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DETERMINATION OF THE MAXIMUM COOLING CAPACITIES OF TWO-STAGE COOLERS WITH A VARIATION IN THE GEOMETRY OF BRANCHES IN STAGES

Розглянуто вплив геометрії гілок термоелементів в каскадах на параметри і показники надійності двокаскадних термоелектричних охолоджувачів різних конструкцій при послідовному електричному з'єднані каскадів в режимі максимального перепаду температури. Одержані співвідношення для визначення оптимальної геометрії гілок термоелементів в каскадах, що відповідає найбільшому значенню перепаду температури для різних конструкцій охолоджувачів при заданому робочому струмі.

Ключові слова: *термоелектричний охолоджуючий пристрій, геометрія гілок термоелементів, максимальний перепад температури, конструкції охолоджувачів.*

1. Introduction

Thermoelectric cooling devices are among the most promising devices for providing thermal regimes for radio electronic equipment. This is due to the lack of moving components, small dimensions, high speed, mechanical and impact strength. The disadvantage of thermoelectric coolers (TEC) is lower cooling capacity compared to compression cooling devices, which makes research relevant to increase their cooling capacity relevant. It is obvious that the main method of increasing the TEC cooling capacity is selection of the material of the thermoelements of the branches with the maximum value of thermoelectric efficiency. However, the choice of semiconductor materials for thermoelements for industrial applications is rather limited, therefore, with the existing technology and specified materials, constructive methods are needed to increase the cooling capacity of thermoelectric coolers.

2. The object of research and its technological audit

The object of research is an analytical model of the relationship between the reliability of a two-stage thermoelectric cooler and the geometry of the branches of thermoelements and its cooling capabilities.

The thermoelectric cooler is parallel arranged ceramic cold and hot electrodes, between which are installed thermoelements, electrically connected in series. The existing model of a thermoelectric cooling device is based on the law of energy conservation, in particular, on the balance of heat fluxes due to the thermal conductivity between the load, cold electrode, thermoelements, hot electrode, radiator and external environment.

Thermoelectric cooling devices belong to solid-state coolers, the reliability and mass-size characteristics of which significantly exceed the compressors of this purpose up to a cooling power of 500 W [1]. This is especially important for heat-loaded radio-electronic airborne elements operating in a wide range of climatic and mechanical effects [2].

The spectrum of use of thermoelectric converters is wide: from systems for providing thermal regimes for electronic equipment, for medical systems for the formation of temperature fields, for household refrigerators and air conditioners to generators of electrical energy [3]. The cooling capacity of thermoelectric cooling devices, which is lower than the compressible cooling capacity, has made the problem of increasing the power parameters of the thermal power plant is urgent, since they are beyond competition by other indicators.

Another problem is reliability indicators, since modern heat-loaded elements operate under conditions close to critical. Under the appropriate conditions, thermoelectric systems also operate to ensure their thermal conditions [4]. The increased thermal load significantly worsens the reliability index of the power plant [5], therefore the design of the device by the criterion of maximum cooling capacity should be carried out taking into account this circumstance. In [6], the influence of changing the geometry of thermoelements on the reliability indicators of single-stage TEC is analyzed, however, two-stage coolers have a number of features that are mandatory [7]. The expediency of revealing the connection of reliability indicators with variation in the geometry of the branches of a stage thermoelectric cooling device is due to the potential possibility of improving the quality of two-stage coolers. At the same time, the existing technology of their manufacture remains unchanged.

3. The aim and objectives of research

The aim of research is revealing the relationship between the cooling capabilities and reliability indicators of a two-stage thermoelectric cooler with the geometry of the branches of thermoelements during their subsequent electrical connection.

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

1. To develop a model for coupling the failure rate with design parameters and energy parameters of a two-stage thermoelectric cooling device.

2. To analyze the simulation results to determine the conditions for achieving the maximum temperature difference.

4. Research of existing solutions of the problem

Among the main directions for eliminating the problem of increasing the cooling capacity of thermoelectric cooling devices identified in the resources of the world scientific periodicals, the following can be singled out:

– creation of new materials with increased thermoelectric efficiency [8, 9];

– use of thin-film technologies for manufacturing thermoelement materials [10–12];

– transition to nanostructural technologies for manufacturing thermoelement materials [13–15];

– attraction of external electromagnetic fields for control of charge transfer in the thermoelement material [16];

– optimization of heat transfer in a thermoelectric device [17, 18];

– involving elements of reliability theory in the technology of manufacturing of thermoelectric coolers [19–21].

As follows from the approaches presented in the world periodicals, the main direction is the creation of new materials with higher values of thermoelectric efficiency and materials manufacturing technologies, which directly determines the cooling capacity of the thermoelectric device. At the same time, industrially used thermoelectric materials have a very limited value of thermoelectric efficiency already for half a century [4, 5]. Control of the thermoelectric cooler parameters by electromagnetic fields significantly complicates the system of providing thermal conditions, therefore it can be recommended only in special applications.

