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RELIABLY-ORIENTED ANALYSIS OF A SINGLE STAGE COOLER THERMOELEMENT CONSTRUCTION

Наведено порівняльний аналіз основних параметрів і показників надійності однокаскадного термоелектричного охолоджуючого пристрою при варіації відношення довжини термоелемента до його перетину. Аналіз виконано для перепадів температури в діапазоні працездатності пристрою і різних режимів функціонування з урахуванням енергетичних і конструктивних обмежень. Показана можливість вибору геометрії гілок термоелементу за критерієм мінімуму інтенсивності відмов.

Ключові слова: *термоелектричний охолоджуючий пристрій, режим роботи, показники надійності, геометрія гілок термоелементів.*

1. Introduction

Requirement strengthening for modern radio electronic equipment and increasing its complexity lead to a decrease in reliability indicators. This is especially true for thermally-loaded elements, which can't function without heat regimes, since the increase in thermal load significantly affects their viability. The most promising systems of this type are thermoelectric coolers (TEC), which differ from air and liquid systems with small dimensions and weight and increased reliability. This is due to the fact that thermoelectric coolers do not have mobile components, which ensures reliable operation in conditions of vibrations, position in space, changes in external environment pressure. Since the thermally-loaded element and the thermoelectric cooler are connected in series according to the reliability model, the reliability of the cooler directly affects the failure rate of the thermally-loaded elements and the entire system as a whole. The result can be not only the failure of the electronic control system of the object, but also the facility's failure, resulting in significant material costs and human losses. Therefore, the issues of improving the reliability of thermoelectric coolers as systems for ensuring the thermal regimes thermally-loaded elements are topical.

2. The object of research and its technological audit

The object of research is the model of the relationship between the reliability index and the energy indicators and constructive parameters of thermoelectric cooler thermoelements.

In thermoelectric instrument engineering, various unified module constructions and devices based on them with different geometry (the ratio of length to section) of the thermoelement branches are used. Therefore, there is a question for equipment developer about choosing the optimal geometry of the thermoelement branches taking into account the weight of each of the limiting factors and various operating conditions. The problems of the effect of the geometry of thermoelements on the cooling capacity are considered in sufficient detail [1], however, the relationship with the reliability indicators of the thermoelectric cooler has not been investigated. The prospect of the problem consists in revealing the connection between the geometry of thermoelements and reliability indicators, as one of the components of the operational reliability of thermoelectric coolers.

3. The aim and objectives of research

The aim of the work is a comparative analysis of the models of interrelation of reliability indicators and the geometry of the thermoelement branches for increasing the reliability indicators of a single stage TEC in various operating conditions.

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

1. To carry out a study of the relationship between reliability indicators and energy parameters and constructive parameters of the fuel and energy complex.
2. To analyze the effect of the geometry of the thermoelements on the energy and structural parameters of the thermoelectric cooler to ensure the choice of the best option based on the criterion of the minimum failure rate.

4. Research of existing solutions of the problem

The future of thermoelectric coolers for fundamental applications in heat-supply systems is based on high speed and easy control of the cooler [2]. One of the main factors constraining the distribution of the thermoelectric cooling method is the lower cooling capacity in comparison with the compression systems. Therefore, much attention is paid to the development of materials with increased thermoelectric efficiency [3]. However, the most important indicator of the power plant is reliability [4], and, first of all, operational. The reliability of the cooler is determined by the value of the thermal load [5], the operating mode in the range from the maximum cooling capacity to the minimum of the failure rate [6], the number of thermocouples [7], the dynamics of the operating current change [8]. The structural features of the thermoelectric cooler also have a significant impact on the reliability indexes [9]. The transition from a volumetric technology of constructing thermoelectric devices to a planar one represents a promising direction, but at the same time the cooling capacity

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is significantly deteriorated, which is caused by an increase in thermal losses between the plates through thermoelements [10]. This led to the fact that the vast majority of modern thermoelectric coolers are manufactured using volumetric technology [11].

5. Methods of research

As methods of research, let's use mathematical modeling [12], since it is the analytical reliability-oriented approach that will allow to obtain solutions that can be used at the design stage. This allows to predict reliability indicators at the design stage and compare design solutions based on reliability criteria and energy indicators. The result is not only a cheaper production of thermoelectric coolers, but also an increase in their operational reliability.

5.1. Analysis of interrelation models of reliability indicators with energy indicators and constructive parameters. Let's analyze the geometry effect of the thermoelement branches on the main parameters and reliability indicators of a single stage TEC for various temperature differences ΔT in the range from 0 to 60 K. For this let's use the relations [12].

