_{min} increases.

Fig. 3 shows the dependence of K_{min} TEC on the magnitude of the thermal load Q_0 for various supply voltages U at T=300K, ΔT=40K, l/S=4.5.

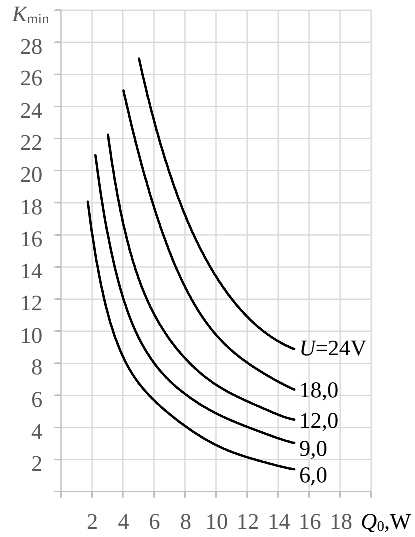

Fig.3. **Dependence of the K_{min} value of a single-stage TEC on the thermal load Q_0 for different supply voltage U at T=300K; ΔT=40K; l/S=4.5**
Source: **compiled by the authors**

As the heat load Q_0 increases, the value of K_{min} decreases. With an increase in the supply voltage U, the value of K_{min} increases at a given thermal load Q_0.

Let's consider parallel connections of TEC.

With an increase in the thermal load Q_0 with an electrically parallel connection of the TEC in the complex for various values of the supply voltage U at T=300K, ΔT=40K, l/S=4.5:

− the relative operating current B increases (Fig. 4). For a given thermal load Q_0, as the supply voltage U increases, the relative operating current B decreases;

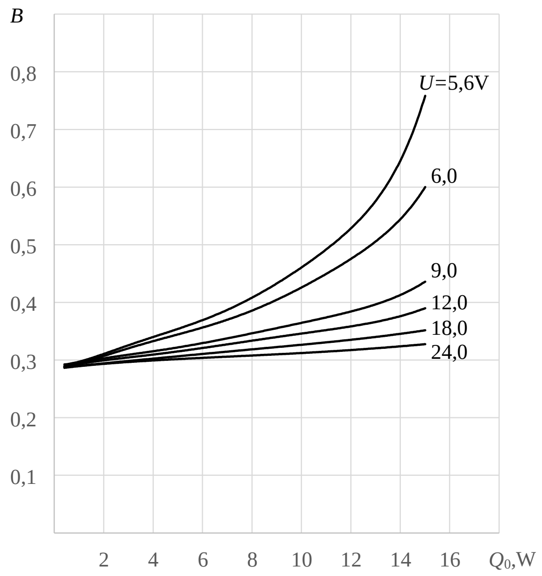

Fig.4. **Dependence of the relative operating current B of a single-stage TEC on the magnitude of the thermal load Q_0 for various values of the supply voltage U at T=300K; ΔT=40K; l/S=4.5**
***Source:* compiled by the authors**

− the magnitude of the operating current I increases (Fig.5). At a given thermal load Q_0, with an increase in the supply voltage U, the value of the operating current I decreases;

− the number of thermoelements n decreases (Fig.6). At a given thermal load Q_0, as the supply voltage U increases, the number of thermoelements n increases;

− the coefficient of performance E increases (Fig.7). At a given thermal load Q_0, with increasing supply voltage U, the coefficient of performance E increases;

− the amount of spent energy N decreases (Fig. 8).

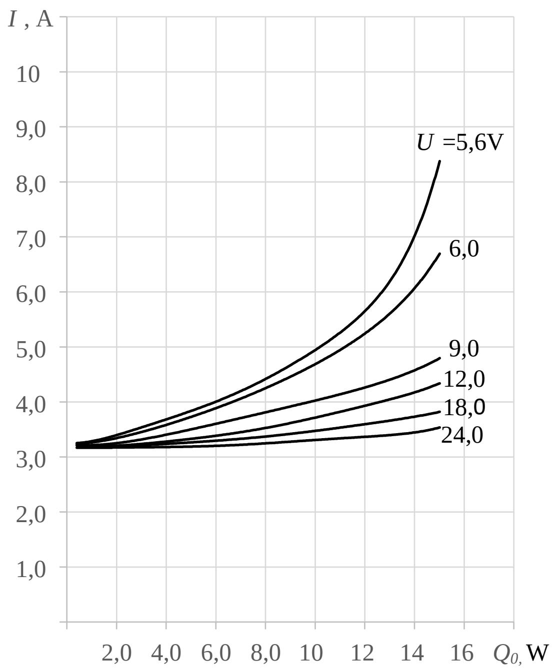

Fig.5. **Dependence of the value of the operating current I of the TEC complex on the value of the thermal load Q_0 for different values of the supply voltage U at T=300K; ΔT=40K; l/S=4.5**
***Source:* compiled by the authors**

