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Control of thermal regime of thermoelectric coolers in uniform temperature field

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ABSTRACT

The possibility of using a complex of thermoelectric coolers to control the thermal regime of heat-loaded elements of radio electronic equipment, the parameters of which significantly depend on the temperature conditions of operation, is considered. The analysis was carried out for conditions of the same level of cooling of semiconductor elements for typical temperature drops, range of dissipation power, current modes of operation, and geometry of thermoelement legs. It is shown that it is rational to use distributed active cooling systems to ensure the required thermal regime of spatially distributed heat-loaded elements with different dissipation power. To ensure the required thermal conditions, it is proposed to use both individual and group variants of the structure layout: heat-loaded element-thermoelectric cooler-radiator. The developed mathematical models of the relationship between the number of thermoelements and the thermal load, the power consumption with the temperature difference and the operating current are analyzed. Models of the main operational characteristics of coolers that are significant for control systems are presented: the relative failure rate and the time to reach a stationary mode. The results of calculations of the main parameters, reliability indicators and dynamic characteristics for an individual version of the layout of thermoelectric coolers with different dissipation power and current operating modes are presented. The group diagram of the arrangement of the object-cooler with series connection and located on the same heat sink and their comparative analysis is considered. When choosing the current mode, it is necessary to take into account the mutual influence and weight of each of the limiting factors, by varying which, when designing the complex and thermoelectric coolers, it is possible to choose compromise modes of operation.

Keywords: Distributed cooler control; models of dynamics and failure rate; layout options; current modes; temperature difference

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INTRODUCTION

The process of improving electronic equipment is characterized by an increase in its complexity and layout density, including a stable increase in the degree of integration of the element base. A high packing density is especially typical for special-purpose equipment, which must have the necessary functionality, high performance and reliability at the lowest possible mass and overall dimensions. A significant part of the consumed power from 40 to 75 %, used by the element base, is inevitably converted into heat, causing unacceptable overheating of the elements. In some cases, the required parameters of the elements can be obtained only at relatively low temperatures. Under these

conditions, technical implementation of effective methods of ensuring thermal conditions is necessary, taking into account the design features of the equipment and operating conditions.

One of the most acceptable ways to ensure the thermal conditions of the elements and components of the equipment is thermoelectric, as the most effective in a wide range of operating temperatures from 140 to 350K. Thermoelectric cooling devices allow you to control the amount of heat flux by simply changing the magnitude of the operating current. The main advantages of the thermoelectric cooling method over others are high reliability and small overall dimensions of thermoelectric devices, ease of control and speed. These advantages are inherently a consequence of the solid-state nature of such coolers, i.e. absence of moving parts, pumped liquids and gases.

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LITERATURE REVIEW

Systems for ensuring thermal modes of electronic equipment are its integral component, since 40-75 % of the power supply is converted into heat [1]. For onboard equipment, thermoelectric coolers are the most acceptable in terms of weight, dimensions, and performance [2, 3]. Since thermoelectric coolers are designed to increase the reliability of heat-loaded elements, they are subject to increased reliability requirements [4]. Reliability indicators are increased due to the structural organization [5], modification of the functioning of modules [6, 7], and optimal design [8, 9]. At the same time, the main disadvantage of thermoelectric coolers is associated with the low efficiency of the thermoelement material [10], the creation of which has been devoted to many studies [11]. At the same time, no significant breakthrough has yet been observed in this area. Therefore, modern design is focused on adapting the achieved parameters of coolers to specific applications, where significant progress has been achieved [12]. Thus, it was possible to increase the performance when using graphene [13, 14], due to the thermodynamic analysis of the processes in the module [15], by matching the cooler with an infrared camera [16]. Expansion of the field of application of thermoelectric coolers [17, 18] has led to stricter requirements for systems for providing thermal conditions based on them [19, 20]. These conditions refer to the most important performance indicators: reliability and dynamic characteristics, which always need to be increased and are in conflict [21, 22],[23]. The problem is aggravated by the fact that when using a thermoelectric cooler in the feedback circuit of the control system, an increase in the dynamic characteristics of the cooler is required, which reduces its reliability [24]. In [25], a method is proposed for increasing the dynamic performance by choosing the material of thermoelements without deteriorating the other parameters of the device. However, the interconnection of the parameters of the cooler constitutes a control problem, to which the work [26] is devoted. The issues of reliability of thermoelectric cooling devices were considered in detail in [27], and the dynamic characteristics and their relationship with reliability indicators in [28]. However, the problems of controlling thermoelectric coolers were practically not considered and were limited exclusively to a stationary mode of operation on one heat-loaded element. Modern equipment has many distributed heat sources that need to be provided with a thermal regime (servers, onboard equipment). The inefficiency of general cooling of such equipment is obvious for systems with limited

energy resources. Therefore, the relevance of the development of systems for ensuring thermal conditions, the energy of which adapts to inhomogeneous spatially distributed heat sources, is obvious.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the work is to develop a topology of a thermal regime control system for controlling thermoelectric coolers of distributed heat sources with a priority in terms of dynamic and reliability indicators.

