Розглянуто вплив геометрії гілок термоелементів і розподілу термоелементів в каскадах двокаскадних термоелектричних охолоджуючих пристроїв на показники надійності. Аналіз наведено для робочого діапазону перепаду температур, номінального теплового навантаження в режимі максимальної холодопродуктивності при заданому струмі. Показано, що варіацією геометрії термоелементів і розподілом термоелементів в каскадах можна досягти двократного зниження інтенсивності відмов

Ключові слова: двокаскадний термоелектричний охолоджуючий пристрій, геометрія гілок термоелементів, показники надійності

Рассмотрено влияние геометрии ветвей термоэлементов и распределения термоэлементов в каскадах двухкаскадных термоэлектрических охлаждающих устройств на показатели надежности. Анализ проведен для рабочего диапазона перепада температур, номинальной тепловой нагрузки в режиме максимальной холодопроизводительности при заданном токе. Показано, что вариацией геометрии термоэлементов и распределением термоэлементов в каскадах можно добиться двукратного снижения интенсивности отказов

Ключевые слова: двухкаскадное термоэлектрическое охлаждающее устройство, геометрия ветвей термоэлементов, показатели надежности

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ANALYSIS OF THE MODEL OF INTERRELATION BETWEEN THE GEOMETRY OF THERMOELEMENT BRANCHES AND RELIABILITY INDICATORS OF THE CASCADE COOLER

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1. Introduction

Thermoelectric coolers under conditions of elevated thermal loads or under switching modes significantly decrease their reliability inficators. This is due, among others, to thermal stresses in the places where thermoelements and electrodes are coupled. It is obvious that the higher the range of the generated temperature drops, the lower the reliability indicators of thermoelectric systems for maintaining thermal regimes of thermally-loaded radio electronics. Cascade coolers provide for a larger temperature difference compared with single-cascade devices, which is why the requirements to reliability indicators turn out to be more stringent. Stricter requirements to the operation of thermally-loaded equipment and, consequently, to the thermoelectric systems that maintain thermal regimes makes it a relevant task to search for approaches to improve reliability indicators of cascade coolers. In the present studies, we consider structural approaches for enhancing the reliability indicators of two-cascade thermoelectric coolers.

2. Literature review and problem statement

The issue of operational reliability (failure rate and the probability of non-failure operation) of thermoelectric coolers was addressed in numerous studies, for example [1–3]. Research is carried out from different perspectives: the impact of technology of the fabrication of devices on reliability indicators [4], protection from the effect of moisture [5], mechanical [6] and climatic impacts [7], thermal load [8], temperature differences [9], operating modes [10]. Operational reliability of the thermoelectric devices of the specified design is ensured by the choice of working currents, alignment of energy indicators with temperature drops and thermal load. At the design phase, the potential of reliability is laid out, which may only get worse during operation through the inefficient use of the device. In paper [11], authors rather insufficiently, mainly at the qualitative level, outlined results of the impact of the design of single-stage thermoelectric coolers on reliability indicators. The reliability-oriented quantitative research into a single-cascade thermoelectric cooler, presented by the authors of article [12], cannot be automatically applied to the two-cascade device, because it is necessary to take into account the patterns of temperature distribution in the cascades [13]. Given the fact that the single-stage thermoelectric coolers have a limited range of the generated temperature differential, employing the cascading is a required condition in order to increase temperature differential. And this special feature implies undertaking research into defining a connection between reliability indicators of the two-cascade thermoelectric cooler with the design of thermoelements and their distribution in the cascades.

3. The aim and objectives of the study

The goal of present work is to improve reliability indicators of the two-cascade thermoelectric cooler by optimizing the design of thermoelements and their distribution in the cascades.

To accomplish the set goal, the following tasks have been set:

– to devise a model that connects reliability indicators of the two-cascade cooler with the geometry of thermoelement branches and their distribution in the cascades for different temperature differential and fixed thermal load;

– to analyze the connection between indicators of reliability and the geometry of thermoelements, distribution of thermoelements in the cascades, energy parameters in the operating temperature range of the cooler's functioning.

4. Development and analysis of the connection model between reliability indicators and the design and energy parameters of a two-cascade cooler

4. 1. Model of interrelation between reliability indicators and the geometry of thermoelement branches

Interest in the application of the cascade thermoelectric coolers (CTEC) is caused not only by the necessity to achieve the highest possible level of cooling, but also by improving cooling efficiency at a given temperature differential. In some cases, when designing CTEC, a developer may refer to a number of different designs of CTEC, which differ in the quantity of thermoelements n_1, n_2 in the cascades (n_1/n_2 ratio) and the geometry of their branches. The geometry of branches is understood as the ratio of height l of the cascade branch cascade to the area of its cross-section S. A designer's task is to choose rationally the geometry of thermoelement branches, taking into account various constraints on dimensions, weight, power consumption, reliability indicators at sequential electrical connection of the cascades.

We shall estimate basic parameters and reliability indicators of the two-cascade TEC of different designs (n_1/n_2=var) when used in the cascades of branches of thermoelements with different geometry under condition $(l/S)_1=(l/S)_2$ for different temperature differential ΔT under mode $(Q_0/I)_{\max}$.

In order to solve the set problem, we shall apply ratios [13].

A condition of thermal coupling of the cascades can be written in the form

$$Q_0+W_1=Q_{02}, \qquad (1)$$

where Q_0 is the thermal load, W; W_1 is the power consumption of the first cascade, W:

$$W_1=2n_1I_{\max1}^2R_1B_1\left(B_1+\frac{\Delta T_{\max1}}{T_0}\Theta_1\right); \qquad (2)$$

Q_{02} is the refrigeration capacity of the second cascade, W:

$$Q_{02}=n_2I_{\max2}^2R_2\left(2B_2-B_2^2-\Theta_2\right); \qquad (3)$$

n_1, n_2 is the number of elements in the cascades, pcs.; $I_{\max1}$, $I_{\max2}$ is the maximum operating current in the cascades, A, $I_{\max1}=\bar{e}_1T_0/R_1$, $I_{\max2}=\bar{e}_2T_1/R_2$;

R_1, R_2 is the electric resistance of the thermoelement branch in the cascades, Ohm, $R_1=(l/S)_1/\bar{\sigma}_1$, $R_2=(l/S)_2/\bar{\sigma}_2$;

$\bar{e}_1$, $\bar{\sigma}_1$, $\bar{e}_2$, $\bar{\sigma}_2$ are, respectively, averaged values of the coefficient of thermoEMF, V/C, and electrical conductivity, Cm/cm, of the thermoelement branch in the cascades;

B_1, B_2 is the relative operating current in the cascades, $B_1=I/I_{\max1}$, $B_2=I/I_{\max2}$;

I is the magnitude of operating current, A;

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

T_1 is the intermediate temperature, K;

T is the temperature of the heat-absorbing junction, K;

$\Delta T_{\max1}$, $\Delta T_{\max2}$ is the maximum temperature differential in the cascades, K, $\Delta T_{\max1}=0{,}5\bar{z}_1T_0^2$, $\Delta T_{\max2}=0{,}5\bar{z}_2T_1^2$;

$\bar{z}_1,\bar{z}_2$ are the averaged efficiency values of the material of thermoelement branches in the cascades, 1/K;

Θ_1, Θ_2 is the relative difference of temperature in the cascades, $\Theta_1=\Delta T_1/\Delta T_{\max1}=(T_1-T_0)/\Delta T_{\max1}$, $\Theta_2=\Delta T_2/\Delta T_{\max2}=(T-T_1)/\Delta T_{\max2}$.

