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# Thermal control of a complex of thermoelectric cooling devices

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## ABSTRACT

The paper presents the results of research into the possibility of controlling a complex of thermoelectric cooling devices with parallel electrical connection in a non-uniform temperature field. Such formulation of the problem of creating systems for ensuring thermal conditions of radio-electronic equipment is relevant for on-board information systems, which are subject to stringent requirements for reliability and mass-size characteristics. Research are carried out for the most used temperature range from 295K to 250K in the range of power dissipation from 0.5 W to 15 W for different values of supply voltage. The model of the executive body of the system of thermal modes provision based on the complex of thermoelectric coolers with parallel electrical connection is developed. The model takes into account different dissipation power, non-uniform temperature field, different supply voltages and geometry of thermoelectric cell branches. The comparative analysis of basic parameters, reliability indices and dynamic functioning of the complex of thermoelectric coolers for different supply voltages, different temperature levels of cooling with the corresponding thermal load is carried out. The possibility of selecting the optimal supply voltage taking into account the limitations on the operating current, mass, energy, dynamic and reliability characteristics of the thermoelectric cooler complex is shown. The analysis of the research results has shown the possibility of choosing the nominal of supply voltages taking into account the limitations on mass-size, energy, dynamic and reliability characteristics for different geometry of thermoelements branches.

***Keywords:*** Reliability indicators; dynamic characteristics; mass and dimensions; temperature difference; current mode

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## INTRODUCTION

Among the design, features of radio-electronic equipment should include a dispersed arrangement of temperature-dependent and heat-loaded elements with different power dissipation, operating at different temperature levels. One of the most acceptable ways to ensure the thermal mode of elements and components of radio-electronic equipment is thermoelectric, as the most effective in a wide range of operating temperatures from 140K to 350K. Therefore, to ensure a given thermal mode of a number of thermally dependent elements of radio electronic equipment in a non-uniform temperature field, it is advisable to use a set of thermoelectric cooling devices (TEC). Thermoelectric cooling can control the heat flux by simply changing the operating current. The main advantages of thermoelectric cooling method over other cooling methods are high reliability, small overall dimensions, simple control and fast operation. These advantages are inherently a consequence of the solid-state nature of such coolers, i.e. the absence of moving parts, pumped liquids or gases. Therefore, to ensure a given thermal regime of a number of temperature-dependent elements of radio electronic equipment, it is possible to use a complex of thermoelectric coolers located on a single heat sink and connected electrically in parallel with different temperature level of cooling. At the same time, a unified range of voltages can be used to supply the complex, which is the subject of this paper.



## LITERATURE REVIEW

A significant number of publications [1, 2] are devoted to the issues of ensuring thermal conditions of radio electronic equipment, since the released thermal energy significantly exceeds the heat dissipation capacity of the structure into the external environment [3]. Systems for ensuring thermal conditions of radio-electronic equipment in this formulation are a necessary component of information systems, first of all, onboard [4]. Such systems are characterized by inhomogeneous distribution of heat fluxes, since there are always heat-loaded elements (emitters, processors, power converters) whose heat dissipation is significantly higher than average [5]. The inhomogeneous distribution of the temperature field makes it impossible to control the system by the average volumetric temperature [6], and control by the maximum inefficient [7]. Hence, it follows that the control of actuators of the thermal management system should be performed according to a two-stage structure: by the average volumetric temperature and localized by the temperature of the allocated heat-loaded elements [8]. Control systems of distributed executive cooling objects are carried out by systems with many inputs and many outputs (MIMO-systems) [9]. The peculiarity of the actuators of localized heat-loaded elements is that they are practically in the same thermal conditions as the cooled elements [10]. The coolers are subjected to higher requirements in terms of reliability and dynamics, similar to heat-loaded elements, since they are included in series according to the reliability scheme [11]. In terms of reliability, dynamics and mass-size characteristics, thermoelectric coolers are the most suitable for the task at hand [12]. At the same time, the increasing requirements to modern equipment require improvement of both reliability and dynamics indices and controllability of coolers. The work [13] is devoted to the development of a basic reliability-oriented model of a thermoelectric cooling device. However, the work left unexplored the issues of reliability and dynamic performance enhancement, which is the subject of research aimed at studying the influence of design parameters [14] and energy characteristics [15] of coolers. The peculiarity of thermoelectric coolers is the simplicity of current control of cooling capacity [16]. The issues of controlling distributed cooling devices to achieve maximum values of reliability indices and minimum steady-state time remain open [17]. The relationship between reliability indices and dynamic characteristics in terms of controllability of thermoelectric coolers was considered in [18]. In this work, the conditions for finding compromise optimized control solutions for a set of significant parameters and indicators were revealed. However, the research was carried out for a single thermoelectric cooler, while the control of distributed systems with several coolers is of interest, which is the subject of the research in [19]. At the same time, the problem of controlling distributed systems for providing thermal modes of radio electronic equipment remains an urgent research task.

## PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this work is to improve the reliability performance of a complex of thermoelectric coolers with parallel electrical connection in a non-uniform temperature field.

To achieve this goal, the following tasks should be solved:

1) to analyze the model of the complex of parallel distributed coolers in a non-uniform temperature field;

2) to carry out a comparative analysis of parameters, performance, dynamics for different supply voltages and geometry of thermocouple branches.

## MODEL OF THE EXECUTIVE BODY OF THE SYSTEM FOR ENSURING THERMAL REGIMES

Let us use fragments of the previously developed model of a single-cascade thermoelectric cooler as a component of the system for ensuring thermal modes (SETM) of radio electronic equipment [13].

In accordance with this model, the voltage drop $U$ is determined from the relation:

$$U = 2nI_{\max K} R_k (B + \frac{\Delta T_{\max}}{T_o}\Theta), \qquad (1)$$

where $n$ is number of thermocouples; $I_{maxK}$ is maximum operating current; $R_K$ – electrical resistance of the branch; $B$ is relative operating current; $T_{max}$ is maximum temperature difference; $T_0$ – temperature of the heat-absorbing layer; $\Theta$ is relative temperature difference.

The number of thermocouples can be determined from the expression:

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

where $Q_0$ is heat load value.

The refrigeration coefficient $E$ is determined from the expression:

$$E = \frac{Q_0}{W}, \qquad (3)$$

where $W$ is power consumption.

The relative failure rate $\lambda / \lambda_0$ can be determined from the relationship:

$$\frac{\lambda}{\lambda_0} = nB^2(\Theta + c)\frac{\left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}K_T, \quad (4)$$

where $c = \frac{Q_0}{nI_{\max}^2 R}$ is relative thermal load; $\lambda$ =3 $10^{-8}$1/h is nominal failure rate; $K_T$ is significant coefficient of reduced temperatures.

The probability of failure-free operation $P$ of the fuel and energy unit can be determined from the expression:

$$P = \exp[-\lambda t], \quad (5)$$

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

The formula for determining the time of steady-state operation $\tau$ can be presented in the form [18]:

$$\tau = \frac{m_0 c_0 + n\sum_i m_i c_i}{nK(1 + 2B_K \frac{\Delta T_{\max}}{T_0})}\ln\frac{\gamma B_H(2 - B_H)}{eB_K - B_K^2 - \Theta}, \quad (6)$$

where $\gamma = \frac{I_{\max H}^2 R_H}{I_{\max K}^2 R_K}$; $m_0 c_0$ is product of mass by heat capacity of the cooling object. In our case $m_0 c_0 \rightarrow 0$ (no object); $\sum_i m_i c_i$ is total value of the product of heat capacity and mass of the constituent structural and technological elements on the heat-absorbing layer of the module at a given $l/S$. Index $H$ means the initial moment of time. The index $K$ means the final moment.

The expression for determining the relative operating current $B$ relative temperature difference $\Theta$ at supply voltage $U$ can be presented in the form [19]:

$$B = \frac{2k-1}{2k}\left[1 - \sqrt{1 - \frac{4\Theta\left(k + \frac{\Delta T_{\max}}{T_0}\right)}{(2k-1)^2}}\right], \quad (7)$$

where $k = \frac{U \cdot I_{\max}}{2Q_0}$ is a relative value depending on the voltage drop $U$, the magnitude of the thermal load $Q_0$, the cooling temperature level $T_0$ and the geometry of the thermocouple branches (ratio $l/s$).