Studies of influence of the thermoelectric coolers on operational reliability indicators are carried out either at the stage of preparation of the technology of manufacturing products, or after manufacturing [21]. This limits the possibilities of design impact on the resulting reliability indices of the thermoelectric device.

Thus, the results of the analysis allow to conclude that the determination of the relationship between the reliability indices of a thermoelectric device and the design parameters of thermoelements is actual.

5. Methods of research

As the methods of research let's use the methods of mathematical modeling, the theory of heat transfer and reliability, which allow to obtain analytical expressions used for analysis. From an applied point of view, this approach allows to compare design solutions and design stage thermoelectric cooling devices with priority to the reliability criterion. At the same time constructive and energy indicators that meet the requirements of the terms of reference under the existing technology are taken into account.

6. Research results

6.1. Development of a reliability-oriented model. In some cases, the developer has a number of different designs of cascade thermoelectric devices (CTED). These devices can differ from each other by the number of thermocouples n_1, n_2 in stages (ratio n_1/n_2) and the geometry of their branches (the ratio of the height l of the stage branch to the area of its cross section S). There are also possible series of standard (unified) modules, on the basis of which it is possible to construct a CTED at $(l/S)_i = $const or $(l/S)_i = $var.

In [6], the regime of the maximum temperature difference ΔT_{max} of two-stage TECs of various designs ($n_1/n_2 = $var) at $(l/S)_1 = (l/S)_2 = 10$ cm^{-1} and their maximum cooling capabilities and reliability parameters are considered. Calculations of the maximum cooling capabilities, namely, the maximum temperature difference ΔT_{max}, $(l/S)_1 = (l/S)_2 = 40...2.0$ cm^{-1} and different values of n_1/n_2 are carried out. Analysis of the results showed that ΔT_{max} does not depend on the geometry of the branches of thermoelements in stages, but depends on the efficiency of the initial materials.

Let's consider the estimation of cooling capabilities and reliability indicators of two-stage TEC of various designs ($n_1/n_2 = $var) at $(l/S)_1 = var= 20$; 15; 10; 4.5 cm^{-1} and $(l/S)_2 = 10$ cm^{-1} for the series electrical connection of the stages.

To determine the optimal geometry of the branches of thermoelements in the first stage $(l/S)_{1opt}$ corresponding to the largest value of the maximum temperature difference ΔT_{max} of a two-stage TEC for a given geometry of the thermoelement branches in the second stage $(l/S)_2 = $const, let's use the relations [5].

The condition of thermal conjugation of stages can be written in the form:

$$Q_{01} + W_1 = Q_{02}, \tag{1}$$

where $Q_{01} = 0$ for ΔT_{max} – the TEC thermal load, W.

The power consumption of the first stage W_1 and the cooling capacity of the second stage Q_{02} included in this expression are calculated by the formulas:

$$W_1 = 2n_1 \left[I^2 R_1 + \overline{e}_1 I (T_1 - T_0) \right] =$$
$$= 2n_1 \left[I^2 \frac{(l/S)_1}{\overline{\sigma}_1} + \overline{e}_1 I (T_1 - T_0) \right]; \tag{2}$$

$$Q_{02} = 2n_2 \left[\overline{e}_2 I T_1 - 0,5 I^2 R_2 - K_2 (T - T_1) \right] =$$
$$= -2n_2 \left[\overline{e}_2 I T_1 - \frac{0,5 I^2 (l/S)_2}{\overline{\sigma}_2} - \frac{\overline{\chi}_2}{(l/S)_2} (T - T_1) \right], \tag{3}$$

where n_1, n_2 – the number of thermocouples in stages, pieces; I – the working current, A; R_i – the electrical resistance of the branch of the thermoelement in the i-th stage, Ohm, $R_i = (l/S)_i / \overline{\sigma}_i$; $\overline{e}_i$, $\overline{\sigma}_i$, $\overline{\chi}_i$ – respectively, the averaged values of the coefficient of thermo-emf, V/K, electrical conductivity, S/cm, and thermal conductivity, W/(cm·K), the branches of thermoelements in the i-th stage; T_0 – heat-absorbing junction temperature, K; T_1 – intermediate temperature, K; T – heat-absorbing junction temperature, K.