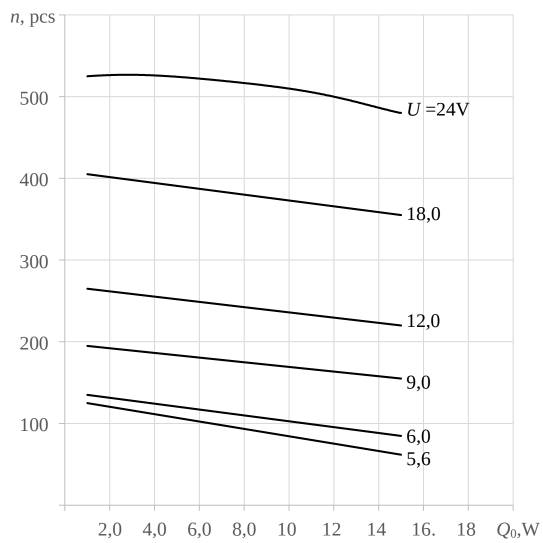

Fig.6. Dependence of the number of thermoelements − n of a single-stage TEC on the magnitude of the thermal load −Q_0 for various values of the supply voltage – U at T=300K; ΔT=40K; l/S=4.5
***Source:* compiled by the authors**

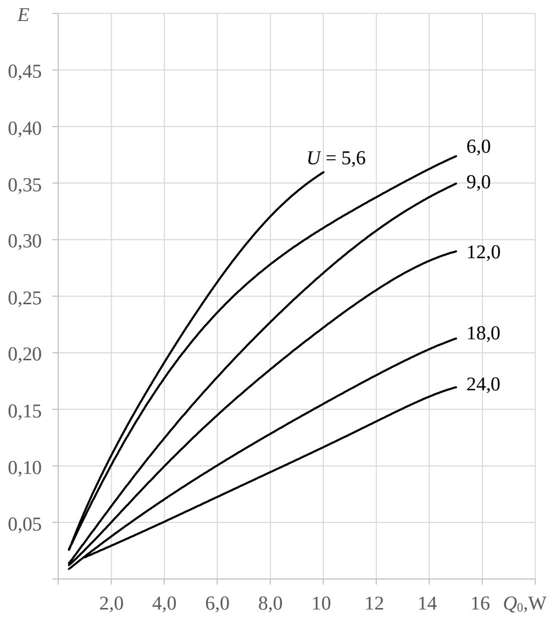

Fig.7. **Dependence of the coefficient of performance *E* of a single-stage TEC on the magnitude of the thermal load *Q₀* for various values of the supply voltage – *U* at *T*=300K; *ΔT*=40K; *l/S*=4.5**

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

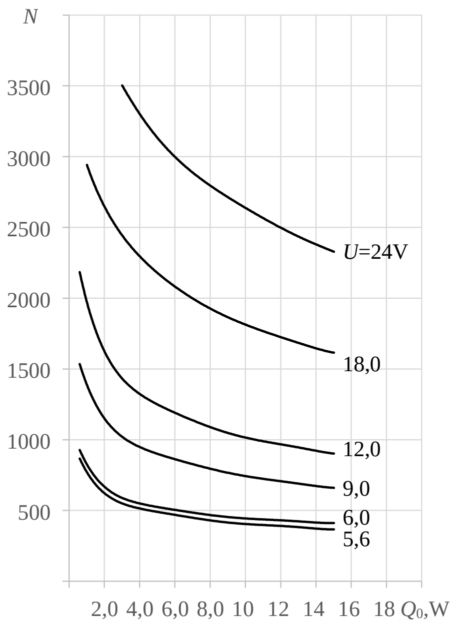

Fig.8. Dependence of the amount of energy consumed *N* of a single-stage TEC on the magnitude of the heat load *Q₀* for various values of the supply voltage *U* at *T*=300K; *ΔT*=40K; *l/S*=4.5