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

1. To develop a mathematical model of the functioning of thermoelectric coolers, which provides control of the time to reach a stationary mode and the relative failure rate.
2. Analyze the model in the range of operating temperature drops and standard energy modes of operation to determine the compromise conditions of use.

DISTRIBUTED THERMOELECTRIC COOLER MODEL

The complexity and relevance of the development of effective means of ensuring the thermal conditions of radio electronic equipment is due to its operation under the influence of many destabilizing factors. Climatic conditions and own heat generation sharply reduce the reliability indicators. To provide the required thermal conditions for a number of spatially dispersed and heat-loaded equipment elements, various designs of complexes of thermoelectric coolers are used [27].

Among the design features of the construction of electronic equipment should be attributed to the dispersed arrangement of heat-dependent elements with different dissipation power. Therefore, to provide the required thermal conditions for a number of dispersed heat-dependent and heat-loaded elements, both individual and group versions of the system layout (heat-loaded element – cooler-radiator) can be used.

To calculate the main parameters, reliability indicators, dynamics of functioning of the complex of thermoelectric coolers (TEC), we use the following relations [27].

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

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

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

$$I_{\max K} = \frac{e_K \bar{T}_0}{R_K} - \text{maximum operating current, A;}$$

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

$$R_K = \frac{l}{\bar{\sigma}_K S} - \text{electrical resistance of the}$$

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;

$$B_K = \frac{I}{I_{\max K}} - \text{relative operating current at the end}$$

of the cooling process.

I – working current value, A;

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

T – heat-generating junction temperature, K;

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

\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:

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

Voltage drop U_K

$$U_K = \frac{W_K}{I}. \quad (3)$$

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

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

The relative value λ/λ_0 of the failure rate can be determined from the expression [27]

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

where: $C = \frac{Q_0}{nI_{\max K}^2 R_K}$ 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:

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

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 [28]:

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

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

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

$m_0 C_0 \rightarrow 0$ – 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, at $\tau = 0$;

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

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

ANALYSIS OF THE MODEL OF PROVIDING THERMAL REGIMES

With an individual version of the layout for each separate heat-loaded element, a TEC of a specific design is used with an individual heat sink. The mode of operation is simultaneous for all elements of the complex. In this case, the dissipated

power of each heat-loaded element of the equipment is constant in time and is, for example, $Q_0 = 0.5; 1.0; 3.0; 5.0; 10.0; 15 \text{ W}$.

In this case, it is necessary to use a number of power sources to ensure the functioning of various designs of thermoelectric cooling devices.

The results of calculations of the main parameters, reliability indicators and the time to reach a stationary mode of operation with an

individual layout, for example, in heat-loaded electronics elements with different dissipation power from $Q_0 = 0.5 \text{ W}$ to $Q_0 = 15 \text{ W}$ and six TECs of various designs at a temperature level of cooling $T_0=260 \text{ K}$ thermoelement leg geometry $l/S=4.5$ and for different current operating modes are given in Table 1.

Table 1. The main indicators of the thermoelectric system for ensuring thermal conditions in various operating modes at $T_0=260\text{K}$; $T=300\text{K}$; $\Delta T=40\text{K}$; $T_c=295\text{K}$; $R=4.55 \cdot 10^{-3}\Omega\text{m}$; $I_{\max}=11,1\text{A}$; $\Delta T_{\max}=79.8\text{K}$; $\theta = 0.5$; $T-T_c = 5\text{K}$