For a cooling system consisting of $M$ independent elements, the probability of failure-free operation of the *i*-th element is equal to $P_i(t)$, then the total probability of failure-free operation of the system is [13]:

$$P_\Sigma(T) = P_1(t) \cdot P_2(t) \cdot \ldots \cdot P_i(t) \cdot \ldots \cdot P_M(t) = \prod_{i=1}^{M} P_i(t). \quad (8)$$

The results of calculations of the main parameters, reliability indicators and dynamic characteristics of the complex of fuel and energy units with parallel electrical connection are given in Table 1 and Table 2. Calculations were performed in a non-uniform temperature field from $T_0$ =295K to $T_0$ =250K at different thermal load from $Q_0$ =0.5W to $Q_0$ =15W, standard values of supply voltage from $U$ =6.0V to $U$ =24V, specified geometry of branches of thermoelements $l/s$ =4.5.

*Table 1*. **Results of calculations of main indicators and parameters at $T$ =300K, $l/s$ =4.5**

| $Q_0$ | $T_0$ | $\Theta$ | $B$ | $K$ | $n$ | $I$ | $W$ | $E$ | $\tau$ | $N$ | $\alpha F$ | $\lambda/\lambda_0$ | $\lambda\ 10^8$ | $P$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U$ = 6.0 V, $I_{max}$ =11,5 A | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.44 | 65.4 | 95.4 | 4.80 | 28.4 | 0.02 | 42.0 | 1194 | 5.8 | 3.8 | 11.4 | 0.68 | 0.99890 |
| 1.0 | 260 | 0.30 | 33.6 | 138.4 | 3.4 | 21.6 | 0.046 | 39.1 | 845 | 4.5 | 1.0 | 3.1 | 0.50 | 0.99969 |
| 3.0 | 270 | 0.21 | 11.4 | 169..4 | 2.4 | 14.27 | 0.21 | 28.5 | 405 | 3.4 | 0.25 | 0.75 | 0.35 | 0.9999925 |
| 5.0 | 280 | 0.13 | 7.0 | 267.3 | 1.5 | 9.1 | 0.55 | 24.7 | 224 | 2.8 | 0.04 | 0.114 | 0.21 | 0.9999989 |
| 10.0 | 290 | 0.066 | 3.6 | 503.6 | 0.80 | 4.8 | 2.1 | 18.0 | 86 | 3.6 | 0.0027 | 0.0082 | 01.0 | 0.999992 |
| 15.0 | 295 | 0.035 | 2.42 | 960 | 0.43 | 2.6 | 5.8 | 14.0 | 36 | 3.5 | 0.00022 | 0.00066 | 0.048 | 0.99999993 |
| 34.5 | - | - | - | - | 13.3 | 80.7 | 0.428 | 0.15 | 2790 | 23.6 | 5.09 | 15.3 | - | 0.9985 |
| $U$ = 9.0 V | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.44 | 98.1 | 149.1 | 4.86 | 43.8 | 0.0114 | 46.3 | 2028 | 8.9 | 5.76 | 17.3 | 0.68 | 0.9983 |
| 1.0 | 260 | 0.2993 | 50.4 | 196.4 | 3.35 | 30.15 | 0.033 | 42.5 | 1282 | 6.2 | 1.42 | 4.25 | 0.50 | 0.9958 |
| 3.0 | 270 | 0.205 | 17.1 | 265 | 2.34 | 21.0 | 0.143 | 33.1 | 696 | 4.8 | 1.26 | 3.8 | 0.35 | 0.99962 |
| 5.0 | 280 | 0.123 | 10.53 | 414.4 | 1.44 | 13.0 | 0.383 | 29.1 | 380 | 3.6 | 0.049 | 0.146 | 0.21 | 0.9999985 |
| 10.0 | 290 | 0.061 | 5.4 | 801 | 0.73 | 6.55 | 1.53 | 22.5 | 147 | 3.3 | 0.003 | 0.009 | 0.10 | 0.9999991 |
| 15.0 | 295 | 0.031 | 3.63 | 1570 | 0.376 | 3.4 | 4.42 | 18.4 | 62.5 | 3.7 | 0.0002 | 0.0006 | 0.048 | 0.9999994 |
| 34.5 | - | - | - | 3396 | 13.1 | 118 | 0.292 | 46.3 | 4596 | 30.5 | 8.492 | 25.48 | - | 0.99745 |

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


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*Table 2.* **Results of calculations of main indicators and parameters at $T$ =300K, $l/s$ =4.5**

| $Q_0$ | $T_0$ | $\Theta$ | $B$ | $K$ | $n$ | $I$ | $W$ | $E$ | $\tau$ | $N$ | $\alpha F$ | $\lambda/\lambda_0$ | $\lambda\ 10^8$ | $P$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U$ = 12 V | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.44 | 98.1 | 199 | 4.80 | 58.2 | 0.0086 | 48.9 | 2847 | 11.7 | 7.6 | 22.8 | 0.68 | 0.9977 |
| 1.0 | 260 | 0.2993 | 50.4 | 262 | 3.33 | 39.8 | 0.025 | 45.5 | 1812 | 8.2 | 1.84 | 5.53 | 0.50 | 0.99945 |
| 3.0 | 270 | 0.205 | 17.1 | 356 | 2.3 | 27.6 | 0.109 | 36.2 | 998 | 6.1 | 0.43 | 1.3 | 0.35 | 0.99987 |
| 5.0 | 280 | 0.123 | 10.53 | 558 | 1.40 | 17.0 | 0.295 | 32.3 | 549 | 4.4 | 0.06 | 0.18 | 0.21 | 0.999982 |
| 10.0 | 290 | 0.061 | 5.4 | 1092 | 0.70 | 8.34 | 1.20 | 25.7 | 214 | 3.7 | 0.0034 | 0.010 | 0.10 | 0.9999989 |
| 15.0 | 295 | 0.031 | 3.63 | 2167 | 0.35 | 4.2 | 3.55 | 21.5 | 91.0 | 3.8 | 0.00022 | 0.00065 | 0.048 | 0.99999993 |
| 34.5 | - | - | - | 4634 | 12.9 | 155.1 | 0.222 | 48.9 | 6511 | 37.9 | 9.93 | 29.8 | - | 0.9970 |
| $U$ = 18 V | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.439 | 130.8 | 199 | 293 | 4.765 | 85.2 | 0.006 | 52.5 | 4471 | 17.1 | 11.0 | 33.0 | 0.9967 |
| 1.0 | 260 | 0.298 | 67.2 | 262 | 404 | 3.315 | 60.9 | 0.0164 | 49.8 | 3032 | 12.4 | 2.8 | 8.4 | 0.99917 |
| 3.0 | 270 | 0.202 | 22.8 | 356 | 545 | 2.27 | 41.2 | 0.073 | 40.6 | 1672 | 8.8 | 0.62 | 1.86 | 0.99981 |
| 5.0 | 280 | 0.121 | 14.04 | 558 | 840 | 1.38 | 24.6 | 0.20 | 36.6 | 900 | 5.9 | 0.082 | 0.247 | 0.999975 |
| 10.0 | 290 | 0.058 | 7.2 | 1092 | 1688 | 0.67 | 12.0 | 0.83 | 30.3 | 364 | 4.4 | 0.004 | 0.013 | 0.999998 |
| 15.0 | 295 | 0.029 | 4.8 | 2167 | 3396 | 0.33 | 6.0 | 2.5 | 26.1 | 156 | 4.2 | 0.0003 | 0.0008 | 0.9999999 |
| 34.5 | - | - | - | 4634 | 7166 | 12.7 | 230 | 0.15 | 52.5 | 10600 | 52.8 | 14.5 | 43.5 | 0.9957 |
| $U$ = 24 V | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.68 | 0.436 | 261.6 | 393 | 4.76 | 113.8 | 0.0044 | 55.3 | 6295 | 22.9 | 14.66 | 44.0 | 0.9956 |
| 1.0 | 260 | 0.50 | 0.295 | 134.4 | 521 | 3.3 | 78.2 | 0.0128 | 52.0 | 4070 | 15.8 | 3.55 | 10.65 | 0.9989 |
| 3.0 | 270 | 0.35 | 0.198 | 45.6 | 724 | 2.26 | 54.2 | 0.055 | 43.6 | 2364 | 11.4 | 0.80 | 2.4 | 0.99976 |
| 5.0 | 280 | 0.213 | 0.117 | 28.1 | 1137 | 1.36 | 32.7 | 0.153 | 40.0 | 1309 | 7.7 | 0.082 | 0.32 | 0.99997 |
| 10.0 | 290 | 0.10 | 0.0545 | 14.4 | 2333 | 0.65 | 15.8 | 0.63 | 33.8 | 534 | 5.2 | 0.004 | 0.016 | 0.999998 |
| 15.0 | 295 | 0.048 | 0.027 | 9.69 | 4604 | 0.32 | 7.7 | 1.94 | 29.5 | 228 | 4.5 | 0.0003 | 0.00093 | 0.9999999 |
| 34.5 | - | - | - | - | 9712 | 12.65 | 302.4 | 0.114 | 55.3 | 14800 | 67.5 | 19.12 | 57.4 | 0.9943 |

