DOI: https://doi.org/10.15276/aait. 05.2022.21
UDC 004.662.99·519.6

Control of complex thermoelectric cooling units with mixed electrical connection in a uniform temperature field

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ABSTRACT

The possibility of optimal thermal management of a number of temperature-dependent and heat-loaded elements of radio electronic equipment with calculated power dissipation is considered. Studies have been carried out in a uniform temperature field using a set of thermoelectric cooling devices and defined geometry of thermocouple branches. The correlation for determining the relative operating current depending on the relative temperature drop for a given supply voltage, thermal load and geometry of thermoelements branches has been obtained; the range of valid values of the relative operating current has been determined. A comparative analysis of the basic parameters, reliability indices and dynamic characteristics of a group of thermoelectric devices included in the complex for different supply voltages and heat loads has been made. The possibility of selecting supply voltages of thermoelectric devices complex with regard to limiting factors for mass-size, power, dynamic and reliability characteristics to ensure the optimum thermal mode of a number of thermo-dependent elements of radio electronic equipment has been shown. With increasing supply voltage of thermoelectric devices complex with mixed electrical connection in uniform temperature field at given thermal load and geometry of thermoelements branches the following results are achieved. Steady-state time increases, the number of thermoelements increases, the cooling coefficient decreases, the amount of consumed energy increases, the heat dissipation capacity of the heat sink increases, and the functional dependence of the probability of failure-free operation on the total supply voltage has a maximum.

Keywords: Thermoelectric cooler; thermal regime; models of communication; reliability indicators; dynamic characteristics

***For citation*: Zaykov V. P., Mescheryakov V. I., Zhuravlov Yu. I. “Control of complex thermoelectric cooling units with mixed electrical connection in a uniform temperature field”. *Applied Aspects of Information Technology*. 2022; Vol. 5 No.4 315–330. DOI: https://doi.org/10.15276/aait. 05.2022.21**

INTRODUCTION

The thermoelectric method of thermal management of heat-loaded elements of radio electronic equipment is the most acceptable due to the absence of moving components of coolers and their solid-state nature. These circumstances ensure small size, high performance and reliability of thermoelectric coolers (TEC). At the same time, the increasingly stringent requirements for on-board equipment place new demands on its thermal management systems as well. This applies first to such fundamental indicators as reliability, responsiveness and controllability. Reliability and responsiveness are antagonistic concepts, as demanding an increase in one automatically leads to a decrease in the other. The design challenge is to find a compromise that achieves acceptable performance relative to the target function. The management of a thermoelectric system for thermal management of apparatuses falls within the range of these objectives. The resulting reliability of a thermally loaded element and its thermal mode support system is directly determined by the reliability performance of the thermoelectric system.

This makes the problem of management of thermoelectric systems of equipment thermal modes with regard to their reliability and dynamic indicators relevant.

LITERATURE REVIEW

Ensuring thermal condition of on board-system [1]. Increased requirements to and dimensions make thermoelectric coolers [2], the main operational advantages of which are increased climatic and mechanical conditions of application and ease of control [3], have no alternative. Increasing demands on the dynamics and reliability of thermally loaded equipment [4, 5] result in the need for higher thermal mode systems [6, 7]. In [8] analysis of influence of thermal loading on reliability indicators of fuel injection equipment is given, however influence of design parameters was not discussed. In [9] results of investigation of influence of design parameters of fuel injection equipment on reliability indexes are presented. In [10] an analysis of relation between current operation modes of the cooler and reliability indices is made, which allowed to choose optimal operation conditions by this criterion. At the same time, the control function requires knowledge of dynamic characteristics, which were not considered in the noted sources [11]. However, increasing the dynamic characteristics leads to decreasing the reliability performance, which is a fundamental problem [12]. For thermoelectric coolers, this is reflected in the fact that the linear thermal expansion of thermocouple and substrate materials leads to cracking of junction sites [13]. Conducted research in [14] showed the relationship of dynamic performance with the design of TEC, in [15] with the number of thermocouples, in [16] with the current modes of the product. In [17, 18], an analysis of the possibility of controlling TECs by complex criteria, including both reliability and dynamics indices, is presented. However, all these studies were conducted for a separate thermoelectric cooler without taking into account their mutual influence. An urgent task is the task of controlling a thermal mode support system that includes thermoelectric coolers connected in parallel and in series.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the work is to improve the quality of thermal management of a set of thermoelectric cooling devices with mixed electrical connection in a uniform temperature field.

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

1. To develop a mathematical model of thermoelectric system of thermal modes provision with regard for reliability indicators and functioning dynamics.
2. To analyze developed model to identify optimal characteristics of thermoelectric cooler model.

DISTRIBUTED THERMOELECTRIC COOLER MODEL

The design features of radio electronic equipment include a dispersed arrangement of heat-loaded elements with different dissipation power. Therefore, in order to provide a given thermal mode of a number of heat-loaded elements, it is possible to use a group system of arrangement of TEC located on one heat sink. In this case, different supply voltages can be used for a group of TECs connected electrically in parallel. In doing so, the most rational ones can be identified, taking into account a number of limiting factors in terms of mass, energy, dynamic and reliability characteristics. For a group of TECs connected electrically in series, selects the mode $Q_{0\max}$, for one TEC in combination with different modes of operation of a group of TECs connected in parallel.

To solve the problem we shall use the known relations [19].

The number of thermocouples in a TEC can be determined from the expression:

$$n = \frac{Q_0}{I_{\max}^2 R(2B - B^2 - \Theta)}, \qquad (1)$$

where Q_0 is the heat load, W; $I_{\max} = \frac{\bar{e} T_0}{R}$ is maximum operating current, A; $\bar{e}$ is average value of coefficient of thermal EMF of thermocouple branch, V/K; T_0 is temperature of the heat-absorbing junction, K; $R = \frac{l}{\bar{\sigma} S}$ is electrical resistance of thermocouple branch. Ohm; l and S are, respectively, the height and the cross-sectional area of the thermocouple branch; $\bar{\sigma}$ is average value of electrical conductivity of the thermocouple branch, Sm/cm; $B = I/I_{\max}$ is relative operating current; I is value of operating current, A; $\Theta = \frac{T - T_0}{\Delta T_{\max}}$ is relative temperature difference; T is temperature of fuel junction, K; $\Delta T_{\max} = 0{,}5 \bar{z} T_0^2$ is maximum temperature difference, K; $\bar{z}$ is average value of thermoelectric efficiency of the thermocouple branch, 1/K.

The power consumption of the TEC can be determined from the expression [19]:

$$W = 2nI_{\max}^2 RB\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right). \qquad (2)$$

The voltage drop U can be written as

$$U = 2nI_{\max} R\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right). \qquad (3)$$

The cooling factor can be determined from the expression:

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

The relative failure rate λ/λ_0 can be calculated using the formula [19]:

$$\frac{\lambda}{\lambda_0} = nB^2(\Theta + c)\frac{\left(B + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)}K_T; \qquad (5)$$

where $c = \frac{Q_0}{nI_{\max}^2 R}$ is the relative heat load; K_T is reduced temperature coefficient [19]; $\lambda_0 = 3\cdot 10^{-8}$ is nominal failure rate, 1/hour.

The probability of failure-free operation P can be written as

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

where t is the designed lifetime, h.