Mode	B	Q_0 , W	n , it.	I , A	W , W	U , V	E	τ , s	αF , W/K	N , W·s	λ/λ_0	$\lambda \cdot 10^8$, 1/h	P
$Q_{0\max}$	1.0	0.5	1.8	11.1	2.3	0.21	0.216	7.6	0.56	17.7	1.84	5.52	0.99945
		1.0	3.6		4.6	0.42			1.12	35.4	3.7	11.1	0.99889
		3.0	10.8		13.9	1.26			3.4	107.0	11.1	33.3	0.99667
		5.0	18.0		23.2	2.1			5.6	178.6	18.5	55.5	0.99446
		10	36.0		46.4	4.2			11.3	357.3	37.0	111.0	0.98896
		15	54.0		69.6	6.3			16.9	535.9	54.2	1626	0.9839
		34.5	124		160	9.5			38.9	1232	126.3	379	0.9628
$(nI)_{\min}$	0.707	0.5	2.2	7.85	1.5	0.19	0.336	9.2	0.40	13.8	0.566	1.7	0.99983
		1.0	4.4		3.0	0.38			0.80	27.6	1.13	3.4	0.99966
		3.0	13.2		9.0	1.14			2.4	82.8	3.4	10.2	0.99898
		5.0	22.0		15.0	1.9			4.0	138	5.66	17.0	0.99830
		10	44.0		30.0	3.8			8.0	276	11.3	34.0	0.99660
		15	66.0		45.0	5.7			12.0	414	17.0	51.0	0.9949
		34.5	152		103.5	13.1			27.6	952	39.0	117.2	0.9883
$(nI\lambda/\lambda_0t)_{\min}$	0.53	0.5	3.2	5.9	1.3	0.22	0.385	12.0	0.36	15.6	0.25	0.75	0.999925
		1.0	6.4		2.6	0.44			0.72	31.2	0.50	1.5	0.99985
		3.0	19.2		7.8	1.32			2.16	93.6	1.5	4.5	0.99955
		5.0	32.0		13.0	2.2			3.6	156	2.5	7.5	0.99925
		10	64.0		26.0	4.4			7.2	312	5.0	15.0	0.9985
		15	96.0		39.0	6.6			10.8	468	7.5	22.5	0.99775
		34.5	221		89.7	15.2			24.8	1076	17.3	51.8	0.9948
$(nI\lambda/\lambda_0)_{\min}$	0.46	0.5	4.3	5.1	1.35	0.27	0.37	14.3	0.37	19.3	0.19	0.556	0.999944
		1.0	8.6		2.70	0.54			0.74	38.6	0.37	1.11	0.999889
		3.0	25.8		8.1	1.62			2.22	115.8	1.11	3.33	0.99967
		5.0	43.0		13.5	2.7			3.7	193	1.85	5.55	0.999445
		10.0	86.0		27.0	5.4			7.4	386	3.7	11.1	0.99889
		15.0	129.0		40.5	8.1			11.0	579	5.55	16.7	0.99833
		34.5	296.7		93.2	18.6			25.4	1332	12.8	38.3	0.9962
λ_{\min}	0.40	0.5	6.4	4.4	1.60	0.36	0.316	17.7	0.42	28.3	0.15	0.46	0.999954
		1.0	12.8		3.20	0.71			0.84	56.6	0.31	0.92	0.999908
		3.0	38.4		9.60	2.16			2.52	170	0.92	2.76	0.99972
		5.0	64.0		16.0	3.60			4.2	283	1.55	4.65	0.99954
		10.0	128.0		32.0	7.2			8.4	566	3.1	9.3	0.99907
		15.0	192		48.0	10.8			12.6	849.6	4.65	14.0	0.9986
		34.5	442		110.4	24.8			29.0	1954	10.7	32.0	0.9968

Source: compiled by the authors

From the point of view of reliability, it should be noted that if the system consists of – independent elements (TEC), and the probability of failure-free operation of the *i*-th element is equal $P_i(t)$, then the total probability of failure-free operation of the system is [27]:

$$P_0(t) = P_1(t) \cdot P_2(t) \dots P_j(t) \dots P_N(t) = \prod_{i=1}^N P_i(t).$$

In this case, it is necessary to use auxiliary data to calculate the main parameters, reliability indicators and dynamics of functioning.

With an increase in the relative operating current *B* at a given temperature difference ΔT and the geometry of the thermoelement legs $l / S = 4.5$ for different heat loads Q_0 , which corresponds to the dissipation power of the elements, the number of thermoelements *n* decreases (Fig. 1).

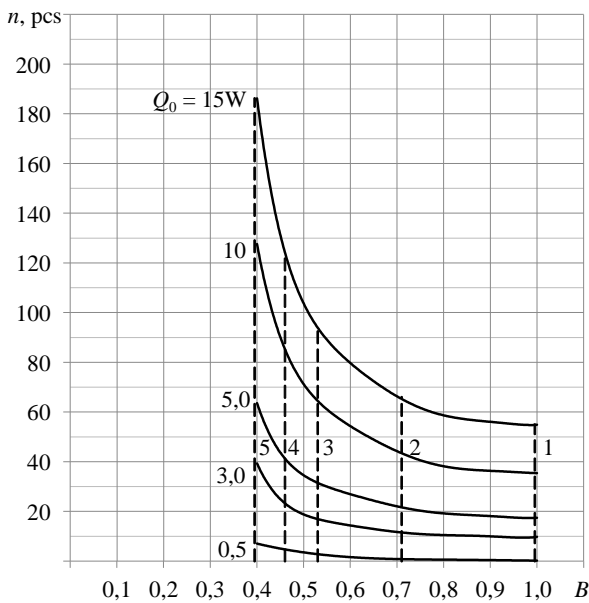


Fig. 1. Dependence of the number of thermoelements *n* in a single-stage TEC on the relative operating current *B* for different heat loads Q_0 at $T=300K$; $l/S=4.5$; $\Delta T=40K$:
1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
3 – $(nI\lambda/\lambda_0 \tau)_{min}$ mode; 4 – $(nI\lambda/\lambda_0)_{min}$;
5 – mode λ_{min}
 Source: compiled by the authors

At a given relative operating current *B*, with an increase in the thermal load Q_0 , the number of thermoelements *n* increases. The minimum number of thermoelements n_{min} is provided in the Q_{0max} mode. and the time of reaching the stationary operating mode τ decreases (Fig. 2).

The time of reaching the stationary operating mode τ decreases from the λ_{min} mode to Q_{0max} .

The minimum time to reach the stationary operating mode $\tau_{min} = 7.6$ sec is provided in the Q_{0max} mode:

- the value of the operating current *I* increases (Fig. 2). The value of the operating current *I* increases from the mode λ_{min} to Q_{0max} . The minimum value of the operating current $I_{min} = 4.4A$ is provided in the λ_{min} mode, and the maximum – $I_{max} = 11.1A$ in the Q_{0max} mode;

- the functional dependence of the coefficient of performance $E=f(B)$ has a maximum at $B = 0.53$, which corresponds to the mode $(nI\lambda/\lambda_0 \tau)_{min}$ (Fig. 2);

- the relative failure rate λ/λ_0 increases (Fig. 3).

