

DOI: <https://doi.org/10.15276/hait.05.2022.12>  
UDC 004.662.99·519.6

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

Vladimir P. Zaykov<sup>1)</sup>

ORCID: <http://orcid.org/0000-0002-4078-3519>; gradan@i.ua. Scopus Author ID: 57192640250

Vladimir I. Mescheryakov<sup>2)</sup>

ORCID: <http://orcid.org/0000-0003-0499-827X>; gradan@ua.fm. Scopus Author ID: 57192640885

Yurii I. Zhuravlov<sup>3)</sup>

ORCID: <http://orcid.org/0000-0001-7342-1031>; ivanovich1zh@gmail.com. Scopus Author ID: 57190425471

<sup>1)</sup> Research Institute STORM, 27, Tereshkova Str. Odessa, 65076, Ukraine

<sup>2)</sup> State Environmental University, 15, Lvivska Str. Odessa, 65026, Ukraine

<sup>3)</sup> National University “Odessa Maritime Academy”, 8, Didrikhson Str. Odessa, 65029, Ukraine

### 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

**For citation:** Zaykov V. P., Mescheryakov V. I., Zhuravlov Yu. I. Thermal control of parallelly connected thermoelectric coolers in a uniform temperature field. *Herald of Advanced Information Technology*. 2022; Vol. 5 No. 2: 143–155. DOI: <https://doi.org/10.15276/hait.05.2022.12>

### 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

© Zaykov V., Mescheryakov V., Zhuravlov Yu., 2022

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/deed.uk>)

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]:

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

where  $n$  is the number of thermoelements, pcs;

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

$\bar{e}$  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;

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

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

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

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

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

$\bar{Z}$  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:

$$I = B I_{\max}. \quad (2)$$

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

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

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

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

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

The relative value of the failure rate  $\lambda/\lambda_0$  can be determined from the expression [19]:

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

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:

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

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

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

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

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  $m_0 C_0 \rightarrow 0$  (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  $\tau=0$ ;

$I_{max H} = \frac{e_H T}{R_H}$  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

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

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  $\Theta$  for a given geometry of the thermoelement legs (ratio  $l/S$ ):

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

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

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

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

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

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

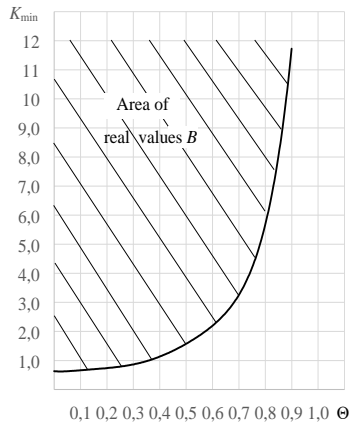


Fig.1. Dependence of the value  $K_{\min} = \frac{U_{\min} I_{\min}}{2Q_0}$  on the relative temperature difference  $\theta$  at a given supply voltage  $U$ , geometry of the thermoelement legs (ratio  $l/S$ ) and thermal

load  $Q_0$  at  $T=300K$

Source: compiled by the authors

Table.1.  $U_{\min}=5.6V$ ;  $l/S=4.5$ ;  $T=300K$ ;  $\Delta T=40K$ ;  $\theta=0.5$ ;  $R=4.55 \cdot 10^{-3} \Omega$ ;  $I_{\max}=11.1A$ ;  $T-T_c=5K$

$Q_0, W$	$B$	$K$	$n$	$I, A$	$W, W$	$E$	$\tau, s$	$N$	$\alpha F, W/K$	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ 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.  $U_{\min}=6.0V$ ;  $l/S=4.5$ ;  $T=300K$ ;  $\Delta T=40K$ ;  $\theta=0.5$ ;  $R=4.55 \cdot 10^{-3} \Omega$ ;  $I_{\max}=11.1A$ ;  $T-T_c=5K$

$Q_0, W$	$B$	$K$	$n$	$I, A$	$W, W$	$E$	$\tau, s$	$N$	$\alpha F, W/K$	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ 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

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]:

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

The results of calculations of the main parameters, reliability indicators and the time to reach the stationary mode of operation  $\tau$  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 3.  $U=7.0V$ ;  $T=300K$ ;  $\Delta T=40K$ ;  $\Theta=0.5$ ;  $l/S=4.5$ ;  $R=4.55 \cdot 10^{-3} \text{Ohm}$ ;  $I_{\max}=11.1A$ 

$Q_0$ , W	$B$	$K$	$n$	$I$ , A	$W$ , W	$E$	$\tau$ ,s	$N$ , W·s	$\alpha F$ , W/K	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ 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.  $U=9.0V$ ;  $T=300K$ ;  $\Delta T=40K$ ;  $\Theta=0.5$ ;  $l/S=4.5$ ;  $R=4.55 \cdot 10^{-3} \text{Ohm}$ ;  $I_{\max}=11.1A$ 

$Q_0$ , W	$B$	$K$	$n$	$I$ , A	$W$ , W	$E$		$N$ , W·s	$\alpha F$ , W/K	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ 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.  $U=12V$ ;  $\Delta T=40K$ ;  $\Theta=0.5$ ;  $l/S=4.5$ ;  $R=4.55 \cdot 10^{-3} \text{Ohm}$ ;  $I_{\max}=11.1A$ 