Refrigeration capacity of the two-cascade TEC is determined by the first cascade:

$$Q_0=n_1I_{\max1}^2R_1\left(2B_1-B_1^2-\Theta_1\right)=n_1\gamma_1\left(2B_1-B_1^2-\Theta_1\right), \qquad (4)$$

while the sequential electric connection of cascades defines equality of operating currents in the cascades:

$$I_{\max1}B_1=I_{\max2}B_2=I. \qquad (5)$$

The total temperature differential on the two-cascade TEC ΔT consists of temperature differentials in cascades ΔT_1 and ΔT_2:

$$\Delta T=\Delta T_1+\Delta T_2=\Delta T_{\max1\Theta1}+\Delta T_{\max2\Theta2}. \qquad (6)$$

We shall transform expression (1) considering (2)–(6) and obtain a formula to calculate relative refrigeration capacity of the two-cascade TEC

$$C_1=\frac{Q_0}{n_1I_{\max1}^2R_1}=\frac{2B_1^3\dfrac{\Delta T_{\max1}}{T_0}-B_1^2\mathrm{A}+2B_1aF-a\dfrac{\Delta T}{\Delta T_{\max2}}}{1+a\dfrac{\Delta T_{\max1}}{\Delta T_{\max2}}-2B_1\dfrac{\Delta T_{\max1}}{T_0}}, \qquad (7)$$

where

$$a=\frac{n_2I_{\max2}^2R_2}{n_1I_{\max1}^2R_1};$$

$$\mathrm{A}=2+4\frac{\Delta T_{\max1}}{T_0}+a\left(\frac{I_{\max1}^2}{I_{\max2}^2}+\frac{\Delta T_{\max1}}{\Delta T_{\max2}}\right);$$

$$F=\frac{I_{\max1}}{I_{\max2}}+\frac{\Delta T_{\max1}}{\Delta T_{\max2}}.$$

From condition $dC_1/(dB_1)=0$, we shall obtain a ratio to determine the optimal relative operating current of the first cascade $B_{1\mathrm{opt}}$, corresponding to a maximum of ratio $(Q_0/I)_{\max}$ of the two-cascade TEC with different designs (n_1/n_2=var):

$$4B_1^4\left(\frac{\Delta T_{\max 1}}{T_0}\right)^2-4B_1^3\frac{\Delta T_{\max 1}}{T_0}\left(1+a\frac{\Delta T_{\max 1}}{\Delta T_{\max 2}}\right)+$$
$$+B_1^2\left(A\left[1+a\frac{\Delta T_{\max 1}}{\Delta T_{\max 2}}\right]-4aF\frac{\Delta T_{\max 1}}{T_0}\right)+$$
$$+4B_1a\frac{\Delta T_{\max 1}}{T_0}\frac{\Delta T}{\Delta T_{\max 2}}-a\frac{\Delta T}{\Delta T_{\max 2}}\left(1+a\frac{\Delta T_{\max 1}}{\Delta T_{\max 2}}\right)=0. \quad (8)$$

The value of intermediate temperature T_1 can be obtained taking into account the temperature dependence of parameters of the thermoelement material employing the method of successive approximations [13]. Next, it is possible calculate basic significant parameters of the two-cascade cooler, such as B_1, B_2, Θ_1 and Θ_2.

Relative magnitude of the failure rate is calculated in the following way

$$\frac{\lambda_\Sigma}{\lambda_0}=\frac{\lambda_1}{\lambda_0}+\frac{\lambda_2}{\lambda_0}=\frac{n_1B_1^2\left(\Theta_1+C_1\right)\left(B_1+\frac{\Delta T_{\max 1}}{T_0}\Theta_1\right)^2}{\left(1+\frac{\Delta T_{\max 1}}{T_0}\Theta_1\right)^2}K_{T1}+$$
$$+\frac{n_2B_2^2\left(\Theta_2+C_2\right)\left(B_2+\frac{\Delta T_{\max 2}}{T_1}\Theta_2\right)^2}{\left(1+\frac{\Delta T_{\max 2}}{T_1}\Theta_2\right)^2}K_{T2}, \quad (9)$$

where λ_0 is the nominal failure rate, $\lambda_0=3\cdot10^{-8}$, 1/h; C_2 is the relative magnitude of thermal load of the second cascade, $C_2=(Q_0+W_1)/(n_2I^2_{\max 2}R_2)$; K_{T1}, K_{T2} are the coefficients of significance, taking into account the impact of reduced temperature [13].

A probability of the failure-free operation P of the two-cascade TEC can be determined from expression

$$P=\exp(-\lambda\Sigma t), \quad (10)$$

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

4. 2. Analysis of results of modeling the energy, design, and reliability indicators of the cooler

Calculations of basic relevant parameters and indicators of reliability of the two-cascade TEC were conducted under the mode of maximum refrigeration capacity at assigned current $(Q_0/I)_{\max}$ for different configurations of the thermoelement branches. Conditions: $(l/S)_1=(l/S)_2=l/S=$var at the averaged efficiency value of thermoelectric module $\overline{z}_m=(2,4–2,5)\cdot10^{-3}$ 1/K, for different values of ratio of the number of thermoelements in the cascades n_1/n_2, temperature differential ΔT at $T=300$ K and thermal load $Q_0=1.0$ W. Results of the calculations are summarized in Table 1–4.

As can be seen from the data obtained, *with a decrease in ratio n_1/n_2* at fixed values of l/S, temperature differential ΔT and thermal load Q_0, basic parameters of TEC change in the following way:

– intermediate temperature T_1 decreases (Fig. 1);

– relative temperature differential in the first cascade Θ_1 decreases, while in the second Θ_2 increases; in this case, there are values of n_1/n_2, for which $\Theta_1=\Theta_2$, in particular, $\Theta_1=\Theta_2=0.4$ at $\Delta T=60$ K and $n_1/n_2=0.4$; $\Theta_1=\Theta_2=0.51$ at $\Delta T=70$ K and $n_1/n_2=$ 0.33; $\Theta_1=\Theta_2=0.66$ at $\Delta T=80$ K and $n_1/n_2=0,22$; $\Theta_1=\Theta_2=0.81$ at $\Delta T=90$ K and $n_1/n_2=0.11$ (Fig. 2);

– relative operating current in cascades B_1 and B_2 increases (Fig. 3);

– relative thermal load of the first cascade C_1 increases, while in the second C_2 second decreases; in this case, there are values of n_1/n_2, for which $C_1=C_2$, in particular: $C_1=C_2=0.38$ at $\Delta T=60$ K and $n_1/n_2=0.45$; $C_1=C_2=0.34$ at $\Delta T=70$ K and $n_1/n_2=0.33$; $C_1=C_2=0.27$ at $\Delta T=80$ K and $n_1/n_2=0.24$; $C_1==C_2=0.17$ at $\Delta T=90$ K and $n_1/n_2=0.125$ (Fig. 4, *a*);

– dependence of refrigeration coefficient E on the ratio n_1/n_2 passes a maximum at $\Delta T=60$ K and $n_1/n_2=0.5$; $\Delta T=70$ K and $n_1/n_2=0.33$; $\Delta T=80$ K and $n_1/n_2=0.20$; $\Delta T=90$ K and $n_1/n_2=0.5$ (Fig. 4, *b*);

– operating current I increases for different values of ratio l/S (Fig. 5);

– functional dependence of the total number of thermoelements n_1+n_2 on the ratio n_1/n_2 passes a minimum at $\Delta T=60$ K and $n_1/n_2=$ 0.33, at $\Delta T=70$ K and $n_1/n_2=0.5$, at $\Delta T=80$ K and $n_1/n_2=0.2$, at $\Delta T=90$ K and $n_1/n_2=0.15$ for different values of l/S (Fig. 6).

– functional dependence of failure rate λ/λ_0 on the ratio n_1/n_2 passes a minimum at $\Delta T=60$ K and $n_1/n_2=0.67$, at $T=70$ K and $n_1/n_2=0.33$, at $\Delta T=80$ K and $n_1/n_2=0.2$, at $\Delta T=90$ K and $n_1/n_2=0.15$ for different values of l/S (Fig. 7);

– functional dependence of the probability of failure-free operation P on the ratio n_1/n_2 passes a maximum at $\Delta T=60$ K and $n_1/n_2=0.67$; $\Delta T=70$ K and $n_1/n_2=0.5$; $\Delta T=80$ K and $n_1/n_2=0.33$; $\Delta T=90$ K and $n_1/n_2=0.2$ (Fig. 8).