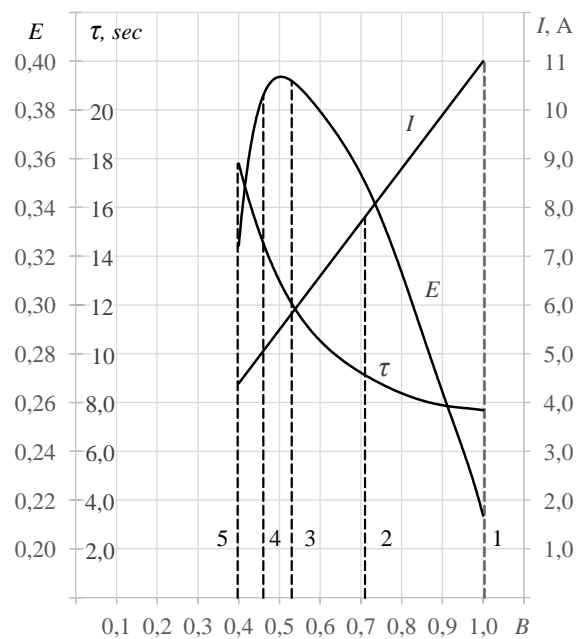


Fig. 2. Dependence of the cooling coefficient – *E*, the time to reach the stationary operating mode – τ and the value of the operating current – *I* of a single-stage TPP on the relative operating current *B* at $T=300K$; $l/S=4.5$; $\Delta T=40K$:
1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
3 – $(nI\lambda/\lambda_0 \tau)_{min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{min}$;
5 – mode λ_{min}
 Source: compiled by the authors

With an increase in the heat load Q_0 , the relative failure rate λ/λ_0 increases at a given relative operating current *B*. The relative failure rate λ/λ_0 decreases from the Q_{0max} mode to the λ_{min} mode. The minimum failure rate $(\lambda/\lambda_0)_{min}$ is provided in the mode $(\lambda/\lambda_0)_{min}$;

- the probability of failure-free operation *P* decreases (Fig. 3).

For a given relative operating current B , with an increase in the thermal load Q_0 , the probability of failure-free operation P decreases. The probability of no-failure operation P increases from the Q_{0max} mode to λ_{min} .

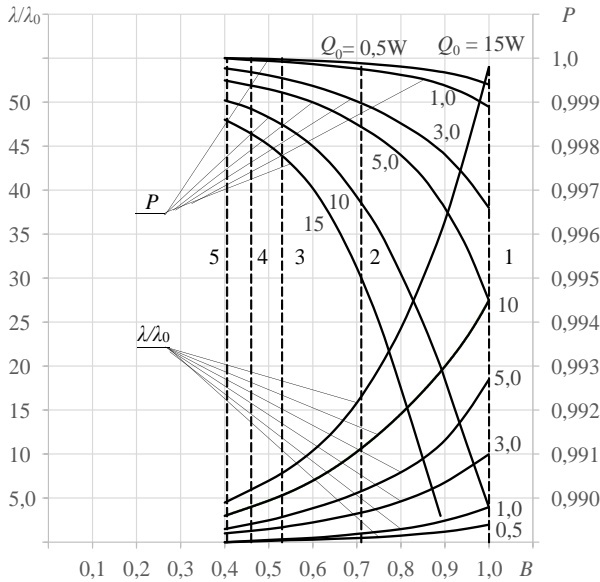


Fig. 3. Dependence of the relative failure rate λ/λ_0 and the probability of failure-free operation P of a single-stage TPP on the relative operating current B for different thermal loads Q_0 at $T=300K$; $I/S=4.5$; $\Delta T=40K$; $\lambda_0=3 \cdot 10^{-8}$ 1/hour; $t=10^4$ hour:

- 1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
- 3 – $(nI\lambda/\lambda_0\tau)_{min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{min}$;
- 5 – mode λ_{min}

Source: compiled by the authors

The maximum probability of no-failure operation P_{max} is provided in the λ_{min} mode:

– the functional dependence of the required heat dissipation capacity of the radiator $\alpha F=f(B)$ has a minimum at $B = 0.53$, which corresponds to the mode $(nI\lambda/\lambda_0\tau)_{min}$ (Fig. 4); With an increase in the heat load Q_0 , the required heat dissipation capacity of the radiator αF increases at a given relative operating current B ;

– the functional dependence of the amount of consumed energy $N = f(B)$ has a minimum at $B = 0.707$ (Fig. 5), which corresponds to the mode $(nI)_{min}$. With an increase in the heat load Q_0 , the amount of consumed energy N increases at a given relative operating current B ;

– the functional dependence of the voltage drop $U = f(B)$ has a minimum at $B = 0.71$, which corresponds to the mode $(nI)_{min}$ (Fig. 6). With an increase in the thermal load Q_0 , the voltage drop U increases at a given relative operating current B .