$Q_0$ , W	$B$	$K$	$n$	$I$ , A	$W$ , W	$E$	$\tau$ ,s	$N$ W·s	$\alpha F$ , W/K	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ 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.  $U=18V$ ;  $\Delta T=40K$ ;  $\Theta=0.5$ ;  $I/S=4.5$ ;  $R=4.55 \cdot 10^{-3} Ohm$ ;  $I_{max}=11.1A$

$Q_0, W$	$B$	$K$	$n$	$I, A$	$W, W$	$E$	$\tau, s$	$N, W \cdot s$	$\alpha F, W/K$	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8, 1/h$	$P$
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.  $U=24V$ ;  $\Delta T=40K$ ;  $\Theta=0.5$ ;  $I/S=4.5$ ;  $R=4.55 \cdot 10^{-3} Ohm$ ;  $I_{max}=11.1A$

$Q_0, W$	$B$	$K$	$n$	$I, A$	$W, W$	$E$	$\tau, s$	$N, W \cdot s$	$\alpha F, W/K$	$B_H$	$\lambda/\lambda_0$	$\lambda \cdot 10^8, 1/h$	$P$
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  $\Theta$  at  $T=300K$ ,  $I/S=4.5$ ,  $Q_{0max}=15W$ .

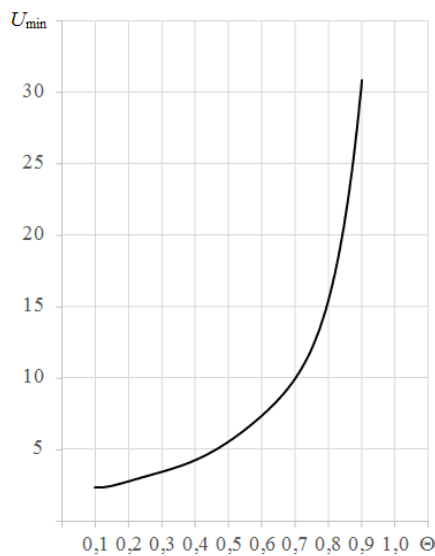


Fig.2. Dependence of the minimum voltage drop  $U_{min}$  of a single-stage TEC on the relative temperature drop  $\Theta$  at  $T=300K$ ;  $I/S=4.5$ ;  $Q_{0min}=15W$

Source: compiled by the authors

As the relative temperature difference  $\Theta$  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  $T=300K$ ,  $\Delta T=40K$ ,  $I/S=4.5$ .

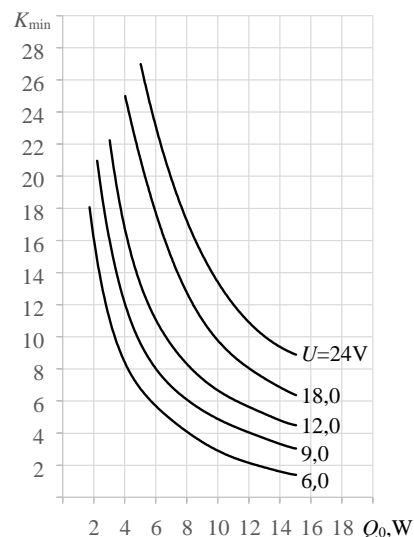


Fig.3. Dependence of the  $K_{min}$  value of a single-stage TEC on the thermal load  $Q_0$  for different supply voltage  $U$  at  $T=300K$ ;  $\Delta T=40K$ ;  $I/S=4.5$

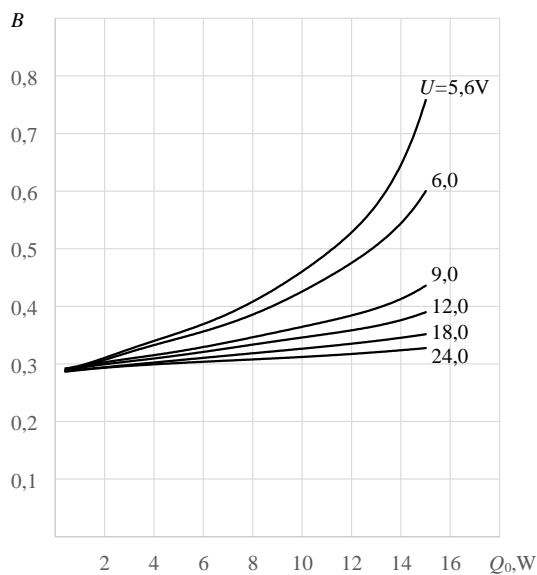
Source: compiled by the authors

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  $T=300K$ ,  $\Delta T=40K$ ,  $l/S=4.5$ :

– 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  $T=300K$ ;  $\Delta T=40K$ ;  $l/S=4.5$**