In this case, it should be noted that the relative operating currents B_1 *and* B_2, relative temperature differentials Θ_1 and Θ_2, refrigeration coefficient E, relative thermal load C_1 and C_2 are not dependent on the geometry of thermoelement branches in the cascades.

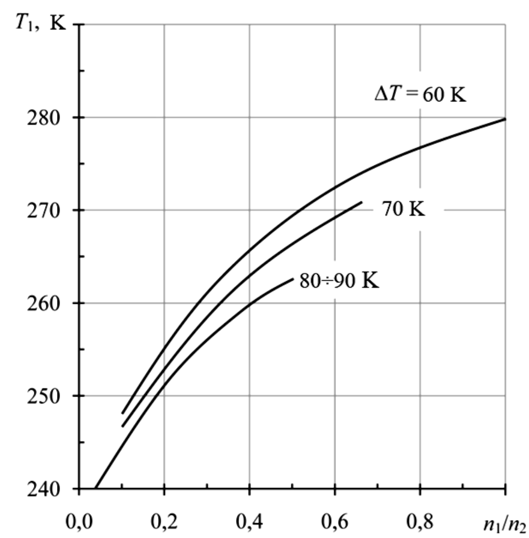


Fig. 1. Dependence of intermediate temperature T_1 of the two-cascade cooler on the ratio n_1/n_2 for different values of ΔT at $T=300$ K; $Q_0=1.0$ W under mode $(Q_0/I)_{\max}$

It follows from the constructed charts that failure rates and the probability of failure-free operation display clearly pronounced extrema, which can be applied when designing the two-cascade thermoelectric cooling devices with enhanced reliability.

Table 1

Basic parameters and indicators of reliability of the two-cascade cooler at ΔT=60 K, T=300 K, Q_0=1.0 W, N=2, $(l/S)_1=(l/S)_2=l/S$=var for different values of ratio n_1/n_2 under mode $(Q_0/I)_{max}$

l/S	$R_1\cdot10^3$, Ohm	$R_2\cdot10^3$, Ohm	I_{max1}, A	I_{max2}, A	I, A	n_1, pcs.	n_2, pcs.	n_1+n_2, pcs.	U_1, V	U_2, V	U_Σ, V	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
n_1/n_2=1,0 –T_1=280 K; B_1=0.435; B_2=0.40; Θ_1=0.62; Θ_2=0.21; K_{T1}=1.035; K_{T2}=1.018; W_1=8.45 W; W_2=8.24 W; W_Σ=16.7 W; E=0.060; C_1=0.062														
40	36.4	41.67	1.215	1.33	0.53	300	300	600	16.0	15.5	31.5	16.6	49.8	0.9950
20	18.2	20.83	2.43	2.66	1.06	150	150	300	8.0	7.8	15.8	8.3	24.9	0.9975
10	9.1	10.4	4.86	5.32	2.10	75.1	75.1	150	4.0	3.9	7.9	4.15	12.4	0.99876
4.5	4.1	4.7	10.8	11.8	4.7	33.8	33.8	67.6	1.8	1.75	3.55	1.87	5.6	0.99944
2.0	1.82	2.08	24.3	26.7	10.6	15.0	15.0	30.0	0.80	0.78	1.58	0.83	2.48	0.99975
n_1/n_2=0.67 T_1=274 K; B_1=0.49; B_2=0.464; Θ_1=0.53; Θ_2=0.29; K_{T1}=1.035; K_{T2}=1.018; W_1=3.0 W; W_2=4.9 W; W_Σ=7.9 W; E=0.127; C_1=0.21														
40	35.1	41.2	1.24	1.31	0.61	89.5	133.6	223.1	4.9	8.1	13.0	10.5	31.4	0.99686
20	17.5	20.6	2.48	2.62	1.21	44.7	66.7	111.4	2.46	4.04	6.50	5.2	15.7	0.99843
10	8.77	10.3	4.95	5.24	2.43	22.3	33.4	55.7	1.23	2.0	3.20	2.6	7.84	0.99922
4.5	3.95	4.64	11.0	11.6	5.40	10.0	15.0	25.0	0.56	0.91	1.47	1.17	3.52	0.99965
2.0	1.75	2.06	24.8	26.2	12.2	4.5	6.7	11.2	0.25	0.40	0.65	0.53	1.6	0.99984
n_1/n_2=0.50 T_1=269 K; B_1=0.525; B_2=0.506; Θ_1=0.46; Θ_2=0.36; K_{T1}=1.035; K_{T2}=1.017; W_1=2.14 W; W_2=5.0 W; W_Σ=7.14 W; E=0.140; C_1=0.32														
40	34.8	40.8	1.24	1.29	0.65	58.7	117.5	176.2	3.3	7.67	11.0	11.5	34.5	0.99655
20	17.4	20.4	2.48	2.58	1.30	29.3	58.6	87.9	1.65	3.85	5.5	5.7	17.2	0.9983
10	8.7	10.2	4.97	5.17	2.61	14.7	29.4	44.1	0.82	1.92	2.74	2.88	8.64	0.99914
4.5	3.91	4.6	11.0	11.5	5.78	6.6	13.3	20.0	0.37	0.865	1.24	1.30	3.9	0.99961
2.0	1.74	2.04	24.8	25.9	13.0	2.9	5.9	8.8	0.165	0.385	0.55	0.57	1.71	0.99983
n_1/n_2=0.33 T_1=262 K; B_1=0.57; B_2=0.56; Θ_1=0.35; Θ_2=0.47; K_{T1}=1.035; K_{T2}=1.021; W_1=1.63 W; W_2=6.2 W; W_Σ=7.8 W; E=0.128; C_1=0.464														
40	34.2	40.0	1.24	1.27	0.71	40.9	122.6	163.5	2.3	8.73	11.0	16.0	48.1	0.9952
20	17.1	20.0	2.48	2.54	1.42	20.4	61.3	81.7	1.15	4.35	5.50	8.0	24.0	0.9976
10	8.55	10.0	5.0	5.08	2.83	10.2	30.6	40.8	0.58	2.16	2.74	4.0	12.0	0.99880
4.5	3.85	4.5	11.0	11.3	6.27	4.6	13.9	18.5	0.26	0.98	1.24	1.82	5.45	0.999455
2.0	1.71	2.0	24.8	25.4	14.2	2.0	6.0	8.0	0.07	0.24	0.31	0.79	2.4	0.99976
n_1/n_2=0.20 T_1=254 K; B_1=0.605; B_2=0.609; Θ_1=0.22; Θ_2=0.60; K_{T1}=1.035; K_{T2}=1.025; W_1=1.29 W; W_2=9.0 W; W_Σ=10.3 W; E=0.097; C_1=0.621														
40	33.9	40.0	1.246	1.237	0.75	30.6	153.0	183.6	1.71	12.0	13.7	25.9	77.7	0.99226
20	17.0	20.0	2.49	2.46	1.51	15.3	76.5	91.8	0.85	6.0	6.85	12.9	38.8	0.9961
10	8.47	10.0	5.0	4.93	3.0	7.6	38.2	45.8	0.43	3.0	3.43	6.46	19.4	0.9981
4.5	3.81	4.5	11.1	10.95	6.71	3.4	17.2	20.6	0.19	1.34	1.53	2.9	8.7	0.99913
2.0	1.69	2.0	25.0	24.6	15.1	1.5	7.6	9.1	0.085	0.60	0.69	1.28	3.85	0.99962
n_1/n_2=0.1 T_1=247 K; B_1=0.632; B_2=0.655; Θ_1=0.11; Θ_2=0.74; K_{T1}=1.035; K_{T2}=1.030; W_1=1.11 W; W_2=16.6 W; W_Σ=17.7 W; E=0.0565; C_1=0.751														
40	33.3	39.2	1.26	1.215	0.80	25.2	252	277.2	1.39	20.75	22.1	54.0	162.2	0.9839
20	16.7	19.6	2.51	2.42	1.58	12.7	127	139.7	0.70	10.5	11.2	27.2	81.7	0.99186
10	8.33	9.8	5.01	4.84	3.17	6.4	63.7	70.1	0.35	5.24	5.6	13.7	41.0	0.9959
4.5	3.75	4.41	11.1	10.75	7.04	2.9	28.6	31.5	0.16	2.36	2.52	6.14	18.1	0.9982
2.0	1.67	1.96	25.0	24.2	15.8	1.3	13.0	14.7	0.07	1.05	1.12	2.8	8.4	0.99916