TEC cooling capacity Q_0 can be written as:

$$Q_0 = nI_{\max}^2 R\left(2B - B^2 - \Theta\right) = n\gamma\left(2B - B^2 - \Theta\right), \qquad (1)$$

where n – the number of thermoelements, pieces; $I_{\max} = \bar{e}T_0/R$ – maximum operating current, A; $R = l/\bar{\sigma}S$ – electrical resistance of the thermoelement branch, Ohm; $\bar{e}$, $\bar{\sigma}$ – average values of thermal EMF, V/K, and electrical conductivity, S/cm, of the thermoelement branches, respectively; T_0 – the heat-absorbing junction temperature, K; B – relative operating current $B = I/I_{\max}$, rel. units; I – the working current, A; Θ – relative temperature drop, $\Theta = \Delta T/\Delta T_{\max} = (T - T_0)/\Delta T_{\max}$, rel. units; T – temperature of heat-removing junction, K; $\Delta T_{\max}$ – the maximum temperature difference, $\Delta T_{\max} = 0.5\bar{z}T_0^2$, K; $\bar{z}$ – average thermoelectric efficiency of the thermoelement branch, 1/K; γ – the maximum thermoelectric cooling power, $\gamma = I_{\max}^2 R = \bar{e}^2\bar{\sigma}T_0^2 S/l$, W.

TEC power consumption W and the cooling coefficient E are determined by the expressions [12]:

$$W = 2n\gamma B(B + (\Delta T_{\max}/T_0)/\Theta). \qquad (2)$$

$$E = Q_0/W = (2B - B^2 - \Theta)/2B(B + (\Delta T_{\max}/T_0)/\Theta). \qquad (3)$$

The relative value of the failure rate λ/λ_0 can be represented in the form [12]:

$$\lambda/\lambda_0 = \frac{nB^2(\Theta + C)\left(B + (\Delta T_{\max}/T_0)\Theta\right)^2}{\left(1 + (\Delta T_{\max}/T_0)\Theta\right)^2} K_T, \qquad (4)$$

where λ_0 – the nominal failure rate, 1/h; C – relative value of the thermal load, $C = Q_0/(nI^2_{\max}R) = Q_0/(n\gamma)$; K_T – coefficient of significance, depending on temperature.

The probability of TEC failure-free operation can be determined from the known formula [13]:

$$P = \exp(-\lambda t), \qquad (5)$$

where t – the assigned resource, h.

The results of calculation of the main parameters and reliability indicators of a single stage TEC obtained for various l/S ratios and operation modes from $Q_{0\max}$ to $\lambda_{\min}$ are given in Tables 1–4.

With the same thermal load Q_0 and temperature difference ΔT for different geometry of the thermoelement branch l/S, the value:

$$n\gamma = \text{const}. \qquad (6)$$

Table 1

The results of calculation of the main parameters and reliability indicators of the thermoelectric device, obtained for various l/S ratios at $Q_0 = 2.0$ W; $T = 300$ K; $\Delta T = 10$ K; $\Delta T_{\max} = 101$ K; $\Theta = 0{,}1$; $\bar{z}_m = 2.4 \cdot 10^{-3}$ 1/K; $\bar{e} = 1.99 \cdot 10^{-4}$ V/K; $\bar{\sigma} = 920$ S/cm; $\lambda_0 = 3 \cdot 10^{-8}$ 1/h; $t = 10^4$ h

l/S, cm^{-1}	Operating mode	B, rel. units	I, A	U, V	W, W	n, items	E	λ/λ_0	$\lambda \cdot 10^8$, 1/h	P	$a \times b$, mm
40.0	$I_{\max} = 1.33$ A; $R = 43.5 \cdot 10^{-3}$ Ohm; $\gamma = 0.077$ W										
	$Q_{0\max}$	1.0	1.33	3.4	4.60	28.9	0.435	29.1	87.3	0.9913	1.0×1.0
	$(Q_0/I)_{\max}$	0.316	0.42	2.45	1.03	60.2	1.94	0.37	1.11	0.999889	
	$(Q_0/I^2)_{\max}$	0.10	0.133	4.51	0.60	289	3.33	0.0094	0.028	0.9999972	
	$\lambda_{\min}$	0.071	0.094	8.64	0.812	709	2.46	0.0052	0.0155	0.99999845	
20.0	$I_{\max} = 2.66$ A; $R = 21.7 \cdot 10^{-3}$ Ohm; $\gamma = 0.154$ W										
	$Q_{0\max}$	1.0	2.66	1.73	4.60	14.5	0.435	14.6	43.8	0.9956	1.41×1.41
	$(Q_0/I)_{\max}$	0.316	0.82	1.23	1.03	30.2	1.94	0.185	1.555	0.999944	
	$(Q_0/I^2)_{\max}$	0.10	0.266	2.26	0.60	144.7	3.33	0.0047	0.0141	0.9999986	
	$\lambda_{\min}$	0.071	0.189	4.30	0.812	336	2.46	0.00245	0.00735	0.99999926	
10.0	$I_{\max} = 5.29$ A; $R = 10.9 \cdot 10^{-3}$ Ohm; $\gamma = 0.305$ W										
	$Q_{0\max}$	1.0	5.29	0.87	4.60	7.30	0.435	7.35	22.0	0.9978	2.0×2.0
	$(Q_0/I)_{\max}$	0.316	1.67	0.62	1.03	15.1	1.94	0.093	0.28	0.999970	
	$(Q_0/I^2)_{\max}$	0.10	0.53	1.13	0.60	72.2	3.33	0.00235	0.0070	0.9999993	
	$\lambda_{\min}$	0.071	0.376	2.16	0.812	167.0	2.46	0.00122	0.00366	0.99999963	
4.5	$I_{\max} = 11.8$ A; $R = 4.89 \cdot 10^{-3}$ Ohm; $\gamma = 0.681$ W										
	$Q_{0\max}$	1.0	11.8	0.39	4.60	3.3	0.435	3.32	9.97	0.9990	3.0×3.0
	$(Q_0/I)_{\max}$	0.316	3.73	0.28	1.03	6.8	1.94	0.042	0.125	0.999997	
	$(Q_0/I^2)_{\max}$	0.10	1.18	0.51	0.60	32.6	3.33	0.00106	0.0032	0.99999970	
	$\lambda_{\min}$	0.071	0.84	0.97	0.812	75.1	2.46	0.00055	0.00164	0.99999984	
2.0	$I_{\max} = 26.6$ A; $R = 2.17 \cdot 10^{-3}$ Ohm; $\gamma = 1.54$ W										
	$Q_{0\max}$	1.0	26.6	0.173	4.60	1.45	0.435	1.46	4.38	0.99956	4.5×4.5
	$(Q_0/I)_{\max}$	0.316	8.40	0.123	1.03	3.0	1.94	0.019	0.057	0.9999943	
	$(Q_0/I^2)_{\max}$	0.10	2.66	0.23	0.60	14.5	3.33	0.00047	0.00141	0.99999986	
	$\lambda_{\min}$	0.071	1.89	0.43	0.812	33.4	2.46	0.00024	0.00073	0.99999993	