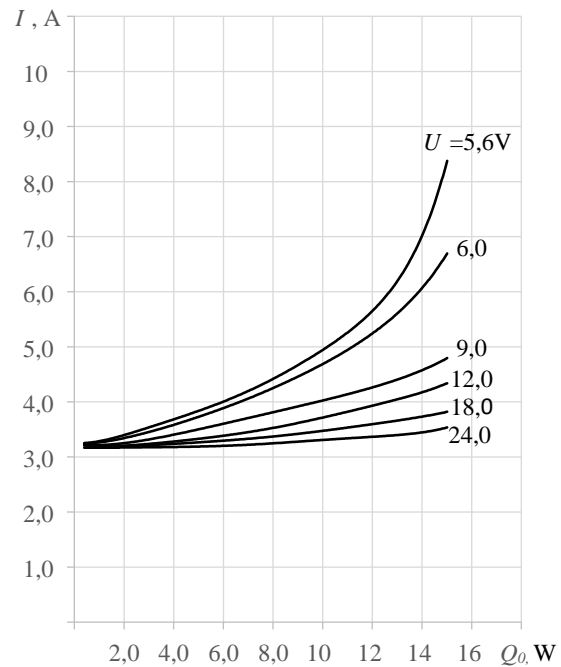
Source: compiled by the authors

– 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;

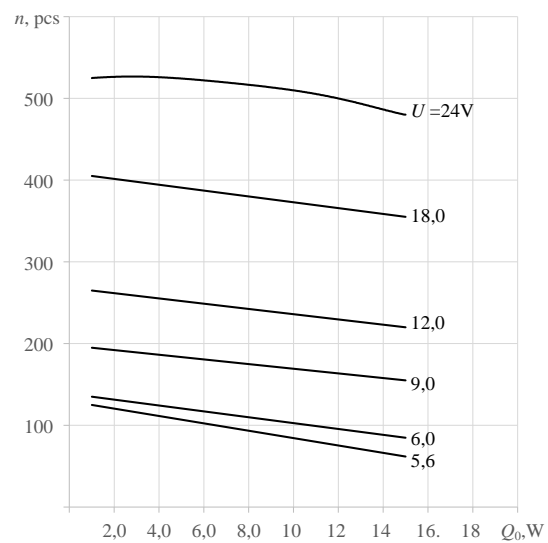
– the coefficient of performance  $E$  increases (Fig.7). At a given thermal load  $Q_0$ , with increasing supply voltage  $U$ , the coefficient of performance  $E$  increases;

– 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  $T=300K$ ;  $\Delta T=40K$ ;  $l/S=4.5$**

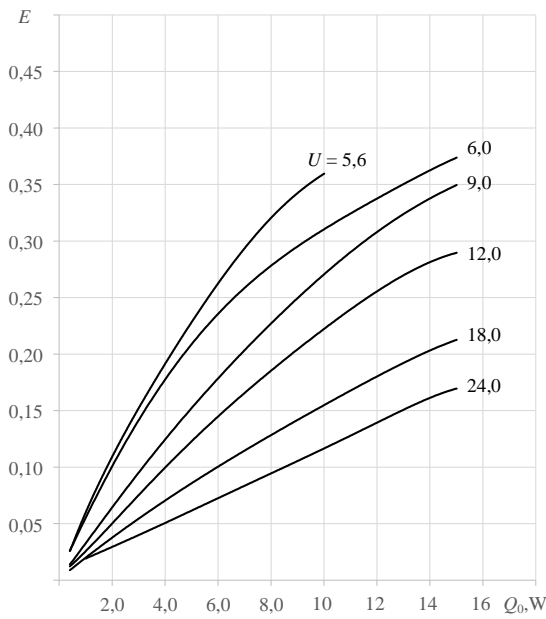
Source: compiled by the authors



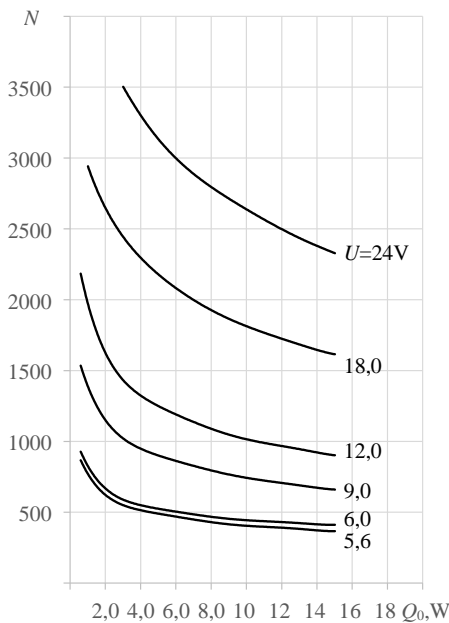
**Fig.6. Dependence of the number of thermoelements –  $n$  of a single-stage TEC on the magnitude of the thermal load –  $Q_0$  for various values of the supply voltage –  $U$  at  $T=300K$ ;  $\Delta T=40K$ ;  $l/S=4.5$**