Table 2

Basic parameters and indicators of reliability of the two-cascade cooler at ΔT=70 K, T=300 K, Q_0=1.0 W, N=2, $(l/S)_1=(l/S)_2=l/S$=var for different values of ratio n_1/n_2 under mode $(Q_0/I)_{max}$

l/S	$R_1\cdot10^3$, Ohm	$R_2\cdot10^3$, Ohm	I_{max1}, A	I_{max2}, A	I, A	n_1, pcs.	n_2, pcs.	n_1+n_2, pcs.	U_1, V	U_2, V	U_Σ, V	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
n_1/n_2=0.67 T_1=271 K; B_1=0.55; B_2=0.506; Θ_1=0.71; Θ_2=0.33; K_{T1}=1.043; K_{T2}=1.016; W_1=8.6 W; W_2=14.0 W; W_Σ=22.6 W; E=0.0442; C_1=0.094														
40	34.2	40.82	1.197	1.31	0.66	218	325	543	13.0	21.2	22.6	22.6	40.9	0.9878
20	17.1	20.4	2.39	2.61	1.32	109	162	271	6.5	10.6	17.1	17.1	20.4	0.9939
10	8.55	10.2	4.79	5.23	2.64	54.5	81.3	136	3.3	5.3	8.6	8.6	10.2	0.9969
4.5	3.85	4.6	10.6	11.6	5.87	24.5	36.6	61.1	1.47	2.39	3.86	3.86	4.6	0.9986
2.0	1.71	2.04	23.9	26.1	13.2	10.9	16.3	27.2	0.65	1.06	1.71	1.71	2.05	0.99939
n_1/n_2=0.50 T_1=266 K; B_1=0.59; B_2=0.556; Θ_1=0.64; Θ_2=0.40; K_{T1}=1.043; K_{T2}=1.018; W_1=4.54 W; W_2=10.5 W; W_Σ=15.0 W; E=0.067; C_1=0.185														
40	33.9	40.8	1.20	1.27	0.71	105	2102	315	6.4	14.8	21.2	32.7	65.4	0.9935
20	17.0	20.4	2.40	2.56	1.42	52.4	105	157	3.2	7.4	10.6	16.3	49.0	0.9951
10	8.5	10.2	4.8	5.1	2.84	26.2	52.3	78.5	1.60	3.7	5.3	8.1	24.4	0.9975
4.5	3.8	4.6	10.7	11.4	6.3	11.8	23.6	35.4	0.72	1.66	2.4	3.67	11.0	0.9989
2.0	1.70	2.04	24.0	25.6	14.2	5.3	10.5	15.8	0.32	0.74	1.06	1.64	4.9	0.99951
n_1/n_2=0.33 T_1=259 K; B_1=0.64; B_2=0.61; Θ_1=0.52; Θ_2=0.51; K_{T1}=1.043; K_{T2}=1.022; W_1=2.8 W; W_2=10.5 W; W_Σ=13.3 W; E=0.0752; C_1=0.351														
40	33.6	40.0	1.198	1.26	0.767	59.1	177.2	236.3	3.65	13.7	17.4	35.0	105	0.9896
20	16.8	20.0	2.40	2.512	1.53	29.5	88.6	118.1	1.83	6.85	8.7	17.5	52.4	0.9948
10	8.4	10.0	4.79	5.03	3.07	14.8	44.3	59.1	0.91	4.33	5.2	8.75	26.2	0.9974
4.5	3.78	4.5	10.65	11.2	6.82	6.7	20.0	26.7	0.41	1.54	1.95	3.9	11.8	0.9988
2.0	1.68	2.0	24.0	25.1	15.3	3.0	9.0	12.0	0.18	0.69	0.87	1.8	5.3	0.99947
n_1/n_2=0.20 T_1=252 K; B_1=0.68; B_2=0.67; Θ_1=0.40; Θ_2=0.64; K_{T1}=1.043; K_{T2}=1.027; W_1=2.14 W; W_2=14.4 W; W_Σ=16.5 W; E=0.0606; C_1=0.50														
40	32.3	39.2	1.218	1.234	0.83	41.7	208.7	250.4	2.54	17.3	19.8	54.2	162.7	0.9839
20	16.1	19.6	2.44	2.47	1.66	20.8	104.1	124.9	1.29	8.67	9.96	27.0	81.2	0.9919
10	8.06	9.8	4.88	4.94	3.32	10.4	52.1	62.5	0.65	4.33	5.0	13.5	40.6	0.9960
4.5	3.63	4.41	10.8	11.0	7.36	4.7	23.5	28.2	0.29	1.96	2.25	6.1	18.3	0.9982
2.0	1.61	1.96	24.4	24.7	16.6	2.1	10.4	12.5	0.13	0.87	1.0	2.7	8.1	0.99919
n_1/n_2=0.1 T_1=246 K; B_1=0.715; B_2=0.722; Θ_1=0.29; Θ_2=0.77; K_{T1}=1.043; K_{T2}=1.031; W_1=1.77 W; W_2=25.4 W; W_Σ=27.1 W; E=0.0369; C_1=0.632														
40	32.0	38.5	1.22	1.21	0.87	33.1	331	364.1	2.03	29.0	31.0	106.5	319.4	0.9686
20	16.0	19.2	2.44	2.42	1.75	16.6	166	182.6	1.01	14.5	15.5	53.4	160	0.9841
10	8.0	9.6	4.89	4.84	3.5	8.3	83	91.3	0.51	7.26	7.8	26.7	80.0	0.9920
4.5	3.6	4.33	10.9	10.75	7.8	3.7	37	40.7	0.23	3.27	3.5	11.9	35.7	0.9964
2.0	1.6	1.92	24.4	24.2	17.5	1.7	17	18.7	0.10	1.45	1.55	5.47	16.4	0.9984

Table 3

Basic parameters and indicators of reliability of the two-cascade cooler at ΔT=80 K, T=300 K, Q_0=1.0 W, N=2, $(I/S)_1=(I/S)_2=I/S$=var for different values of ratio n_1/n_2 under mode $(Q_0/I)_{max}$