Table 2

The results of calculation of the main parameters and reliability indicators of the thermoelectric device, obtained for various l/S ratios at $Q_0=2.0$ W; $T=300$ K; $\Delta T=20$ K; $\Delta T_{max}=93.3$ K; $\Theta=0.214$; $\bar{z}_m=2.4\cdot10^{-3}$ 1/K; $\bar{e}=1.97\cdot10^{-4}$ V/K; $\bar{\sigma}=940$ S/cm; $\lambda_0=3\cdot10^{-8}$ 1/h; $t=10^4$ h

l/S, cm^{-1}	Operating mode	B, rel. units	I, A	U, V	W, W	n, items	E	λ/λ_0	$\lambda\cdot10^8$, 1/h	P	$a\times b$, mm
40.0	$I_{max}=1.295$ A; $R=42.6\cdot10^{-3}$ Ohm; $\gamma=0.071$ W										1.0×1.0
	Q_{0max}	1.0	1.295	4.2	5.45	35.4	0.367	35.4	106.2	0.9894	
	$(Q_0/I)_{max}$	0.463	0.60	3.33	2.0	55.8	1.0	1.35	4.0	0.99960	
	$(Q_0/I^2)_{max}$	0.214	0.28	5.3	1.45	166.4	1.38	0.21	0.63	0.999937	
	λ_{min}	0.146	0.19	11.7	2.23	493	0.90	0.118	0.354	0.999965	
20.0	$I_{max}=2.6$ A; $R=21.3\cdot10^{-3}$ Ohm; $\gamma=0.144$ W										1.40×1.40
	Q_{0max}	1.0	2.6	2.10	5.45	17.8	0.367	17.8	53.4	0.9947	
	$(Q_0/I)_{max}$	0.463	1.20	1.67	2.0	28.2	1.0	1.08	3.2	0.99968	
	$(Q_0/I^2)_{max}$	0.214	0.56	2.64	1.45	83.2	1.38	0.104	0.31	0.999970	
	λ_{min}	0.146	0.38	5.90	2.23	247	0.90	0.059	0.177	0.999982	
10.0	$I_{max}=5.2$ A; $R=10.64\cdot10^{-3}$ Ohm; $\gamma=0.288$ W										2.0×2.0
	Q_{0max}	1.0	5.2	1.05	5.45	8.9	0.367	10.8	32.3	0.9968	
	$(Q_0/I)_{max}$	0.463	2.41	0.83	2.0	14.1	1.0	0.54	1.62	0.99984	
	$(Q_0/I^2)_{max}$	0.214	1.11	1.31	1.45	41.6	1.38	0.52	0.156	0.999984	
	λ_{min}	0.146	0.76	2.90	2.23	123	0.90	0.030	0.089	0.9999911	
4.5	$I_{max}=11.5$ A; $R=4.8\cdot10^{-3}$ Ohm; $\gamma=0.635$ W										3.0×3.0
	Q_{0max}	1.0	11.5	0.47	5.45	4.0	0.367	4.0	12.1	0.9988	
	$(Q_0/I)_{max}$	0.463	5.32	0.38	2.0	6.0	1.0	0.23	0.68	0.999932	
	$(Q_0/I^2)_{max}$	0.214	2.46	0.59	1.45	17.6	1.38	0.022	0.066	0.9999934	
	λ_{min}	0.146	1.68	0.33	2.23	52.2	0.90	0.0125	0.038	0.9999963	
2.0	$I_{max}=25.9$ A; $R=2.13\cdot10^{-3}$ Ohm; $\gamma=1.53$ W										4.5×4.5
	Q_{0max}	1.0	25.9	0.21	5.45	1.8	0.367	1.82	4.46	0.99945	
	$(Q_0/I)_{max}$	0.463	12.0	0.17	2.0	2.8	1.0	0.11	0.32	0.999968	
	$(Q_0/I^2)_{max}$	0.214	5.54	0.26	1.45	8.3	1.38	0.010	0.03	0.999997	
	λ_{min}	0.146	3.78	0.60	2.23	24.7	0.90	0.0059	0.018	0.9999982	