Source: compiled by the authors





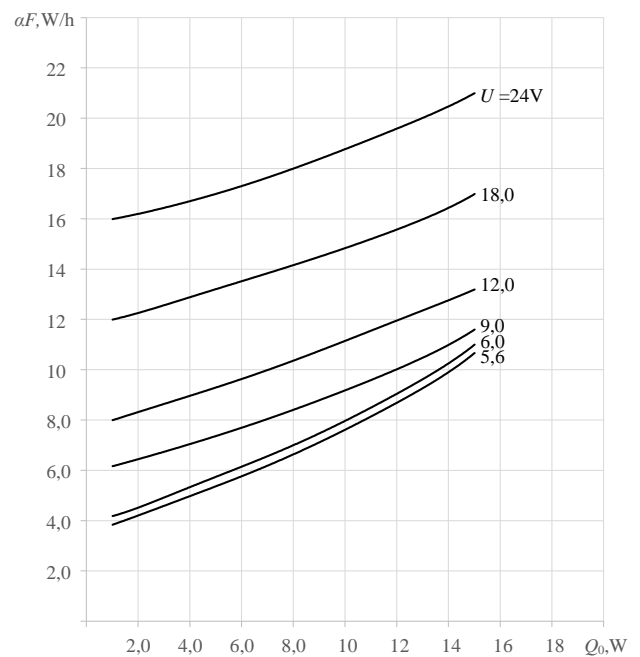
**Fig.7. Dependence of the coefficient of performance  $E$  of a single-stage TEC on the magnitude of the thermal load  $Q_0$  for various values of the supply voltage –  $U$  at  $T=300\text{K}$ ;  $\Delta T=40\text{K}$ ;  $I/S=4.5$**   
 Source: compiled by the authors



**Fig.8. Dependence of the amount of energy consumed  $N$  of a single-stage TEC on the magnitude of the heat load  $Q_0$  for various values of the supply voltage  $U$  at  $T=300\text{K}$ ;  $\Delta T=40\text{K}$ ;  $I/S=4.5$**   
 Source: compiled by the authors

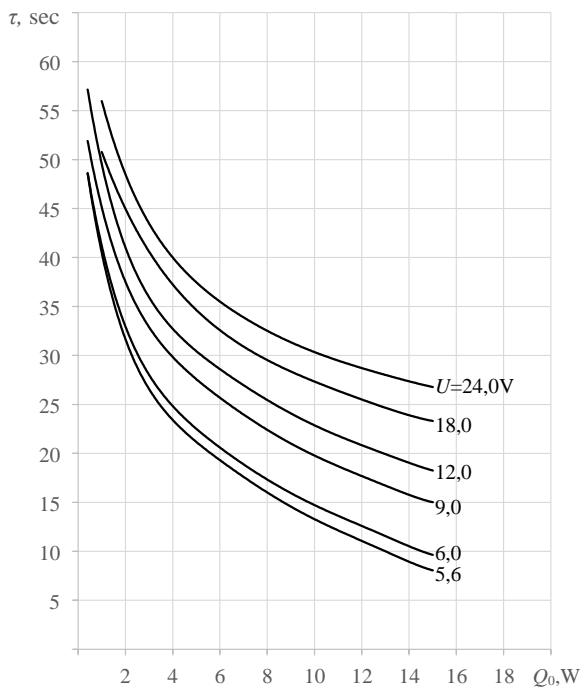
With an increase in the supply voltage  $U$  at a given thermal load  $Q_0$ , the amount of energy expended increases:

- the required heat dissipation capacity of the radiator  $\alpha F$  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  $\alpha F$  increases;
- the time to reach the stationary mode of operation  $\tau$  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  $\lambda/\lambda_0$  increases (Fig.11). With an increase in the supply voltage  $U$  at a given thermal load  $Q_0$ , the relative failure rate  $\lambda/\lambda_0$  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.

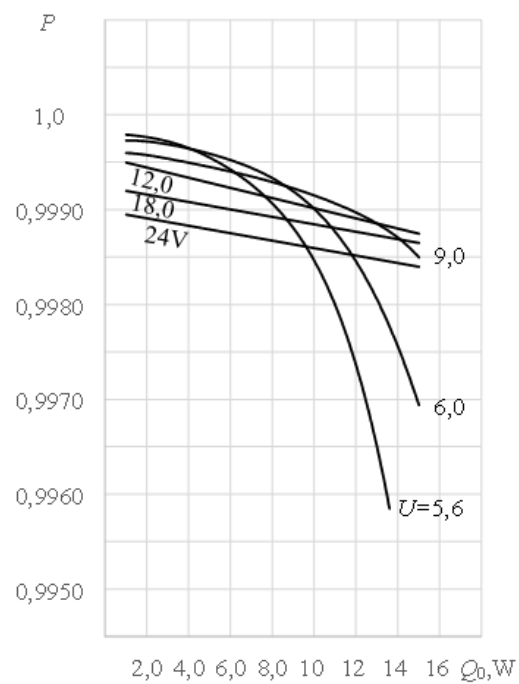


**Fig. 9. Dependence of the heat dissipation capacity of the radiator  $\alpha F$  of a single-stage TEC on the value of the thermal load  $Q_0$  for various values of the supply voltage –  $U$  at  $T = 300\text{K}$ ;  $\Delta T = 40\text{K}$ ;  $I / S = 4.5$**   
 Source: compiled by the authors

