Розглянуто вплив конструктивних і технологічних елементів на основні параметри, показники надійності і динаміку функціонування термоелектричних охолоджуючих пристроїв в різних струмових режимах в робочому діапазоні перепадів температур. Проаналізовані співвідношення зв'язку часу виходу на стаціонарний режим і відносної інтенсивності відмов охолоджувача з енергетичними показниками, термоелектричними параметрами термоелементів, конструктивними і технологічними показниками.

Проведено аналіз часу виходу на стаціонарний режим для різних режимів роботи від максимальної холодопродуктивності до мінімуму інтенсивності відмов. Показано, що для скорочення часу виходу на стаціонарний режим охолоджувача при заданій геометрії гілок термоелементів і перепаді температур необхідно використовувати режим максимальної холодопродуктивності.

Кількісний аналіз показав, що при заданій геометрії гілок термоелементів час виходу на стаціонарний режим роботи не залежить від кількості термоелементів термоелектричного охолоджувача. При перепаді температур, близькому до максимального значення, час виходу на стаціонарний режим роботи відрізняється незначно для всіх режимів роботи. Порівняльний аналіз основних параметрів, показників надійності і динамічних характеристик надає можливість вибору компромісних рішень при створенні термоелектричних пристроїв з врахуванням значимості кожного з обмежувальних факторів.

З практичної точки зору, одержані результати свідчать про те, що для підвищення швидкості охолоджування не потрібно міняти існуючу технологію побудови термоелектричних охолоджувачів. Управління швидкодією переходу з одного стаціонарного стану в інший відбувається вибором струмових режимів роботи термоелектричного пристрою. При цьому є можливість вибрати умови, при яких показники надійності будуть знаходитися в допустимих межах

Ключові слова: термоелектричний охолоджувач, геометрія термоелементів, вихід на стаціонарний режим, показники надійності

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ANALYSIS OF DYNAMICS AND PREDICTION OF RELIABILITY INDICATORS OF A COOLING THERMOELEMENT WITH THE PREDEFINED GEOMETRY OF BRANCHES

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1. Introduction

When designing thermoelectric cooling devices (TED), one of the main requirements in some cases is to ensure the minimum time to enter a stationary working mode. Thus, the application of laser radiation sources with thermoelectric cooling in surgery is characterized by the pulse operating mode with a variation over a wide range of energy at coagulation and tissue cutting. Reliability indicators of the semiconductor laser directly depend on its temperature, that is, on performance speed and reliability of the system that ensures thermal regimes. The dynamic characteristics of TED are defined by the thermophysical properties of the material for thermoelements, for hot and cold electrodes, the mass of thermocouples, constraints for the permissible local temperature gradients that do not promote cracking of the material. However, the cooling rate is influenced by the structural and technological elements at the heat-absorbing weld joint, which are the necessary component of the cooler. To analyze their impact under various current operational modes of TED over the working range of temperatures for the assigned geometry of thermo-elements, it is required to have a dynamic model of the cooler with respect to the structural and technological elements at a heat-absorbing weld joint. Analysis of the model in terms of minimizing the dynamic parameters of a thermoelectric cooler and in relation to the indicators of reliability is of great interest for critical systems, for which these indicators are crucial.

2. Literature review and problem statement

Modern trends in the development of radio-electronic equipment are associated with a decrease in the elements' weight and dimension parameters, expanding of the temperature range, higher operating frequencies, resulting in the elevated local temperature gradients and decreased indicators of operational reliability [1]. Thermally-loaded receiving and transmitting semiconductor elements cannot work without thermal systems that ensure thermal modes since the permissible temperature of their operation does not exceed 80 °C. The most promising, in terms of indicators for performance speed, reliability, weight, and dimensions are the thermoelectric cooling devices [2]. Stricter requirements to operating conditions for the thermo-loaded equipment in critical systems call for the same requirements to the system that ensure their thermal regimes.