Table 3

The results of calculation of the main parameters and reliability indicators of the thermoelectric device, obtained for various l/S ratios at $Q_0=2.0$ W; $T=300$ K; $\Delta T=40$ K; $\Delta T_{max}=79.8$ K; $\Theta=0.5$; $\bar{z}_m=2.37\cdot10^{-3}$ 1/K; $\bar{e}=1.94\cdot10^{-4}$ V/K; $\bar{\sigma}=980$ S/cm

l/S, cm^{-1}	Operating mode	B, rel. units	I, A	U, V	W, W	n, items	E	λ/λ_0	$\lambda\cdot10^8$, 1/h	P	$a\times b$, mm
40.0	$I_{max}=1.295$ A; $R=42.6\cdot10^{-3}$ Ohm; $\gamma=0.071$ W										1.0×1.0
	Q_{0max}	1.0	1.24	7.45	9.24	64.0	0.216	65.4	196.2	0.9806	
	$(Q_0/I)_{max}$	0.71	0.88	6.7	5.90	76.7	0.34	20.4	61.2	0.9939	
	$(Q_0/I^2)_{max}$	0.50	0.62	8.4	5.21	128.0	0.38	7.98	23.6	0.9976	
	λ_{min}	0.40	0.49	12.8	6.34	229	0.315	5.52	16.6	0.99	
20.0	$I_{max}=2.6$ A; $R=21.3\cdot10^{-3}$ Ohm; $\gamma=0.144$ W										1.40×1.40
	Q_{0max}	1.0	2.47	3.74	9.24	32.0	0.216	32.7	98.1	0.9902	
	$(Q_0/I)_{max}$	0.71	1.75	3.40	5.90	38.5	0.34	10.2	30.6	0.9969	
	$(Q_0/I^2)_{max}$	0.50	1.24	4.22	5.21	64.0	0.38	3.94	11.8	0.9988	
	λ_{min}	0.40	1.0	6.40	6.27	114.3	0.32	2.76	8.30	0.99917	
10.0	$I_{max}=5.2$ A; $R=10.64\cdot10^{-3}$ Ohm; $\gamma=0.288$ W										2.0×2.0
	Q_{0max}	1.0	4.95	1.87	9.24	16.1	0.216	16.45	49.4	0.9951	
	$(Q_0/I)_{max}$	0.71	3.50	1.70	5.90	19.3	0.34	5.1	15.4	0.9985	
	$(Q_0/I^2)_{max}$	0.50	2.48	2.10	5.21	32.1	0.38	1.98	5.94	0.99941	
	λ_{min}	0.40	2.0	3.20	6.27	57.4	0.32	1.39	4.20	0.99958	
4.5	$I_{max}=11.5$ A; $R=4.8\cdot10^{-3}$ Ohm; $\gamma=0.635$ W										3.0×3.0
	Q_{0max}	1.0	11.0	0.84	9.24	7.2	0.216	7.40	22.1	0.9978	
	$(Q_0/I)_{max}$	0.71	7.8	0.76	5.90	8.7	0.34	2.30	6.9	0.99931	
	$(Q_0/I^2)_{max}$	0.50	5.50	0.95	5.21	14.4	0.38	0.89	2.67	0.99973	
	λ_{min}	0.40	4.4	1.44	6.27	25.8	0.32	0.625	1.87	0.99981	
2.0	$I_{max}=25.9$ A; $R=2.13\cdot10^{-3}$ Ohm; $\gamma=1.53$ W										4.5×4.5
	Q_{0max}	1.0	25.2	0.37	9.24	3.2	0.216	3.27	3.27	0.9990	
	$(Q_0/I)_{max}$	0.71	17.5	0.34	5.90	3.9	0.34	1.02	1.02	0.99970	
	$(Q_0/I^2)_{max}$	0.50	12.4	0.42	5.21	6.4	0.38	0.40	0.40	0.99988	
	λ_{min}	0.40	10.0	0.64	6.27	11.5	0.32	0.28	0.28	0.999917	