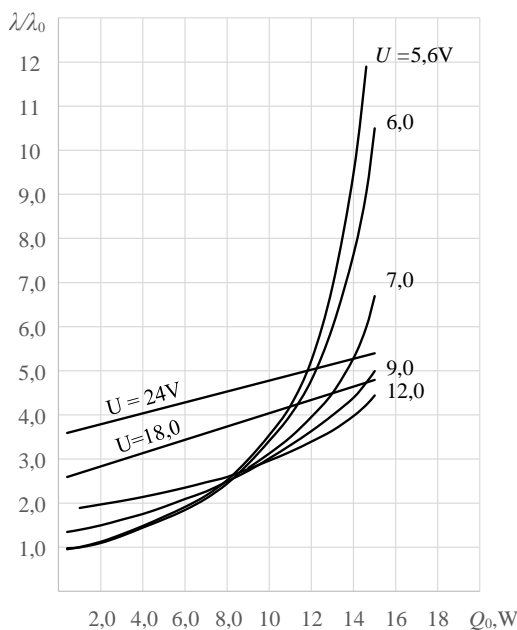




**Fig.10. The dependence of the time to reach the stationary mode of operation  $\tau$  of a single-stage TED on the magnitude of the thermal load  $Q_0$  for various values of the supply voltage  $U$  at  $T = 300\text{K}$ ;  $\Delta T = 40\text{K}$ ;  $l/S = 4.5$**   
 Source: compiled by the authors



**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  $T = 300\text{K}$ ,  $\Delta T = 40\text{K}$ ;  $l/S = 4.5$ ;  $t = 10^4$  hours**  
 Source: compiled by the authors



**Fig.11. Dependence of the relative value of the failure rate  $\lambda/\lambda_0$  of the TEC on the magnitude of the thermal load  $Q_0$  for various values of the supply voltage  $U$  at  $T = 300\text{K}$ ;  $\Delta T = 40\text{K}$ ;  $l/S = 4.5$ ;  $\lambda_0 = 3 \cdot 10^{-8}$  1/hour**  
 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  $T=300\text{K}$ ,  $\Delta T=40\text{K}$ ,  $l/S=4.5$ ,  $Q_0=34.5\text{W}$  are given in Table 8.

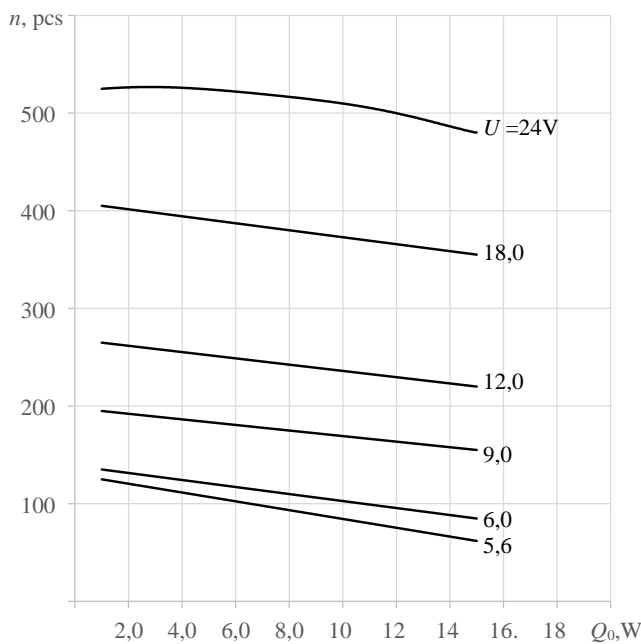
With an increase in the supply voltage  $U$  of the TEC complex with a thermal load  $Q_0=34.5\text{W}$  and a temperature difference  $\Delta T=40\text{K}$ :

- the total number of thermoelements  $n\Sigma$  increases (Fig. 14 p.1);
- the total operating current  $I\Sigma$  decreases (Fig.13 p. 2);
- the coefficient of performance  $E$  decreases;
- the total heat dissipation capacity of the radiator  $aF$  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  $\lambda/\lambda_{0min} = 14$  at  $U=9\text{V}$  (Fig.15);
- functional dependence of the probability of failure-free operation of the TEC complex  $P_{tot}=f(U)$  has a maximum at  $U=9\text{V}$   $P_{tot}=0.9958$ ;
- the time to reach the stationary mode of operation  $\tau$  increases

**Table 8. Key parameters, energy indicators, dynamics and reliability at  $T=300\text{K}$ ,  $\Delta T=40\text{K}$ ,  $l/S=4.5$ ,  $Q_0=34.5\text{ W}$**

$U, \text{ V}$	$I_{\Sigma}, \text{ A}$	$N, \text{ W}\cdot\text{s}$	$\tau, \text{ s, max value}$	$\alpha F, \text{ w/h}$	$n$	$E$	$\lambda/\lambda_0$	$\lambda \cdot 10^8, \text{ 1/h}$	$P_{\Sigma}$
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