The time of reaching the steady-state operation mode τ can be determined from the expression [20]:

$$\tau = \frac{\sum_i m_i c_i + m_0 c_0}{R = K\left(1 + 2B\frac{\Delta T_{\max}}{T_0}\right)} \ln\frac{\gamma B_H(2 - B_H)}{2B - B^2 - \Theta}, \qquad (7)$$

where $m_0 c_0$ is product of mass and heat capacity of the cooling object. In our case $m_0 c_0 \to 0$ (object is absent).

$\sum_i m_i c_i$ is the total value of products of heat capacity and mass of structural and technological elements (KTE) at the heat-absorbing junction of the module at a given geometry of thermocouple branches (relations l/S):

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

$\kappa = \frac{\varsigma \bar{S}}{l}$ is heat transfer coefficient, W/(cmK).

The indices *H* and *K* correspond to the start and end of the cooling process.

For an electrical connection in series, the condition must be fulfilled

$$I = B_H I_{\max H} = B_K I_{\max K}. \qquad (8)$$

Hereinafter we shall consider the mixed electrical connection of TEC in the complex consisting of six TEC, three of which are connected electrically in series with heat loads Q_0 =3 W, 1.0 W, 0.5 W.

The electrical diagram of the mixed connection of the TEC complex is shown in Fig. 1.

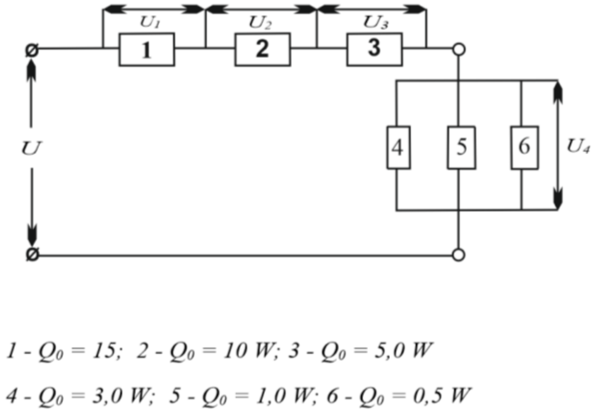

Fig. 1. **Connection diagram of thermoelectric coolers:**
1 – Q_0 =15W; 2 – Q_0 =10W; 3 – Q_0 =10W;
4 – Q_0 =3W; 5 – Q_0 =1.0W; 6 – Q_0 =0.5W.
TEC 1, 2, 3 are connected electrically in series and TEC 4, 5, 6 are connected in parallel
***Source:* compiled by the authors**

Let's consider the electrical connection of a group of TECs in series.

Results of calculations of basic parameters, reliability indices and dynamic characteristics of the group of fuel and energy units in series electrical connection of TEC in uniform temperature field T_0 =260K with different thermal load Q_0 = 5.0, 10.0, 15.0 W at fixed geometry of thermoelement branches (ratio l/S) are given in Table 1.

Table 1. **Series electrical connection of TECs (TEC 1. 2, 3).**
Mode $Q_{\max}$ $(B_1 = 1), \Theta = 0{,}5, l / S = 4{,}5, E = 0{,}216, \tau = 7{,}6s, T - T_c = 5K$

Q_0, W	n, pcs	W, W	U, V	$\alpha F, W/K$	$N, W \cdot s$	λ/λ_0	$\lambda \cdot 10^8, 1/h$	P
15.0	53.5	69.3	6.2	16.9	527	54.7	164	0.9837
10.0	35.7	46.2	4.2	11.2	351	36.5	110	0.9891
5.0	17.8	23.0	2.1	5.6	175	18.2	54.6	0.9946
$\sum$ 30.0	107	138.5	12.5	33.7	1054	109.4	328	0.9677

Source: **compiled by the authors**

With growth of thermal load Q_0 at a given temperature difference ΔT=40K for a group of TEC (1, 2, 3) with series connection: the number of thermoelements n, voltage drop U, required heat dissipation capacity of the radiator αF, power consumption W, relative failure rate λ/λ_0, amount of energy N consumed increase, probability of no-failure operation P decreases.

At the same time the value of operation current I=11.1A, cooling factor E=0.216, time to the steady-state operation τ=7.6 s remain constant and do not depend on the value of thermal load Q_0.

Let's consider a group of TECs with parallel electrical connection in a cascade.

Using relations (1) and (3) we can write the expression for the supply voltage U of the TEC:

$$U = \frac{2Q_0\left((B + \frac{\Delta T_{\max}}{T_0}\Theta \right)}{I_{\max}\left(2B - B^2 - \Theta\right)},$$

or

$$A = \frac{2B - B^2 - \Theta}{B + \frac{\Delta T_{\max}}{T_0}\Theta},$$

where $A = \dfrac{2Q_0}{UI_{\max}}$.

Fig. 2 shows the dependence of the value A on the relative operating current B for different temperature drops ΔT at T=300K, l / S=4.5. The functional dependence $A = f(B)$ has a maximum for different temperature drops ΔT. With increasing temperature difference ΔT the value A decreases. The geometric location of the points corresponding to the maximum values $A_{\max}$ of is indicated by a dotted line.

The optimum operating current B_{opt} corresponding to the maximum values $A_{\max}$ of the value $\dfrac{dA}{dB} = 0$ for different drops in temperature ΔT can be determined from the condition:

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

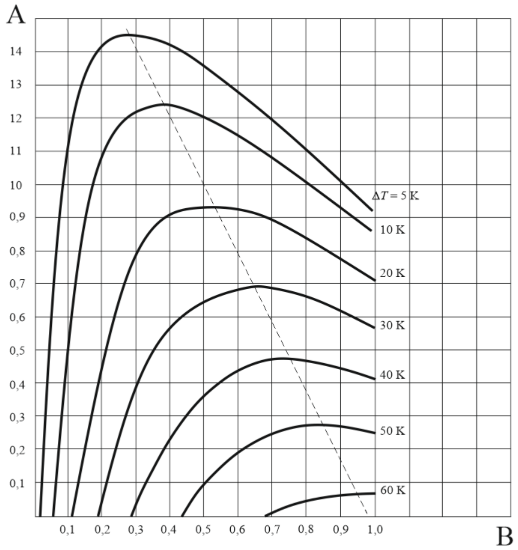

Fig. 2. **Dependence of the value** $A = \dfrac{2Q_0}{UI_{\max}}$ **of the group of TECs with parallel electric connection on the relative operating current** B **for different temperature drops** ΔT **at** T **=300K;** l / S **=4.5**

Source: **compiled by the authors**

Fig. 3 shows the dependence $B_{opt} = f(\Theta)$ of the optimum relative operating current B_{opt} on the relative temperature drop Θ.

As the relative temperature drop Θ increases, the optimum relative operating current B_{opt} increases at, $\Theta \to 1$ $B_{opt} \to 1.0$.

