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THERMAL REGIME CONTROL OF THERMOELECTRIC COOLERS IN AN UNIFORM TEMPERATURE FIELD

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An analysis of the control model for a thermoelectric device for providing thermal modes of electronic equipment is presented, the reliability indicators of which are significantly determined by the temperature of the elements. Model studies were carried out for conditions of a non-uniform temperature field in the ranges of typical temperature drops, current operating modes and dissipation power. The analysis was carried out for various ratios of height to cross-sectional area of thermoelectric element legs. The advantage of distributed active thermoelectric cooling of radio-electronic systems with spatially spaced heat-loaded elements in comparison with general cooling is substantiated. The possibility of optimal control of the thermal regime of a complex of thermoelectric coolers with a series electrical connection at different cooling levels and thermal load is considered. The main parameters, reliability indicators and dynamic characteristics of the coolers have been determined. The current modes in the construction of the complex are analyzed taking into account the energy, weight and size and reliability characteristics. A comparative analysis of the main parameters, reliability indicators and dynamic characteristics of a complex of thermoelectric coolers at different cooling levels, a given unification of the geometry of thermoelement legs and current operating modes is carried out. The research results have shown the possibility of controlling the thermal regime of the complex of thermoelectric coolers by choosing the thermal regime of operation, taking into account the weight of each of the limiting factors in terms of weight and size, energy and dynamic characteristics. When choosing the current modes, the mutual influence of each of the limiting factors is taken into account, changing which, when designing a system for ensuring thermal modes, it is possible to choose compromise modes of operation.

Key words: *cooler control, dynamics and failure rate, current modes, temperature difference, thermoelement branches.*

Журавльов Ю.І. Управління тепловим режимом термоелектричних охолоджувачів у нерівномірному полі температур
У статті представлено аналіз моделі управління термоелектричним пристроєм забезпечення теплових режимів радіоелектронної апаратури, показники надійності якої суттєво визначаються температурою елементів. Модельні дослідження проведено для умов неоднорідного температурного поля в діапазонах типових перепадів температур, струмових режимів роботи та потужності розсіяння. Аналіз проведено для різних відношень висоти до площі перетину гілок термоелектричних елементів. Розкрито перевагу розподіленого активного термоелектричного охолодження радіоелектронних систем із просторово рознесеними теплонавантаженими елементами порівняно із загальним охолодженням. Розглянуто можливість оптимального управління тепловим режимом комплексу термоелектричних охолоджувачів із послідовним електричним з'єднанням за різного рівня охолодження й теплового навантаження. Визначено основні параметри, показники надійності та динамічні характеристики охолоджувачів. Проаналізовано струмові режими у процесі побудови комплексу з урахуванням енергетичних, масогабаритних характеристик і характеристик надійності. Проведено порівняльний аналіз основних параметрів, показників надійності та динамічних характеристик комплексу термоелектричних охолоджувачів за різного рівня охолодження, заданої уніфікації геометрії гілок термоелементів і струмових режимів роботи. Результати досліджень показали можливість управління тепловим режимом комплексу термоелектричних охолоджувачів за рахунок вибору теплового режиму роботи з урахуванням значущості кожного з обмежувальних факторів за масогабаритними, енергетичними й динамічними характеристиками. У процесі вибору струмових режимів враховано взаємний вплив кожного з обмежувальних факторів, за допомогою зміни яких під час проєктування системи забезпечення теплових режимів можна вибрати компромісні режими роботи.

Ключові слова: *управління охолоджувачами, динаміка й інтенсивність відмов, струмові режими, перепад температур, гілки термоелементів.*

Introduction. Systems for ensuring thermal conditions are a necessary means of functioning of electronic equipment, the reliability of the element base of which depends significantly on temperature. For systems with inhomogeneous heat release of elements, including semiconductor lasers, processors, ultrasonic emitters, receivers of intense radiation, thermoelectric coolers are promising. Thermoelectric device (TEC) allows you to control the amount of heat flow by simply changing the magnitude of the operating current. Therefore, to ensure the required thermal regime of a number of dispersed heat-dependent and heat-loaded elements, various designs of TEC complexes can be used. This approach is designed to achieve different levels of cooling T_0 for a given heat load Q_0, which gives an energy gain over the overall cooling of the blocks.

Literature review. Since thermoelectric coolers are designed to increase the reliability of heat-loaded elements, they are subject to increased reliability requirements [1; 2]. The reliability indices of TEC depend on the structural organization [3; 4], design features [5; 6], the efficiency of thermoelectric materials [7; 8], manufacturing technology [9]. However, the presented studies are aimed at static modes of operation of thermoelectric coolers and do not take into account the dynamics of the processes. Indicators of dynamics and reliability are among the most important characteristics of control; they are in contradiction, an increase in the rate of temperature drop leads to cracking of the junction of inhomogeneous materials of the cooler [10]. The problem is aggravated by the fact that when a thermoelectric cooler is included in the feedback loop of the control system, an increase in the dynamic characteristics of the TEC is required, which decreases the reliability indicators [11]. The interrelation of the parameters of a thermoelectric cooler is a control problem [12], therefore, the issues of increasing the reliability indicators and the associated dynamic characteristics were considered in detail in [13; 14]. The issues of optimization of the control of the structure of thermoelectric coolers were practically not considered and were limited to a stationary mode on one heat-loaded element. The system of distributed sources of heat release of modern electronic equipment requires an economical system for providing thermal modes of onboard equipment, since the overall cooling of the unit is focused on the maximum loaded element. The relevance of the development of a system for ensuring thermal conditions, the energy of which adapts to inhomogeneous spatially distributed heat sources, is obvious.