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

## ANALYSIS OF THE MODEL

With the increase of the supply voltage $U$ of the TEC complex at the total thermal load $Q_{0\Sigma}$ =34.5 W in a non-uniform temperature field: the value increases $k = \frac{U \cdot I_{\max}}{2Q_0}$ (Fig. 1) for different geometry of the thermocouple branch (ratio $l/s$).

As the ratio $l/s$ increases, the value $k$ decreases at a given supply voltage $U$:

– the number of thermocouples $n$ increases (Fig. 2 p. 1);

– the total operating $I$ current is reduced (Fig. 2 p. 2);

– the refrigeration coefficient E decreases (Fig. 2 p. 3);

– the amount of energy input $N$ increases (Fig. 3 p.1);

– the required heat dissipation capacity of the heat sink $\alpha$F increases (Fig. 3 p. 2);

– the time to reach steady-state operation $\tau$ increases (Fig. 3 p. 3);

– relative failure rate $\lambda/\lambda_0$ increases (Fig. 4 p. 1);

– the probability of failure-free operation $P$ decreases (Fig. 4 p. 2).

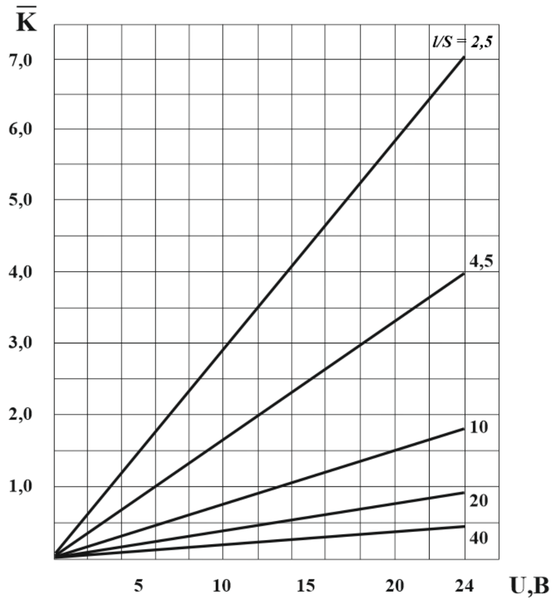
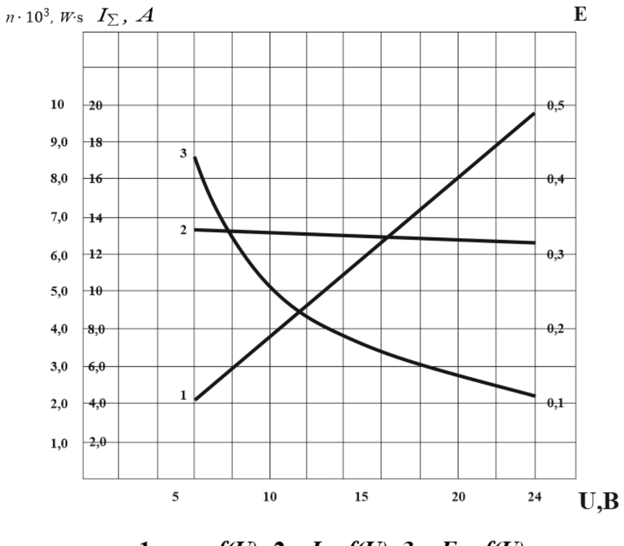



*Fig. 1.* **Dependence of the averaged value $\bar{k} = UI_{\max}/2Q_0$ of the TEC complex on the supply voltage $U$ for different geometry of thermocouple-branches $l/s$ at $T$ =300K; $Q_0$ =34.5W**

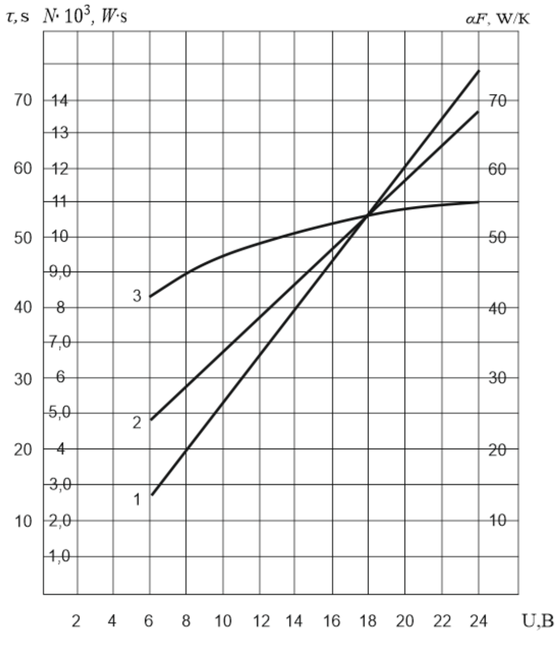
***Source:*** **compiled by the authors**




**1 – *n = f(U)*; 2 – *I = f(U)*; 3 – *E = f(U)***

*Fig. 2.* **Dependence of the number $n$ of thermocouples, the total value of the operating current $I_\Sigma$, the refrigeration coefficient $E$ of the complex with parallel electrical connection in a non-uniform temperature field on the supply voltage $U$ for different geometry of thermocouple branches $l/s$ at $T$ =300K; $T$ =4.5**

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

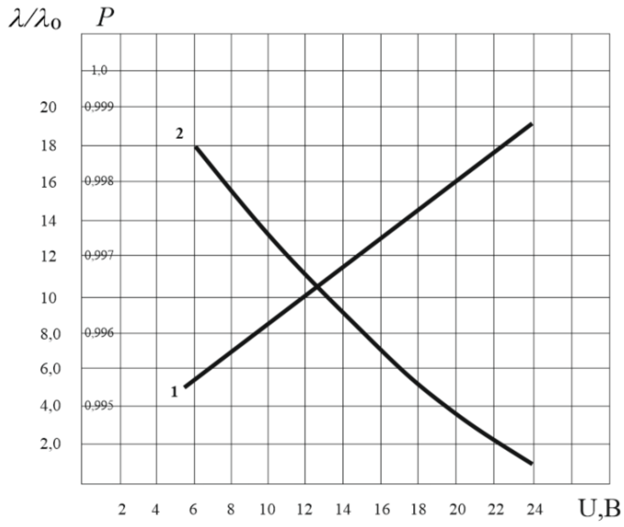



**1 – N = *f(U)*; 2 – *αF = f(U)*; 3 – *τ = f(U)***

*Fig. 3.* **Dependence of the time of steady-state operation $\tau$, the amount of expended energy $N$, the heat dissipation capacity of the heat sink $\alpha F$ of the complex with parallel electrical connection on the supply voltage $U$ at $T$ =300K; $l/s$ =4.5**

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

Analysis of the results of studies of the main parameters of the complex of fuel and energy units when using standard voltages $U$ showed the need to use current operating modes close to the mode $Q_0$ =0 ($B < \Theta$). This leads to an increase in the number of thermocouples $n$, dimensions and mass of the used complex of fuel and energy units is given when using the geometry of the vertexes of thermocouples 4.5.




*1 - $\lambda/\lambda_0 = f(U)$ 2 – $P = f(U)$*

*Fig. 4.* **Dependence of relative intensity of failures $\lambda/\lambda_0$, probability of failure-free operation $P$ of the complex of fuel and energy units with parallel electrical connection on the supply voltage $U$ at $T$ =300K; $l/s$ =4.5**

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

Therefore, in the following we will consider the possibility of application of characteristic current modes of operation of the TEC complex for different branch geometry $l/s$ =4.5, 10, 20 for the values of supply voltage obtained by calculation.