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

With an increase in the supply voltage U at a given thermal load Q_0, the amount of energy expended increases:

– the required heat dissipation capacity of the radiator αF increases (Fig.9). At a given thermal load Q_0, with an increase in supply voltage U, the required heat dissipation capacity of the radiator αF increases;

– the time to reach the stationary mode of operation τ decreases (Fig. 10). With an increase in the supply voltage U at a given thermal load Q_0, the time to reach the stationary mode of operation increases;

– the relative failure rate λ/λ_0 increases (Fig.11). With an increase in the supply voltage U at a given thermal load Q_0, the relative failure rate λ/λ_0 increases;

– the probability of non-failure operation P decreases (Fig.12). With an increase in the supply voltage U at a given thermal load Q_0, the probability of failure-free operation P increases.

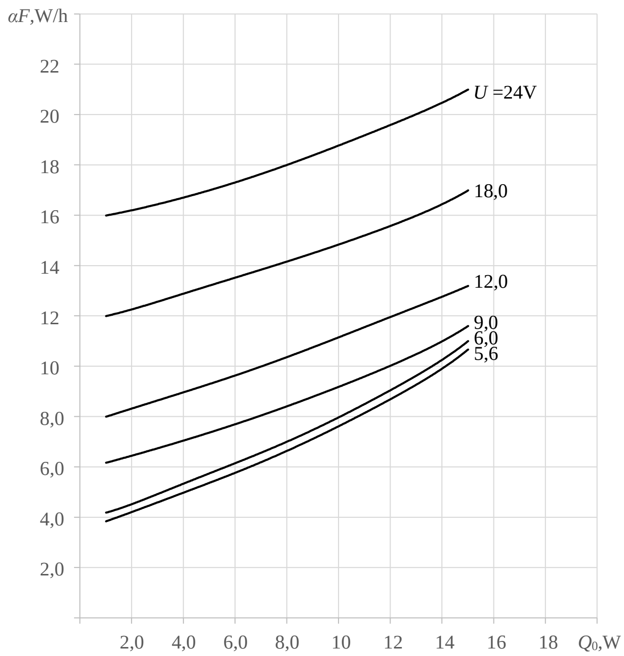

Fig. 9. **Dependence of the heat dissipation capacity of the radiator *αF* of a single-stage TEC on the value of the thermal load *Q₀* for various values of the supply voltage – *U* at**

***T* = 300K; *ΔT* = 40K; *l / S* = 4.5**

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

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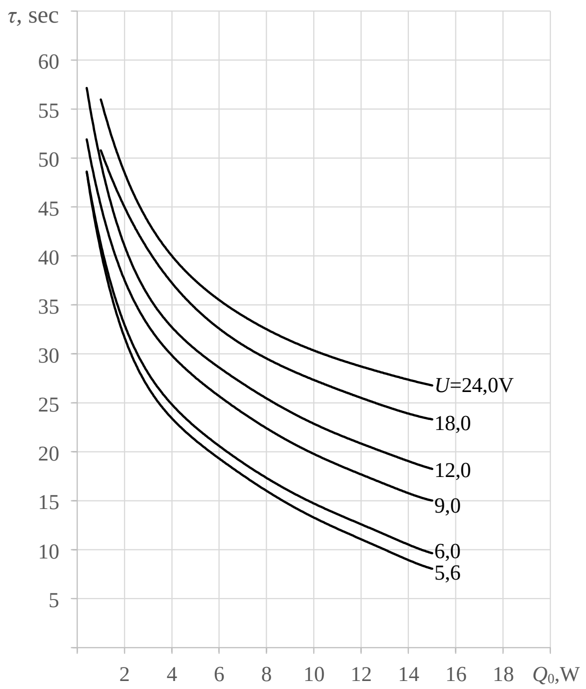

Fig.10. **The dependence of the time to reach the stationary mode of operation τ of a single-stage TED on the magnitude of the thermal load Q0 for various values of the supply voltage U at T = 300K; ΔT = 40K; l / S = 4.5**