The purpose and objectives of the study. The aim of the work is to create a structure of a thermoelectric system to provide thermal modes of distributed heat-loaded electronic elements of equipment by controlling the current modes of coolers.

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

1) to develop a model of functioning of distributed thermoelectric coolers, which provides control of the time to reach the steady state and reliability indicators;

2) analyze the model in standard current modes of operation and temperature drops to clarify the compromise conditions of operation.

Thermoelectric cooler model. A significant part of the energy consumed by radio electronic equipment inevitably turns into heat, sometimes causing unacceptable overheating of the elements. One of the most acceptable ways to ensure the thermal regime of elements and components of radio electronic equipment is thermoelectric, as the most effective in a wide range of operating temperatures from 140 to 350K [13]. The thermoelectric device allows you to control the magnitude of the heat flux by simply changing the magnitude of the operating current. Therefore, to ensure the required thermal regime of a number of dispersed heat-dependent and heat-loaded elements, various designs of TEC complexes can be used. To ensure a different level of cooling T_0 at a given heat load Q_0, consider the series electrical connection of the TEC in the complex. To calculate the main parameters, reliability indicators, dynamics of functioning of the complex of thermoelectric coolers, we use the following relationships [13].

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

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

where:

Q_0 is the value of the heat load, or the power of the heat release of the cooling object, W;

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

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

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

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

$\bar{\sigma}_K$ – average value of thermoelement branch electrical conductivity, S/cm;

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

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

I – working current value, A;

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

T – heat-generating junction temperature, K;

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

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

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

$$W_K = 2nI^2_{\max K} R_K B_K (B_K + \frac{\Delta T_{\max}}{T_0}\Theta) \tag{2}$$

Voltage drop U_K

$$U_K = \frac{W_K}{I} \tag{3}$$

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

$$E = \frac{Q_0}{W_K} \tag{4}$$

The relative value λ/λ_0 of the failure rate can be determined from the expression

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

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

K_T – coefficient of lowered temperatures.

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

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

where t is the assigned resource, hour.

The expression for determining the time of reaching the stationary mode of operation τ can be represented in the form [14]:

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

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

$m_0 C_0$ – product of mass and heat capacity of the object of cooling;

$m_0 C_0 \to 0$ in the absence of a cooling object; $\sum_i m_i C_i$ – 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 at a given l/S;

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

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

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

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

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

Analysis of the cooler control model. First, we will consider the possibility of optimal control of the thermal regime of the TEC complex with a series electrical connection for different temperature levels of cooling. Initial data: temperature T0 from T_0 = 295K to T_0 = 250K, heat load Q_0 from Q_0 = 0.5W to Q_0 = 15W when using constant geometry of the thermoelement leg (the ratio of the thermoelement height to the cross-sectional area l/S = 40). The selected unified value (l/S = 40) makes it possible to reduce the operating current of the complex in the range $I \le I_{max}$ for various operating modes.

We select one basic module out of six TECs of the complex with a cooling temperature T_0 = 250K and a thermal load Q_0 = 0.5W. The calculation of the main parameters, reliability indicators and dynamic characteristics is carried out first for the Q_{0max} mode (B = 1) and we determine the value of the operating current $I = I_{max}$. Since in the complex all six TECs are connected electrically in series, the value of the operating current remains constant I=*const* for all TECs included in the complex.Next, consider the operation of the next TEC in the cooling mode T_0 = 260K and heat load Q_0 = 1.0W. In this case, the relative operating current B_2 changes, since the condition must be met

$$B_i I_{\max i} \ldots B_2 I_{\max 2} = B_1 I_{\max 1} = I .$$

So, we consistently consider the operation of all six TPPs included in the complex and determine the main parameters, reliability indicators and dynamic characteristics. Then we carry out calculations for other current operating modes of the base TEC and all six TECs included in the complex.

The calculation results of the main parameters, reliability indicators and dynamic characteristics of the six TECs included in the complex for various current operating modes of the basic TEC are shown in table 1.