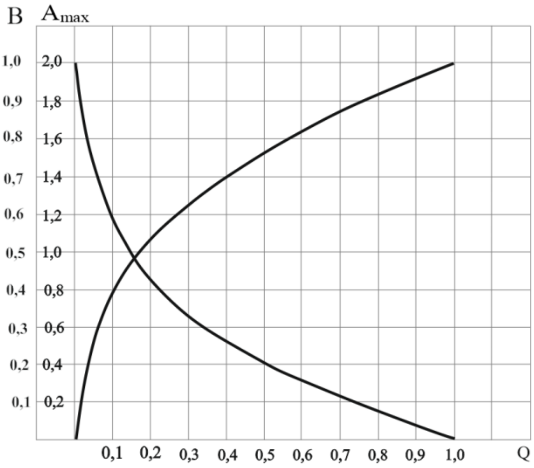

Fig. 3. **Dependence of optimum relative operating current B_{opt} and $A_{\max} = \dfrac{2Q_0}{UI_{\max}}$ on relative temperature difference Θ at T =300K; l/S =4.5**

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

Fig. 3 shows the dependence $A_{\max} = f(\Theta)$ of the maximum value $A_{\max}$ on the relative temperature drop Θ. With increasing relative temperature difference Θ the value $A_{\max}$ decreases and at $\Theta \to 1.0$ $A_{\max} \to 0$.

Using the relation $A = \dfrac{2Q_0}{UI_{\max}}$ it is possible to determine the minimum value of the supply voltage $U_{\min}$ of a group of TECs with parallel electric connection at a given geometry of thermocouple branches (ratio l/S =4.5) for different thermal load Q_0:

$$U_{\min} = \frac{2Q_0}{A_{\max} I_{\max}}.$$

Fig. 4 shows the dependence of the minimum supply voltage $U_{\min}$ of a group of parallel-connected TEC units on the value $A_{\max}$ for different temperature gradients ΔT and heat loads Q_0.

As the thermal load Q_0 increases, the value of the minimum supply voltage $U_{\min}$ increases for different temperature differences ΔT. By evaluating the value $U_{\min}$, it is possible to select the supply voltage value $U \geq U_{\min}$ for the group of TECs with parallel electrical connection.

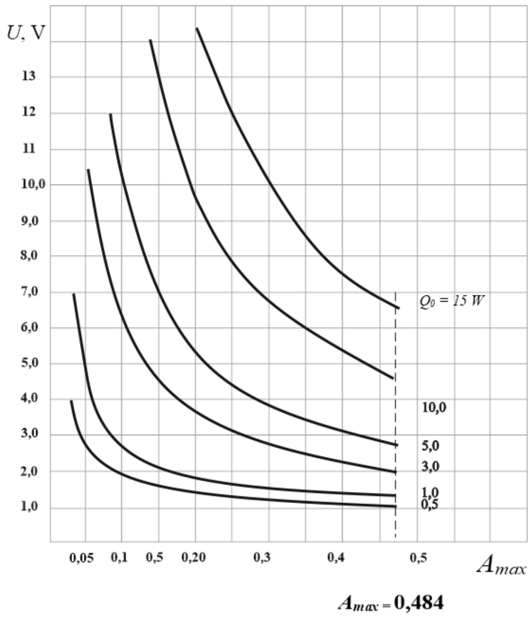

Fig. 4. **Dependence of the minimum voltage drop $U_{\min}$ of a parallel-coupled TEC complex on the value A for different heat loads Q_0 at l/S =4.5; ΔT =40K**

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

Using relations (1) and (3) it is possible to determine the relative operating current B for the parallel electric connection of TEC in the complex at a given supply voltage U, heat load Q_0 and relative temperature drop Θ with fixed geometry of thermocouple branches l/S:

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

where $A = \dfrac{2Q_0}{UI_{\max}}$.

Analysis of relation (9) shows that in the absence of a heat load $Q_0 = 0,\ A \to 0$, expression (9) can be written as

$$B = 1 - \sqrt{1-\Theta}\,. \tag{10}$$

The range of valid values relative to the operating current B can be determined according to (9) from the condition:

$$\frac{4\Theta\left(1 + A\dfrac{\Delta T_{\max}}{T_0}\right)}{(2-A)^2} \le 1\,. \tag{11}$$

The maximum value of the value $A_{\max}$ can be determined from the expression:

$$A_{\max} = 2\left(1+\frac{\Delta T_{\max}}{T_0}\Theta\right)\left[1-\sqrt{1-\frac{1-\Theta}{\left(1+\dfrac{\Delta T_{\max}}{T_0}\Theta\right)^2}}\right] \tag{12}$$

As the relative temperature difference Θ increases, the value $A_{\max}$ decreases (Fig. 3). With a given value $A = \dfrac{2Q}{UI_{\max}}$, the relative operating current B can be determined for different temperature differences ΔT (Fig. 5). As the value A increases from A=0 to $A_{\max}$ the relative operating current B increases and reaches its maximum value.

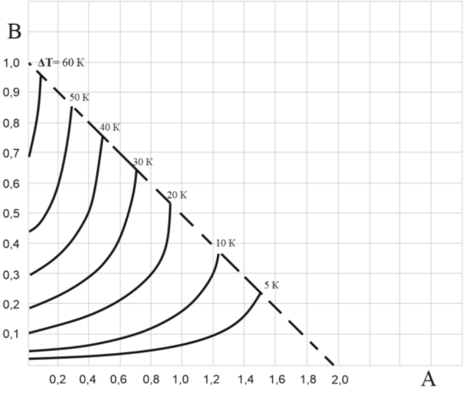

Fig. 5. **Dependence of the relative operating current B of a group of TECs with parallel electric connection on the value A for different temperature differences ΔT at T =300K; l/S =4.5**

Source: **compiled by the authors**

From relation (9) it can be written:

$$U_{\min} = \frac{2U_0}{A_{\max} I_{\max}}\,. \tag{13}$$

The value A of the minimum supply voltage decreases $U_{\min}$ with increasing magnitude. As the thermal load Q_0 increases, the minimum supply voltage $U_{\min}$ increases with a fixed value of A.

It should be noted that if the cooling system consists M of independent elements (TEC) and the probability of failure of the i-th element is equal to $P_i(t)$, then the total probability of failure of the system is [19]:

$$P_{\Sigma}(t) = P_1(t)\cdot P_2(t)\cdot\ldots\cdot P_i(t)\cdot\ldots\cdot P_M(t) = \prod_{i=1}^{M} P_i(t) \tag{14}$$

The total refrigeration factor E_{Σ} for a mixed electrical connection of the TEC unit can be determined from the expression:

$$E_{\Sigma} = \frac{\sum\limits_{i}^{M} Q_{0i}}{\sum\limits_{i=1}^{M} W_i} = \frac{\sum\limits_{i} Q_{0i}}{\sum\limits_{i=1}^{M=3} W_i + I_{\Sigma}U_4}\,, \tag{15}$$

where I_{Σ} is the value of the operating current depending on the selected current mode of operation of the TEC in series; U_4 is the set supply voltage for the three TECs in parallel connection.

Power supply of the complex with mixed electrical connection of TECs is provided by the value of the current of the selected current mode of operation by the group of TECs with series electrical connection, and the group of TECs connected in parallel by the value of the current, determined by the relation (9) for the given supply voltage.