Source: compiled by the authors

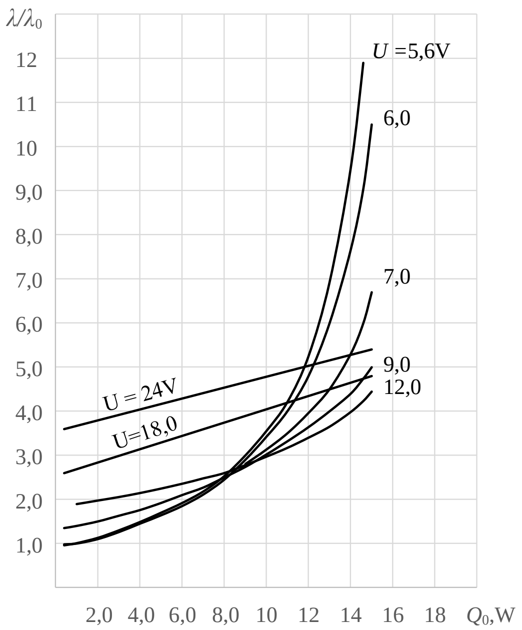

Fig.11. **Dependence of the relative value of the failure rate λ/λ_0 of the TEC on the magnitude of the thermal load Q_0 for various values of the supply voltage *U* at T =300K; *ΔT* =40K; *l/S* =4.5; $\lambda_0 = 3\cdot10^{-8}$ 1/hour**

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

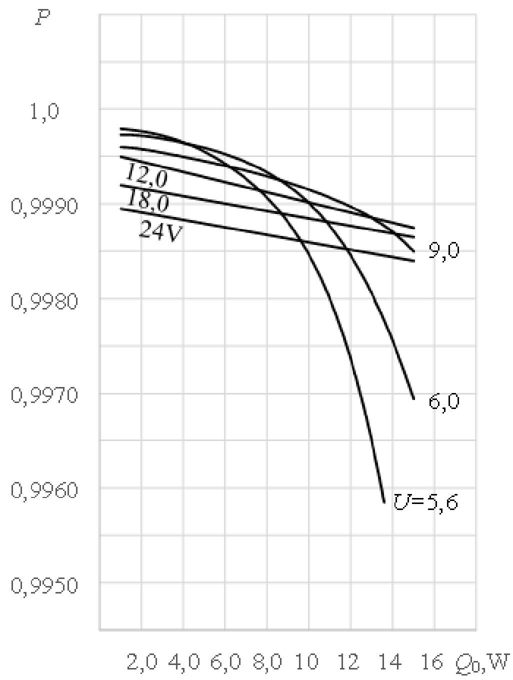

Fig.12. **Dependence of the probability of failure-free operation *P* of a single-stage TEC on the magnitude of the thermal load Q_0 for various supply voltages *U* at *T* = 300K, *ΔT* = 40K; *l / S* = 4.5; *t* = 10^4 hours**

Source: compiled by the authors

DISCUSSION OF RESEARCH RESULTS

To facilitate comparative analysis, the results of calculations of the main parameters, reliability indicators, dynamic characteristics of TEC complexes for various supply voltages *U* at *T*=300K, *ΔT*=40K, *l/S*=4.5, Q_0=34.5W are given in Table 8.

With an increase in the supply voltage *U* of the TEC complex with a thermal load Q_0=34.5W and a temperature difference *ΔT*=40K:

− the total number of thermoelements nΣ increases (Fig. 14 p.1);

− the total operating current I_Σ decreases (Fig.13 p. 2);

− the coefficient of performance *E* decreases;

− the total heat dissipation capacity of the radiator *αF* increases (Fig.4 item 1);

− the amount of consumed energy *N* increases (Fig.14 p. 2);

− functional dependence of relative failure rate $\lambda/\lambda_0=f(U)$ has a minimum λ/λ_{0min} = 14 at *U*=9V (Fig.15);

− functional dependence of the probability of failure-free operation of the TEC complex $P_{tot}=f(U)$ has a maximum at *U*=9B P_{tot}=0.9958;

− the time to reach the stationary mode of operation *τ* increasesю

Table 8. **Key parameters, energy indicators, dynamics and reliability at T=300K, ΔT=40K, l/S=4.5, Q_0=34.5 W**

U, V	I_Σ, A	N, W·s	τ,s , max value	αF, w/h	n	E	λ/λ_0	$\lambda\cdot10^8$ 1/h	P_Σ
27.6	154.6	3530	48.6	37.8	625	0.223	29.2	87.6	0.99913
25.6	153.6	3808	48.0	37.6	682	0.225	18.6	55.6	0.99445
22.7	203.9	6215	51.9	47.7	1084	0.169	14.2	42.6	0.99575
21,7	260	8950	57.0	58.9	1389	0.133	15.8	47.4	0.9953
20.9	375.9	14695	61.8	82.1	2282	0.092	19.9	59.8	0.9940
20.5	492.3	20865	63.0	105	3092	0.070	25.2	75.6	0.9925