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Table 4

The results of calculation of the main parameters and reliability indicators of the thermoelectric device, obtained for various l/S ratios at $Q_0=2.0$ W; $T=300$ K; $\Delta T=60$ K; $\Delta T_{max}=66.8$ K; $\Theta=0.9$; $\bar{z}_m=2.32\cdot10^{-3}$ 1/K; $\bar{e}=1.89\cdot10^{-4}$ V/K; $\bar{\sigma}=1030$ S/cm; $\lambda_0=3\cdot10^{-8}$ 1/h; $t=10^4$ h

l/S, cm^{-1}	Operating mode	B, rel. units	I, A	U, V	W, W	n, items	E	λ/λ_0	$\lambda\cdot10^8$, 1/h	P	$a\times b$, mm
40.0	$I_{max}=1.295$ A; $R=42.6\cdot10^{-3}$ Ohm; $\gamma=0.071$ W										
	Q_{0max}	1.0	1.17	42.7	50.0	378	0.040	391	1172	0.8894	1.0×1.0
	$(Q_0/I)_{max}$	0.95	1.11	42.3	47.0	389	0.043	333	998	0.9050	
	$(Q_0/I^2)_{max}$	0.90	1.05	43.9	46.1	420	0.043	295	884	0.9154	
	λ_{min}	0.855	1.0	47.9	47.9	477.8	0.042	277	830	0.9204	
20.0	$I_{max}=2.6$ A; $R=21.3\cdot10^{-3}$ Ohm; $\gamma=0.144$ W										
	Q_{0max}	1.0	2.34	21.4	50.0	189	0.040	195	586	0.9431	1.40×1.40
	$(Q_0/I)_{max}$	0.95	2.22	21.2	47.0	195	0.043	166	500	0.9512	
	$(Q_0/I^2)_{max}$	0.90	2.10	22.0	46.1	210	0.043	147	442	0.9568	
	λ_{min}	0.855	2.0	24.0	47.9	239	0.042	138	415	0.9594	
10.0	$I_{max}=5.2$ A; $R=10.64\cdot10^{-3}$ Ohm; $\gamma=0.288$ W										
	Q_{0max}	1.0	4.67	10.7	50.0	94.3	0.040	97.6	293	0.9711	2.0×2.0
	$(Q_0/I)_{max}$	0.95	4.44	10.6	47.0	97.3	0.043	83.2	250	0.9753	
	$(Q_0/I^2)_{max}$	0.90	2.20	11.0	46.1	105	0.043	73.7	221.1	0.9781	
	λ_{min}	0.855	4.0	12.0	47.9	119.4	0.042	69.2	207.5	0.9795	
4.5	$I_{max}=11.5$ A; $R=4.8\cdot10^{-3}$ Ohm; $\gamma=0.635$ W										
	Q_{0max}	1.0	10.4	4.81	50.0	42.5	0.040	44.0	132.0	0.9869	3.0×3.0
	$(Q_0/I)_{max}$	0.95	9.88	4.76	47.0	43.8	0.043	37.5	112.4	0.9888	
	$(Q_0/I^2)_{max}$	0.90	9.36	4.93	46.1	47.2	0.043	33.2	99.6	0.9901	
	λ_{min}	0.855	8.89	5.39	47.9	53.8	0.042	31.1	93.3	0.9907	
2.0	$I_{max}=25.9$ A; $R=2.13\cdot10^{-3}$ Ohm; $\gamma=1.53$ W										
	Q_{0max}	1.0	23.4	2.14	50.0	18.9	0.040	19.6	58.7	0.9941	4.5×4.5
	$(Q_0/I)_{max}$	0.95	22.2	2.12	47.0	19.5	0.043	16.6	50.0	0.9950	
	$(Q_0/I^2)_{max}$	0.90	21.1	2.18	46.1	21.0	0.043	14.8	44.4	0.9956	
	λ_{min}	0.855	20.0	2.40	47.9	23.9	0.042	13.8	41.4	0.9959	

Based on the data in the tables, let's perform a comparative analysis and present the results in the form of graphical dependencies.

5.2. Analysis of modeling results. Analysis of calculated data shows the following.

In all the operating modes of a single stage TEC with a decrease in the l/S ratio of the thermoelement branch for a fixed temperature difference ΔT and a given thermal load Q_0:

– the maximum cooling power γ increases (Fig. 1, curve 1);
– the required number of thermoelements n reduces (Fig. 1, curve 4);
– the value of the maximum operating current I_{max} increases (Fig. 1, curve 2);
– the value of the electrical resistance R decreases (Fig. 1, curve 3);
– the value of voltage drop U decreases;
– the intensity of failures λ decreases (Fig. 2);
– the probability of failure-free operation P increases (Fig. 3).

Such values as γ, R, I_{max} do not depend on the operating mode.