Let's substitute (2) and (3) into (1) and obtain an expression for the intermediate temperature:

$$T_1 = T_0 \left(1 + \frac{\overline{e}_1 I}{\overline{\chi}_1} (l/S)_1 \right) - 0,5 I^2 \frac{(l/S)_1^2}{\overline{\sigma}_1 \overline{\chi}_1}. \tag{4}$$

Substituting (2)–(4) in (1), obtain an expression for determining the heat-absorbing junction temperature:

$$T_0 = \cfrac{1}{\bar{e}_2 I + \dfrac{\bar{\chi}_2}{(l/S)_2} + I \dfrac{\bar{e}_1(l/S)_1}{\bar{\chi}_1}\left(\bar{e}_2 I + \dfrac{\bar{\chi}_2}{(l/S)_2}\right) - I^2 \dfrac{n_1}{n_2}\dfrac{\bar{e}_1^2(l/S)_1}{\bar{\chi}_1}} \times$$

$$\times \left[\dfrac{\bar{\chi}_2}{(l/S)_2}T + 0.5I^2 \dfrac{(l/S)_1^2}{\bar{\sigma}_1\bar{\chi}_1}\left(\bar{e}_2 I + \dfrac{\bar{\chi}_2}{(l/S)_2}\right) + 0.5I^2 \dfrac{(l/S)_2}{\bar{\sigma}_2} + \right.$$

$$\left. + I^2 \dfrac{n_1}{n_2}\dfrac{(l/S)_1}{\bar{\sigma}_1} - 0.5I^3 \dfrac{n_1}{n_2}\dfrac{\bar{e}_1(l/S)_1^2}{\bar{\sigma}_1\bar{\chi}_1}\right]. \qquad (5)$$

Let's introduce the following notation:

$$A = \frac{\bar{\chi}_2}{(l/S)_2}T; \quad B = 0.5I^2 \frac{1}{\bar{\sigma}_1\bar{\chi}_1}; \quad f = \bar{e}_2 I + \frac{\bar{\chi}_2}{(l/S)_2};$$

$$C = 0.5I^2 \frac{(l/S)_2}{\bar{\sigma}_2}; \quad D = I^2 \frac{n_1}{n_2\bar{\sigma}_1};$$

$$E = 0.5I^3 \frac{n_1}{n_2}\frac{\bar{e}_1}{\bar{\sigma}_1\bar{\chi}_1}; \quad p = I\frac{\bar{e}_1}{\bar{\chi}_1}; \quad K = I^2 \frac{n_1}{n_2}\frac{\bar{e}_1^2}{\bar{\chi}_1}.$$

Taking this into account, expression (5) takes the form:

$$T_0 = \frac{A + Bf(l/S)_1^2 + C + D(l/S)_1 - E(l/S)_1^2}{f + (l/S)_1(pf - K)}. \qquad (6)$$

From condition $\dfrac{dT_0}{d(l/S)_1} = 0$:

$$(l/S)_{1opt} = \frac{f}{pf - K} \times$$

$$\times \left(\sqrt{1 - \frac{D(pf - K)}{(Bf - E)f} + \frac{(A + C)(pf - K)^2}{(Bf - E)f^2}} - 1\right). \qquad (7)$$

The failure rate λ/λ_0 of a two-stage TEC can be determined from the expression:

$$\frac{\lambda}{\lambda_0} = n_1 B_1^2 (\Theta_1 + C_1)\left(\frac{B_1 + \dfrac{\Delta T_{\max 1}}{T_0}\Theta_1}{1 + \dfrac{\Delta T_{\max 1}}{T_0}\Theta_1}\right)^2 K_{T1} +$$

$$+ n_2 B_2^2 (\Theta_2 + C_2)\left(\frac{B_2 + \dfrac{\Delta T_{\max 2}}{T_1}\Theta_2}{1 + \dfrac{\Delta T_{\max 2}}{T_1}\Theta_2}\right)^2 K_{T2}, \qquad (8)$$

where Θ_i – the relative temperature drop in the i-th stage, $\Theta_1 = (T_1 - T_0)/\Delta T_{\max 1}$, $\Theta_2 = (T - T_1)/\Delta T_{\max 2}$; $\Delta T_{\max i}$ – the maximum temperature drop in the i-th stage, K, $\Delta T_{\max i} = 0.5\bar{z}_i T_{i-1}^2$;

C_i – relative thermal load in the i-th stage, $C_1 = \dfrac{Q_{01}}{n_1 I_{\max 1}^2 R_1}$,

$C_2 = \dfrac{W_1 + Q_{01}}{n_2 I_{\max 2}^2 R_2}$; B_i – the relative operating current in the i-th stage, $B_i = I/I_{\max i}$; $I_{\max i}$ – the maximum operating current in

the i-th stage, A, $I_{\max i} = \bar{e}_i T_{i-1}/R_i$; $\bar{z}_i$ – the average value of the material efficiency of the branches of the thermocouples of the i-th stage, 1/K; K_{Ti} – a significance factor that takes into account the effect of a lowered temperature in the i-th stage.

The probability of failure-free operation P of a two-stage TEC can be determined from the expression:

$$P = \exp(-\lambda t), \qquad (9)$$

where t is the assigned resource, h.

The voltage drop of a two-stage TEC can be determined from the expression:

$$U_\Sigma = W_\Sigma/I. \qquad (10)$$

Expressions are the basis for calculating the parameters and reliability indicators of a two-stage cooler.