Source: **compiled by the authors**

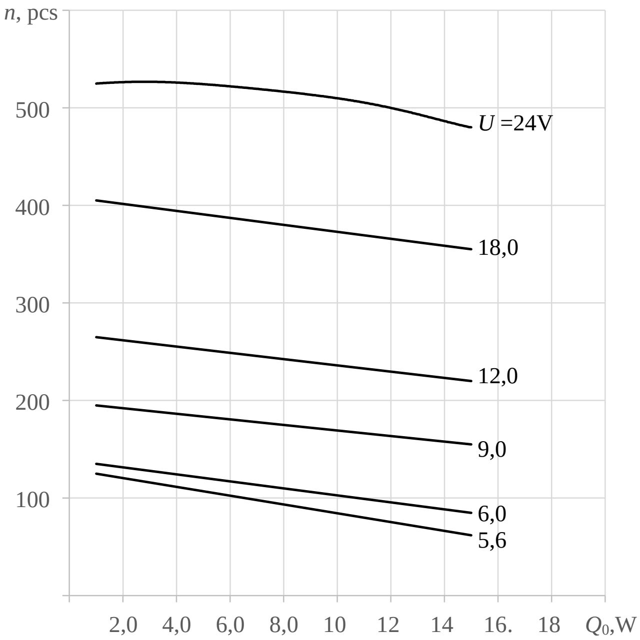

Fig.13. Dependence of the total number of thermoelements n_Σ, the value of the operating current I_Σ and the cooling coefficient E of the complex on the supply voltage U at T =300K; ΔT =40K; l/S =4.5:
1 – $n = f(U)$; 2 – $I = f(U)$; 3 – $E = f(U)$
Source: **compiled by the authors**

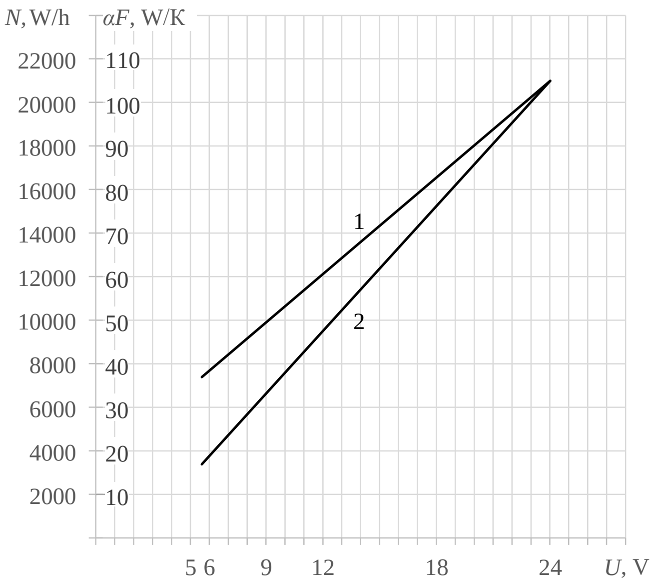

Fig.14. Quantity dependency energy expended - N, heat dissipation capacity of the radiator αF of the TEC complex from the supply voltage – U at T = 300K; ΔT = 40K; l / S = 4.5:
1 – $\alpha F = f(U)$; 2 – $N = f(U)$
Source: **compiled by the authors**

CONCLUSIONS

1. A mathematical model of a thermoelectric system for providing thermal regimes for heat-loaded elements of radio-electronic equipment in the power dissipation range of 0.5–15W in a uniform temperature field with a temperature level of cooling T_0=260K using a parallel electrical connection of a TEC has been developed.

2. Relationships have been obtained to determine the relative operating current B for given values of supply voltage U, thermal load Q_0 and a fixed geometry of thermoelement legs, taking into account the temperature level of cooling. The range of real values of the relative operating current B at $K \geq K_{min}$ is determined.