In all the operating modes of a single stage TEC with increasing temperature difference ΔT for a given thermal load Q_0 for different fixed values of the l/S ratio of the thermoelement branch:

– the maximum cooling power γ decreases (Fig. 4);
– the functional dependence of $n=f(\Delta T)$ in TEC has a pronounced minimum (except for the Q_{0max} mode), which can be explained by the presence of the maximum cooling capacity at the optimal value of ΔT (Fig. 5);
– the value of the maximum operating current I_{max} increases (Fig. 6);
– the refrigerating coefficient E decreases (Fig. 7);
– the relative operating current B increases (except for the Q_{0max} mode) (Fig. 8);
– the intensity of failures λ/λ_0 increases (Fig. 9);
– the probability of failure-free operation P decreases (Fig. 10).

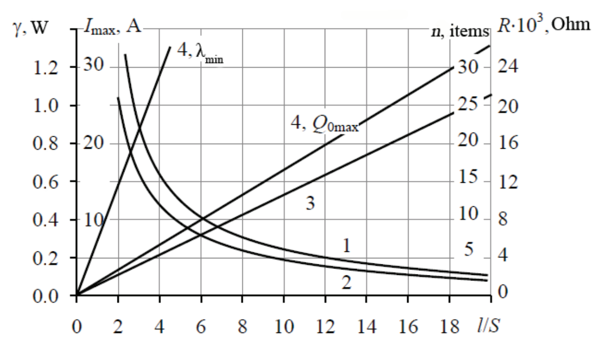

Fig. 1. Dependence of the values g, I_{max}, n, R of a single stage cooler on l/S ratio at $T=300$ K; $Q_0=2.0$ W; $\Delta T=40$ K; $l=4$ mm for different operating modes: Q_{0max} and λ_{min}: 1 – γ, 2 – I_{max}, 3 – R, 4 – n

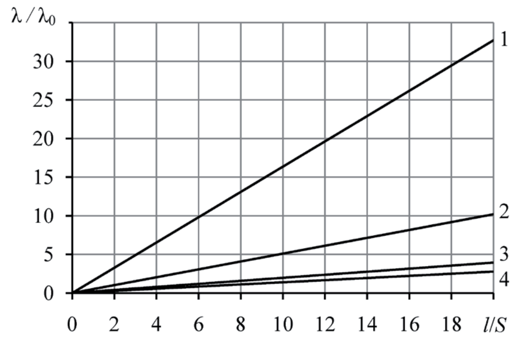

Fig. 2. Dependence of relative failure rate λ/λ_0 of a single stage cooler on l/S ratio at $T=300$ K; $Q_0=2.0$ W; $\Delta T=40$ K; $l=4$ mm for different operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

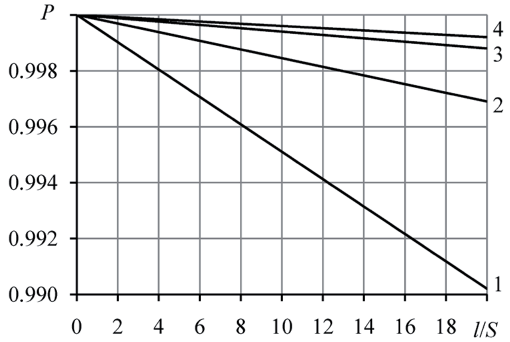

Fig. 3. Dependence of failure-free operation probability P of a single stage cooler on l/S ratio at $T=300$ K; $Q_0=2.0$ W; $\Delta T=40$ K; $l=4$ mm for different operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

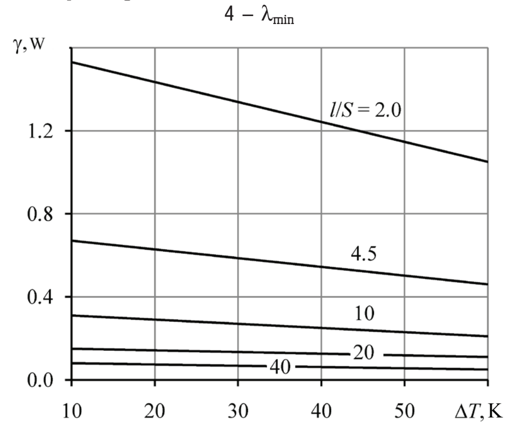

Fig. 4. Dependence of the maximum cooling power g of a single stage cooler on the temperature difference ΔT for different values of l/S ratio at $T=300$ K; $Q_0=2.0$ W; $l=4$ mm

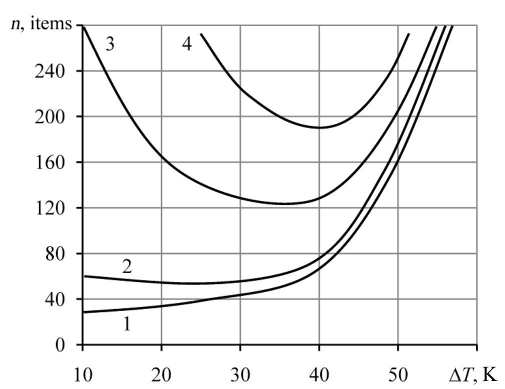

Fig. 5. Dependence of the number of thermoelements n of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W; $l/S=40$ for different operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