l/S	$R_1\cdot10^3$, Ohm	$R_2\cdot10^3$, Ohm	I_{max1}, A	I_{max2}, A	I, A	n_1, pcs.	n_2, pcs.	n_1+n_2, pcs.	U_1, V	U_2, V	U_Σ, V	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
n_1/n_2=0.5 T_1=263 K; B_1=0.665; B_2=0.602; Θ_1=0.846; Θ_2=0.445; K_{T1}=1.052; K_{T2}=1.02; W_1=27.5 W; W_2=64.0 W; W_Σ=91.5 W; E=0.0109; C_1=0.0416														
40	33.0	40.4	1.153	1.274	0.767	548	1096	1644	35.8	83.4	119.2	261.2	783.5	0.9246
20	16.5	20.2	2.307	2.549	1.53	273.7	547.5	821.2	18.0	41.8	59.8	130.4	391.3	0.9616
10	8.26	10.1	4.61	5.10	3.07	137	273.9	411.0	8.96	20.8	29.8	65.2	195.7	0.9801
4.5	3.72	4.55	10.23	11.31	6.80	61.8	123.5	185.3	4.0	9.41	13.4	29.4	58.8	0.9941
2.0	1.65	2.02	23.1	25.5	15.4	27.3	54.6	81.9	1.8	4.2	6.0	13.0	39.0	0.9961
n_1/n_2=0.33 T_1=258 K; B_1=0.715; B_2=0.667; Θ_1=0.746; Θ_2=0.552; K_{T1}=1.052; K_{T2}=1.025; W_1=7.35 W; W_2=27.5 W; W_Σ=34.8 W; E=0.0287; C_1=0.1726														
40	32.26	40.0	1.159	1.242	0.83	133.7	401.1	534.8	8.86	33.2	42.0	120.7	362.0	0.9644
20	16.1	20.0	2.32	2.503	1.66	66.7	200.0	266.7	4.42	16.6	21.0	60.2	180.6	0.9821
10	8.06	10.0	4.64	5.0	3.32	33.4	100.2	133.6	2.21	8.28	10.5	30.2	90.5	0.9910
4.5	3.63	4.5	10.3	11.12	7.36	15.0	45.1	60.1	1.0	3.74	4.74	13.6	40.7	0.9959
2.0	1.61	2.0	23.2	25.0	16.6	6.67	20.0	26.7	0.44	1.66	2.10	6.0	18.0	0.9982
n_1/n_2=0.2 T_1=251 K; B_1=0.765; B_2=0.728; Θ_1=0.63; Θ_2=0.68; K_{T1}=1.052; K_{T2}=1.027; W_1=4.34 W; W_2=14.42 W; W_Σ=18.8 W; E=0.0532; C_1=0.318														
40	31.75	39.2	1.164	1.223	0.89	73.2	365.5	438.6	4.88	16.2	21.2	136.7	273.3	0.9730
20	15.87	19.6	2.329	2.459	1.78	36.5	182.5	219.0	2.44	8.10	10.5	68.2	204.7	0.97974
10	7.94	9.8	4.655	4.92	3.56	18.3	91.4	109.7	1.22	4.05	5.3	34.2	102.5	0.9898
4.5	3.57	4.41	10.35	10.93	7.92	8.2	41.1	49.3	0.55	1.89	2.37	15.3	45.9	0.9954
2.0	1.59	1.96	23.3	24.6	17.8	3.6	18.3	21.9	0.24	0.81	1.05	6.82	20.46	0.9980
n_1/n_2=0.1 T_1=245 K; B_1=0.815; B_2=0.80; Θ_1=0.52; Θ_2=0.81; K_{T1}=1.052; K_{T2}=1.031; W_1=3.39 W; W_2=47.6 W; W_Σ=51.0 W; E=0.0196; C_1=0.4474														
40	30.77	38.46	1.173	1.196	0.956	52.8	528	580.8	3.55	49.8	53.4	259.4	778.2	0.9251
20	15.4	19.23	2.343	2.42	1.91	26.4	264.0	290.4	1.77	24.9	26.7	129.7	389.1	0.9618
10	7.69	9.62	4.69	4.84	3.82	13.2	132	145.2	0.89	12.46	13.4	64.85	194.6	0.9807
4.5	3.46	4.33	10.43	10.75	8.50	5.9	59.0	64.9	0.40	5.6	6.0	29.0	87.0	0.99134
2.0	1.54	1.92	23.4	24.2	19.1	2.64	26.4	29.0	0.18	2.49	2.67	13.0	38.9	0.9961

Table 4

Basic parameters and indicators of reliability of the two-cascade cooler at ΔT=90 K, T=300 K, Q_0=1.0 W, N=2, $(I/S)_1=(I/S)_2=I/S$=var for different values of ratio n_1/n_2 under mode $(Q_0/I)_{max}$

l/S	$R_1\cdot10^3$, Ohm	$R_2\cdot10^3$, Ohm	I_{max1}, A	I_{max2}, A	I, A	n_1, pcs.	n_2, pcs.	n_1+n_2, pcs.	U_1, V	U_2, V	U_Σ, V	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
n_1/n_2=0.2 T_1=250 K; B_1=0.845; B_2=0.772; Θ_1=0.866; Θ_2=0.71; K_{T1}=1.062; K_{T2}=1.029; W_1=15.8 W; W_2=105.0 W; W_Σ=120.8 W; E=0.0083; C_1=0.11; C_2=0.24														
40	30.77	39.2	1.12	1.224	0.945	236	1180	1416	16.7	111.0	127.7	584.8	1754	0.83912
20	15.4	19.6	2.239	2.43	1.89	117.9	589.5	707.4	8.35	55.5	63.9	292.2	876.5	0.9161
10	7.69	9.8	4.48	4.86	3.79	58.9	295	353.5	4.17	27.8	32.0	146.0	438.0	0.9571
4.5	3.46	4.41	9.95	10.8	8.41	26.5	132.6	159.1	1.88	12.5	14.4	65.7	197.2	0.9805
2.0	1.54	1.96	22.4	24.3	18.9	11.8	59.0	70.8	0.84	5.55	6.40	29.3	87.8	0.99126
n_1/n_2=0.1 T_1=244 K; B_1=0.89; B_2=0.85; Θ_1=0.80; Θ_2=0.83; K_{T1}=1.062; K_{T2}=1.032; W_1=9.84 W; W_2=135.8 W; W_Σ=145.6 W; E=0.0069; C_1=0.19; C_2=0.146														
40	29.85	38.46	1.133	1.186	1.0	137.4	1374	1511	9.84	135.8	145.6	866.8	2600	0.77105
20	14.92	19.23	2.266	2.41	2.0	68.7	687	755.7	4.92	67.9	72.8	433.4	1300	0.871
10	7.463	9.62	4.53	4.82	4.03	34.4	344	378.4	2.44	33.7	36.1	217.0	651	0.9370
4.5	3.36	4.33	10.0	10.71	8.9	15.7	157	172.7	1.11	15.3	16.4	99.0	297.0	0.9707
2.0	1.49	1.92	22.7	24.15	20.2	6.9	69	75.9	0.49	6.72	7.20	43.5	130.6	0.9870
n_1/n_2=0.05 T_1=240 K; B_1=0.912; B_2=0.88; Θ_1=0.71; Θ_2=0.91; K_{T1}=1.062; K_{T2}=1.036; W_1=6.81 W; W_2=194.7 W; W_Σ=201.5 W; E=0.0050; C_1=0.282; C_2=0.079														
40	29.80	38.4	1.133	1.176	1.03	92.5	1851	1944	6.62	189.0	195.6	1253	3757	0.6868
20	14.93	19.23	2.264	2.371	2.06	46.3	926.8	973.1	3.31	94.5	97.8	633.5	1900	0.8270
10	7.46	9.62	4.53	4.74	4.13	23.2	463.1	486.3	1.65	47.1	48.8	316.6	949.8	0.9094
4.5	3.36	4.33	10.0	10.53	9.12	10.6	211.0	221.6	0.75	21.3	22.0	144.2	432.7	0.9577
2.0	1.49	1.92	22.7	23.75	20.7	4.6	92.4	97.0	0.33	9.40	9.73	63.1	189.4	0.9812