A variant of the group layout of the system, consisting of 6 heat-loaded elements and 6 coolers (TEC) on one heat sink, is considered.

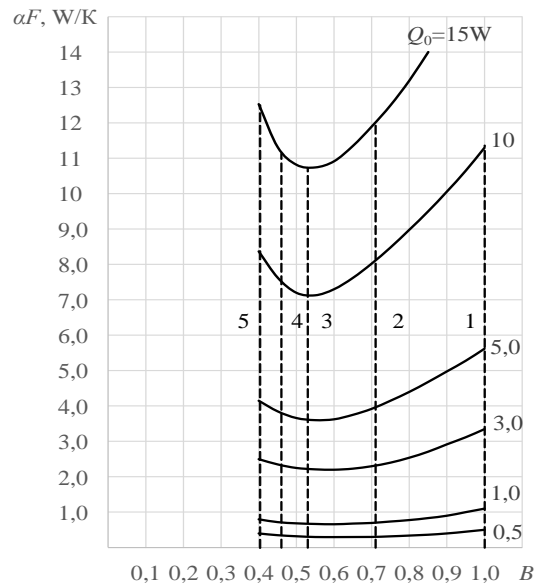


Fig. 4. Dependence of the heat-removing capacity of the radiator αF of a single-stage TEC on the relative operating current B for different heat loads Q_0 at $T=300K$; $I/S=4.5$; $\Delta T=40K$:

- 1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
- 3 – $(nI\lambda/\lambda_0\tau)_{min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{min}$;
- 5 – mode λ_{min}

Source: compiled by the authors

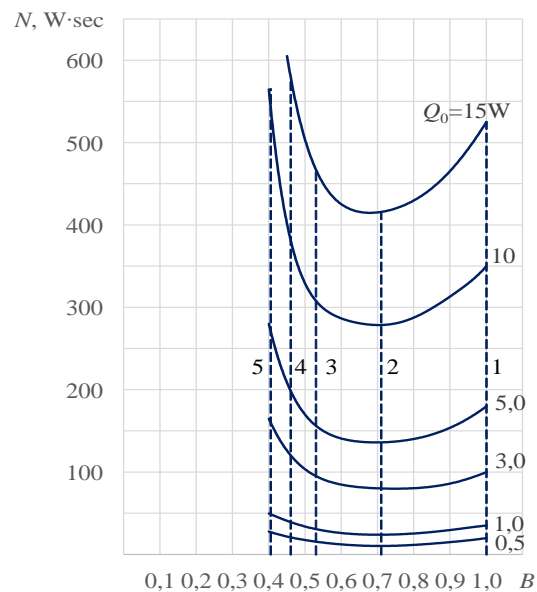


Fig.5. Dependence of the amount of consumed energy $N = W \cdot \tau$ of a single-stage TPP on the relative operating current B for different heat loads Q_0 at $T=300K$; $I/S=4.5$; $\Delta T=40K$:

- 1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
- 3 – $(nI\lambda/\lambda_0\tau)_{min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{min}$;
- 5 – mode λ_{min}

Source: compiled by the authors

In this case, one heat-loaded element is installed on each TEC, and all TECs together with cooling objects are located on one common heat-removing radiator with separate power supply to each TEC.

The results of calculations of the main parameters, reliability indicators and dynamics of functioning with separate power supply (object-cooler) are shown in Table 1. Conditions: temperature level of cooling $T_0 = 260K$, heat load range $Q_0 = 0.5-15W$ for various current operating modes.

A positive point in this layout is the overall heat sink. The disadvantages of this layout option, as with an individual scheme, include the need to use a number of power supplies (see Table 1).

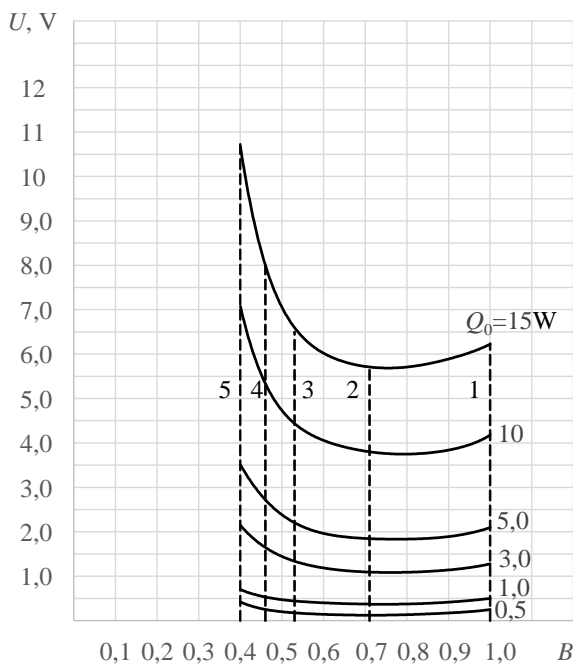


Fig. 6. Dependence of the voltage drop U of a single-stage TPP on the relative operating current B for the different heat loads Q_0 at $T=300K$; $l/S=4.5$; $\Delta T=40$:

**1 – Q_{0max} mode; 2 – $(nI)_{min}$ mode;
3 – $(nI/\lambda_0 \tau)_{min}$ mode; 4 – mode $(nI/\lambda_0)_{min}$;
5 – mode λ_{min}**
Source: compiled by the authors

The mode of operation is simultaneous. That is, the simultaneous inclusion of all elements included in the complex. Consider a group layout system (cooler object) with serial electrical connection of coolers in a complex; located on one heat sink.