We will use a system of equations to determine the main parameters, reliability indices and dynamic characteristics of the part of the TEC complex with electrical connection in parallel:

$$\begin{cases} B_{\Sigma} = B_1 + B_2 + B_3 \\ B_1^2 - B_1(2-A_1) + \Theta\left(1 + A_1\dfrac{\Delta T_4}{T_0}\right) = 0 \\ B_2^2 - B_2(2-A_2) + \Theta\left(1 + A_2\dfrac{\Delta T_4}{T_0}\right) = 0 \\ B_3^2 - B_3(2-A_3) + \Theta\left(1 + A_3\dfrac{\Delta T_4}{T_0}\right) = 0 \end{cases},$$

where B_Σ is the relative operating current of a part of a series-connected TEC complex operating in $Q_{0\max}$, i.e. B_Σ=0.956. B_1, B_2, B_3 are respectively, the relative operating currents of the three parallel circuits.

$$A_1 = \frac{2Q_{01}}{U_4 I_{\max}};\ A_2 = \frac{2Q_{02}}{U_4 I_{\max}};\ A_3 = \frac{2Q_{03}}{U_4 I_{\max}},$$

where Q_{01}, Q_{02}, Q_{03} are, respectively, the heat load of the corresponding parallel circuit. The geometry of thermocouple branches is the same and is chosen to be $l/S = 4.5$; U_4 is the supply voltage is given and can take design values; Θ =0.5 is the relative difference is the same in all chains in a uniform temperature field.

MODEL ANALYSIS OF THE THERMOELECTRIC COOLER COMPLEX

Results of calculations of basic parameters, reliability indices, dynamic characteristics of the whole complex of thermoelectric coolers with parallel electric connection in uniform temperature field T_0=260K with different thermal load Q_0=0.5, 1.0, 3.0 W at fixed geometry of thermoelements branches (ratio $l/S = 4.5$), using different supply voltages, are presented in Table 2.

A graphical method can be used to determine the relative operating current B in each parallel circuit (TEC from a group with parallel electrical connection).

Fig. 6 shows the dependence of the supply voltage U of a group of TECs in parallel connection on the relative operating current B for different thermal loads Q_0 in a uniform temperature field T_0=260 K.

The functional dependence $U = f(B)$ has a minimum:

1. $U_{\min}$ =1.10V at B_{opt} =0.8 for Q_0 =3.0W;
2. $U_{\min}$ =0.75V at B_{opt} =0.8 for Q_0 =2.0W;
3. $U_{\min}$ =0.35V at B_{opt} =0.8 for Q_0 =1.0W;
4. $U_{\min}$ =0.15V at B_{opt} =0.8 for Q_0 =0.5W.

When selecting the supply voltage U for a group of TECs with parallel electric connection, the condition $U \geq U_{\min}$ must be observed.

As the supply voltage U increases for a group of parallel-connected TECs for different thermal loads Q_0 in a uniform temperature field T_0=260K:

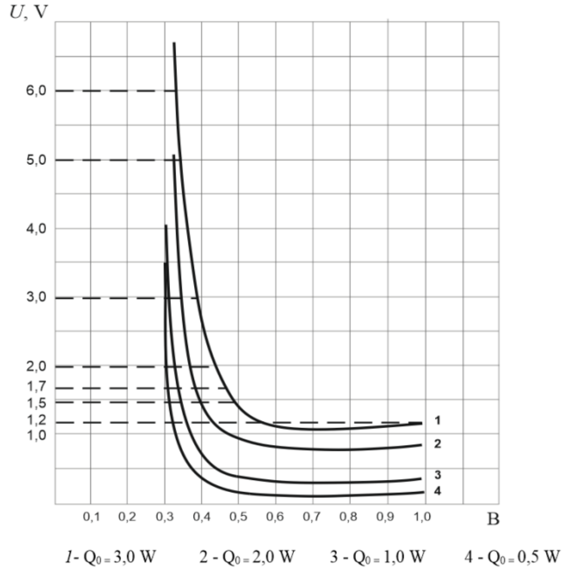

Fig. 6. **Dependence of the supply voltage U of a group of parallel-connected TECs on the relative operating current B for different heat loads Q_0 at T =300K; l/S =4.5; ΔT =40K**

Source: **compiled by the authors**

− the magnitude of the operating current I decreases (Fig. 7). As the thermal load Q_0 increases, the operating current I increases at a fixed supply voltage U;

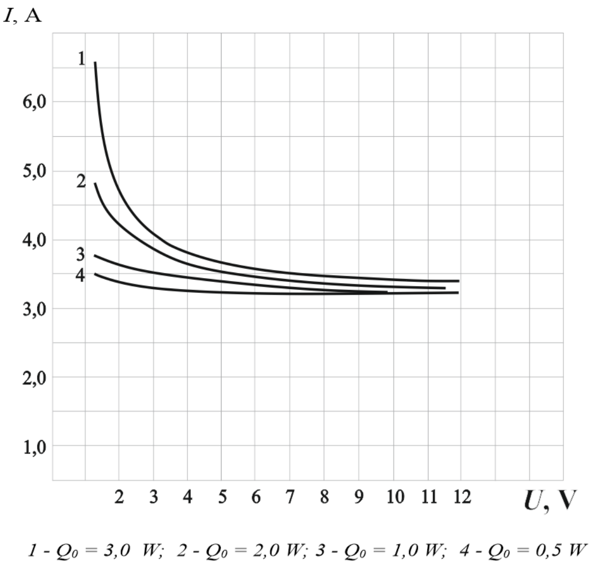

Fig. 7. **Dependence of the operating current I of the TEC from the group with parallel electric connection on the supply voltage U for different thermal loads Q_0 at T =300K; l/S =4.5; ΔT =40K**

Source: **compiled by the authors**

Table 2. **Parallel connection of a group of TEC's in a complex.**
$T = 300\,K, \Theta = 0.5, l/S = 4.5, T - T_0 = 5K$