6.2. Analysis of the developed reliability-oriented model. The calculation of the main parameters and reliability indices is carried out for various designs of a two-stage TEC ($n_2/n_2 = $var) with a fixed number of thermocouples in the second stage $n_2 = 27$, the optimum value $(l/S)_1$ and $(l/S)_2 = 10$ cm^{-1}. To find the optimal geometry of the branches of the first-stage $(l/S)_{1opt}$ thermoelements, let's use a parameter that takes into account the geometry of the branches in two stages:

$$a = \frac{(l/S)_1}{(l/S)_2}.$$

The results of the calculations are given in Table 1 and in Fig. 1–6.

Analysis of the calculated data shows that for fixed values of the parameter a with a decrease in the ratio n_1/n_2:
– the intermediate temperature T_1 decreases (Fig. 1);
– the relative operating current in the stages B_1 and B_2 increases (Fig. 2);
– the relative temperature drop in the first stage Θ_1 increases for $a = 0.45$ and $a = 1.0$ and decreases, passing through a maximum for $a = 1.5$ and $a = 2.0$ (Fig. 3, a). In the second stage, Θ_2 increases for different values of a (Fig. 3, b);
– the value of the operating current I increases (Fig. 4);
– the optimal value of the geometry parameter of the branches of thermoelements a_{opt} decreases, passing through a minimum at $n_1/n_2 = 0.5$ (Fig. 4);
– the maximum temperature difference $\Delta T_{\max}$ increases (Fig. 5);
– the failure rate λ/λ_0 increases (Fig. 6, a) due to the growth of the relative operating currents B_1 and B_2, as well as the growth of relative temperature differences Θ_1 and Θ_2;
– the probability of failure-free operation P decreases (Fig. 6, b).

Analysis of the calculated data showed that *for fixed values of the ratio n_1/n_2 with increasing parameter a*:
– the intermediate temperature T_1 increases (Fig. 1);
– the relative operating current of the first stage B_1 increases, and the second stage B_2 slightly decreases (Fig. 2);
– the relative temperature drop in the second stage Θ_2 increases (Fig. 3, b);
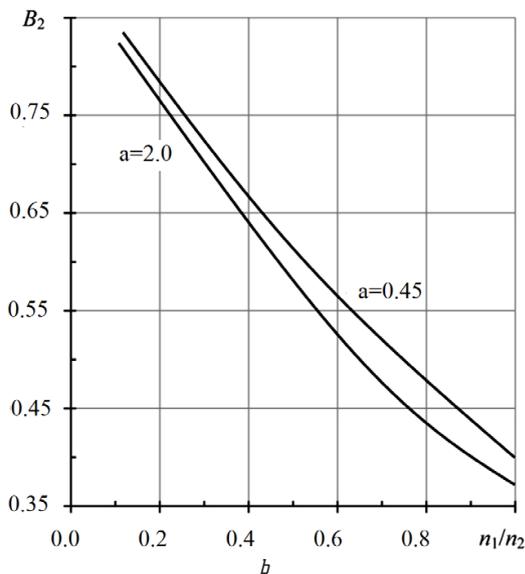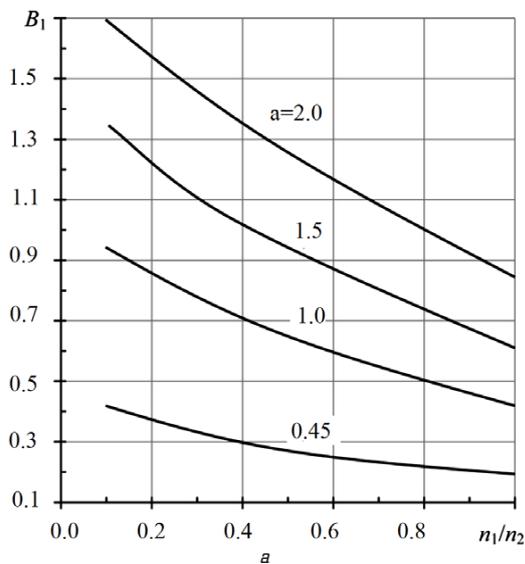– the probability of failure-free operation P decreases (Fig. 6, b).