Table 1

Main parameters, reliability indicators and dynamic characteristics of the cooler complex at T=300K, l/s=40

Q_0, W	T_0, K	n, pcs	Θ	W, W	U, V	E	B_2	R' 10^3, Ohm	I_{max}, A	τ, s	N, W' s	αF, W/K	λ/λ_0	λ' 10^8, 1/h	P
Mode Q_{0max} (B_1=1) – base module I =1,22A															
0,50	250	27	0,68	3,8	3,1	0,13	1,0	39,2	1,22	8,2	31,0	0,85	27,8	83,3	0,9917
1,0	260	31,6	0,50	4,4	3,6	0,23	0,97	40,0	1,26	5,3	23,2	1,10	28,8	86,5	0,9914
3,0	270	67,6	0,35	9,4	7,7	0,32	0,95	41,7	1,28	3,5	32,4	2,50	56,8	170	0,9830
5,0	280	87	0,21	11,9	9,8	0,42	0,93	42,6	1,31	2,0	24,1	3,4	66,0	198	0,980
10,0	290	142	0,10	19,3	15,8	0,52	0,91	43,5	1,35	0,90	17,6	5,9	98	294	0,971
15,0	295	195	0,048	26,0	21,3	0,58	0,896	44,0	1,36	0,44	11,4	8,2	125	375	0,9632
34,5	–	550	–	73,2	60,0	0,47	–	–	–	8,2	131	21,6	402	1207	0,8863
Mode $(nI)_{min}$ – base module I=1,0A B_1= 0,825															
0,50	250	29,6	0,68	2,9	2,9	0,17	0,825	39,2	1,22	9,0	26,1	0,68	14,6	43,8	0,9956
1,0	260	34,4	0,50	3,3	3,3	0,30	0,79	40,0	1,26	5,3	17,5	0,86	14,3	43,0	0,9957
3,0	270	72,9	0,35	5,4	5,4	0,55	0,78	41,7	1,28	3,5	19,2	1,7	27,7	83,1	0,9917
5,0	280	93,6	0,21	8,7	8,7	0,57	0,76	42,6	1,31	2,3	20,0	2,7	31,6	94,7	0,9906
10,0	290	151	0,10	13,8	13,8	0,72	0,74	43,5	1,35	1,0	14,0	4,8	43,8	131	0,9870
15,0	295	209	0,048	18,8	18,8	0,80	0,735	44,0	1,36	0,50	9,3	6,8	57,4	172	0,9829
34,5	–	590	–	52,9	52,9	0,65	–	–	–	9,0	106	17,5	189	568	0,9448
Mode $(nI\lambda/\lambda_0\tau)_{min}$ – base module I= 0,86A, B_1= 0,706															
0,50	250	36,9	0,68	2,75	3,2	0,18	0,706	39,2	1,22	10,3	28,4	0,65	9,8	29,4	0,9971
1,0	260	39,5	0,50	2,87	3,3	0,35	0,683	40,0	1,26	6,8	19,5	0,77	8,9	26,8	0,9973
3,0	270	81,0	0,35	5,83	6,8	0,52	0,679	41,7	1,28	4,2	24,3	1,8	16,5	49,4	0,9951
5,0	280	102	0,213	7,1	8,3	0,70	0,656	42,6	1,31	2,4	17,3	2,4	18,1	54,2	0,9946
10,0	290	164	0,10	11,1	12,9	0,90	0637	43,5	1,35	1,1	12,3	4,2	24,5	73,6	0,9927
15,0	295	226	0,048	15,1	17,5	1,0	0,632	44,0	1,36	0,54	8,1	6,2	31,8	95,3	0,9905
34,5	–	649	–	44,8	52,0	0,77	–	–	–	10,3	110		109,6	329	0,9676
Mode λ_{min} – base module I= 0,705A, B_1= 0,578															
0,50	250	60,3	0,68	3,15	4,5	0,16	0,578	39,2	1,22	11,0	34,7	0,73	7,1	21,3	0,9979
1,0	260	51,4	0,50	2,6	3,7	0,38	0,56	40,0	1,26	7,8	20,4	0,72	5,1	15,3	0,9985
3,0	270	98,1	0,35	4,88	6,9	0,615	0,55	41,7	1,28	4,9	23,7	1,6	8,5	25,6	0,9971
5,0	280	119,0	0,21	5,7	8,1	0,877	0,54	42,6	1,31	2,8	15,9	2,1	8,9	26,6	0,9973
10,0	290	188	0,10	8,7	12,3	1,15	0,522	43,5	1,35	1,3	10,9	3,7	11,5	34,6	0,9965
15,0	295	256	0,048	11,5	16,4	1,30	0,518	44,0	1,36	0,60	6,8	5,3	14,6	43,8	0,9956
34,5	–	773	–	36,5	51,9	0,95	–	–	–	11,0	112,4	14,2	55,7	167	0,9834

Figure 1 shows the dependence of the relative operating current $B_2=f(T_0)$ on the temperature of the heat-absorbing junction of various TECs included in the complex, with the corresponding heat load Q_0, for different operating modes of the basic TEC.