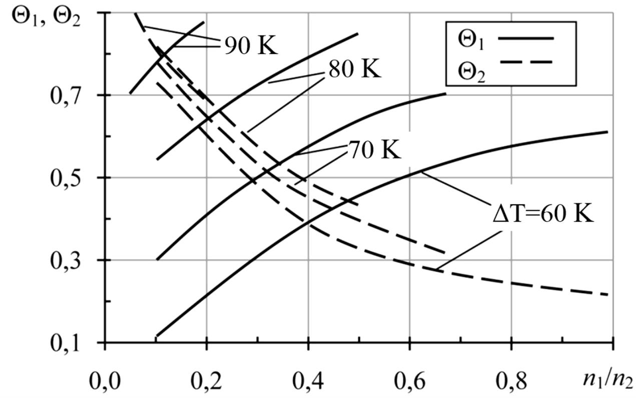
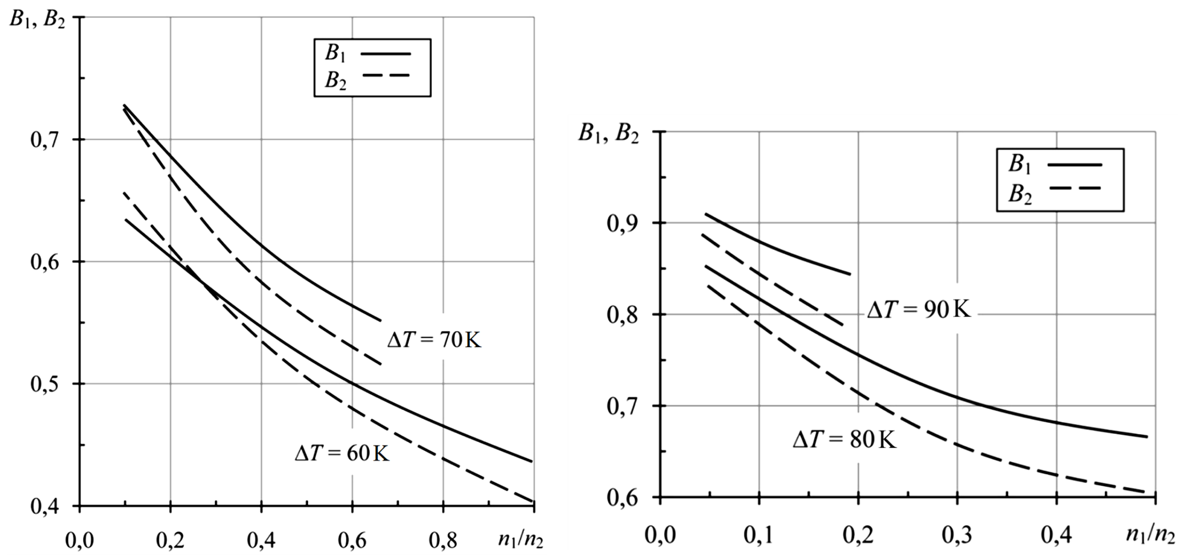
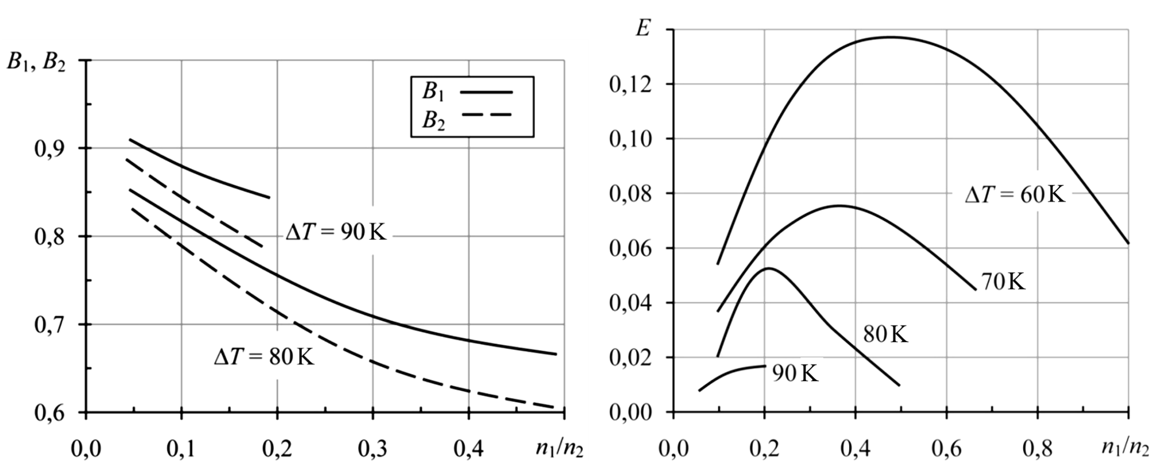


Fig. 2. Dependence of relative temperature differential of the first (Θ_1) and the second (Θ_2) cascades of the two-cascade cooler on the ratio n_1/n_2 for different values of ΔT at T=300 K; Q_0=1.0 W under mode $(Q_0/I)_{max}$



a *b*

Fig. 3. Dependence of relative operating current of the first (B_1) and the second (B_2) cascades of the two-cascade cooler on the ratio n_1/n_2 at T=300 K; Q_0=1.0 W; under mode $(Q_0/I)_{max}$: *a* – ΔT=60, 70 K; *b* – ΔT=80, 90 K



a *b*

Fig. 4. Dependence of relative thermal load C_1 and refrigeration coefficient E of the two-cascade cooler on the ratio n_1/n_2 for different values of ΔT at T=300 K; Q_0=1.0 W under mode $(Q_0/I)_{max}$: *a* – thermal load C_1; *b* – refrigeration coefficient E

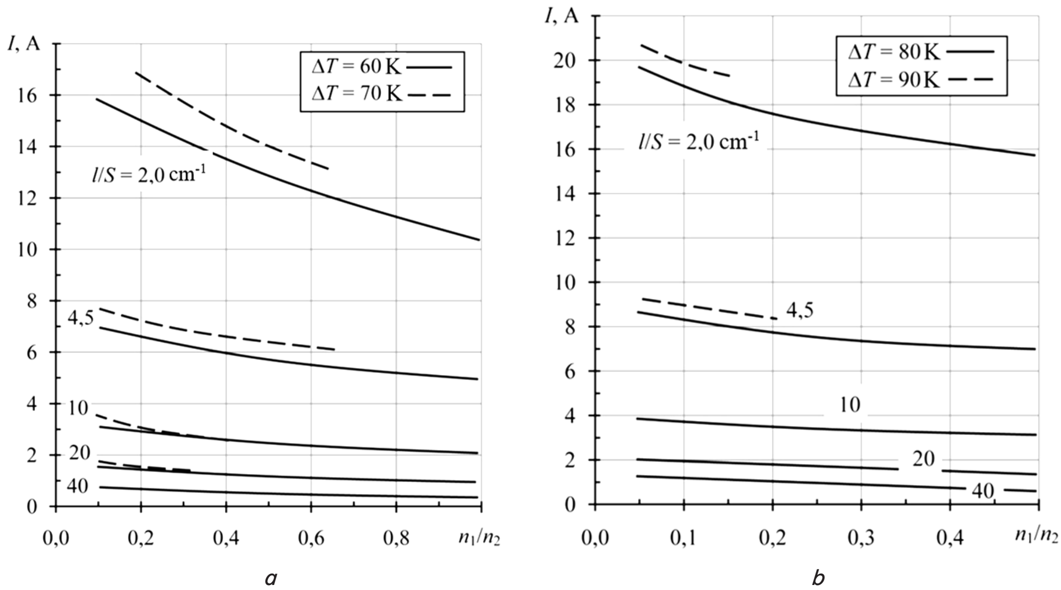


Fig. 5. Dependence of operating current I of the two-cascade cooler on the ratio n_1/n_2 for different values of l/S at T=300 K; Q_0=1.0 W under mode $(Q_0/I)_{max}$: *a* – ΔT=60, 70 K; *b* – ΔT=80, 90 K