Q_0, W	B	I, A	n, *pcs*	A	W, W	E	τ, s	αF, W/K	N, W·s	λ/λ_0	$\lambda \cdot 10^8$ 1/h	P
$U = 1.2V$												
3.0	0.60	6.6	15.7	0.45	8.0	0.375	10.5	2.2	84.0	210	6.2	0.99938
2.0	0.43	4.8	20.4	0.298	5.77	0.347	14.8	1.55	85.0	0.66	2.0	0.99980
1.0	0.35	3.8	23.8	0.15	4.7	0.216	23.4	1.14	110	0.32	0.96	0.99990
0.50	0.31	3.5	26.0	0.075	4.3	0.12	31.0	1.0	133	0.24	0.71	0.999930
4.5	-	13.9	65.5	-	17.0	0.265	31.0	4.3	327	2.66	8.0	0.99920
$U = 1.5V$												
3.0	0.48	5.3	23.4	0.36	8.0	0.376	13.4	2.2	197	1.2	3.6	0.99964
2.0	0.392	4.39	27.2	0.238	6.58	0.304	17.1	1.7	113	0.605	1.82	0.99982
1.0	0.33	3.7	30.2	0.12	5.6	0.18	25.7	1.3	144	0.35	1.06	0.99989
0.5	0.31	3.4	32.0	0.06	5.2	1.10	33.3	1.1	173	0.28	0.83	0.99992
4.5	-	12.4	85.6	-	18.8	0.24	33.3	4.6	424	1.83	5.5	0.99945
$U = 2.0V$												
3.0	0.41	4.55	35	0.27	9.1	0.33	16.0	2.4	146	0.95	2.8	0.99972
2.0	0.362	4.05	38.1	0.179	8.05	0.248	20.0	2.0	162	0.606	1,82	0.99982
1.0	0.32	3,60	42	0.09	7.2	0.14	27.3	1.6	196	0.42	1.25	0.99987
0.5	0.31	3.40	43	0.045	6.8	0.07	34.2	1.5	231	0.32	1.0	0.99990
4.5	-	11.5	120	-	23.1	0.195	34.2	5.5	573	1.69	5.07	0.99949
$U = 3.0V$												
3.0	0.36	4.0	58.0	0.18	12.1	0.25	21.3	3.0	258	0.91	274	0.99973
2.0	0.335	3.6	60.8	0.119	11.3	0.177	24.4	2.7	275	0,70	2.10	0.99979
1.0	0.31	3.5	64.0	0.06	10.5	0.10	33.3	2.3	350	0.55	1.7	0.99983
0.5	0.30	3.3	63.0	0.03	9.8	0.05	41.5	2.0	405	0.52	1.6	0,99984
4.5	-	10.8	184	-	32.4	0.139	41.5	7.3	1013	2.0	6.0	0.99940
$U = 4.0V$												
3.0	0.342	3.80	80.0	0.135	15.2	0.20	25	3.6	372	1.0	3.0	0,99970
2.0	0.324	3.63	82.4	0.089	14.4	0.14	27	3.3	393	0,824	2,47	0.99975
1.0	0.31	3.42	86.0	0.045	13.7	0.073	36	2.9	496	0,70	2.1	0,99979
0.15	0.30	3.33	89.0	0.0225	13,6	0.040	44	2.8	602	0.65	1.95	0.99980
4.5	-	10.6	255	-	42.5	0.106	44	9.4	1470	2.3	6.9	0.99931
$U = 6.0V$												
3.0	0.324	3.60	125	0.09	21.7	0.14	28.9	4.9	627	1.25	3.7	0.99962
2.0	0.313	3.5	126.5	0.0595	20,9	0.0956	31.4	4.6	657	1.10	3.3	0.99967
1.0	0.303	3.40	130	0.03	20.2	0.05	40.7	4.2	822	0.98	2.9	0.99971
0.15	0.298	3.3	131	0.015	19.8	0.025	48.2	4.1	954	0.93	2.8	0.99972
4.5	-	10.3	385	-	61.7	0.073	48.2	13.2	2403	3.2	9.6	0.99905
$U = 9.0V$												
3.0	0.313	3.5	191	0.06	31.4	0.096	33.3	6.9	1046	1.66	5.0	0.99950
2.0	0.306	3.4	193	0.04	30.7	0.065	35.4	6.5	1086	1.52	4.6	0.99954
1.0	0.30	3.35	198	0.02	30.2	0.033	45.2	6.2	1365	1.43	4.3	0.99957
0.5	0.296	3.29	203	0.01	30.3	0.017	52.9	6.15	1603	1.40	4.2	0.99958
4.5	-	10/1	592	-	91.9	0.049	52.9	19/3	4014	4.5	13.5	0.9987
$U = 12.0V$												
3.0	0.308	3.42	256	0.045	40.5	0.074	34.2	8.7	1385	2.0	6.9	0.99938
2.0	0.308	3.39	260	0.030	40.6	0.049	38.0	8.2	1543	1.97	5.9	0.99941
1.0	0.298	3.30	266.4	0.015	39.8	0.025	45.3	8.2	1803	1.88	5.6	0.99944
0.5	0.2953	3.28	265.2	0.0075	39.1	0.013	52.3	7.9	2045	1.80	5.4	0.99946
4.5	-	10.0	788	-	119.4	0.038	52.3	24.8	5233	5.68	17.0	0,9983

Source: **compiled by the authors**

– the number of thermocouples n increases (Fig. 8). As the heat load Q_0 increases, the number of thermocouples n decreases at a fixed supply voltage U ;

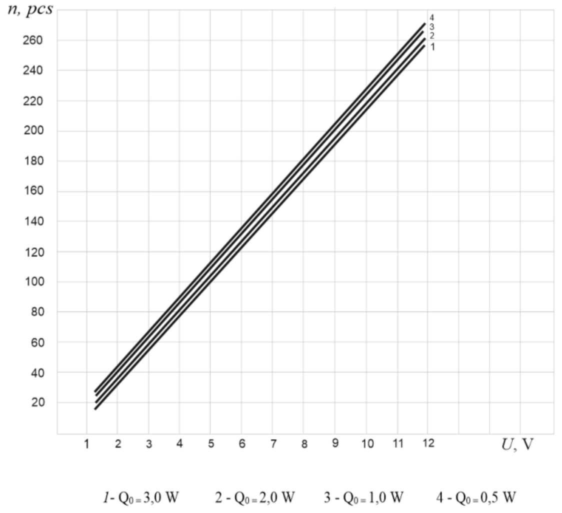

Fig. 8. **Dependence of the number of thermoelectric cells n of the group with parallel electric connection on the supply voltage U for different heat loads Q_0 at T =300K; l / S =4.5; ΔT =40K**
***Source:* compiled by the authors**

– the cooling factor E decreases (Fig. 9). As the heat load Q_0 increases, the cooling factor E increases at a fixed supply voltage U ;

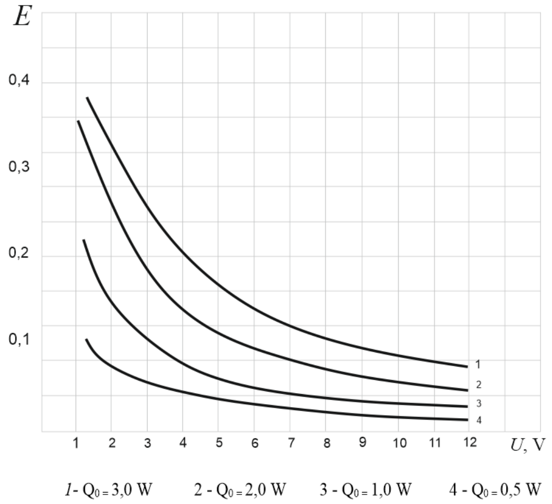

Fig. 9. **Dependence of the cooling factor E of the TEC from the group with parallel electric connection on the supply voltage U for different heat loads Q_0 at T =300K; l / S =4.5; ΔT =40K**
***Source:* compiled by the authors**

– the ramp-up time τ increases (Fig. 10). As the heat load Q_0 increases, the ramp-up time τ at a fixed supply voltage decreases U ;

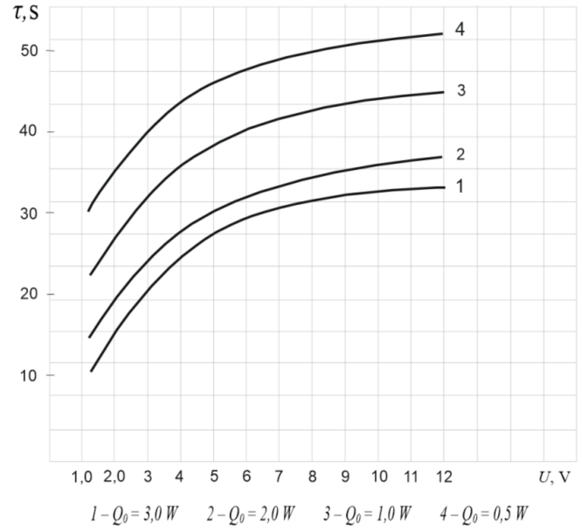

Fig. 10. **Dependence of the steady-state operation time τ of the TEC from the group with parallel electric connection on the supply voltage U for different loads Q_0 at T =300K; l / S =4.5; ΔT =40K**
***Source:* compiled by the authors**