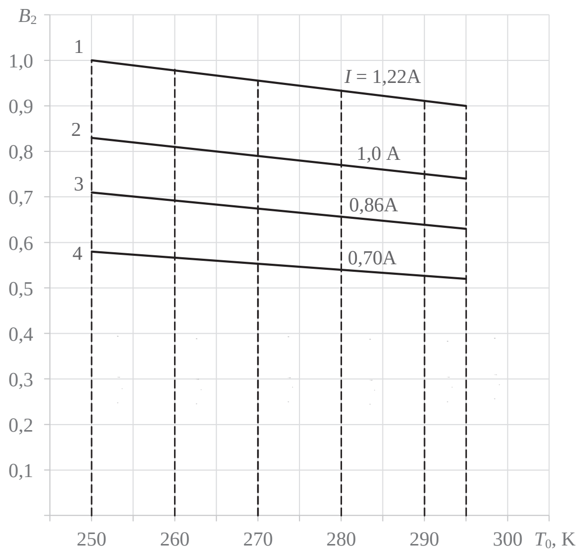

Fig. 1. Dependence of the relative operating current B_2 of TEC included in complex on the cooling temperature mode T_0 with the corresponding heat load Q_0 for various current operating modes B_1 of the basic TEC at T=300K, l/S=40: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

As the temperature rises in the cooling mode T_0, the relative operating current B_2 decreases.

With an increase in the operating current of the *I* complex of the TEC:

− the number of thermoelements *n* decreases (fig. 2). The minimum number of thermoelements n_{min} = 550 pcs is provided in the Q_{0max} mode;

− the refrigerating coefficient *E* decreases (fig. 2). The maximum refrigerating coefficient E_{max} = 0.95 is provided in the λ_{min} mode;

− the voltage drop *U* increases (fig. 2). The minimum voltage drop U_{min} = 51.9V is provided in the λ_{min} mode, and the maximum U_{max} = 60V in the Q_{0max} mode;

− the time of reaching the stationary operating mode τ decreases (fig. 2). The minimum time for reaching the stationary operating mode τ_{min} = 8.2 sec is provided in the Q_{0max} mode;

− the functional dependence of the amount of consumed energy $N = f(I)$ on the value of the operating current I has a minimum of N_{min} = 106 W'sec at *I* = 1.0A in the $(nI)_{min}$ mode (fig. 3);

− the required heat dissipation capacity of the radiator αF increases (fig. 3).

The minimum heat dissipation capacity of the radiator αF_{min} = 14.2W/K is provided in the λ_{min} mode:

– the relative failure rate λ/λ_0 increases (fig. 4). The minimum relative failure rate $(\lambda/\lambda_0)_{min}$ = 55.7 is provided in the λ_{min} mode;

– the probability of failure-free operation *P* decreases (fig. 4). The maximum probability of no-failure operation P_{max} = 0.9834 is provided in the λ_{min} mode.

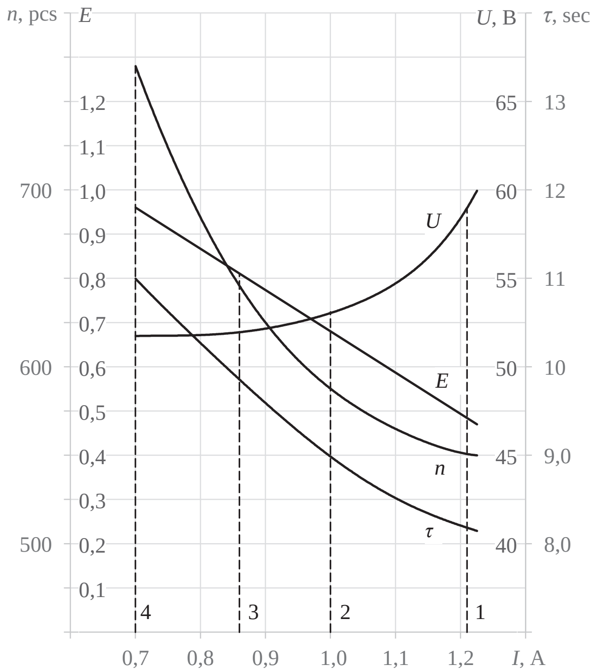

Fig. 2. Dependence of number of thermoelements n, cooling coefficient E, voltage drop U and the time to reach the stationary operating mode TEC complex on value of operating current I for different operating modes at T = 300K, l/S = 40: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

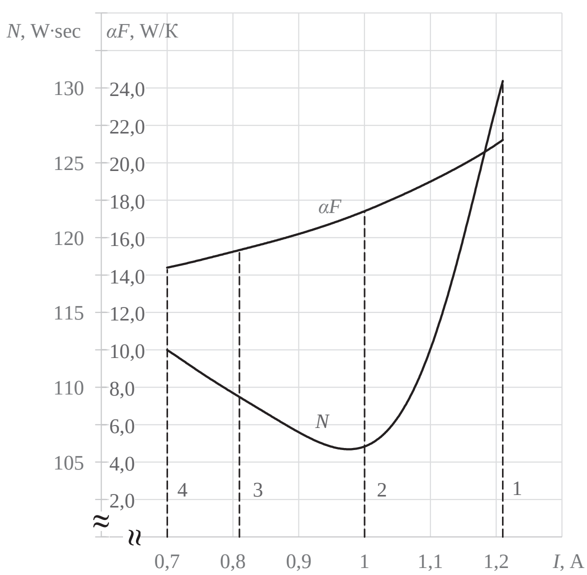

Fig. 3. Dependence of the amount of consumed energy N and heat removal capacity of radiator αF of TEC complex on the value of operating current I for different operating modes at T=300K, l/S=40: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