The result of calculations of the main parameters, dynamic characteristics and reliability indices of the complex of TEC, consists of 6 elements of radio-electronic equipment. Modeling conditions: power dissipation from $Q_0$ =0.5W to 15W, temperature cooling level from $T_0$ =250K to $T_0$ =295K using different characteristic current modes of operation and different geometry of thermoelements branches ($l/s$ =4.5, 10, 20). The data are summarized in Tables 3.

*Table 3.* **Results of calculations of indicators, characteristics of the TEC complex at $T$ =300K; $T-T_c$ =10K**

| $Q_0$ | $T_0$ | $B$ | $n$ | $I$ | $W$ | $U$ | $E$ | $\alpha F$ | $\Theta$ | $R\cdot 10^3$ | $I$ | $\tau$ | $N$ | $\lambda/\lambda_0$ | $\lambda_0$ $10^{-8}$ | $P$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mode $Q_{max}$ $(B=1)$ $l/s$ =4.5 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 1.0 | 3.0 | 10.9 | 3.8 | 0.35 | 0.13 | 0.43 | 0.68 | 4.41 | 10.9 | 11.3 | 43.0 | 3.1 | 9.3 | 0.99907 |
| 1.0 | 260 | 1.0 | 3.5 | 11.2 | 4.6 | 0.41 | 0.22 | 0.56 | 0.50 | 4.5 | 11.2 | 7.1 | 32.7 | 3.6 | 10.7 | 0.99893 |
| 3.0 | 270 | 1.0 | 7.5 | 11.4 | 10.2 | 0.89 | 0.30 | 1.3 | 0.35 | 4.69 | 11.4 | 4.4 | 44.8 | 8.0 | 24.0 | 0.9976 |
| 5.0 | 280 | 1.0 | 9.7 | 11.7 | 13.6 | 1.17 | 0.37 | 1.9 | 0.21 | 4.79 | 11.7 | 2.3 | 31.0 | 9.8 | 29.4 | 0.9971 |
| 10.0 | 290 | 1.0 | 15.8 | 12.0 | 23.0 | 1.9 | 0.43 | 3.3 | 0.10 | 4.89 | 12.0 | 0.7 | 16.2 | 15.9 | 47.7 | 0.9952 |
| 15.0 | 295 | 1.0 | 21.7 | 12.1 | 31.9 | 2.6 | 0.47 | 4.7 | 0.048 | 4.95 | 12.1 | 0.05 | 1.6 | 21.7 | 65.1 | 0.9935 |
| 34.5 | - | 1.0 | 61.2 | 69.3 | 87.0 | 7.4 | 0.40 | 12.2 | - | - | - | 11.3 | 169.3 | 62.1 | 186.3 | 0.9815 |
| Mode $(nI)_{min}$ $l/s$ =4.5 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.83 | 3.3 | 9.0 | 2.96 | 0.33 | 0.17 | 0.35 | 0.68 | 4.41 | 10.9 | 12.5 | 36.9 | 1.65 | 5.0 | 0.99950 |
| 1.0 | 260 | 0.71 | 4.3 | 7.9 | 3.0 | 0.37 | 0.34 | 0.40 | 0.50 | 4.5 | 11.2 | 8.7 | 26.0 | 1.14 | 3.4 | 0.99966 |
| 3.0 | 270 | 0.59 | 10.2 | 6.7 | 5.1 | 0.76 | 0.59 | 0.80 | 0.35 | 4.69 | 11.4 | 6.2 | 31.7 | 1.2 | 3.6 | 0.99964 |
| 5.0 | 280 | 0.46 | 15.3 | 5.4 | 4.9 | 0.92 | 1.0 | 1.0 | 0.21 | 4.79 | 11.7 | 4.2 | 20.6 | 0.57 | 1.71 | 0.99983 |
| 10.0 | 290 | 0.32 | 32.9 | 3.8 | 5.2 | 1.36 | 1.9 | 1.5 | 0.10 | 4.89 | 12.0 | 2.3 | 12.0 | 0.21 | 0.64 | 0.999936 |
| 15.0 | 295 | 0.22 | 60.5 | 2.65 | 4.5 | 1.71 | 1.9 | 1.95 | 0.048 | 4.95 | 12.1 | 1.4 | 6.1 | 0.062 | 0.19 | 0.999998 |
| 34.5 | - | 0.52 | 126 | 35.4 | 25.4 | 5.1 | 1.4 | 6.1 | - | - | - | 12.5 | 133.3 | 4.83 | 14.5 | 0.99855 |
| Mode $(nI \lambda/\lambda_0 \tau)_{min}$ $l/s$ =4.5 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.68 | 4.4 | 7.5 | 2.8 | 0.37 | 0.18 | 0.33 | 0.68 | 4.41 | 10.9 | 15.1 | 42.3 | 1.0 | 3.0 | 0.99970 |
| 1.0 | 260 | 0.50 | 7.1 | 5.6 | 2.6 | 0.47 | 0.38 | 0.36 | 0.50 | 4.5 | 11.2 | 12.5 | 32.5 | 0.44 | 1.31 | 0.99987 |
| 3.0 | 270 | 0.35 | 21.8 | 3.9 | 4.2 | 1.07 | 0.70 | 0.72 | 0.35 | 4.69 | 11.4 | 10.9 | 45.8 | 0.27 | 0.81 | 0.999919 |
| 5.0 | 280 | 0.21 | 45.5 | 2.5 | 3.6 | 1.45 | 1.4 | 0.86 | 0.21 | 4.79 | 11.7 | 10.4 | 37.4 | 0.056 | 0.17 | 0.999983 |
| 10.0 | 290 | 0.10 | 158 | 1.2 | 3.0 | 2.5 | 3.3 | 1.3 | 0.10 | 4.89 | 12.0 | 9.2 | 27.7 | 0.004 | 0.0117 | 0.9999988 |
| 15.0 | 295 | 0.048 | 453 | 0.58 | 2.0 | 3.5 | 7.5 | 1.7 | 0.048 | 4.95 | 12.1 | 9.0 | 18.0 | 0.0004 | 0.0012 | 0.99999988 |
| 34.5 | - | 0.315 | 690 | 21.3 | 18.2 | 9.4 | 1.9 | 5.3 | - | - | - | 15.1 | 204 | 1.77 | 5.31 | 0.99947 |