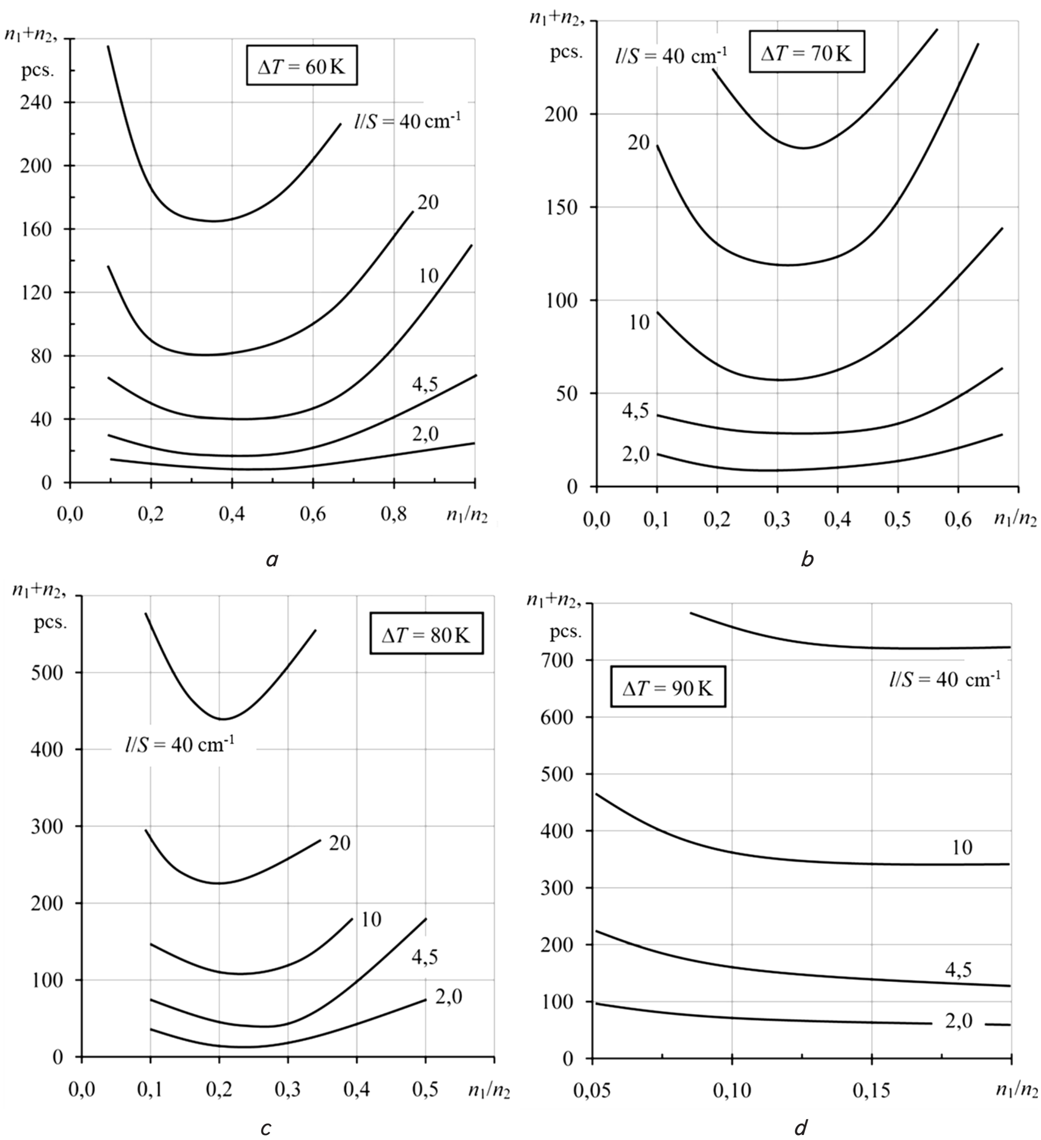


Fig. 6. Dependence of the total number of thermos elements of the two-cascade cooler on the ratio n_1/n_2 for different values of l/S at T=300 K; Q_0=1.0 W under mode $(Q_0/I)_{max}$: *a* – ΔT=60 K; *b* – ΔT=70 K; *c* – ΔT=80 K; *d* – ΔT=90 K

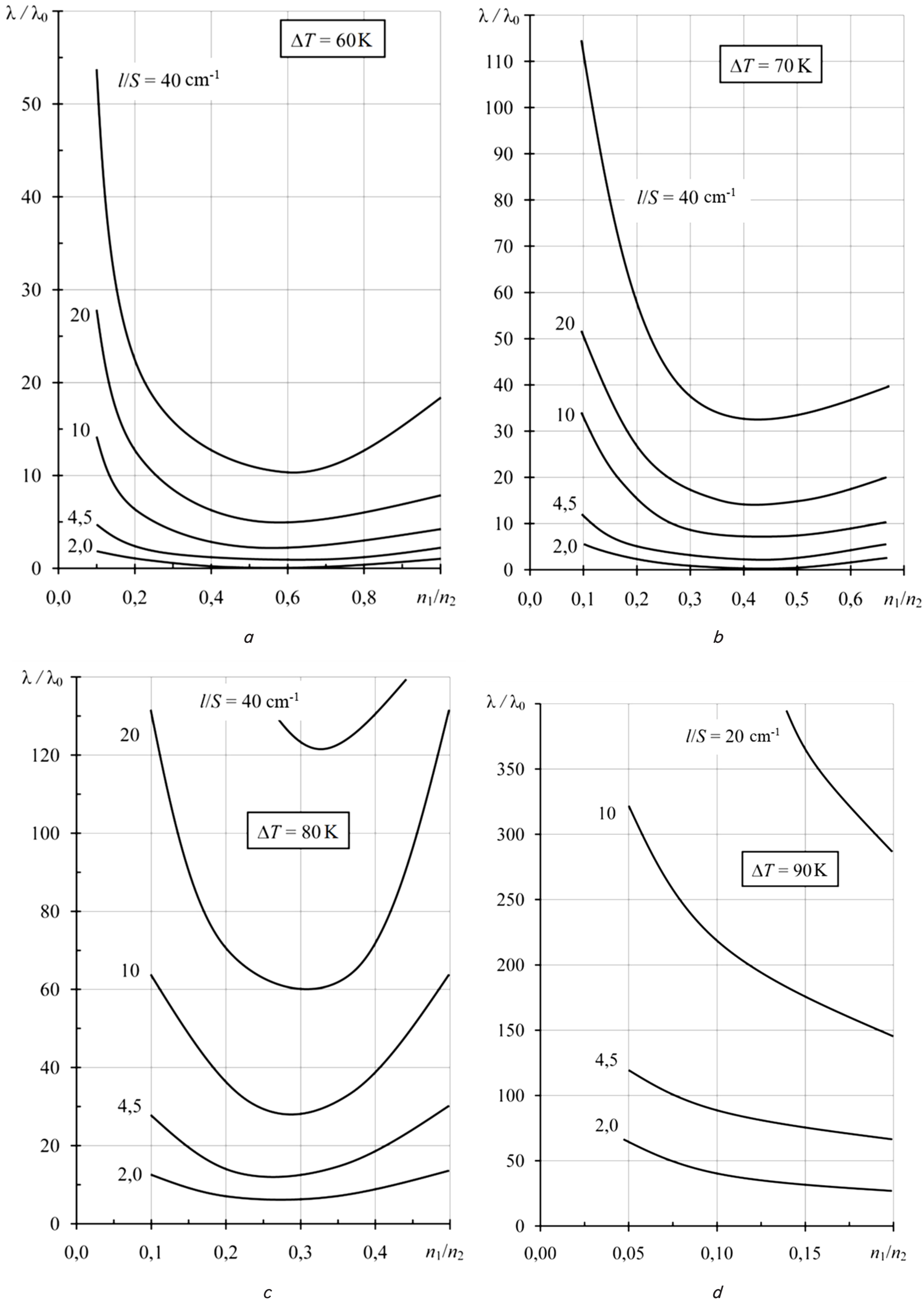


Fig. 7. Dependence of relative failure rate λ/λ_0 of the two-cascade cooler on the ratio n_1/n_2 for different values of l/S at T=300 K; Q_0=1.0 W; λ_0=3·10^{-8} 1/h; under mode $(Q_0/I)_{max}$: *a* – Δ*T*=60 K; *b* – Δ*T*=70 K; *c* – Δ*T*=80 K; *d* – Δ*T*=90 K