Analysis of the results of the main parameters, indicators of reliability and dynamics of the functioning of the TEC complex shows that:

– the maximum refrigerating coefficient Emax is provided in the λ_{min} mode (E_{max} = 0.95);

– the minimum heat dissipation capacity of the radiator $(\alpha F)_{min}$ is also provided in the λ_{min} mode (αF_{min} = 14.2W/K);

– the minimum relative failure rate $(\lambda/\lambda_0)_{min}$ = 55.7 and the maximum probability of failure-free operation P_{max} = 0.9834 is provided in the λ_{min} mode.

Thus, the use of the current mode λ_{min} is the most appropriate when building a complex, taking into account the energy, weight and size and reliability characteristics. This ensures the minimum value of the operating current I_{min} = 0.7A at l/S = 40.

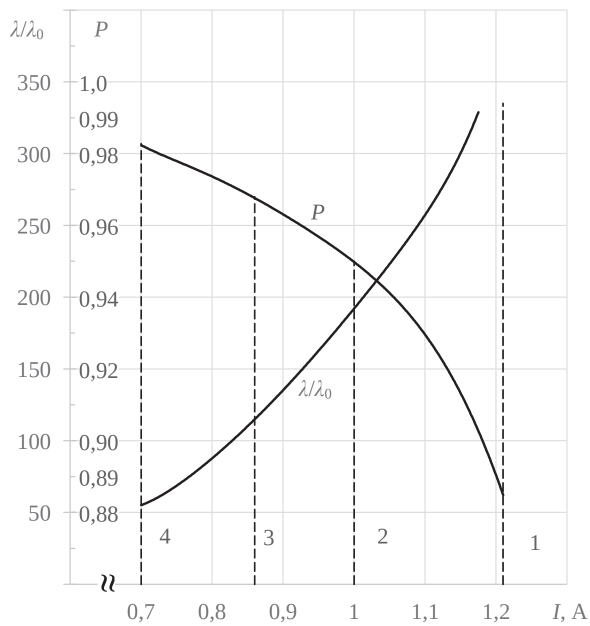

Fig. 4. Dependence of the relative failure rate λ/λ_0 and the probability of failure-free operation P of the TEC complex on the value of the operating current I for various operating modes at T = 300K, l/S = 40, λ/λ_0=3' 10^{-8} 1/hour, t =10^4 hour: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

At the same time, when using the geometry of thermoelement legs with l / S = 40, the required number of thermoelements is n = 773 units in the λ_{min} mode, which increases the cost of the complex. Therefore, for comparison, let us calculate the main parameters of the complex at l/S = 4.5. The results of calculating the main parameters, reliability indicators and dynamic characteristics are shown in table 2.

Fig. 5 shows the dependence of the relative operating current $B_2 = f\ (T_0)$ on the temperature of the heat-absorbing junction T_0 with the corresponding heat load Q_0 for various operating modes at l/S = 4.5.

With an increase in the temperature of the heat-absorbing junction T_0, TECs included in the complex with the corresponding heat load Q_0: the relative operating current B_2 decreases for different operating modes and operating currents I of the base module.

Table 2

Main parameters, reliability indicators and dynamic characteristics at T = 300K, l/S = 4.5