| Mode $\lambda_{min}$, $l/s$ =4.5 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.58 | 6.8 | 6.3 | 3.22 | 0.51 | 0.155 | 0.37 | 0.68 | 4.41 | 10.9 | 18.7 | 60.3 | 0.81 | 2.43 | 0.99976 |
| 1.0 | 260 | 0.40 | 12.7 | 4.5 | 3.2 | 0.71 | 0.31 | 0.42 | 0.50 | 4.5 | 11.2 | 17.4 | 55.8 | 0.31 | 0.93 | 0.999910 |
| 3.0 | 270 | 0.27 | 42.7 | 3.0 | 5.2 | 1.72 | 0.58 | 0.82 | 0.35 | 4.69 | 11.4 | 16.4 | 84.1 | 0.174 | 0.52 | 0.999948 |
| 5.0 | 280 | 0.16 | 97.8 | 1.8 | 4.6 | 2.5 | 1.1 | 0.96 | 0.21 | 4.79 | 11.7 | 14.9 | 68.6 | 0.034 | 0.10 | 0.999990 |
| 10.0 | 290 | 0.07 | 260 | 0.88 | 2.9 | 3.3 | 3.5 | 1.3 | 0.10 | 4.89 | 12.0 | 15.7 | 45.9 | 0.002 | 0.006 | 0.9999994 |
| 15.0 | 295 | 0.035 | 1035 | 0.42 | 2.7 | 6.4 | 5.6 | 1.8 | 0.048 | 4.95 | 12.1 | 15.0 | 40.5 | 0.00023 | 0.0006 | 0.99999993 |
| 34.5 | - | 0.25 | 1455 | 17.0 | 21.7 | 15.1 | 1.6 | 5.6 | - | - | - | 18.7 | 355 | 1.33 | 4.0 | 0.99960 |
| Mode $Q_{0\,max}$, $l/s$ =10 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 1.0 | 6.7 | 4.9 | 3.8 | 0.78 | 0.13 | 0.43 | 0.68 | 9.8 | 4.9 | 10.8 | 38.9 | 6.9 | 20.7 | 0.9979 |
| 1.0 | 260 | 1.0 | 8.0 | 5.0 | 4.6 | 0.92 | 0.22 | 0.56 | 0.50 | 10.0 | 5.0 | 6.6 | 30.2 | 8.2 | 24.5 | 0.9976 |
| 3.0 | 270 | 1.0 | 16.7 | 5.13 | 10.2 | 2.0 | 0.29 | 1.3 | 0.35 | 10.42 | 5.13 | 4.3 | 43.6 | 17.0 | 51.0 | 0.9949 |
| 5.0 | 280 | 1.0 | 21.6 | 5.26 | 13.6 | 2.6 | 0.37 | 1.86 | 0.21 | 10.64 | 5.26 | 2.5 | 33.0 | 21.8 | 65.5 | 0.9935 |
| 10.0 | 290 | 1.0 | 35.2 | 5.40 | 23.0 | 4.3 | 0.44 | 3.3 | 0.10 | 10.84 | 5.40 | 1.1 | 25.8 | 35.4 | 106.3 | 0.9894 |
| 15.0 | 295 | 1.0 | 48.4 | 5.44 | 32.0 | 5.9 | 0.47 | 4.7 | 0.048 | 11.0 | 5.44 | 0.6 | 17.6 | 48.4 | 145.2 | 0.9856 |
| 34.5 | - | 1.0 | 137 | 31.1 | 87.2 | 16.4 | 0.40 | 12.2 | - | - | - | 10.2 | 189.1 | 138 | 413 | 0.9595 |
| Mode $(nI)_{min}$, $l/s$ =10 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.83 | 3.3 | 9.0 | 2.96 | 0.33 | 0.17 | 0.35 | 0.68 | 4.41 | 10.9 | 12.5 | 36.9 | 1.65 | 5.0 | 0.99950 |
| 1.0 | 260 | 0.71 | 4.3 | 7.9 | 3.0 | 0.37 | 0.34 | 0.40 | 0.50 | 4.5 | 11.2 | 8.7 | 26.0 | 1.14 | 3.4 | 0.99966 |
| 3.0 | 270 | 0.59 | 10.2 | 6.7 | 5.1 | 0.76 | 0.59 | 0.80 | 0.35 | 4.69 | 11.4 | 6.2 | 31.7 | 1.2 | 3.6 | 0.99964 |
| 5.0 | 280 | 0.46 | 15.3 | 5.4 | 4.9 | 0.92 | 1.0 | 1.0 | 0.21 | 4.79 | 11.7 | 4.2 | 20.6 | 0.57 | 1.71 | 0.99983 |
| 10.0 | 290 | 0.32 | 32.9 | 3.8 | 5.2 | 1.36 | 1.9 | 1.5 | 0.10 | 4.89 | 12.0 | 2.3 | 12.0 | 0.21 | 0.64 | 0.999936 |
| 15.0 | 295 | 0.22 | 60.5 | 2.65 | 4.5 | 1.71 | 1.9 | 1.95 | 0.048 | 4.95 | 12.1 | 1.4 | 6.1 | 0.062 | 0.19 | 0.999998 |
| 34.5 | - | 0.52 | 126 | 35.4 | 25.4 | 5.1 | 1.4 | 6.1 | - | - | - | 12.5 | 133.3 | 4.83 | 14.5 | 0.99855 |
| Mode $(nI \lambda/\lambda_0 \tau)_{min}$, $l/s$ =10 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.68 | 9.8 | 3.85 | 2.78 | 0.83 | 0.18 | 0.33 | 0.68 | 9.8 | 4.9 | 13.4 | 37.3 | 2.23 | 6.7 | 0.99933 |
| 1.0 | 260 | 0.50 | 16.0 | 2.5 | 2.6 | 1.05 | 0.38 | 0.36 | 0.50 | 10.0 | 5.0 | 11.0 | 28.8 | 0.986 | 2.96 | 0.99970 |
| 3.0 | 270 | 0.35 | 48.4 | 1.77 | 4.2 | 2.4 | 0.72 | 0.71 | 0.35 | 10.42 | 5.13 | 9.7 | 40.7 | 0.58 | 1.74 | 0.99983 |
| 5.0 | 280 | 0.21 | 84.2 | 1.12 | 3.0 | 2.7 | 1.67 | 0.80 | 0.21 | 10.64 | 5.26 | 9.0 | 27.0 | 0.105 | 0.316 | 0.999968 |
| 10.0 | 290 | 0.10 | 352 | 0.54 | 3.0 | 5.6 | 3.3 | 1.3 | 0.10 | 10.87 | 5.4 | 8.3 | 25.0 | 0.011 | 0.034 | 0.9999966 |
| 15.0 | 295 | 0.048 | 1008 | 0.26 | 2.6 | 10.0 | 5.8 | 1.76 | 0.048 | 11.0 | 5.44 | 8.0 | 21.0 | 0.0009 | 0.0027 | 0.9999997 |
| 34.5 | - | 0.315 | 1518 | 9.5 | 18.2 | 22.5 | 1.9 | 5.3 | - | - | - | 13.4 | 180 | 3.91 | 11.7 | 0.9988 |