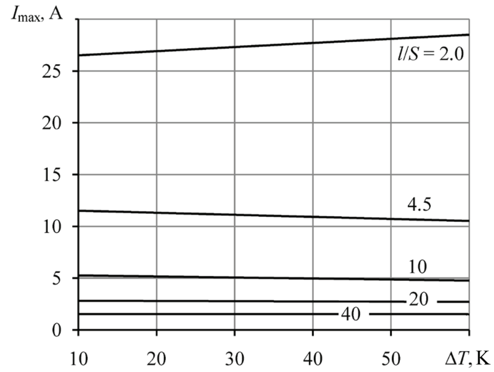

Fig. 6. Dependence of the maximum operating current $I_{\max}$ of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W; $l=4$ mm for different l/S values

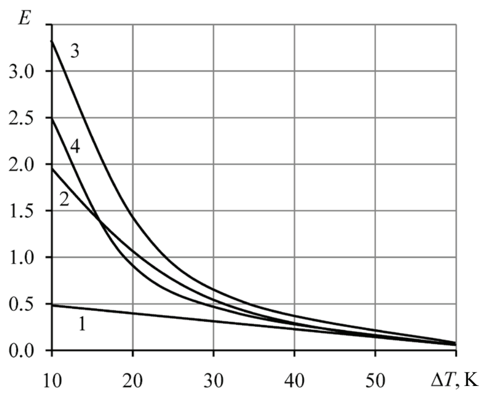

Fig. 7. Dependence of the refrigerating coefficient E of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W; $l=4$ mm for different l/S values and different operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

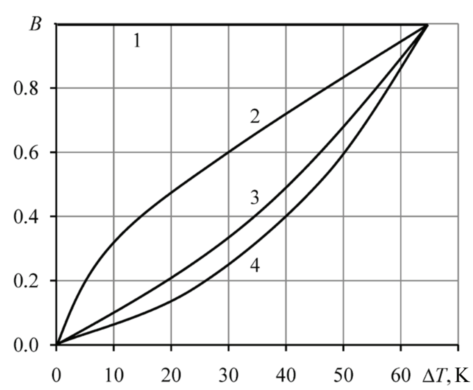

Fig. 8. Dependence of the relative operating current B of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W; $l/S=\text{var}$ for different operating modes: 1 – $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

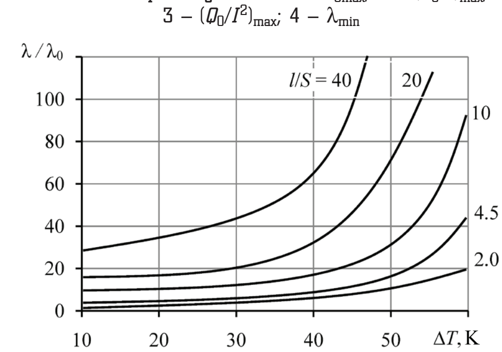

Fig. 9. Dependence of the relative failure rate λ/λ of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W for different l/S values in $Q_{0\max}$ mode

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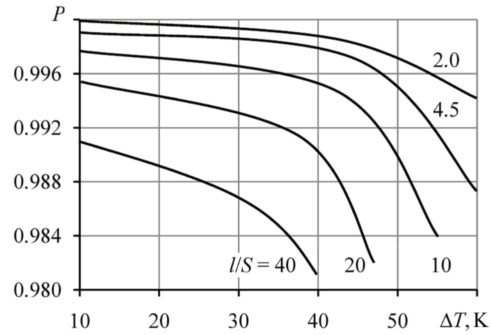

Fig. 10. Dependence of failure-free operation probability P of a single stage cooler on the temperature drop ΔT at $T=300$ K; $Q_0=2.0$ W for different l/S values in $Q_{0\max}$ mode

The values of the maximum thermoelectric cooling power and the maximum operating current $I_{\max}$ are independent of the operating mode.

6. Research results

Let's consider the possibility of choosing a construction variant of a single stage TEC that provides increased reliability indicators at acceptable power consumption and mass-dimensional characteristics.

The results of calculation of the main parameters and reliability indicators of a single stage TEC obtained for the maximum energy efficiency $(Q_0/I^2)_{\max}$ and minimum failure rates $\lambda_{\min}$ are shown in Table 5. Initial data and limiting factors:

– thermal load $Q_0=2.0$ W;
– working differential temperature $\Delta T=40$ K;
– temperature of heat-removing junction $T=300$ K;
– magnitude of the operating current I is not more than 5 A;
– failure rate λ is not more than $10\cdot10^{-8}$ 1/h;
– voltage drop U is not less than 1.5 V.