Table 1

The main parameters and reliability indices of a two-stage thermoelectric cooler at $T = 300$ K, $Q_0 = 1.0$ W, $\bar{z}_m = 2{,}4 \cdot 10^{-3}$ 1/K, $n_2 = 27$, $(l/S)_2 = 10$ cm^{-1} and variation of parameter a for different values of n_1/n_2 in the ΔT_{max} mode
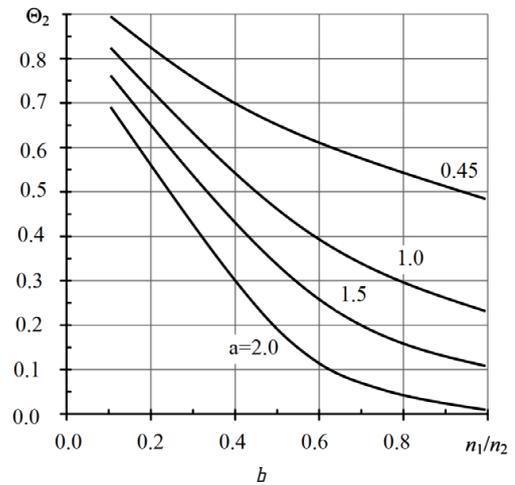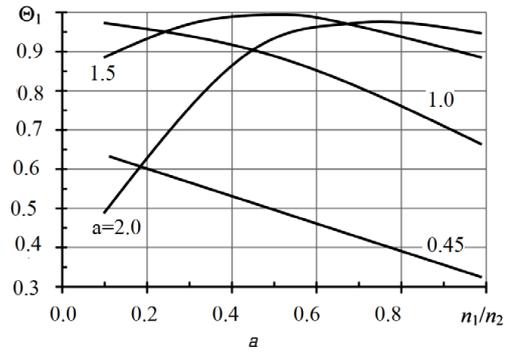
| Design (modules in cascades (stages))	a	$R_1 \cdot 10^3$, Ω	$R_2 \cdot 10^3$, Ω	I_{max1}, A	I_{max2}, A	B_1	B_2	Θ_1	Θ_2	T_1, K	ΔT_{max}	W_Σ, Вт	U_Σ, В	$(l/S)_1$	λ/λ_0	$\lambda \cdot 10^8$, 1/h	P
					$n_1/n_2 = 1.0$; $n_1 = 27$; $I = 2$ A												
M4.5-27/ M10-27	0.45	3.88	10.1	1.11	5.02	0.18	0.40	0.33	0.48	261.0	59.6	3.87	1.94	4.5	0.63	1.89	0.99981
M10-27/ M10-27	1.0	9.43	10.53	4.7	5.25	0.43	0.380	0.67	0.23	279.0	64.0	5.63	2.82	10	1.33	4.0	0.99960
M13.8-27/ M10-27	1.38	12.1	10.42	3.51	5.38	0.57	0.372	0.825	0.174	283.3	66.6	6.23	3.11	13.8	3.52	10.6	0.99894
M15-27/ M10-27	1.5	13.9	10.64	3.13	5.41	0.64	0.37	0.87	0.124	287.7	66.1	6.64	3.33	15	5.38	16.1	0.9984
M20-27/ M10-27	2.0	18.9	11.1	2.37	5.40	0.84	0.37	0.95	0.0	300	62.2	9.75	4.9	20	14.7	44.2	0.9956
					$n_1/n_2 = 0.67$; $n_1 = 18$; $I = 2.6$ A												
M4.5-18/ M10-27	0.45	3.81	10.0	10.6	4.97	0.245	0.523	0.43	0.57	255.9	68.7	6.2	2.4	4.5	2.11	6.32	0.99937
M10-18/ M10-27	1.0	8.47	10.42	4.65	5.06	0.56	0.51	0.80	0.36	269.0	74.7	7.43	2.86	10	3.56	10.7	0.99893
M11.3-18/ M10-27	1.13	9.58	10.42	4.1	5.04	0.634	0.516	0.81	0.38	267.7	75.7	7.73	3.0	11.3	4.85	14.55	0.99855
M15-18/ M10-27	1.5	12.9	10.42	3.14	5.27	0.83	0.49	0.980	0.226	279.0	75.3	8.43	3.24	15	10.9	32.6	0.9967
M20-18/ M10-27	2.0	18.2	10.9	2.36	5.35	1.10	0.49	0.987	0.084	291.4	68.6	9.70	3.72	20	27.3	82.0	0.99183
					$n_1/n_2 = 0.50$; $n_1 = 13.5$; $I = 3.1$ A												
M4.5-13.5/ M10-27	0.45	3.69	9.8	10.47	4.95	0.30	0.63	0.50	0.656	251.3	75.4	8.0	2.6	4.5	4.58	13.75	0.99862
M9.5-13.5/ M10-27	0.95	7.8	10.1	4.83	5.11	0.64	0.61	0.91	0.44	263.5	82.4	9.1	2.95	9.5	6.27	18.8	0.99812
M10-13.5/ M10-27	1.0	8.20	10.1	4.6	5.10	0.67	0.61	0.895	0.455	262.8	82.2	9.2	3.0	10	6.75	20.2	0.9980
M15-13.5/ M10-27	1.5	12.1	10.1	3.1	5.3	1.0	0.59	1.0	0.32	272	79.0	10.0	3.25	15	17.25	51.8	0.99483