*Table 3.* **Continued**

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mode $\lambda_{\min}$, $l/s$ =10 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.58 | 15.2 | 2.8 | 3.2 | 1.14 | 0.16 | 0.37 | 0.68 | 9.8 | 4.9 | 16.5 | 52.7 | 1.8 | 5.4 | 0.99946 |
| 1.0 | 260 | 0.40 | 28.6 | 2.0 | 3.18 | 1.6 | 0.32 | 0.42 | 0.50 | 10.0 | 5.0 | 15.3 | 48.6 | 0.69 | 2.07 | 0.99979 |
| 3.0 | 270 | 0.27 | 95.1 | 1.36 | 5.2 | 3.8 | 0.58 | 0.82 | 0.35 | 10.42 | 5.13 | 14.3 | 74.5 | 0.39 | 1.16 | 0.99988 |
| 5.0 | 280 | 0.16 | 218 | 0.83 | 4.65 | 5.6 | 1.08 | 0.97 | 0.21 | 10.64 | 5.26 | 13.4 | 62.1 | 0.075 | 0.23 | 0.999977 |
| 10.0 | 290 | 0.073 | 779 | 0.39 | 3.85 | 9.8 | 2.6 | 1.4 | 0.10 | 10.87 | 5.39 | 13.5 | 52.1 | 0.0064 | 0.019 | 0.9999981 |
| 15.0 | 295 | 0.035 | 2194 | 0.19 | 2.6 | 13.6 | 5.8 | 1.8 | 0.048 | 11.0 | 5.44 | 13.3 | 24.6 | 0.00048 | 0.00145 | 0.9999998 |
| 34.5 | - | 0.253 | 3330 | 7.6 | 22.7 | 35.6 | 1.5 | 5.7 | - | - | - | 16.5 | 32.5 | 2.96 | 8.89 | 0.99911 |
| Mode $Q_{0\max}$, $l/s$ =20 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 1.0 | 13.4 | 2.45 | 3.8 | 1.54 | 0.13 | 0.43 | 0.68 | 19.6 | 2.45 | 9.9 | 37.7 | 13.8 | 41.3 | 0.9959 |
| 1.0 | 260 | 1.0 | 15.7 | 2.52 | 4.6 | 1.8 | 0.22 | 0.56 | 0.50 | 20.0 | 2.52 | 6.4 | 29.3 | 16.0 | 48.0 | 0.9952 |
| 3.0 | 270 | 1.0 | 33.3 | 2.57 | 10.2 | 4.0 | 0.29 | 1.3 | 0.35 | 20.83 | 2.57 | 4.1 | 41.9 | 33.8 | 101.5 | 0.9900 |
| 5.0 | 280 | 1.0 | 43.1 | 2.63 | 13.6 | 5.2 | 0.37 | 1.9 | 0.21 | 21.3 | 2.63 | 2.4 | 32.4 | 43.6 | 131 | 0.9870 |
| 10.0 | 290 | 1.0 | 70.2 | 2.7 | 23.0 | 8.5 | 0.44 | 3.3 | 0.10 | 21.7 | 2.70 | 1.06 | 24.4 | 70.7 | 212 | 0.9790 |
| 15.0 | 295 | 1.0 | 96.8 | 2.72 | 32.0 | 11.8 | 0.47 | 4.7 | 0.048 | 22.0 | 2.72 | 0.52 | 16.6 | 96.8 | 290 | 0.9714 |
| 34.5 | - | 1.0 | 273 | 15.6 | 87.2 | 32.8 | 0.40 | 122 | - | - | - | 9.9 | 145 | 274.7 | 324 | 0.9210 |
| Mode $(nI)_{\min}$, $l/s$ =20 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.83 | 14.9 | 2.0 | 3.0 | 1.47 | 0.17 | 0.35 | 0.68 | 19.6 | 2.45 | 10.8 | 32.4 | 7.47 | 22.4 | 0.9978 |
| 1.0 | 260 | 0.71 | 19.0 | 1.78 | 2.9 | 1.65 | 0.34 | 0.39 | 0.50 | 20.0 | 2.52 | 7.6 | 22.0 | 5.0 | 15.0 | 0.9985 |
| 3.0 | 270 | 0.59 | 45.0 | 1.51 | 5.1 | 3.4 | 0.59 | 0.81 | 0.35 | 20.83 | 2.57 | 5.5 | 28.0 | 5.29 | 15.9 | 0.9984 |
| 5.0 | 280 | 0.46 | 68.1 | 1.21 | 4.9 | 4.1 | 1.0 | 1.0 | 0.21 | 21.3 | 2.63 | 3.7 | 18.3 | 2.52 | 7.6 | 0.99924 |
| 10.0 | 290 | 0.32 | 146 | 0.85 | 5.1 | 6.0 | 2.0 | 1.5 | 0.10 | 21.7 | 2.70 | 2.1 | 10.8 | 0.94 | 2.83 | 0.99972 |
| 15.0 | 295 | 0.22 | 270 | 0.60 | 4.6 | 7.6 | 3.3 | 2.0 | 0.048 | 22.0 | 2.72 | 1.5 | 6.7 | 0.276 | 0.83 | 0.999917 |
| 34.5 | - | 0.52 | 563 | 8.0 | 25.6 | 24.2 | 1.35 | 6.0 | - | - | - | 10.8 | 118 | 21.5 | 64.5 | 0.9936 |
| Mode $(nI\,\lambda/\lambda_0)_{\min}$, $l/s$ =20 | | | | | | | | | | | | | | | | |
| 0.5 | 250 | 0.68 | 19.7 | 1.70 | 2.8 | 1.67 | 0.18 | 0.33 | 0.68 | 19.6 | 2.45 | 13.1 | 36.6 | 4.48 | 13.4 | 0.9987 |
| 1.0 | 260 | 0.50 | 31.5 | 1.26 | 2.6 | 2.1 | 0.38 | 0.36 | 0.50 | 20.0 | 2.52 | 10.8 | 28.0 | 1.94 | 5.8 | 0.9994 |
| 3.0 | 270 | 0.35 | 96.5 | 0.89 | 4.2 | 4.7 | 0.71 | 0.72 | 0.35 | 20.83 | 2.57 | 9.4 | 39.5 | 1.10 | 3.57 | 0.99964 |
| 5.0 | 280 | 0.21 | 203 | 0.56 | 3.6 | 6.5 | 1.4 | 0.86 | 0.21 | 21.3 | 2.63 | 8.8 | 31.6 | 0.23 | 0.70 | 0.999930 |
| 10.0 | 290 | 0.10 | 702 | 0.27 | 3.0 | 11.1 | 3.3 | 1.3 | 0.10 | 21.7 | 2.70 | 8.0 | 24.1 | 0.023 | 0.068 | 0.999993 |
| 15.0 | 295 | 0.048 | 2017 | 0.13 | 2.0 | 15.6 | 7.5 | 1.7 | 0.48 | 22.0 | 2.72 | 7.8 | 15.5 | 0.0018 | 0.00053 | 0.99999947 |
| 34.5 | - | 0.315 | 3070 | 4.8 | 18.2 | 41.7 | 1.9 | 5.3 | - | - | - | 13.1 | 175 | 7.86 | 23.6 | 0.9976 |

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

With the increase of the average relative operating current of TEC for different geometry of thermocouple branches (ratio $l/s$) and characteristic current operating modes:

– the value of operating current $I$ increases (Fig. 5). As the ratio $l/s$ increases, the operating current $I$ decreases with a fixed relative operating current $B$ (for different operating modes);

– the number of thermocouples $n$ decreases (Fig. 6). As the ratio $l/s$ increases, the number of thermocouples $n$ increases at a fixed relative operating current $B$;

– functional dependence of voltage drop $U = f(B)$ on relative operating current $B$ has a minimum at $B$=0.52 (mode $(nI)_{\min}$) for different geometry of thermocouple branches $l/s$ (Fig. 7). As the ratio $l/s$ increases, the voltage drop $U$ increases at a fixed relative operating current $B$;

– the functional dependence of the cooling coefficient $E = f(B)$ on the relative operating current $B$ has a maximum at $B$=0.32 for the current mode $(nI\,\lambda/\lambda_0\,\tau)_{\min}$) and does not depend on the geometry of the thermocouple branches (ratios $l/s$) (Fig. 8);

– functional dependence of the heat sink heat dissipation capacity $\alpha F = f(B)$ on the relative operating current $B$ has a maximum at $B$=0.32 in the mode $(nI\,\lambda/\lambda_0\,\tau)_{\min}$ and does not depend on the geometry of the thermocouple branches (Fig. 9);

– decreases the time to steady-state operation $\tau$ (Fig. 10). As the ratio $l/s$ increases, the time to steady-state operation $\tau$ decreases at a fixed relative operating current $B$. The minimum time to steady-state operation $\tau_{\min}$ is provided in the mode $Q_{0\max}$;

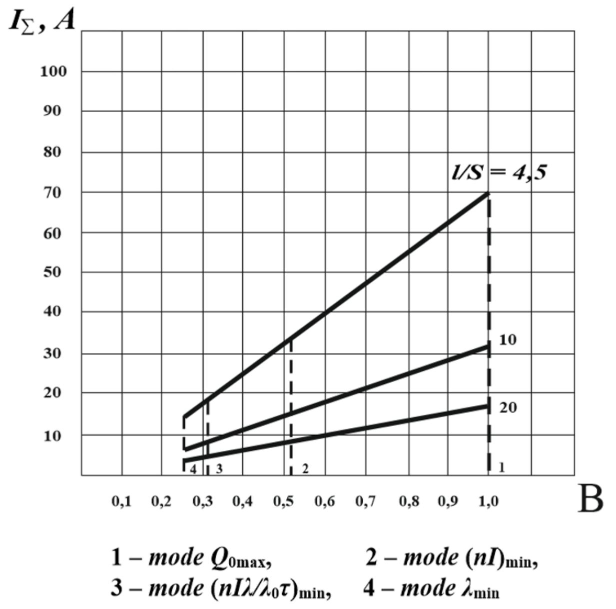



*Fig. 5.* **Dependence of the total operating current $I_\Sigma$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermoelements branches $l/s$ and current operating modes at $T$ =300K; $Q_0$ =34.5W**

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

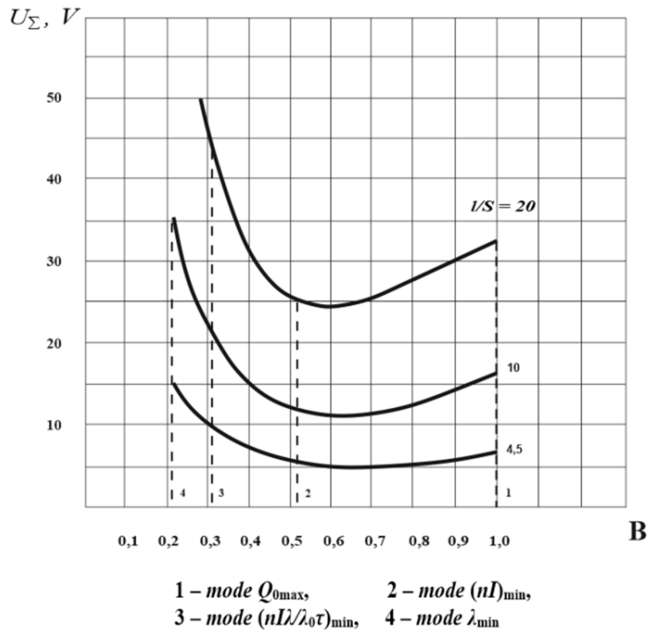



*Fig. 7.* **Dependence of the total voltage drop $U_\Sigma$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermocouple branches $l/s$ and current modes of operation at $T$ =300K; $Q_0$ =34.5W**