Table 5

The results of calculation of the main parameters and reliability indicators of the cooler, obtained for the modes $(Q_0/I^2)_{\max}$ and $\lambda_{\min}$ at $Q_0=2.0$ W; $T=300$ K; $\Delta T_{\max}=40$ K; $\Theta=0.5$; $l=4$ mm

l/S, cm^{-1}	Operating mode	B, rel. units	I, A	U, V	W, W	n, items	E	λ/λ_0	$\lambda\cdot10^8$, 1/h	P	$a\times b$, mm	The name of the modules and their number in TEC
20	$(Q_0/I^2)_{\max}$	0.5	1.2	4.2	5.2	64.0	0.38	3.9	11.8	0.9988	1.4×1.4	2 M20-27 2 M20-5
	$\lambda_{\min}$	0.4	1.0	6.4	6.3	114	0.32	2.8	8.3	0.99917		4 M20-27
10	$(Q_0/I^2)_{\max}$	0.5	2.5	2.1	5.2	32	0.38	2.0	6.0	0.99941	2.0×2.0	1 M10-27 1 M10-5
	$\lambda_{\min}$	0.4	2.0	3.2	6.3	57	0.32	1.4	4.2	0.99958		2 M20-27
4.5	$\lambda_{\min}$	0.4	4.4	1.5	6.3	26	0.32	0.63	1.9	0.99981	3.0×3.0	1 M4.5-27

From the data analysis it follows that from the point of view of reliability, power consumption and mass-dimension characteristics the most acceptable option is a construction with one unified module M4.5-27. The geometry of the branches of the module thermoelements is $l=4.5$ mm, $a\times b=3\times3$ mm. In this case, TEC consists of a single module, which simplifies the construction of the thermoelectric system to ensure thermal conditions. The main parameters of the thermoelectric cooler satisfy the advanced requirements:

– operating current $I=4.4$ A, which does not exceed 5 A;
– voltage drop corresponds to the requirement $U\geq1.5$ V;
– failure rate is $\lambda=1.9\cdot10^{-8}$ 1/h, which is less than the required value of $10\cdot10^{-8}$ 1/h.

At the same time, the power consumption is $W=6.3$ W, which is 20 % more than in the mode of the highest energy efficiency with minimum weight and size characteristics.

7. SWOT analysis of research results

Strengths. The strength of this research is the proof of the possibility of improving the reliability of a thermoelectric cooler by varying the geometry of thermoelements. The approach does not require a change in the technology of manufacturing coolers and the material of thermoelements. The process of calculating the geometry of thermoelements can be done at the stage of computer-aided design of thermoelectric coolers. This allows to predict the reliability of thermoelectric coolers before the production of products.

Weakness. The weak side of this research is the fact that in determining reliability indicators, the adhesion properties of the thermoelement connection with the substrate are not taken into account, which should change with decreasing the cut-off area of the thermoelement. Previously conducted experimental studies did not reveal a quantitative relationship between the cross-sectional area of the thermoelement and the reliability index of the thermoelectric cooler. This component is not taken into account by the used model and requires additional research.

Opportunities. Additional opportunities to increase the reliability of thermoelectric coolers are included in the algorithm of computer-aided design, in addition to the geometry of thermoelements, the effect of thermal load, thermoelectric material efficiency, operating modes. The result of this approach is an increase in the quality indicators (operational reliability) of thermoelectric coolers produced by the enterprise without changing the manufacturing technology and used thermoelectric materials.

Threats. Threats of practical use of the obtained results are related to the need to include in the automated design cycle algorithms for optimization calculations of the geometry of thermoelements and energy parameters of the thermoelectric cooler functioning. Therefore, in the future, it seems necessary to create an integrated reliability-oriented model and an algorithm for the design of coolers based on it. The enterprise bears the costs only for the purchase of an additional software product for the automated design of thermoelectric coolers.

Thus, SWOT analysis allows defining the main stages for improving design quality, using the proposed variant of increasing the operational reliability of thermoelectric coolers.

8. Conclusions

1. The analytical model relating the geometry of the thermoelement branches with basic parameters and reliability indicators of a single stage thermoelectric cooler is presented. The model is applicable for cooler operation modes from the maximum cooling capacity to the minimum of failure rates, temperature drop from 0 to 60 K, operating current ranges from 0.1 to 12 A, supply voltage 0.1–8 V, cooling coefficient from 0.43 to 3.3.

2. The possibility of choosing a variant of the thermoelement geometry in the range from 4.5 to 20 is shown, which provides a reduction in the failure rate of the thermoelectric cooler by more than 3 times at acceptable energy consumption and overall dimensions.

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НАДЕЖНОСТНО-ОРИЕНТИРОВАННЫЙ АНАЛИЗ КОНСТРУКЦИИ ТЕРМОЭЛЕМЕНТОВ ОДНОКАСКАДНОГО ОХЛАДИТЕЛЯ

Приведен сравнительный анализ основных параметров и показателей надежности однокаскадного термоэлектрического охлаждающего устройства при вариации отношения длины термоэлемента к его сечению. Анализ выполнен для перепадов температуры в диапазоне работоспособности устройства и различных режимов функционирования с учетом энергетических и конструктивных ограничений. Показана возможность выбора геометрии ветвей термоэлемента по критерию минимума интенсивности отказов.

Ключевые слова: термоэлектрическое охлаждающее устройство, режим работы, показатели надежности, геометрия ветвей термоэлементов.

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