Q_0, W	T_0, K	*n*, pcs	*Θ*	*W*, W	*U*, V	*E*	B_2	*R*' 10^3, Ohm	I_{max}, A	*τ*, s	*N*, W' s	*αF*, W/K	λ/λ_0	*λ*' 10^8, 1/h	*P*
Mode Q_{0max}(*B*=1) – base module *I* =10,9A															
0,50	250	3,0	0,68	3,75	0,35	0,13	1,0	4,4	10,9	10,8	40,6	0,85	3,1	9,3	0,9991
1,0	260	3,5	0,50	4,3	0,40	0,23	0,97	4,5	11,2	7,2	31,0	1,10	3,2	9,2	0,99904
3,0	270	7,6	0,35	9,4	0,87	0,32	0,95	4,7	11,4	4,7	43,9	2,50	6,45	19,4	0,9981
5,0	280	9,8	0,21	12,0	1,1	0,42	0,93	4,8	11,7	2,7	32,6	3,4	7,4	22,3	0,9978
10,0	290	15,9	0,10	19,1	1,8	0,52	0,91	4,9	12,0	1,2	23,3	5,8	10,8	32,4	0,9967
15,0	295	22,0	0,048	26,3	2,4	0,57	0,90	4,95	12,1	0,60	15,8	8,3	14,3	42,8	0,9957
34,5	–	61,8	–	74,9	6,9	0,46	–	–	–	10,8	187	22,0	45,2	136	0,9865
Mode $(nI)_{min}$ – base module *I*=9,0A															
0,50	250	3,3	0,68	2,9	0,32	0,17	0,825	4,41	10,9	11,8	34,3	0,68	1,6	4,9	0,99951
1,0	260	3,8	0,50	3,3	0,37	0,30	0,80	4,5	11,2	7,8	25,7	0,86	1,7	5,1	0,99949
3,0	270	8,1	0,35	7,0	0,78	0,43	0,79	4,7	11,4	5,0	35,4	2,0	3,2	9,6	0,99904
5,0	280	10,4	0,21	8,8	1,0	0,57	0,77	4,8	11,7	3,0	26,4	2,8	3,6	10,8	0,9989
10,0	290	17,0	0,10	14,0	1,6	0,71	0,75	4,9	12,0	1,3	18,7	4,8	5,1	15,4	0,9985
15,0	295	23,4	0,048	19,1	2,1	0,79	0,74	4,95	12,1	0,65	12,3	6,8	6,7	20,7	0,9980
34,5	–	66,0	–	55,1	6,2	0,63	–	–	–	11,8	15,3	18,0	21,7	65,1	0,9935
Mode $(nI\lambda/\lambda_0\tau)_{min}$ – base module I_1= 7,7A															
0,50	250	4,1	0,68	2,7	0,36	0,18	0,706	4,41	10,9	13,5	37,0	0,65	1,13	3,4	0,99966
1,0	260	4,4	0,50	2,87	0,37	0,35	0,686	4,5	11,2	8,7	25,1	0,77	1,0	3,0	0,99970
3,0	270	9,0	0,35	5,8	0,76	0,52	0,674	4,7	11,4	5,6	32,4	1,8	1,9	5,6	0,99944
5,0	280	11,4	0,21	7,2	0,93	0,70	0,656	4,8	11,7	3,2	23,0	2,4	2,0	6,0	0,99940
10,0	290	18,4	0,10	11,2	1,5	0,89	0,640	4,9	12,0	1,5	16,3	4,2	2,8	7,9	0,99920
15,0	295	25,3	0,048	15,2	2,0	1,0	0,635	4,95	12,1	0,70	10,6	6,0	3,9	11,5	0,99885
34,5	–	72,6	–	45,0	5,9	0,77	–	–	–	13,5	144	15,8	12,7	38,2	0,9962
Mode λ_{min} – base module *I*= 6,3A															
0,50	250	6,7	0,68	3,1	0,50	0,16	0,578	4,41	10,9	17,6	55,0	0,73	0,79	2,4	0,99976
1,0	260	5,8	0,50	2,6	0,42	0,38	0,562	4,5	11,2	10,5	27,7	0,73	0,58	1,75	0,99983
3,0	270	10,9	0,35	5,2	0,83	0,57	0,55	4,7	11,4	6,5	34,1	1,6	0,96	2,9	0,9971
5,0	280	13,3	0,21	5,7	2,91	0,87	0,54	4,8	11,7	3,7	21,2	2,1	1,0	3,0	0,99970
10,0	290	21,0	0,10	8,7	1,4	1,15	0,524	4,9	12,0	1,7	14,5	3,7	1,3	3,9	0,99961
15,0	295	28,7	0,048	11,6	1,8	1,3	0,520	4,95	12,1	0,80	9,2	5,3	1,7	5,0	0,99950
34,5	–	86,4	–	36,9	4,1	0,95	–	–	–	17,6	162	14,2	6,3	19,0	0,9981

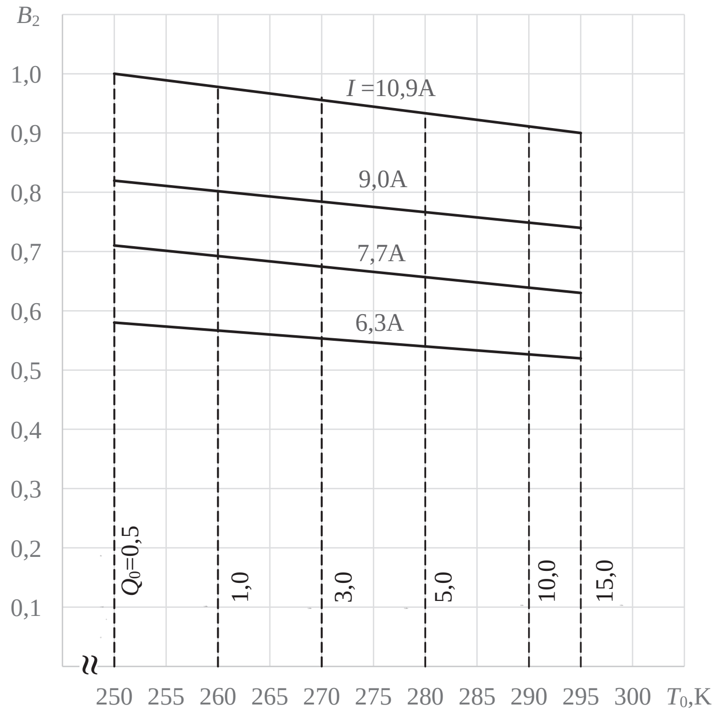

Fig. 5. Dependence of the relative operating current B_2 of the TECs included in the complex on the temperature regime of cooling T_0 with the corresponding thermal load Q_0 for different current modes of operation of the basic TEC (B_2) at T=300K, l/S=4,5: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