With serial electrical connection of coolers, the complex provides:

- the same operating current I depending on the selected current operating mode;
- the value of the heat load Q_0 is provided by the calculated number of thermoelements – n in the TEC at a given current operating mode;

- total supply voltage of the TEC complex;
- one and the same refrigerating coefficient E , and the time of reaching the stationary operating mode τ ;
- the ability to use one power source;
- the possibility of using one thermoelectric module with total cooling capacity.

When carrying out a comparative analysis of the calculated data of the main parameters, reliability indicators and the dynamics of the functioning of the TPP complex, consisting of M -modules, to ensure both for different temperature levels of cooling and the same with a total thermal load for different current operating modes, the following ratios can be used.

The power consumption of the complex W_K is equal to the sum of the power consumption of each TEC included in the complex, at a given current operating mode:

$$W_K = \sum_{i=1}^M W_i . \tag{9}$$

The number of thermoelements of the complex n_K is equal to the sum of thermoelements in the TEC included in the complex, at a given current operating mode:

$$n_K = \sum_{i=1}^M n_i . \tag{10}$$

The refrigerating coefficient of the complex E_K is equal to the ratio of the total heat load $Q_{0\Sigma}$ to the power consumption of the complex W_K at a given current operating mode:

$$E_K = \frac{Q_{0\Sigma}}{W_K} . \tag{11}$$

The amount of energy expended by the N_K complex is equal to the sum of the energy expended by each TEC included in the complex, for a given current operating mode:

$$N_K = \sum_{i=1}^M N_i . \tag{12}$$

The time of reaching the stationary mode of operation of the TEC complex τ_K is equal to the maximum time of reaching the stationary mode of operation of the TPP included in the complex, at a given current operating mode:

$$\tau_K = \tau_{maxTEC} . \tag{13}$$

When determining the reliability indicators of the TEC complex under operating conditions, namely, the relative failure rate λ/λ_0 and the probability of failure-free operation P , we assume

that, firstly, all n terminals in the TEC are electrically connected in series, the failure of any thermoelement leads to failure building the TEC and the complex as a whole. Events involving the failure of thermoelements are taken independently.

Under the assumptions made, the reliability indicator of the TEC complex $P_K(t)$ can be represented as the product of the reliability of the TEC $P_i(t)$:

$$P_K(t) = \prod_{i=1}^M P_i(t), \tag{14}$$

or taking into account the fact that the value of reliability of the i -th TEC during time t is determined by the expression:

$$P(t) = \exp\left[-\int_0^t \lambda(t)dt\right]. \tag{15}$$

Then the expression for determining the reliability of the TPU complex will take the form:

$$P_K(t) = \exp\left[-\sum \lambda_i(t)dt\right]. \tag{16}$$

With a serial electrical connection of the TEC in the complex, the total voltage drop of the U_K complex is equal to the sum of the voltage drops on the TEC included in the complex, at a given current operating mode:

$$U_K = \sum_{i=1}^M U_i. \tag{17}$$

The required heat dissipation capacity of the radiator of the TEC αF_K complex is equal to the sum of the heat removal capabilities of the TEC radiators included in the complex, at a given current operating mode:

$$\alpha F_K = \sum_{i=1}^M \alpha F_i. \tag{18}$$

The value of the operating current I of the TEC complex with a serial electrical connection can be determined from the ratio for a given current operating mode:

$$I_K = \frac{W_K}{U_K}. \tag{19}$$

The results of calculations of the main parameters, reliability indicators and the time to reach a stationary mode of operation for a group layout (cooling object) of a complex with a series electrical connection of coolers are shown in Table 2.

DISCUSSION OF RESEARCH RESULTS

With an increase in the relative operating current B of the complex at a given temperature drop $\Delta T = 40K$ and heat load $Q_0 = 34.5W$ and the geometry of thermoelement legs $l/S = 4.5$:

- the value of the operating current I (Fig. 2) increases from $I_{min} = 4.4A$ in the mode λ_{min} to $I_{max} = 11.1A$ in the mode Q_{0max} ;
- the time of reaching the stationary operating mode τ decreases (Fig. 2).

The minimum time to reach the stationary operating mode $\tau_{min} = 7.7$ sec is provided in the Q_{0max} mode.

- the number of thermoelements n decreases (Fig. 7).

The minimum number of thermoelements $n_{min} = 124$ pcs is provided in the Q_{0max} mode:

- the functional dependence of the voltage drop $U = f(B)$ has a minimum at $B = 0.707$ in the $(nI)_{min}$ mode (Fig. 7), $U_{min} = 13.1V$;
- the functional dependence of the coefficient of performance $E = f(B)$ has a maximum at $B = 0.53$, which corresponds to the mode $(nI\lambda / \lambda_0\tau)_{min}$. $E_{max} = 0.385$ (Fig. 2).