– the required heat dissipation capacity of the heat sink αF increases (Figure 11). With increasing thermal load Q_0, the amount of energy N expended decreases at a fixed supply voltage U ;

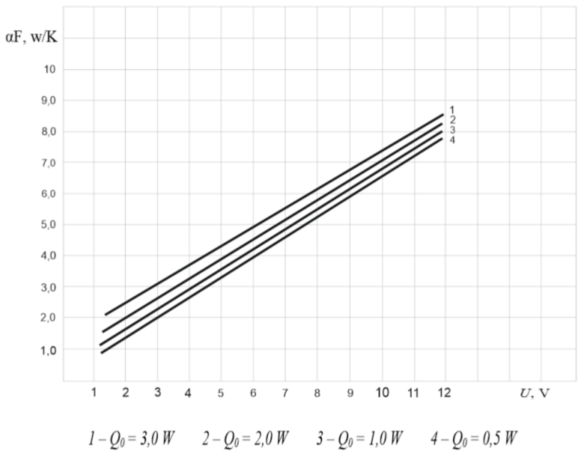

Fig. 11. **Dependence of heat dissipation capacity of the heat sink αF of the TEC from the group with parallel electric connection on supply voltage U for different heat loads Q_0 at T =300K; l / S =4.5; ΔT =40K**
***Source:* compiled by the authors**

– the amount of energy consumed N increases (Fig. 12). As the heat load Q_0 increases, the amount of energy expended N decreases at a fixed supply voltage U;

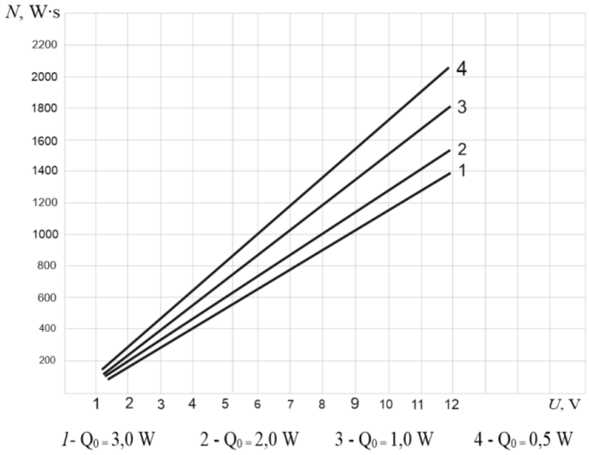

Fig. 12. **Dependence of the amount of energy expended N by a TECs from a group with parallel electric connection on the supply voltage U for different heat loads Q_0 at T =300K; l/S =4.5; ΔT =40K**

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

– the functional dependence of the relative failure rate $\lambda/\lambda_0 = f(U)$ on the supply voltage U has a minimum for different thermal loads Q_0 (Fig. 13).

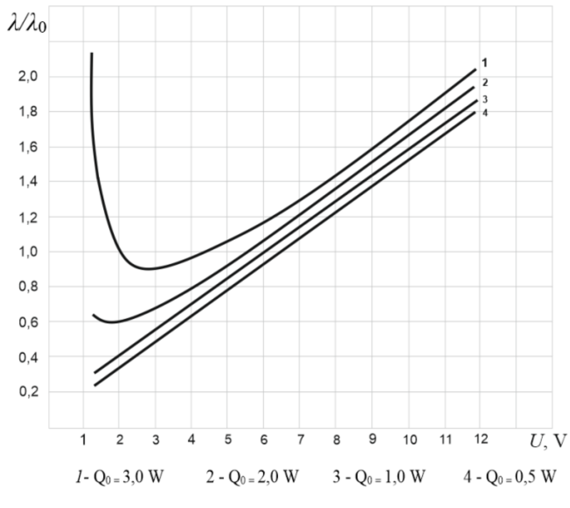

Fig. 13. **Dependence of the relative failure rate λ/λ_0 from the group with parallel electrical connection on the supply voltage U for different thermal loads Q_0 at T =300K; l/S =4.5; ΔT =40K**

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

As the thermal load Q_0 increases, the relative failure rate λ/λ_0 increases with a fixed supply voltage U;

– the functional dependence of the probability of failure-free operation $P = f(U)$ on the supply voltage U has a maximum for different thermal load Q_0 (Fig. 14). As the thermal load Q_0 increases, the failure probability Q_0 decreases at a fixed supply voltage U.

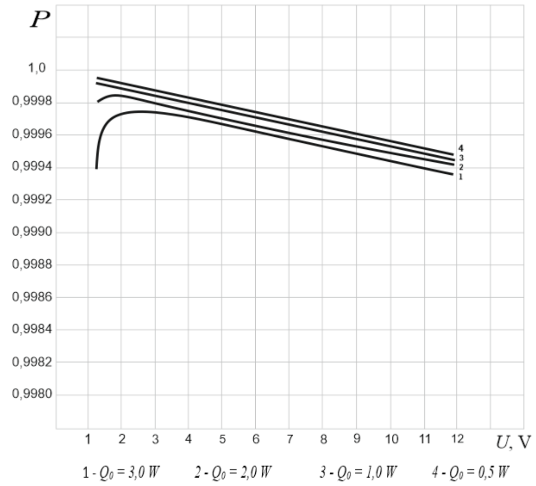

Fig. 14. **Dependence of the probability of no-failure operation P of the TEC from the group with parallel electric connection on the supply voltage U for different heat loads Q_0 at T =300K; T =4.5; ΔT =40K**

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

Thus, at a given supply voltage U for each TEC of the group with parallel electric connection, as the thermal load Q_0 increases in a uniform temperature field T_0=260K:

– increases: relative operating current B, operating current magnitude I, power consumption W, cooling factor E, required heat dissipation capacity of the heat sink αF, relative failure rate λ/λ_0;

– decreases number of thermocouples n, power consumption N, probability of no-failure operation P, time to steady-state operation τ.

To facilitate comparative analysis, the basic parameters, reliability indexes and dynamic characteristics of a group of three electrically connected in parallel TECs, arranged in a uniform temperature field, are shown in Table 3.