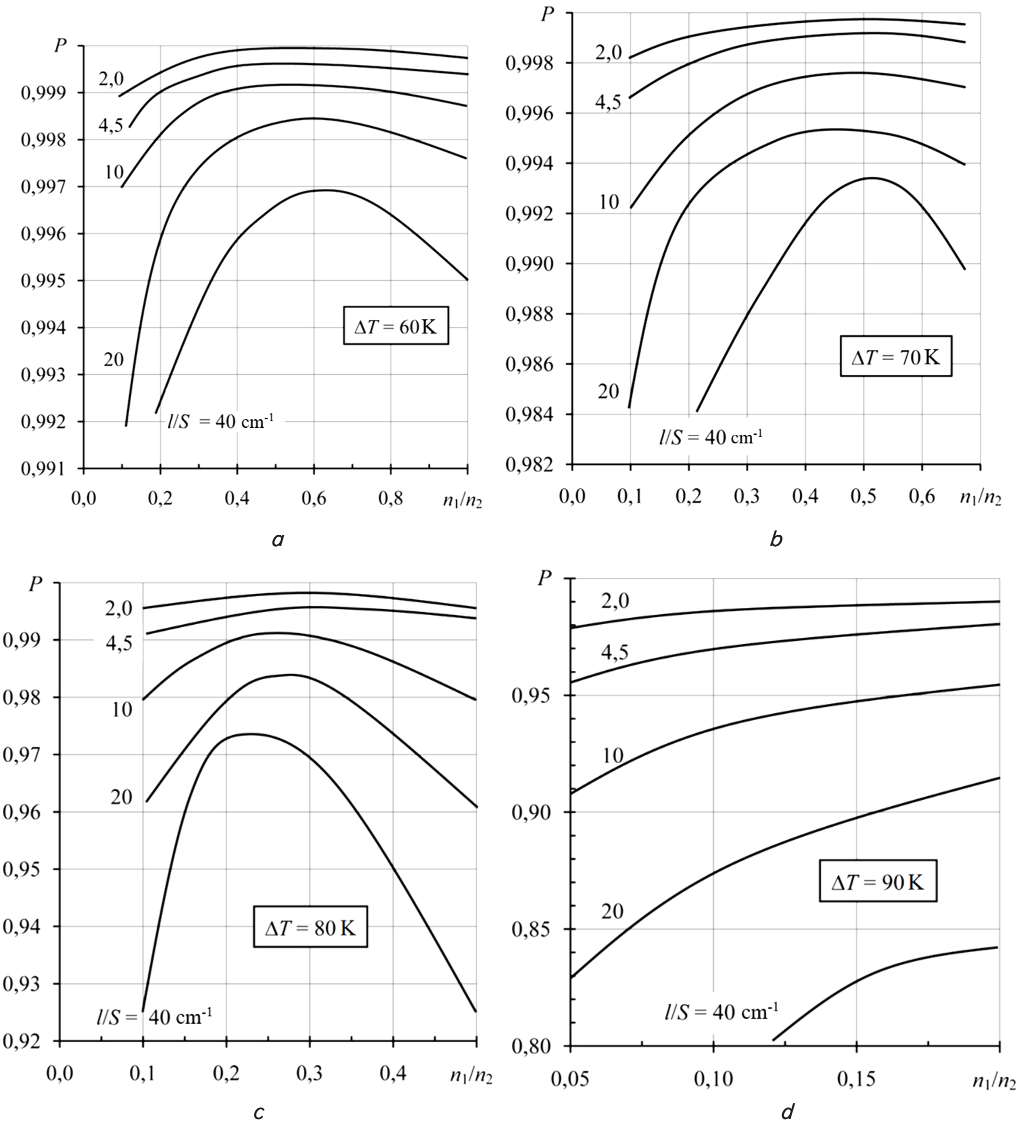


Fig. 8. Dependence of the probability of failure-free operation P of the two-cascade cooler on the ratio n_1/n_2 for different values of l/S at T=300 K; Q_0=1.0 W; t=10^4 h; under mode $(Q_0/I)_{max}$: *a* – Δ*T*=60 K; *b* – Δ*T*=70 K; *c* – Δ*T*=80 K; *d* – Δ*T*=90 K

6. Discussion of results of the analysis of influence of the geometry of branches and the distribution of thermoelements in cascades on the reliability indicators of the two-cascade TEC

Research into influence of the geometry of thermoelement branches in the cascades of thermoelectric cooler on the basic parameters and reliability indicators was performed for the regime of maximum refrigeration capacity at the assigned current, different temperature differential Δ*T*=60 K; 70 K; 80 K; 90 K and thermal load Q_0=1.0 W. In contrast to [13], where the geometry of branches of the cascades is fixed $(l/S)_1=(l/S)_2$=10, and, therefore, operating currents of the cascades are also fixed, we examined the variant $(l/S)_1=(l/S)_2$=var=40; 20; 10; 4.5; 2.0.

It follows form the conducted research that at the preset values of Δ*T* and n_1/n_2, a decrease in the ratio l/S leads to increased operating current and reduced number of thermoelements. Given the sequential order of turning on the thermoelements in a cooler, the probability of failure-free operation for which equals to the product of probabilities of separate elements, a reduction of the quantity of thermoelements leads to a growth of the probability of failure-free operation and reduction in the failure rate.

These changes could be quite considerable. For example, when reducing l/S from 10 to 4.5, the value of I increases by more than two times at Δ*T*=60 K and n_1/n_2=0.5 (from 2.6 to 2.8 A), at Δ*T*=70 K and n_1/n_2=0.5 (from 2.8 to 6.3 A), at Δ*T*=80 K and n_1/n_2=0.5 (from 3.1 to 6.8 A), at Δ*T*=90 K and n_1/n_2=0.2 (from 3.8 to 8.4 A). When reducing l/S from 10 to 4.5, the total quantity of thermoelements n_1+n_2 decreases by more than twice at Δ*T*=60 K and n_1/n_2=0.5 (from 44 to 20 pcs.), at Δ*T*=70 K and n_1/n_2=0.5 (from 80 to 35 pcs.), at Δ*T*=80 K and n_1/n_2=0.33 (from 130 to 60 pcs.), at Δ*T*=90 K and n_1/n_2=0.2 (from 355 to 160 pcs.).

As far as the failure rate is concerned, at lowering l/S from 20 to 10, the value of λ/λ_0 decreases by more than 2 times at Δ*T*=60 K and n_1/n_2=0.5 (from 6.0 to 2.5), at Δ*T*=70 K and n_1/n_2=0.5 (from 16.3 to 8.0), at Δ*T*=80 K and n_1/n_2= 0.33 (from 60 to 30), at Δ*T*=90 K and n_1/n_2=0.2 (from 290 to 145).

It is shown that the dependences of refrigeration coefficient of the two-cascade cooler and relative failure intensity on the distribution of thermoelements in the cascades demonstrate clearly expressed extrema in the operating temperature range, which makes it possible to receive additional gain on the mass and weight parameters of designed products by reducing the required number of thermoelements and by the optimization of energy distribution in the cascades.

7. Conclusions

1. We designed a reliability-oriented model of the two-cascade thermoelectric cooling device that links reliability indicators of the cooler and the geometry of thermoelements, distribution of thermoelements in the cascades, differences of temperatures in the cascades, operating currents, and thermal load.

2. It is shown that with a decrease in the geometry of thermoelements in the cascades from 10 to 2, the total number of thermoelements decreases and the failure rate reduces by more than twice. Joint application of the variation of geometry and the optimized distribution of thermoelements in the cascades within the operating range of temperature differential makes it possible to lower the failure rate up to 10 times and to reduce mass and weight parameters of the two-cascade coolers.

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