M20-13.5/ M10-27	2.0	17.9	10.5	2.37	5.4	1.31	0.575	0.93	0.135	286.7	69.0	11.4	3.67	20	37.5	112.6	0.9988
					$n_1/n_2 = 0.33$; $n_1 = 9$; $I = 3.3$ A												
M4.5-9/ M10-27	0.45	3.46	9.62	10.67	4.88	0.31	0.68	0.524	0.744	247.1	78.9	8.4	2.54	4.5	6.32	19.0	0.99810
M10-9/ M10-27	1.0	7.69	10.0	4.61	4.94	0.72	0.668	0.924	0.594	254.7	87.6	9.4	2.84	10	10.8	32.5	0.9968
M11-9/ M10-27	1.11	8.54	10.0	4.14	4.93	0.80	0.67	0.925	0.61	254.0	88.1	9.56	2.83	11.1	9.85	29.6	0.99705
M15-9/ M10-27	1.5	1.1	10.0	3.03	5.09	1.09	0.648	1.0	0.485	261	86.8	10.1	3.07	15	18.1	54.2	0.9946
M20-9/ M10-27	2.0	17.0	10.0	2.3	5.20	1.43	0.635	0.81	0.41	265.6	77.3	10.9	3.30	20	33.4	100	0.9900
					$n_1/n_2 = 0.20$; $n_1 = 5$; $I = 3.8$ A												
M4.5-5/ M10-27	0.45	3.40	9.52	10.1	4.85	0.38	0.78	0.61	0.835	243	84.6	10.3	2.71	4.5	10.9	32.7	0.9967
M9.99-5/ M10-27	0.993	7.64	9.62	4.39	4.91	0.86	0.77	0.984	0.71	248.7	95.5	10.9	2.86	9.93	13.2	39.6	0.9960
M10-5/ M10-27	1.0	7.69	9.62	4.41	4.92	0.86	0.77	0.98	0.71	248.7	93.4	10.9	2.86	10	13.2	39.6	0.9960
M15-5/ M10-27	1.5	11.5	10.0	3.04	4.89	1.25	0.78	0.94	0.64	252	90.0	11.6	3.06	15	21.9	65.7	0.9935
M20-5/ M10-27	2.0	16.1	10.0	2.39	5.03	1.59	0.755	0.66	0.535	258	76.6	12.0	3.16	20	29.0	86.9	0.99135
					$n_1/n_2 = 0.1$; $n_1 = 3$; $I = 4$ A												
M4.5-3/ M10-27	0.45	3.40	9.52	9.97	4.79	0.40	0.835	0.637	0.90	240	88.1	11.1	2.78	4.5	14.4	43.2	0.9957
M9.99-3/ M10-27	1.0	7.52	9.52	4.32	4.85	0.926	0.825	0.99	0.83	243.1	96.9	11.4	2.86	9.997	15.9	47.7	0.99524
M10-3/ M10-27	1.0	7.52	9.52	4.32	4.85	0.926	0.825	0.99	0.83	243	96.8	11.4	2.86	10	15.9	47.7	0.9952
M15-3/ M10-27	1.5	11.3	9.52	2.96	4.91	1.35	0.815	0.875	0.769	246	91.2	11.6	2.91	15	21.5	64.4	0.9936
M20-3/ M10-27	2.0	15.9	9.62	2.35	4.91	1.70	0.815	0.51	0.71	248.7	77.3	12.0	3.0	20	25.2	75.5	0.9925
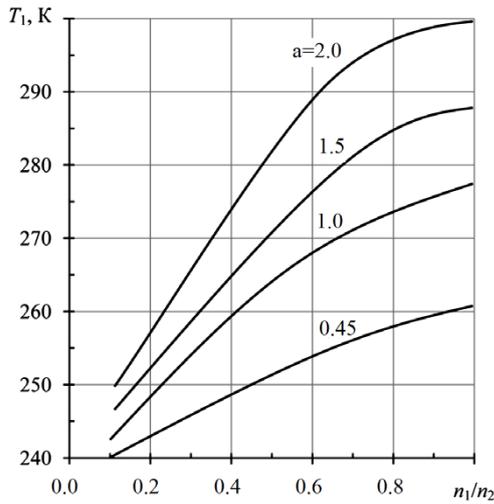
Fig. 1. Dependence of the intermediate temperature T_1 of a two-stage thermoelectric cooler on the ratio n_1/n_2 for different values of the parameter a at $T = 300$ K; $(l/S)_2 = 10$ cm^{-1}; $n_2 = 27$ in the ΔT_{max} mode
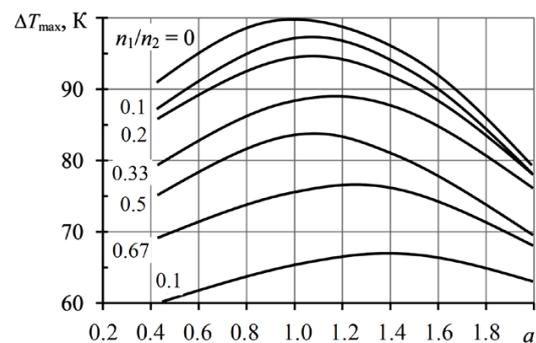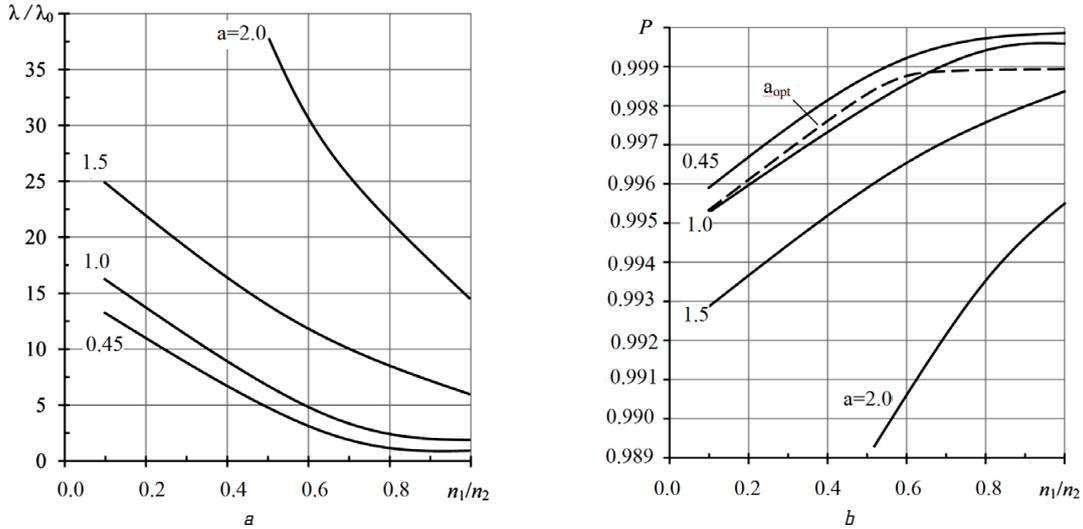