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

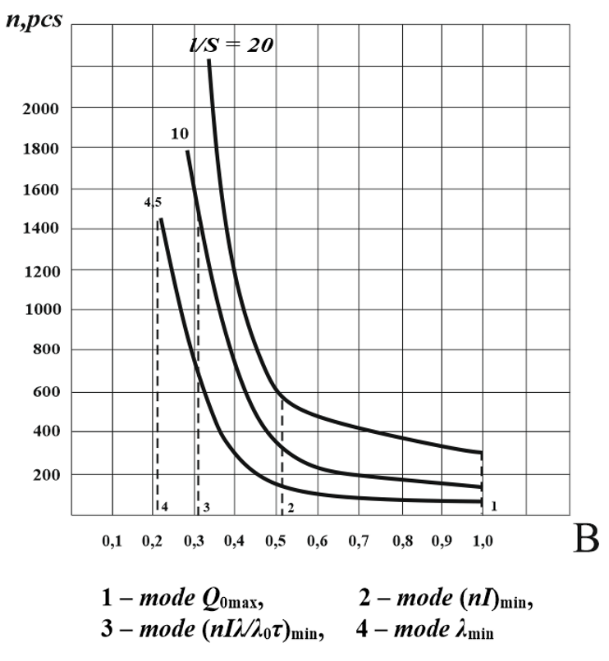



*Fig. 6.* **Dependence of the number of thermocouples $n$ in a complex of thermoelements on the averaged relative operating current $B$ for different geometry of branches $l/s$ of thermocouples and current modes of operation at $T$ =300K; $Q_0$ =34.5W**

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

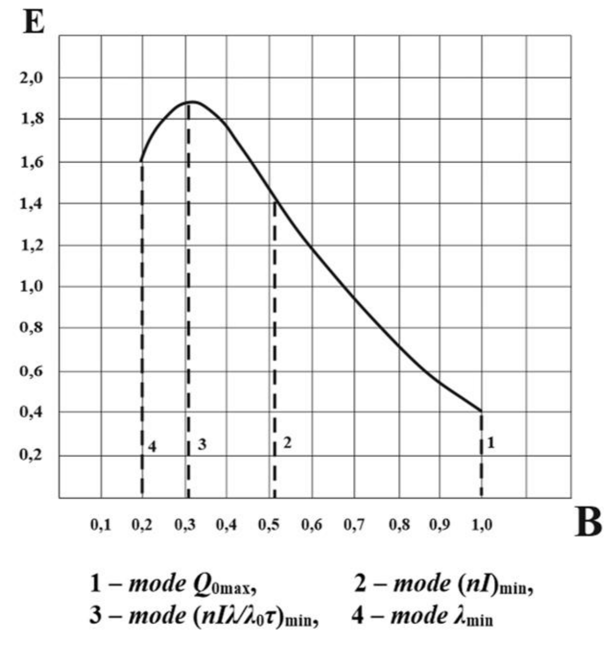
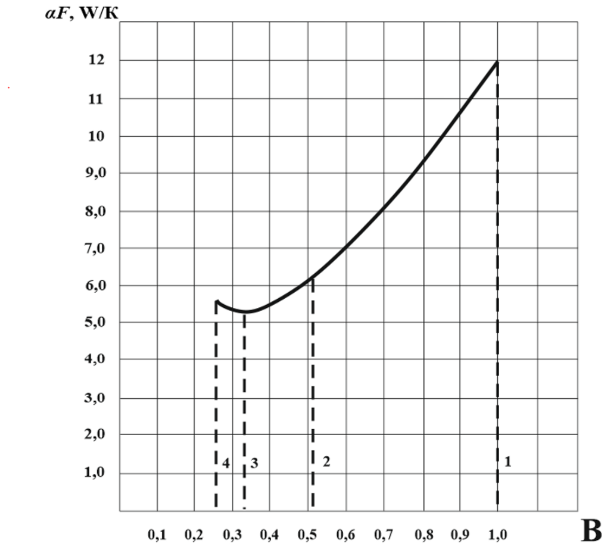



*Fig. 8.* **Dependence of the refrigeration coefficient $E$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermocouple branches $l/s$ and current operating modes at $T$ =300K; $Q_0$ =34.5W**

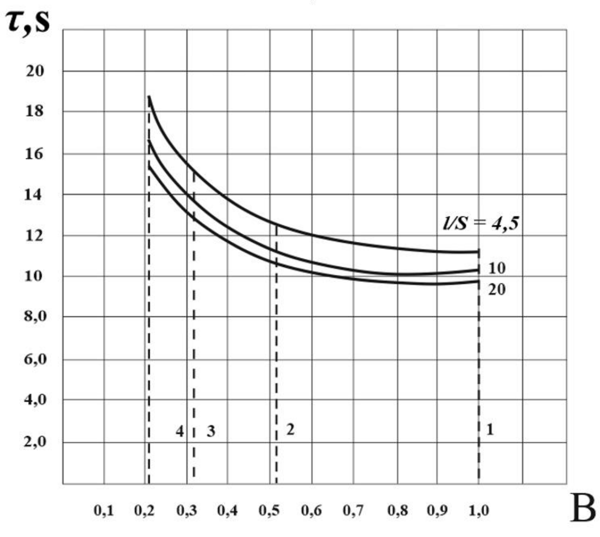
***Source:* compiled by the authors**




1 – *mode* $Q_{0max}$, 2 – *mode* $(nI)_{min}$,
3 – *mode* $(nI\lambda/\lambda_0\tau)_{min}$, 4 – *mode* $\lambda_{min}$

*Fig. 9.* **Dependence of heat dissipation capacity $\alpha F$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermocouple branches $l/s$ and current operating modes at $T$ =300K; $Q_0$ =34.5W; $T - T_c$ =10K**

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

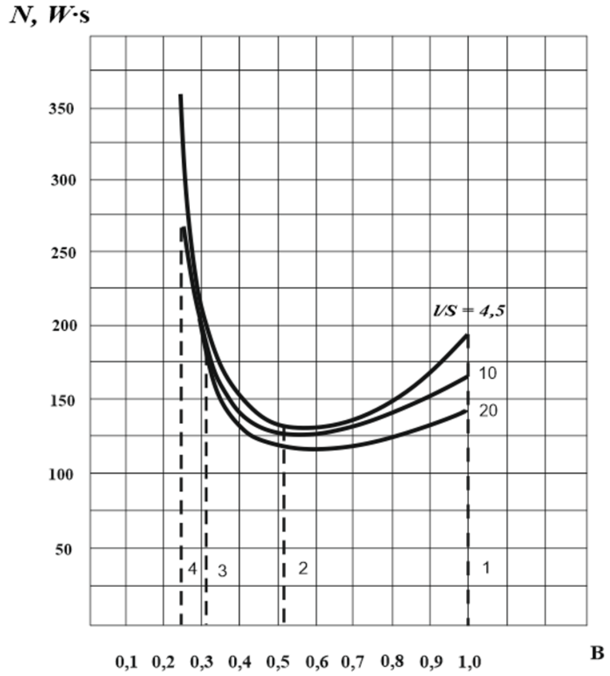



1 – *mode* $Q_{0max}$, 2 – *mode* $(nI)_{min}$,
3 – *mode* $(nI\lambda/\lambda_0\tau)_{min}$, 4 – *mode* $\lambda_{min}$

*Fig. 10.* **Dependence of the time to reach the stationary mode $\tau$ of operation of the TEC complex on the averaged relative operating current $B$ for different geometry of branches of thermoelements $l/s$ and current modes of operation at $T$ =300K, $Q_0$ =34.5W**

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

– functional dependence of the amount of expended energy $N = f(B)$ on the relative operating current $B$ has a minimum at $B$ =0.52 in the mode $(nI)_{\min}$ (Fig. 11). As the ratio $l/s$ increases, the amount of expended energy $N$ decreases at a fixed relative operating current $B$;




1 – *mode* $Q_{0max}$, 2 – *mode* $(nI)_{min}$,
3 – *mode* $(nI\lambda/\lambda_0\tau)_{min}$, 4 – *mode* $\lambda_{min}$

*Fig. 11.* **Dependence of the amount of expended energy $N$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermocouple branches $l/s$ and current operating modes at $T$ =300K; $Q_0$ =34.5W**

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

– the relative failure rate $\lambda/\lambda_0$ increases (Fig. 12). As the ratio $l/s$ increases, it increases at a fixed relative operating current $B$;

– the probability of failure-free operation $P$ decreases (Fig. 13). As the ratio $l/s$ increases, the probability of failure $P$ decreases for a fixed relative operating current $B$.