With an increase in the value of the operating current *I* of the TEC complex:

− the number of thermoelements n decreases (fig. 6). The minimum number of thermoelements n_{min} = 61.8 pcs is provided in the Q_{0max} mode;

− the refrigerating coefficient *E* decreases (fig. 6). The maximum refrigerating coefficient E_{max} = 0.95 is provided in the λ_{min} mode;

− the voltage drop *U* increases (fig. 6). The maximum voltage drop U_{max} = 6.9V is provided in the Q_{0max} mode;

− the time of reaching the stationary operating mode *τ* decreases (fig. 6). The minimum time to reach the stationary operating mode τ_{min} = 10.8 sec is provided in the Q_{0max} mode;

− the functional dependence of the amount of consumed energy *N = f (I)* on the value of the operating current I has a minimum at *I* = 7.7A, *N* = 144 W’sec in the mode $(nI\lambda/\lambda_0\tau)_{min}$ (fig. 7);

− the heat dissipation capacity of the radiator *αF* increases (fig. 7). The minimum heat dissipation capacity of the radiator αF_{min} = 14.21 W/K is provided in the λ_{min} mode;

− the relative failure rate λ/λ_0 increases (fig. 8). The minimum relative failure rate $(\lambda/\lambda_0)_{\min}$ = 6,3 is provided in the λ_{min} mode;

− the probability of no-failure operation *P* decreases (fig. 8). The maximum probability of no-failure operation P_{max} = 0.9981 is provided in the λ_{min} mode.

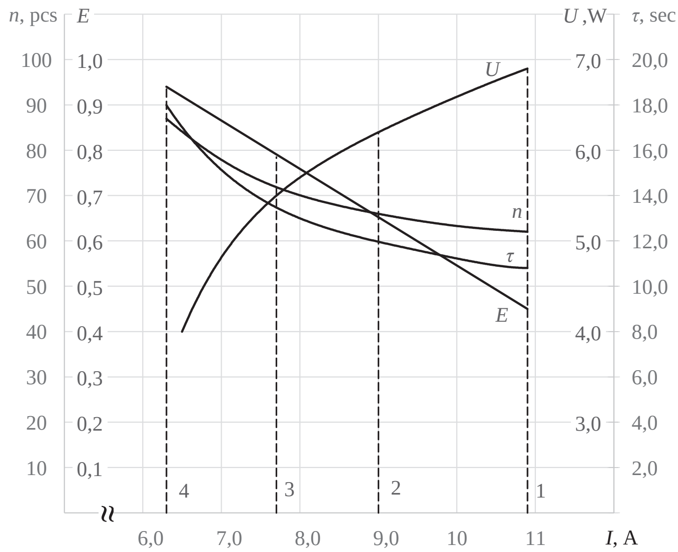

Fig. 6. Dependence of number of thermoelements n, cooling coefficient E, voltage drop U and time of setting to stationary operation mode of TEC complex on the value of operating current I for different operating modes at T=300K, l/S=4,5. = 300K: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

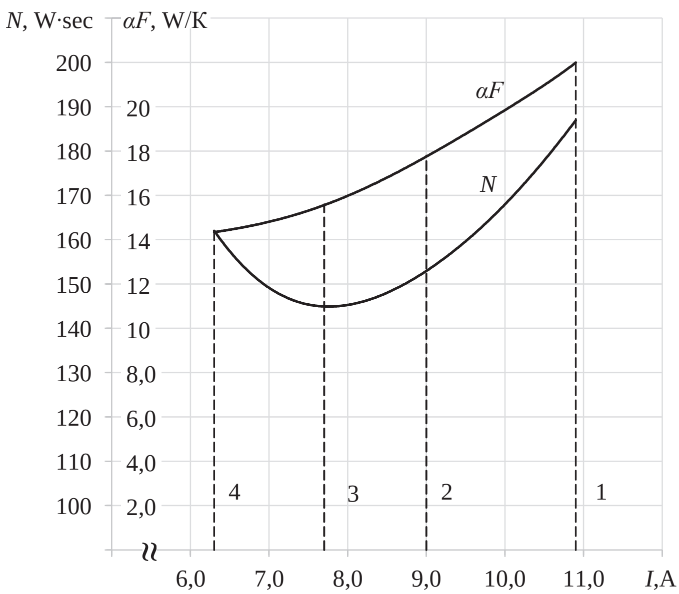

Fig. 7. Dependence of the amount of consumed energy – N and heat removal capacity of the radiator αF of the TECs complex on the value of the operating current I for different operating modes at T=300K, l/S=4,5: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