Fig. 3. Dependence of the temperature drop difference of cascades (stages) of a two-stage thermoelectric cooler on the ratio n_1/n_2 for different values of the parameter a at $T = 300$ K; $(l/S)_2 = 10$ cm^{-1}; $n_2 = 27$ in the ΔT_{max} mode: a – the first stage Θ_1; b – the second stage Θ_2
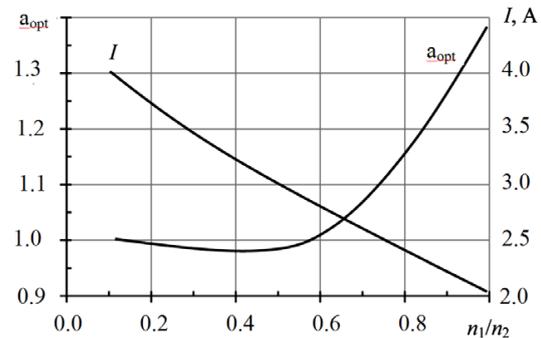
Fig. 4. Dependence of the optimum value of the parameter a corresponding to the largest value of the temperature drop: the vertex geometry parameter a and the working current I of the two-stage thermoelectric cooler on the ratio n_1/n_2 at $T = 300$ K; $(l/S)_2 = 10$ cm^{-1}; $n_2 = 27$ in the ΔT_{max} mode

Fig. 5. Dependence of the maximum temperature difference ΔT_{max} of a two-stage thermoelectric cooler on the parameter a for different values of the ratio n_1/n_2 at $T = 300$ K; $(l/S)_2 = 10$ cm^{-1}; $n_2 = 27$ in the ΔT_{max} mode

Fig. 2. Dependence of the relative operating current of cascades (stages) of a two-stage thermoelectric cooler on the ratio n_1/n_2 for different values of the parameter a at $T = 300$ K; $(l/S)_2 = 10$ cm^{-1}; $n_2 = 27$ in the ΔT_{max} mode: a – the first stage B_1; b – the second stage B_2

Fig. 6. Dependence of the relative failure rate λ/λ_0 and the probability of failure-free operation P of a two-stage thermoelectric cooling device on the ratio n_1/n_2 for different values of the parameter a at $T=300$ K; $(l/S)_2=10$ cm^{-1}; $n_2=27$ in the ΔT_{max} mode: a – relative failure λ/λ_0; b – probability of failure-free operation P

As can be seen from Fig. 5, the functional dependence $\Delta T_{max}=f(a)$ for different values of the ratio n_1/n_2 has a pronounced maximum for a given value of the operating current I. For each value of the ratio n_1/n_2, it is possible to determine the optimal geometry of the branches of the thermoelements $a_{opt}=(l/S)_1/(l/S)_2$, corresponding to the largest value of the maximum temperature difference ΔT_{max}. It should be noted that as the ratio n_1/n_2 grows, the parameter a_{opt} shifts towards higher values from the traditional $a=1$ (when $(l/S)_1=(l/S)_2=10$).