3. Analysis of the research results showed that with an increase in the thermal load Q_0 and a fixed geometry of the thermoelement legs (ratio l/S) and various supply voltages U:

− increases: the value of the operating current I, the required heat dissipation capacity of the radiator αF, the coefficient of performance E, the relative failure rate λ/λ_0;

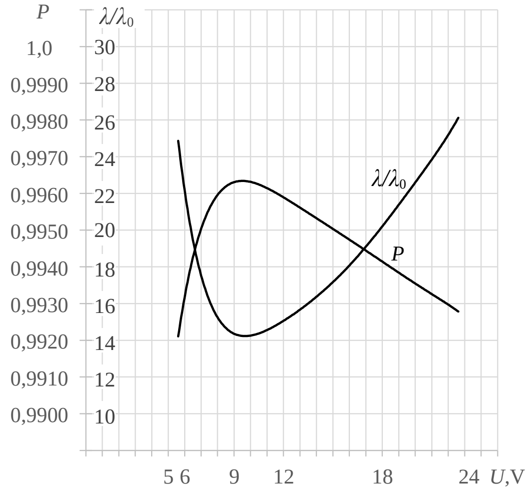

Fig.15. **Dependence of the relative failure rate** ***λ/λ₀*** **and the probability of failure-free operation** ***P*** **of the TEC complex on the supply voltage** ***U*** **at** ***T*** **=300K;** ***ΔT*** **= 40K;** ***l/S*** **=4.5;** ***λ₀*** **=3·10**$^{-8}$ **1/hour;** ***t*** **=10**^{4} **hour**

Source: **compiled by the authors**

− the number of thermoelements *n* decreases, the amount of consumed energy *N*, the time to reach the stationary mode of operation *τ*, the probability of failure-free operation *P*.

With an increase in supply voltages *U* for different thermal load Q_0 and a fixed geometry of thermoelement legs (ratio *l/S*=4.5):

− increases: the number of thermoelements *n*, the amount of consumed energy *N*, the required heat-removing capacity of the radiator *αF*, the time to reach the stationary operation mode *τ*, the relative failure rate λ/λ_0;

– decreases: the value of the operating current *I*, the coefficient of performance *E*, the probability of failure-free operation *P*.

4. The possibility of choosing the optimal supply voltage U_{opt}=9V is shown to ensure the minimum relative failure rate λ/λ_0=14.0, and, consequently, the maximum probability of failure-free operation P_{max}= 0.9958 with a parallel electrical connection of the TEC in a uniform temperature field.

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Управління тепловим режимом паралельно з’єднаних термоелектричних охолоджувачів у рівномірному температурному полі

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АНОТАЦІЯ

Розглянуто можливість використання комплексу термоелектричних пристроїв для керування тепловим режимом ряду термозалежних та теплонавантажених елементів радіоелектронної апаратури, до яких пред'являються підвищені вимоги до показників надійності та динамічних характеристик. Розроблено математичну модель термоелектричного пристрою для рівномірного температурного поля, типового діапазону потужності розсіювання використовуваних виробів, діапазону стандартних значень напруги живлення, фіксованої геометрії гілок термоелементів. Отримано співвідношення визначення відносного робочого струму залежно від відносного перепаду температури при заданому напрузі живлення, геометрії гілок термоелементів і величині теплового навантаження. Визначено область дійсних значень відносного робочого струму в зоні відносних перепадів температур при заданій геометрії гілок та тепловому навантаженні. Проведено аналіз зв'язку відносного робочого струму однокаскадного термоелектричного охолоджувача з холодильним коефіцієнтом, кількістю енергії, що витрачається, тепловідвідною здатністю радіатора, часом виходу на стаціонарний режим і ймовірністю безвідмовної роботи. Досліджено залежність відносної інтенсивності відмов та ймовірності безвідмовної роботи, кількості енергії, що витрачається, тепловідвідної здатності радіатора та кількості термоелементів від напруги живлення термоелектричного охолоджувача. Це дозволило оцінити керуючі ознаки та виявити ефективність впливу керуючих впливів при паралельному з'єднанні охолоджувачів у рівномірному температурному полі. Показано можливість вибору оптимальної напруги з урахуванням ряду обмежувальних факторів за масогабаритними, енергетичними, динамічними та надійними характеристиками комплексу термоелектричних охолоджувачів у складі систем забезпечення теплових режимів теплонавантаженої радіоелектронної апаратури.

Ключові слова: Математична модель, термоелектричний охолоджувач, Тепловий режим, Моделі зв’язку, Робочий струм, Показники надійності, Динамічні характеристики

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