Table 2. Main parameters, indicators of reliability and time to reach steady-state mode in the group version of the layout of thermoelectric coolers

Mode	B	I , A	n , it.	W , W	U , V	E	τ , s	αF , W/K	N , W·s	λ/λ_0	$\lambda \cdot 10^8$, 1/h	P
Q_{0max}	1.0	11.1	124	160	14.5	0.216	7.7	39.0	1232	126.3	379.0	0.9628
$(nI)_{min}$	0.707	7.85	152	104	13.1	0.336	9.2	27.6	956.8	39.0	117.2	0.9883
$(nI\lambda/\lambda_0\tau)_{min}$	0.53	5.9	221	90.0	15.2	0.385	12.0	24.8	1080	17.3	51.8	0.9948
$(nI\lambda/\lambda_0)_{min}$	0.46	5.1	297	93	18.6	0.37	14.3	25.4	1330	12.8	38.3	0.9962
λ_{min}	0.40	4.4	442	110	24.8	0.316	17.7	29.0	1947	10.7	32.0	0.99680

Source: compiled by the authors

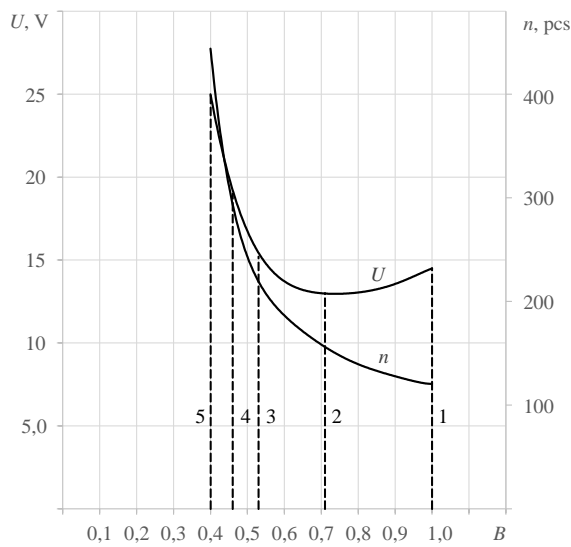


Fig. 7. Dependence of the number of thermoelements n and the voltage drop U of the TPP complex with their serial electrical connection on the relative operating current B at $T_c=300\text{K}$; $\Delta T=40\text{K}$; $l/S=4.5$:
1 – $Q_{0\max}$ mode; 2 – $(nI)_{\min}$ mode;
3 – $(nI\lambda/\lambda_0\tau)_{\min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{\min}$;
5 – mode λ_{\min}
 Source: compiled by the authors

The minimum number of thermoelements $n_{\min} = 124$ pcs is provided in the $Q_{0\max}$ mode:

– the functional dependence of the voltage drop $U = f(B)$ has a minimum at $B = 0.707$ in the $(nI)_{\min}$ mode (Fig. 7), $U_{\min} = 13.1\text{V}$;

– the functional dependence of the required heat dissipation capacity of the radiator $\alpha F = f(B)$ has a minimum at $B = 0.53$ $\alpha F_{\min} = 24.8\text{W/K}$, which corresponds to the mode $(nI\lambda/\lambda_0\tau)_{\min}$ (Fig. 8);

– the functional dependence of the amount of consumed energy $N = f(B)$ has a minimum at $B = 0.71$ $N_{\min} = 957$ W/s, which corresponds to the mode $(nI)_{\min}$ (Fig. 8);

– the relative failure rate λ / λ_0 increases and the probability of failure-free operation P decreases (Fig. 9).

Thus, the criterion for choosing the current mode of operation can be both one- and multifactorial. In most cases, it is necessary to consider the mutual influence and weight of each of the limiting factors. Since the conditions for the design of the TEC complex to ensure the thermal regime of a number of dispersed elements can be very diverse. By varying simultaneously several limiting factors ($n, I, E, \lambda / \lambda_0, \tau$), one can choose compromise modes of operation.

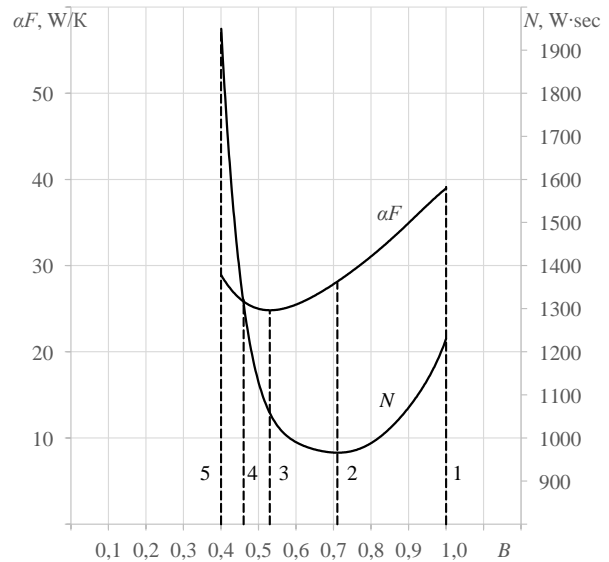


Fig. 8. Dependence of the $N, \alpha F$ values of the TPP complex with their serial electrical connection on the relative operating current B at $T_c=300\text{K}$; $\Delta T=40\text{K}$; $l/S=4.5$:
1 – $Q_{0\max}$ mode; 2 – $(nI)_{\min}$ mode;
3 – $(nI\lambda/\lambda_0\tau)_{\min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{\min}$;
5 – mode λ_{\min}
 Source: compiled by the authors