The results of calculating the maximum temperature difference ΔT_{max} for a_{opt} ($\Delta T_{max\ a_{opt}}$) and for $a=1$ ($\Delta T_{max\ a=1}$) are given in Table 2.

Table 2

The results of calculating the maximum temperature difference

n_1/n_2	A_{opt}	$\Delta T_{max\ aopt}$	$\Delta T_{max\ a=1}$	$\gamma=\Delta T_{max\ aopt}/\Delta T_{max\ a=1}$
1.0	1.38	66.6	64.0	1.041
0.67	1.13	75.7	74.7	1.01
0.50	0.95	82.4	82.2	1.0024
0.33	1.11	88.1	87.6	1.005
0.20	0.993	95.5	93.4	1.022
0.11	1.0	96.9	96.8	1.001
0.0	1.0	100	100	1.0

As follows from the last column of Table 2, the gain depends on the ratio of the number of thermoelements in the cascades (stages) and reaches a maximum at a ratio of thermoelements equal to unity.

7. SWOT analysis if research results

Strengths. The strength of this research is the justification of the possibility of increasing the reliability of two-stage thermoelectric cooling devices to 4 % without improving the existing technology of industrial production and changing the material of thermocouples. From an applied point of view, this makes it possible to maintain the technical operating conditions for climatic, mechanical and radiation indicators of manufactured products unchanged with an increase in their qualitative characteristics.

Weaknesses. The weak side of this research is the fact that the proposed model takes into account a limited number of influencing factors, in particular, the thermal deformations do not take into account that occur at the junction of thermoelements with heat-removing ceramic electrodes. In cascade thermoelectric coolers, the temperature conditions for the functioning of thermocouples in cascades (stages) differ, which may affect the plastic properties of soldered joints. This component is not taken into account by the proposed model, and its effect on reliability indicators of thermoelectric coolers requires further research and corresponding financial costs.

Opportunities. Additional opportunities for increasing reliability indicators of two-stage thermoelectric cooling devices consist in taking into account the geometry of thermoelements and the distribution of thermoelements in cascades (stages). This allows to optimize the design solutions to achieve the maximum values of temperature differences. With the introduction of elements of research data at enterprises, it becomes possible to lay products already at the design stage with enhanced reliability indicators.

Threats. Threats for practical use of the obtained results are connected with the expansion of the nomenclature of produced two-stage coolers tied to specific operating conditions. Therefore, this function should be incorporated into the algorithm of the automated system of design and manufacturing, which is the general trend of modern production. Additional costs are associated with the completion of the software product of the computer-aided design of thermoelectric coolers in the direction of accounting for the investigated reliability component.

Thus, SWOT analysis allows to assess the main directions of improving the design and manufacturing quality of two-stage thermoelectric cooling devices based on a reliability-oriented criterion.

8. Conclusions

1. A model of the relationship between the reliability indices of two-stage TECs of various designs with the geometry of the branches of thermoelements in cascades (stages) in the ΔT_{max} mode with electrical series of the cascades (stages) is proposed and analyzed. The obtained relationships enable to estimate the maximum cooling capacities and reliability indices of two-stage coolers of various designs.

2. The possibility of increasing the maximum temperature difference ΔT_{max} to 4 % is shown by choosing the optimal geometry of the branches of the thermoelements in the cascades (stages) $(l/S)_1 > (l/S)_2$, which differs from the traditional $(l/S)_1 = (l/S)_2$, at a given operating current. The proposed approach makes it possible to estimate the maximum cooling capacities of two-stage coolers and to optimize the design of systems for providing thermal regimes for radio electronic equipment.

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ОПРЕДЕЛЕНИЕ МАКСИМАЛЬНЫХ ОХЛАЖДАЮЩИХ ВОЗМОЖНОСТЕЙ ДВУХКАСКАДНЫХ ОХЛАДИТЕЛЕЙ ПРИ ВАРИАЦИИ ГЕОМЕТРИИ ВЕТВЕЙ В КАСКАДАХ

Рассмотрено влияние геометрии ветвей термоэлементов в каскадах на параметры и показатели надежности двухкаскадных термоэлектрических охладителей различных конструкций при последовательном электрическом соединении каскадов в режиме максимального перепада температуры. Получены соотношения для определения оптимальной геометрии ветвей термоэлементов в каскадах, соответствующей наибольшему значению перепада температуры для различных конструкций охладителей при заданном рабочем токе.

Ключевые слова: термоэлектрическое охлаждающее устройство, геометрия ветви термоэлементов, максимальный перепад температуры, конструкции охладителей.

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