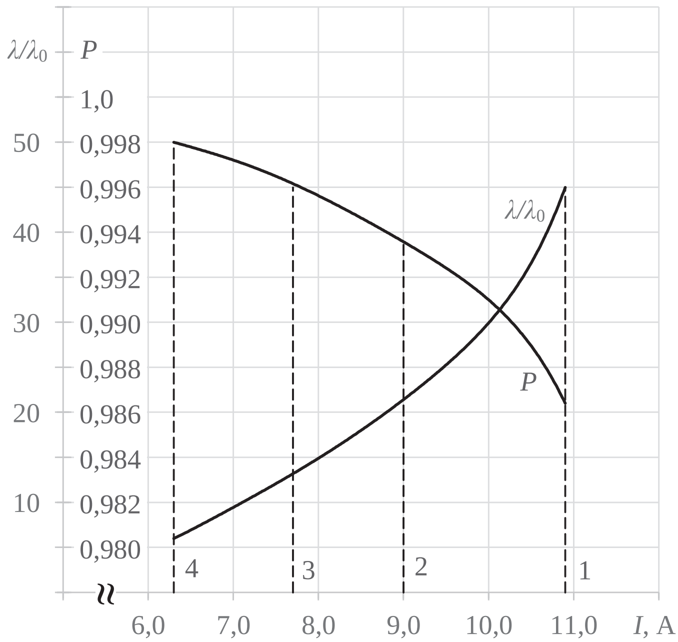

Fig. 8. Dependence of the relative failure rate λ/λ_0 and the probability of failure-free operation P of the TEC complex on the value of the operating current I for different operating modes at T=300K, l/S=4,5, $\lambda_0=3\cdot10^{-8}$ 1/hour, $t=10^4$ hour: 1 – Q_{0max} mode, 2 – $(nI)_{min}$ mode, 3 – mode $(nI\lambda/\lambda_0\tau)_{min}$, 4 – λ_{min} mode

Comparative analysis of the results of calculations of the main parameters, reliability indicators and dynamic characteristics of the TEC complex for different geometry of thermoelement legs (ratio *l/S* = 40 and *l/S* = 4.5) showed that with a decrease in the ratio *l/S*:

– the number of thermoelements *n* of the complex decreases:

1. In the Q_{0max} mode at *l/S* = 40 from *n* = 550 pieces to *l/S* = 4.5 *n* = 61.8 pieces, i.e. 9 times,

2. In the $(nI)_{min}$ mode: from *n* = 590 pieces at *l/S* = 40 to *n* = 66 pieces at *l/S* = 4.5, i.e. 9 times,

3. In the mode $(nI\lambda/\lambda_0\tau)_{min}$: from *n* = 649 pieces at *l/S* = 40 to *n* = 72.6 pieces at *l/S* = 4.5, i.e. 9 times,

4. In the λ_{min} mode: from *n* = 773 pieces at *l/S* = 40 to *n* = 86.4pieces at *l/S* = 4.5, i.e. 9 times;

– the relative intensity of failures λ/λ_0 decreases: almost 9 times for different operating modes;

– in the Q_{0max} mode: from λ/λ_0 = 402 at *l/S* = 40 to λ/λ_0 = 45.2 at *l/S* = 4.5, i.e. 9 times;

– the probability of failure-free operation *P* increases, for example, in the Q_{0max} mode from *P* = 0.8863 at *l/S* = 40 to *P* = 0.9865 at *l/S* = 4.5;

– the time of reaching the stationary operating mode *τ* increases insignificantly by 20%.

At the same time, such parameters as: the refrigerating coefficient *E*, the heat transfer capacity of the radiator *αF* remain constant.

Conclusions. A thermophysical model of a system for ensuring temperature regimes has been developed for controlling the temperature regime of operation of a number of heat-dependent and heat-loaded elements of electronic equipment based on a TEC complex with a series electrical connection at different temperature levels of cooling T_0 from T_0 = 295K to T_0 = 250K with different heat loads Q_0 from Q_0 = 0.5W to Q_0 = 15W for various current operating modes.

A comparative analysis of the main parameters, reliability indicators and dynamic characteristics of the TEC complex at different temperature levels of cooling, a given unified geometry of thermoelement legs (*l/S* ratio) and different current operating modes.

The research results showed the possibility of controlling the thermal regime of the ТУС complex by choosing the current operating mode, taking into account the weight of each of the limiting factors in terms of weight and size, energy and dynamic characteristics.

In addition, the analysis showed that with an increase in the ratio *l/S*: a decrease in the value of the operating current *I*; the time to reach the stationary operating mode τ, the amount of consumed energy *N*; Lowering the voltage *U*, the number of thermoelements *n*, the relative dependence of failures λ/λ_0 and a decrease in the probability of failure-free operation *P*. In this case, the coefficient of performance remains.

With serial electrical connection of the TEC in combination with the possibility of using one TEC and one heat sink.

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