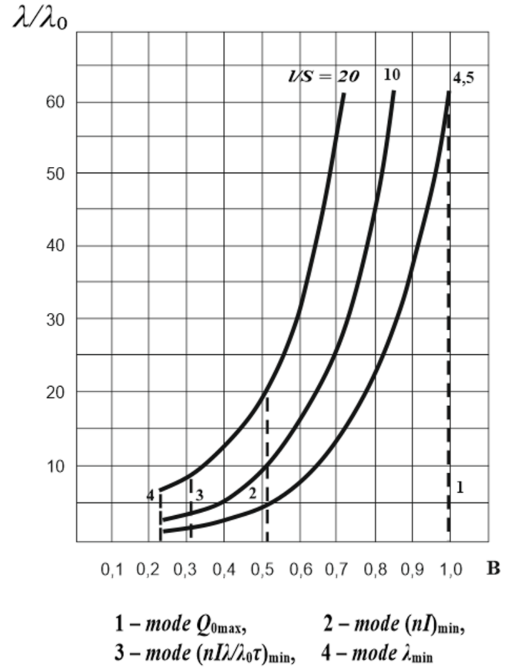



*Fig. 12.* **Dependence of relative intensity $\lambda/\lambda_0$ of failures on the averaged relative operating current $B$ for different geometry of branches of thermoelements $l/s$ and current operating modes at $T$ =300K, $Q_0$ =34.5W; $\lambda_0$ =3 10^-8^**

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

## DISCUSSION OF THE RESEARCH RESULTS

When selecting the nominal supply voltage for the complex with parallel electrical connection of TECs, it is necessary to take into account the limiting requirements: on the value of operating current $I$, the number of thermocouples $n$, the cooling coefficient $E$, the power consumption $W$, and, consequently, the size and weight of the heat sink $\alpha F$, the intensity of failures $\lambda/\lambda_0$ and dynamics of operation $\tau$.

It is necessary to evaluate the weight of each of the limiting factors and choose an acceptable variant of the complex design.

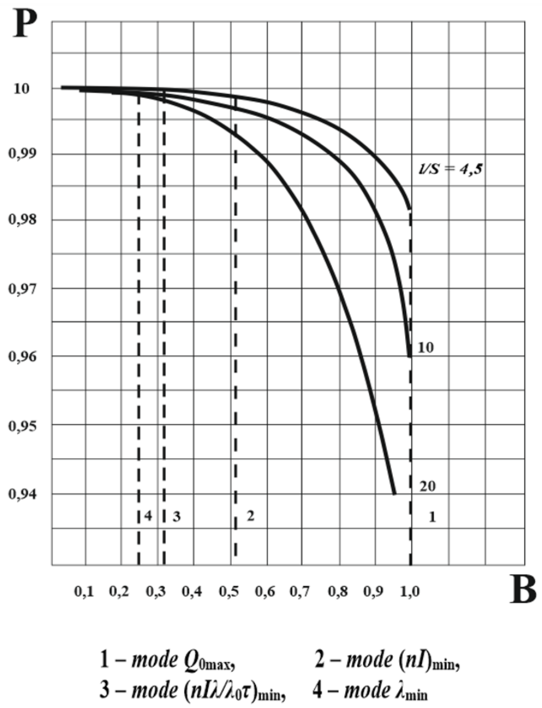



*Fig. 13.* **Dependence of the probability of failure free operation $P$ of the TEC complex on the averaged relative operating current $B$ for different geometry of thermocouple branches and current operating modes at $T$ =300K; $Q_0$ =34.5W; $\lambda_0$ =3 $10^{-8}$; $t$ =$10^4$ h**

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

The offered variant allows carrying out rational designing of the complex of fuel and power unit with a choice of the most acceptable variant.

For clarity and the possibility of comparative analysis, all design data are given in Table 4.

## CONCLUSIONS

The model of SETM based on the complex of TECs with parallel electrical connection for controlling the thermal mode of a number of thermally dependent elements of TEC with different power dissipation in a non-uniform temperature field for different supply voltages and geometry of branches of thermoelements has been developed.

*Table 4.* **Main significant parameters and indicators at $Q_0^{\Sigma}$ = 34.5 W; $T - T_c$ =10 K**

| Mode | $l/s$ | $U$ | $n$ | $I$ | $W$ | $E$ | $\alpha$ F | $\tau$ | $N$ | $\lambda/\lambda_0$ | $\lambda \cdot 10^8$ | $P$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Q_{0\,max}$ | 10 | 16.0 | 137 | 31.0 | 87/0 | 0,40 | 12.2 | 10 | 190 | 138 | 413 | 0.9595 |
| $(nI)_{min}$ | 4.5 | 5.1 | 126 | 35.0 | 25.4 | 1.40 | 6.1 | 12 | 133 | 4.8 | 14.5 | 0.9986 |
| | 10 | 12.0 | 283 | 16.0 | 26.0 | 1.30 | 6.0 | 11 | 126 | 11.1 | 33.3 | 0.9967 |
| | 20 | 24.0 | 563 | 8.0 | 26.0 | 1.35 | 6.0 | 11 | 120 | 21.5 | 64.5 | 0.9936 |
| $(nI \lambda/\lambda_0 \tau)_{min}$ | 4.5 | 9.4 | 690 | 21.0 | 18.2 | 1.9 | 5.3 | 15 | 200 | 1.8 | 5.3 | 0.99947 |

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

A comparative analysis of the main parameters, reliability indices and dynamic characteristics of the thermoelements complex for different supply voltages has been carried out.

The analysis of the research results has shown the possibility of selecting the nominal supply voltages taking into account the limitations on mass-size, energy, dynamic and reliability characteristics for different geometry of thermocouple branches.

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# Управління тепловим режимом комплексу термоелектричних охолоджуючих пристроїв

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## АНОТАЦІЯ

У роботі представлено результати досліджень можливості керування комплексом термоелектричних охолоджувальних пристроїв з їхнім паралельним електричним з'єднанням у нерівномірному температурному полі. Така постановка задачі створення систем забезпечення теплових режимів радіоелектронної апаратури актуальна для бортових інформаційних систем, до яких висуваються жорсткі вимоги щодо надійності та масогабаритних характеристик. Дослідження виконано для найуживанішого температурного діапазону від 295К до 250К у діапазоні потужностей розсіювання від 0.5 Вт до 15 Вт для різних значень живильної напруги. Розроблено модель виконавчого органу системи забезпечення теплових режимів на основі комплексу термоелектричних охолоджувачів з паралельним електричним з'єднанням для керування тепловим режимом низки термозалежних елементів радіоелектронної апаратури з різною потужністю розсіювання в нерівномірному температурному полі для різних живильних напруг і геометрії гілок термоелементів. Проведено порівняльний аналіз основних параметрів, показників надійності та динамічності функціонування комплексу термоелектричних охолоджувачів для різних напруг живлення, різних температурних рівнів охолодження з відповідним тепловим навантаженням. Показано можливість вибору оптимальної напруги живлення з урахуванням обмежень за величиною робочого струму, масовими, енергетичними, динамічними та характеристиками надійності комплексу термоелектричних охолоджувачів. Аналіз результатів досліджень показав можливість вибору номіналу живильних напруг з урахуванням обмежень за масогабаритними, енергетичними, динамічними та характеристиками надійності для різної геометрії гілок термоелементів.

***Ключові слова***: показники надійності; динамічні характеристики; маса та габарити; перепад температур струмовий режим

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