Table 3. **Basic parameters for a group of parallel-connected TECs in a uniform temperature field** $T = 300\,K, Q_0 = 4.5W, l/S = 4.5, T - T_c = 5K, \Delta T = 40K$

U,V	n, pcs	W,W	E	τ, s	N, W·s	α F,W/K	I, A	λ/λ_0	$\lambda \cdot 10^8$ 1/h	P
1.2	65.5	17.0	0.265	31.0	327	4.3	13.9	2.66	8.0	0.99920
1.5	85.6	18.8	0.24	33.0	424	4.6	12.4	1.83	5.5	0.99945
2.0	120	23.1	0.20	34.0	573	5.5	11.5	1.70	5.1	0.99949
3.0	184	32.4	0.14	42.0	1010	7.3	10.8	2.0	6.0	0.99940
4.0	255	42.5	0.11	44.0	1470	9.4	10.6	2.3	6.9	0.99981
6.0	385	61.7	0.073	48.0	2400	13.2	10.3	3.2	9.6	0.99905
9.0	592	92.0	0.05	53.0	4000	19.3	10.1	4.5	13.5	0.9987
12.0	788	119.4	0.04	52.0	5200	24.8	10.0	5.7	17.0	0.9983

Source: **compiled by the authors**

As the supply voltage U of a group of parallel-connected TECs increases with a thermal load Q_0 = 4.5 W, thermocouple branch geometry Q_0 =4.5 in a uniform temperature field T_0 =260K:

– the number of thermocouples n increases (Fig. 15, item 1);

– cooling coefficient E decreases (Fig. 15, item 2);

– steady-state operation time τ increases (Fig. 15, item 3);

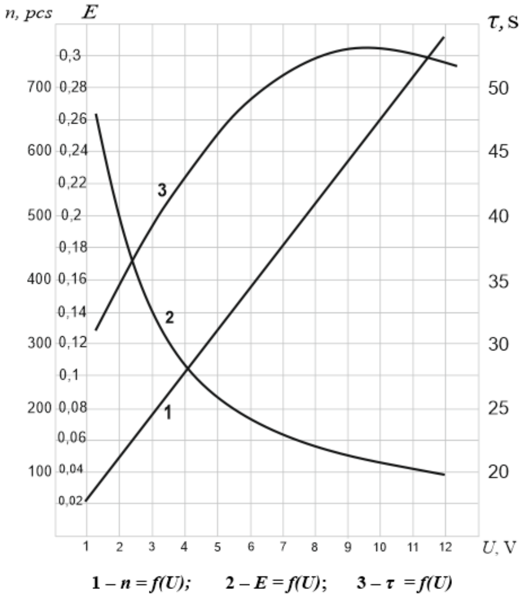

Fig. 15. **The dependence of the number of thermocouples n, refrigeration coefficient E, time to steady state operation of a group of TECs with parallel electric connection on the supply voltage U in a uniform temperature field at l/S =4.5; Q_0 =4.5 W; $T - T_c$ =5K; ΔT =40K**

Source: **compiled by the authors**

– the required heat dissipation capacity of the heat sink αF increases (Fig. 16, item 1);

– the amount of consumed energy N increases (Fig. 16, item 2);

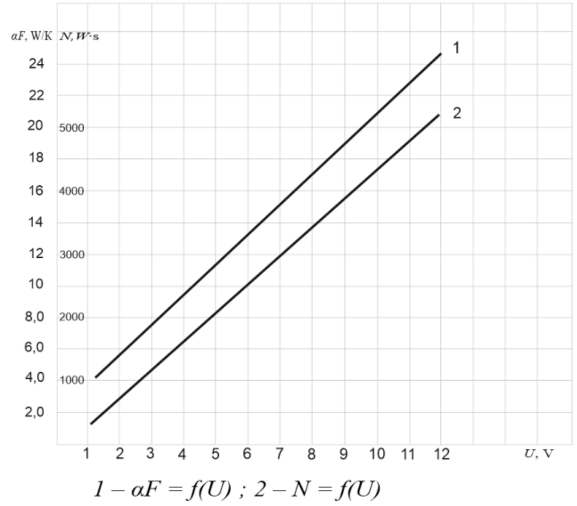

Figure 16: Dependence of heat dissipation capacity of the heat sink αF, amount of energy expended N by the group of TEC with parallel electric connection on supply voltage U in a uniform temperature field at l/S =4.5, Q_0 =4.5W, $T - T_c$ =5K, ΔT =40K

Source: **compiled by the authors**

– the functional dependence of relative failure rate $\lambda/\lambda_0 = f(U)$ on supply voltage has a maximum at U =2.0 V (Fig. 17, item 1);

– the functional dependence of the probability of no-failure operation $P = f(U)$ on the supply voltage U has a maximum at U =2.0 V (Fig. 17, item 2).

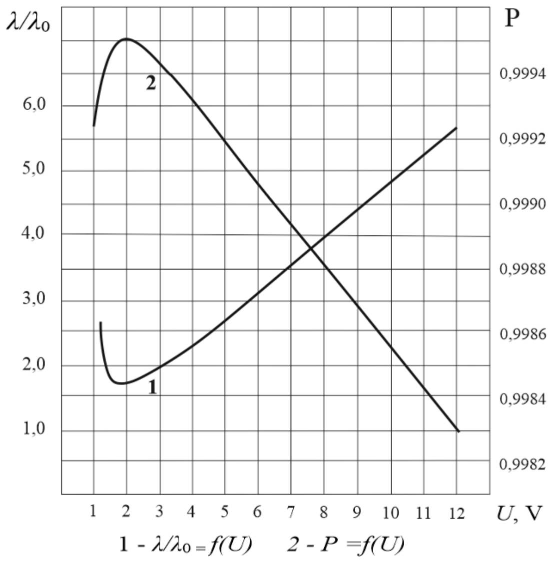

Fig. 17. **Relative failure rate λ/λ_0 and probability of failure P for a group of parallel-connected TECs versus supply voltage U at T =300K; l/S =4.5; Q_0 =4.5W; ΔT =40K, λ_0 =3 10^{-8}1/h; t =10^4h**

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

DISCUSSION OF RESEARCH RESULTS

The results of calculations of the basic parameters, reliability indicators and dynamic characteristics of the TEC complex with mixed electrical connection (three TEC connected in series, the other three in parallel) in a uniform temperature field T_0=260K and thermal load $Q_{0\Sigma}$=34.5W, are given in Table 4.

As the supply voltage U_0 of a mixed electrical connection TEC complex increases in a uniform temperature field T_0=260K at a thermal load Q_0=34.5W and a branch geometry of thermocouples l/S=4.5:

– the time to reach steady-state operation τ increases (Fig. 18, item 1);

– number of thermocouples n increases (Fig. 18, item 2);

– cooling factor E decreases (Fig. 18, item 3);

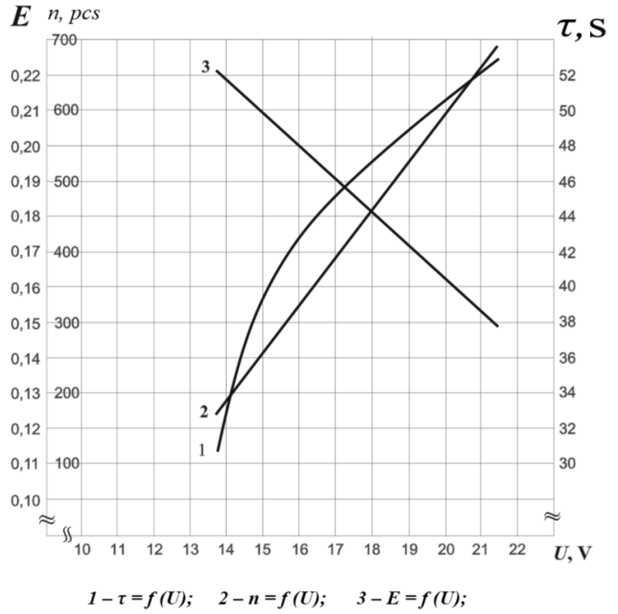

Fig. 18. **Dependence of refrigerating factor E, number of thermocouples n, time of steady-state operation of TEC complex with mixed electrical connection on total supply voltage U at T =300K; l/S =4.5; Q_0 =4.5W; ΔT =40K; $Q_{0\Sigma}$ =34.5W**