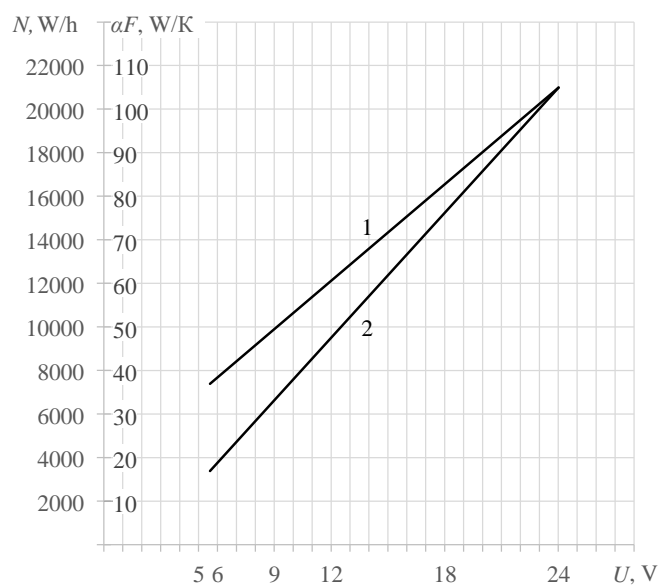
**Fig.13. Dependence of the total number of thermoelements  $n_{\Sigma}$ , the value of the operating current  $I_{\Sigma}$  and the cooling coefficient  $E$  of the complex on the supply voltage  $U$  at  $T = 300\text{K}$ ;  $\Delta T = 40\text{K}$ ;  $l/S = 4.5$ :**

$1 - n = f(U)$ ;  $2 - I = f(U)$ ;  $3 - E = f(U)$   
 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  $T_0=260\text{K}$  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



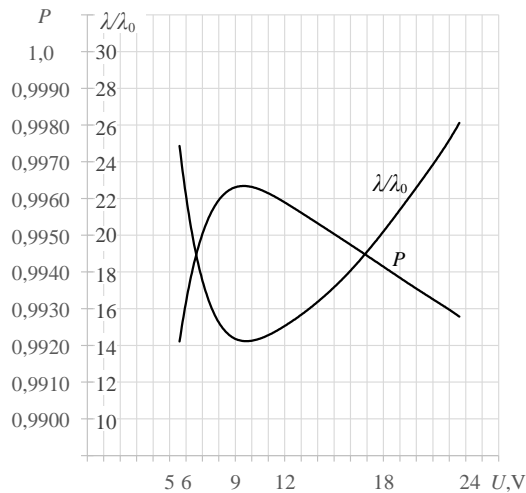
**Fig.14. Quantity dependency energy expended -  $N$ , heat dissipation capacity of the radiator  $\alpha F$  of the TEC complex from the supply voltage -  $U$  at  $T = 300\text{K}$ ;  $\Delta T = 40\text{K}$ ;  $l/S = 4.5$ :**

$1 - \alpha F = f(U)$  ;  $2 - N = f(U)$   
 Source: compiled by the authors

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  $\alpha F$ , the coefficient of performance  $E$ , the relative failure rate  $\lambda/\lambda_0$ ;



**Fig.15. Dependence of the relative failure rate  $\lambda/\lambda_0$  and the probability of failure-free operation  $P$  of the TEC complex on the supply voltage  $U$  at  $T=300\text{K}$ ;  $\Delta T=40\text{K}$ ;  $l/S=4.5$ ;  $\lambda_0=3\cdot 10^{-8}$  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  $\tau$ , 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  $\alpha F$ , the time to reach the stationary operation mode  $\tau$ , the relative failure rate  $\lambda/\lambda_0$ ;

– 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  $U_{\text{opt}}=9\text{V}$  is shown to ensure the minimum relative failure rate  $\lambda/\lambda_0=14.0$ , and, consequently, the maximum probability of failure-free operation  $P_{\text{max}}=0.9958$  with a parallel electrical connection of the TEC in a uniform temperature field.

## REFERENCES

1. Ellison, G. N. “Thermal Computations for Electronics”. *CRC Press. Boca Raton*. 2020. DOI: <https://doi.org/10.1201/9781003029328>.
2. Sulaiman, A. C., Amin, N. A. M., Basha, M. H., Majid, M. S. A., Nasir, N. F. b. M. & Zaman, I. “Cooling Performance of Thermoelectric Cooling (TEC) and Applications: A Review”. *MATEC Web Conf*. 2018; 225. DOI: <https://doi.org/10.1051/mateconf/201822503021>.
3. Venkatesan, K., & Venkataramanan, M. “Experimental and simulation studies on thermoelectric cooler: a performance study approach”. *International Journal of Thermophysics*. 2020; 41 (4). DOI: <https://doi.org/10.1007/s10765-020-2613-2>.
4. Wang, L. Q., Zhou, L. & Fan, H. T. “Design of cooling system for infrared CCD camera used to monitor burden surface of blast furnace based on thermoelectric coolers”. *Applied Mechanics and Materials*. 2013; Vol.419: 778-783. DOI: <https://doi.org/10.4028/www.scientific.net/AMM.419.778>.
5. Yu, J., Zhu, Q., Li Kong, Wang, H. & Zhu, H. “Modeling of an integrated thermoelectric generation-cooling system for thermoelectric cooler waste heat recovery”. *Energies*. 2020; 13(18): 4691. DOI: <https://doi.org/10.3390/en13184691>.
6. Manikandan, S., Kaushik, S. C. & Yang Ronggui. “Modified pulse operation of thermoelectric coolers for building cooling applications”. *Energy Conversion and Management*. 2017; 140: 145–156. DOI: <https://doi.org/10.1016/j.enconman.2017.03.003>.
7. Dong, X. & Liu, X. “Multi-objective optimal design of microchannel cooling heat sink using topology optimization method”. 2020; 77 (1): 90–104. DOI: <https://doi.org/10.1080/10407782.2019.1682872>.
8. Ebale, L. O., Pierre Gomat, L. J., Nzonzolo, L., Mavoungou, M. R. & Kibongani, F. “Optimization of a thermoelectric cooling system with peltier effect”. *American Journal of Energy Engineering*. 2019; 7 (3): 55–63. DOI: <https://doi.org/10.11648/j.ajee.20190703.11>.
9. Erturun, U, & Mossi, K. “Feasibility. Investigation on improving structural integrity of thermoelectric modules with varying geometry”. 2012. p. 939–945 DOI: <https://doi.org/10.1115/SMASIS2012-8247>.
10. Cai, Y., Wang, Y., Liu, D. & Zhao, F.-Y. “Thermoelectric cooling technology applied in the field of electronic devices: updated review on the parametric investigations and model developments”. *Appl. Therm. Eng.* 2019; 148: 238–255. DOI: <https://doi.org/10.1016/j.applthermaleng.2018.11.014>.
11. Kashif Irshad, Abdulmohsen Almalawi, Asif Irshad Khan, Md Mottahir Alam, Md. Hasan Zahir & Amjad Ali. “An IoT-based thermoelectric air management framework for smart building applications: a case