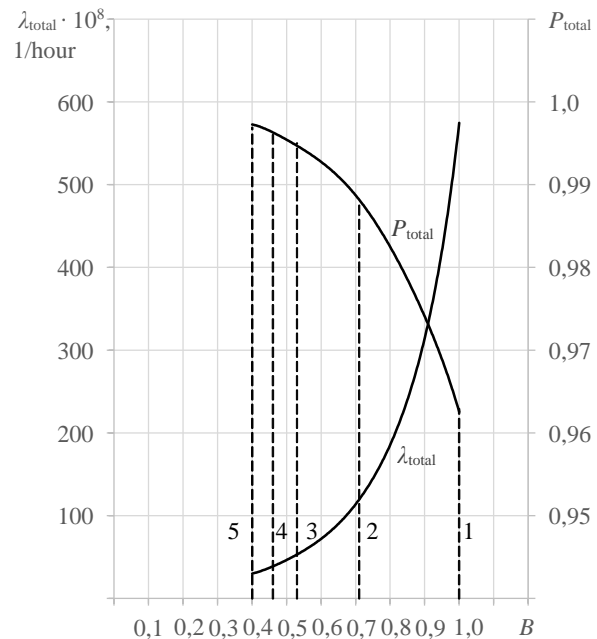


Fig. 9. Dependence of the failure rate λ_{total} and the probability of failure-free operation P_{total} of the TPP complex on the relative operating current B at $T=300\text{K}$; $\Delta T=T=40\text{K}$; $Q_0=0.5$; $\div 15.0$ W; $T-T_c = 5\text{K}$; $\lambda_0=3\cdot 10^{-8}$ 1/hour; $t = 10^4$ hour:
1 – $Q_{0\max}$ mode; 2 – $(nI)_{\min}$ mode;
3 – $(nI\lambda/\lambda_0\tau)_{\min}$ mode; 4 – mode $(nI\lambda/\lambda_0)_{\min}$;
5 – mode λ_{\min}
 Source: compiled by the authors

CONCLUSIONS

1. A mathematical model of a thermoelectric cooler has been developed, which connects the energy and design parameters with the dynamics and reliability indicators of the device, which makes it possible to determine a compromise between competing characteristics already at the design stage.
2. The analysis of the model has been carried out and the conditions for obtaining the extrema of the required energy, heat-removing capacity of the

radiator, and the coefficient of performance, which are significant for on-board systems, have been identified.

3. Variants of the structures of systems for ensuring temperature regimes of heat-loaded equipment are proposed, the control system of which is based on taking into account the extreme values of energy and design indicators, their comparative analysis is carried out.

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Управління тепловим режимом термоелектричних охолоджувачів у рівномірному полі температур

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АНОТАЦІЯ

Розглянута можливість використання комплексу термоелектричних охолоджувачів для забезпечення управління тепловим режимом тепло навантажених елементів радіо електронної апаратури, параметри якої суттєво залежать від температурних умов експлуатації. Аналіз проведено для умов однакового рівня охолодження напівпровідникових елементів для типових перепадів температур, діапазону потужності розсіювання, струмових режимів роботи та геометрії гілок термоелементів. Показано, що для забезпечення необхідного теплового режиму просторово розподілених тепло навантажених елементів з різною потужністю розсіювання раціонально використовувати розподілені системи активного охолодження. Для забезпечення необхідного теплового режиму запропоновано використовувати як індивідуальний, так і груповий варіант компоновки структури: тепло навантажений елемент-термоелектричний охолоджувач-радіатор. Проаналізовано розроблені математичні моделі зв'язку кількості термоелементів з тепловим навантаженням, споживаною потужністю з перепадом температур та робочим струмом. Представлені моделі основних експлуатаційних характеристик охолоджувачів, значущі для систем управління: відносної інтенсивності відмов та часу виходу на стаціонарний режим. Наведено результати розрахунків основних параметрів, показників надійності та динамічних характеристик при індивідуальному варіанті компоновки термоелектричних охолоджувачів з різною потужністю розсіювання та струмових режимах роботи. Розглянуто групову схему компоновки об'єкта-охолоджувача при послідовному з'єднанні та розташованих на одному тепловідвідному радіаторі та їх порівняльний аналіз. При виборі струмового режиму необхідно враховувати взаємний вплив та вагомість кожного з обмежувальних факторів, варіюючи якими при проектуванні комплексу та термоелектричних охолоджувачів можна вибрати компромісні режими роботи.

Ключові слова: управління розподіленими охолоджувачами; моделі динаміки та інтенсивності відмов; варіанти компоновки; токові режими; перепад температур

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