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

– increases the energy N input (Fig. 19, item 1);

– the heat dissipation capacity of the heat sink αF increases (Fig. 19, item 2);

Table 4. **Main relevant parameters of the TEC complex in mixed electrical connection**

$$T = 300\,K,\, \Delta T = 40\,K,\, l/S = 4.5,\, T - T_c = 5K,\, Q_{02} = 34.5W,\, I_0 = 11.1A$$

No.	$U_{=}, V$	W, W	U_{--}, V	E	τ, s	α F, W/K	$N, W\cdot$s	n, pcs	λ/λ_0	$\lambda\cdot10^8$ 1/h	P
1	1.2	155.4	13.7	0.222	310	38.0	1380	172	112.1	336.3	0.96693
2	1.5	157.3	14.0	0.219	33.0	38.4	1478	192	111.2	333.6	0.96719
3	2.0	161.6	14.5	0.213	36.0	39.2	1662	226	111.1	333.4	0.967219
4	3.0	171.0	15.5	0.202	41.5	41.1	2067	291	111.4	334.1	0.96714
5	4.0	181.0	16.5	0.191	44.1	43.1	2524	362	111.7	335.2	0.96704
6	6.0	200.0	18.5	0.173	48.2	46.9	3457	492	112.6	337.7	0.96680
7	9.0	230.0	21.5	0.150	52.9	53.0	5068	700	113.9	341.7	0.96640

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

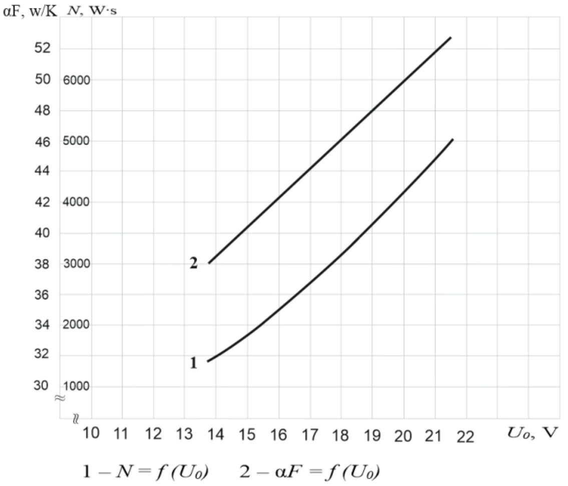

Fig. 19. **Dependence of heat dissipation capacity of the heat sink αF, the amount of energy expended N by the mixed electrical connection of the TEC complex on the total supply voltage U at T =300K; l/S =4.5; Q_0 =4.5W; ΔT =40K; $Q_{0\Sigma}$ =34.5W**

Source: **compiled by the authors**

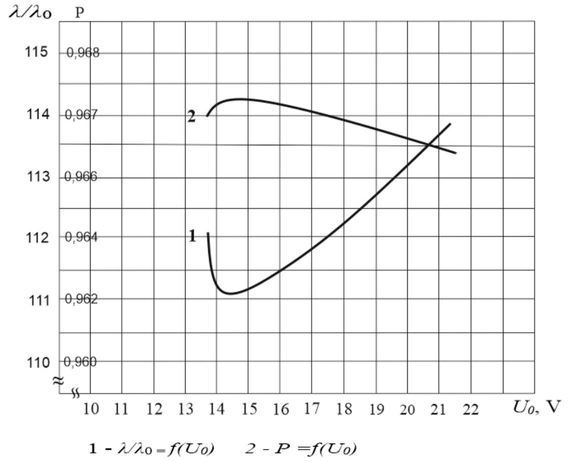

Fig. 20. **Dependence of relative failure rate λ/λ_0, probability P of no-failure operation of mixed electrical connection TEC complex on total supply voltage U at T =300K; l/S =4.5; Q_0 =4.5W; ΔT =40K; $Q_{0\Sigma}$ =34.5W**

Source: **compiled by the authors**

– functional dependence of relative failure rate $\lambda/\lambda_0 = f(U_0)$ on total supply voltage U_0 has a minimum at U_0 =14.5V ($(\lambda/\lambda_0)_{\min}$ =111.1 (Fig. 20, item 1);

– the functional dependence of the probability of no-failure operation $P = f(U_0)$ on the total supply voltage U_0 has a maximum at U_0 =14.5V, $P_{\max}$ =0.96722 (Fig.20, item 2).

CONCLUSIONS

A mathematical model of a thermal mode support system based on a set of thermoelectric coolers (3 TECs connected electrically in series and the other three connected in parallel) has been developed. The cooling system is designed to control thermal conditions of a number of temperature-dependent elements of electronic equipment in the uniform temperature field with different thermal load at fixed geometry of thermoelement branches.

2. Relations for determining a relative operating current at given supply voltage and temperature difference and thermal load for a group of thermoelements with parallel electric connection have been obtained.

3. The comparative analysis of the main parameters, reliability indices and dynamic characteristics of the complex of fuel injection equipment with mixed electric connection depending on supply voltage of the group of fuel injection equipment with parallel electric connection is carried out.

Analysis of the research results showed the possibility of selecting the optimum supply voltage, taking into account the requirements for mass-dimensional, energy, dynamic characteristics of the fuel-electric power unit complex and increasing its reliability indicators.

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Conflicts of Interest: the authors declare no conflict of interest

Received 15.10.2022
Received after revision. 11.12.2022
Accepted 19.12.2022

DOI: https://doi.org/10.15276/aait. 05.2022.21

УДК 004.662.99·519.6

Управління комплексом термоелектричних охолоджуючих пристроїв зі змішаним електричним з’єднанням у рівномірному температурному полі

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АНОТАЦІЯ

Розглянуто можливість оптимального управління тепловим режимом ряду термозалежних та теплонавантажених елементів радіоелектронної апаратури з розрахунковою потужністю розсіювання. Дослідження проведено в рівномірному температурному полі з використанням комплексу термоелектричних охолоджувальних пристроїв та певною геометрією гілок термоелементів. Отримано співвідношення для визначення відносного робочого струму залежно від відносного перепаду температури для заданої напруги перепаду для заданої напруги живлення, теплового навантаження та геометрії гілок термоелементів, визначено область дійсних значень відносного робочого струму. Проведено порівняльний аналіз основних параметрів, показників надійності та динамічних характеристик групи термоелектричних пристроїв, що входять до комплексу для різних напруг живлення та теплового навантаження. Показано можливість вибору напруг живлення комплексу термоелектричних пристроїв з урахуванням обмежувальних факторів за масогабаритними, енергетичними, динамічними та надійними характеристиками для забезпечення оптимального теплового режиму низки термозалежних елементів радіоелектронної апаратури. Зі зростанням напруги живлення комплексу термоелектричних пристроїв зі змішаним електричним з'єднанням у рівномірному температурному полі при заданому тепловому навантаженні та геометрії гілок термоелементів досягаються наступні результати. Збільшується час виходу на стаціонарний режим, збільшується кількість термоелементом, зменшується холодильний коефіцієнт, збільшується кількість витраченої енергії, збільшується тепловідвідна здатність радіатора, функціональна залежність ймовірності безвідмовної роботи від загальної напруги має максимум.

Ключові слова: термоелектричний охолоджувач; тепловий режим; моделі зв’язку; показники надійності; динамічні характеристики

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