study for tropical climate”. *Sustainability. MDPI*. 2020; Vol. 12(4): 1–18. – Available from: <https://ideas.repec.org/a/gam/jsusta/v12y2020i4p1564-d322657.html>. – [Accessed Nov 2020].

12. Ngo, T.-T., Wang, C.-C., Chen, Y.-T. & Than, V.-T. “Developing a thermoelectric cooling module for control temperature and thermal displacement of small built-in spindle”. *Therm. Sci. Eng. Prog.* 2021; 25: 100958. DOI: <https://doi.org/10.1016/j.tsep.2021.100958>.

13. Choi, H.-S., Seo, W.-S. & Choi, D.-K. “Prediction of reliability on thermoelectric module through accelerated life test and physics-of-failure”. *Electronic Materials Letters*. 2011; 7 (3): 271–275. DOI: <https://doi.org/10.1007/s13391-011-0917-x>.

14. Song, H., Song, K. & Gao, C. “Temperature and thermal stress around an elliptic functional defect in a thermoelectric material”. *Mechanics of Materials*. 2019; Vol.130: 58–64. DOI: <https://doi.org/10.1016/j.mechmat.2019.01.008>.

15. Karri, N.K., & Mo, C. . “Structural reliability evaluation of thermoelectric generator modules: influence of end conditions, leg geometry, metallization, and processing temperatures”. *Journal of Electronic Materials*. 2018; Vol. 47 (10): 6101–6120. DOI: <https://doi.org/10.1007/s11664-018-6505-1>. 16. Hee Seok Kim, Tianbao Wang, Weishu Liu & Zhifeng Ren. “Engineering thermal conductivity for balancing between reliability and performance of bulk thermoelectric generators”. *Advanced Functional Materials*. 2016; Vol.26: 3678–3686. DOI: <https://doi.org/10.1002/adfm.201600128>.

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

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

19. Zaykov, V. P., Kinshova, L. A. & Moiseev, V.F. “Prediction of reliability indicators, thermoelectric cooling devices”. Book 1. One-stage devices. Odessa: Ukraine. *Publ. Polytehprirodika*. 2009.

20. Zaykov, V., Mescheryakov, V. & Zhuravlov Yu. “Prediction of reliability indicators, thermoelectric cooling devices”. Book 4. Dynamics of functioning of single-stage TED. *Publ. Polytehprirodika*. 2019.

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

Received 22.04.2022

Received after revision 10.06.2022

Accepted 16.06.2022

DOI: <https://doi.org/10.15276/hait.05.2022.12>

УДК 004.662.99·519.6

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

**Володимир Петрович Зайков**<sup>1)</sup>

ORCID: <http://orcid.org/0000-0002-4078-3519>; gradan@i.ua. Scopus Author ID: 57192640250

**Володимир Іванович Мещеряков**<sup>2)</sup>

ORCID: <http://orcid.org/0000-0003-0499-827X>; gradan@ua.fm. Scopus Author ID: 57192640885

**Юрій Іванович Журавльов**<sup>3)</sup>

ORCID: <http://orcid.org/0000-0001-7342-1031>; ivanovich1zh@gmail.com. Scopus Author ID: 57190425471

<sup>1)</sup> Науково-дослідницький інститут ШТОРМ, вул. Терешкової, 27. Одеса, 65076, Україна

<sup>2)</sup> Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна

<sup>3)</sup> Національний університет «Одеська морська академія», вул. Дідріхсона, 8. Одеса, 65029, Україна

### 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

study for tropical climate”. *Sustainability. MDPI*. 2020; Vol. 12(4): 1–18. – Available from: <https://ideas.repec.org/a/gam/jsusta/v12y2020i4p1564-d322657.html>. – [Accessed Nov 2020].

12. Ngo, T.-T., Wang, C.-C., Chen, Y.-T. & Than, V.-T. “Developing a thermoelectric cooling module for control temperature and thermal displacement of small built-in spindle”. *Therm. Sci. Eng. Prog.* 2021; 25: 100958. DOI: <https://doi.org/10.1016/j.tsep.2021.100958>.

13. Choi, H.-S., Seo, W.-S. & Choi, D.-K. “Prediction of reliability on thermoelectric module through accelerated life test and physics-of-failure”. *Electronic Materials Letters*. 2011; 7 (3): 271–275. DOI: <https://doi.org/10.1007/s13391-011-0917-x>.

14. Song, H., Song, K. & Gao, C. “Temperature and thermal stress around an elliptic functional defect in a thermoelectric material”. *Mechanics of Materials*. 2019; Vol.130: 58–64. DOI: <https://doi.org/10.1016/j.mechmat.2019.01.008>.

15. Karri, N.K., & Mo, C. . “Structural reliability evaluation of thermoelectric generator modules: influence of end conditions, leg geometry, metallization, and processing temperatures”. *Journal of Electronic Materials*. 2018; Vol. 47 (10): 6101–6120. DOI: <https://doi.org/10.1007/s11664-018-6505-1>.

16. Hee Seok Kim, Tianbao Wang, Weishu Liu & Zhifeng Ren. “Engineering thermal conductivity for balancing between reliability and performance of bulk thermoelectric generators”. *Advanced Functional Materials*. 2016; Vol.26: 3678–3686. DOI: <https://doi.org/10.1002/adfm.201600128>.

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

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

19. Zaykov, V. P., Kinshova, L. A. & Moiseev, V.F. “Prediction of reliability indicators, thermoelectric cooling devices”. Book 1. One-stage devices. Odessa: Ukraine. *Publ. Polytehprirodika*. 2009.

20. Zaykov, V., Mescheryakov, V. & Zhuravlov Yu. “Prediction of reliability indicators, thermoelectric cooling devices”. Book 4. Dynamics of functioning of single-stage TED. *Publ. Polytehprirodika*. 2019.

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

Received 22.12.2020

Received after revision 27.02.2021

Accepted 14.03.2021

DOI: <https://doi.org/10.15276/hait.05.2022.12>

УДК 004.662.99·519.6

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

**Володимир Петрович Зайков**<sup>1)</sup>

ORCID: <http://orcid.org/0000-0002-4078-3519>; gradan@i.ua. Scopus Author ID: 57192640250

**Володимир Іванович Мещеряков**<sup>2)</sup>

ORCID: <http://orcid.org/0000-0003-0499-827X>; gradan@ua.fm. Scopus Author ID: 57192640885

**Юрій Іванович Журавльов**<sup>3)</sup>

ORCID: <http://orcid.org/0000-0001-7342-1031>; ivanovich1zh@gmail.com. Scopus Author ID: 57190425471

<sup>1)</sup> Науково-дослідницький інститут ШТОРМ, вул. Терешкової, 27. Одеса, 65076, Україна

<sup>2)</sup> Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна

<sup>3)</sup> Національний університет «Одеська морська академія», вул. Дідріхсона, 8. Одеса, 65029, Україна

### 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

## ABOUT THE AUTHORS



**Vladimir P. Zaykov** - Candidate of Engineering Sciences, Associate Professor, Head of Sector Research Institute "STORM", 27, Tereshkova Str. Odessa, 65076, Ukraine

ORCID: <http://orcid.org/0000-0002-4078-3519>; [gradan@i.ua](mailto:gradan@i.ua). Scopus Author ID: 57192640250.

**Research field:** Reliability and dynamic descriptions of thermo-electric cooling devices; design; planning of the systems of providing of the thermal modes of electronic apparatus

**Володимир Петрович Зайков** - кандидат технічних наук (1990), начальник сектору науково-дослідного інституту «ШТОРМ», вул. Терешкової, 27. Одеса, 65076, Україна



**Vladimir I. Mescheryakov** - D.Sc (Eng), Professor, Head of Department of Informatics. State Environmental University. 15, Lvivska Str. Odessa, 65026, Ukraine

ORCID: <http://orcid.org/0000-0003-0499-827X>; [gradan@ua.fm](mailto:gradan@ua.fm). Scopus Author ID: 57192640885

**Research field:** Reliability and dynamic descriptions of thermo-electric cooling devices; design of power processes; biotechnical informative systems

**Володимир Іванович Мещеряков** - доктор технічних наук, зав. кафедри Інформатики. Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна



**Yurii I. Zhuravlov** - Candidate of Engineering Sciences, Associate Professor of the Department of Technology of Materials and Ship Repair. National University "Odessa Maritime Academy", 8, Didrikhson Str. Odessa, 65029, Ukraine

ORCID: <http://orcid.org/0000-0001-7342-1031>; [ivanovich1zh@gmail.com](mailto:ivanovich1zh@gmail.com). Scopus Author ID: 57190425471

**Research field:** Reliability and dynamic descriptions of thermo-electric cooling devices; reliability and reparability of ship equipment

**Юрій Іванович Журавльов** - кандидат технічних наук (2016), доцент кафедри Технології матеріалів і судноремонту. Національний університет "Одеська морська академія", вул. Дідріхсона, 8. Одеса, 65029, Україна