The pulse character of a thermal load requires maximally fast reaction from thermoelectric coolers, because an uncompensated temperature difference can cause a failure in the thermo-loaded element. Improving the performance speed of a thermoelectric cooling system contradicts the improvement of reliability indicators, because in this case there is a rise in the temperature gradients that reduce the reliability of the product. This is a fundamental problem that cannot be resolved by employing a single approach [3].

The task on improving the reliability indicators of thermoelectric coolers is addressed from various standpoints: through rational design [4], technology and structure of modules fabrication [5], selection of a material for thermoelements [6, 7], protection of thermoelements against the effects of external medium [8], designs of thermoelement branches [9], influence of mechanical [10], heat loads [11]. The result of such a multifactor approach is the improved resultant probability for a failure-free TED operation. However, stricter requirements to the performance speed of modern equipment necessitate the search for new ways to improve reliability indicators of thermoelectric coolers.

Studying the dynamic characteristics of TED has been addressed by fewer papers [12], which is related to the fact that in terms of performance speed the air and liquid cooling systems are considerably inferior to the thermoelectric ones. Operation under a switch mode is the most complicated because it creates the maximum temperature gradients at places where thermoelectric branches connect to electrodes. Due to the difference in the materials' thermal expansion coefficients, there form the chips and detachments, which reduces reliability indicators of the product. For this reason, the accelerated bench testing of thermoelectric modules is performed precisely under switch modes at which the products' reliability indicators deteriorate by orders of magnitude.

Construction of thermoelectric coolers, for whom the pulse load regime is the working one, is a relevant task, is aimed at ensuring the design of thermo-loaded radio electronic systems operating under extreme conditions of operation. One of the tasks of this problem is to analyze the relation between dynamic characteristics and indicators of reliability and the geometry of thermoelements' branches under various current modes.

3. The aim and objectives of the study

The aim of this study is to analyze the impact of structural and technological elements in the cooling device at the specified geometry of thermoelements' branches on duration of the transition process in conjunction with indicators of reliability for various current operation modes of TED, temperature differences, and a thermal load.

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

– to analyze the dynamical model of TED with respect to the components of the structural and technological elements of the cooler at the specified geometry of thermoelements;

– to estimate the influence of dynamical characteristics of TED on reliability indicators for basic modes of operation.

4. Analysis of the dynamical model of TED with respect to structural and technological elements

The dynamical model under consideration is an analytic representation of actual thermoelectric cooler, where we take into consideration, at the heat-absorbing weld joint, mass m and heat capacity C of the structural and technological elements (STE) while entering a stationary mode of operation in a range of temperature differences ΔT from ΔT=5 K to ΔT=60 K for different current operation modes of TED. Paper [12] derived the ratios for determining the time required to enter a stationary working mode, taking into consideration the cooled object (m_0C_0), and sufficiently enough addressed those STE that are taken into account when determining the dynamical characteristics of TED at l/S=10 cm^{-1}.

Consider the case when $m_0C_0\to 0$ and the dynamics of TED is determined only by STE:

$$\tau=\frac{\sum_i m_iC_i}{K_K\left(1+2B_K\frac{\Delta T_{\max}}{T_0}\right)}\ln\frac{\gamma B_H\left(2-B_H\right)}{2B_K-B_K^2-\Theta}, \quad (1)$$

where

$$\gamma=\frac{I^2_{\max H}R_H}{I^2_{\max K}R_K},$$

where $I^2_{\max H}R_H$ is, respectively, the maximum operating current and the electrical resistance of a thermoelement branch at the beginning of the cooling process at τ=0; $I_{\max K}$, R_K are, respectively, the maximum operating current and the electrical resistance of a thermoelement branch at the end of the cooling process; $B_K=I/I_{\max K}$ is the relative operating current at τ; $B_H=I/I_{\max H}$ is the relative operating current at τ=0; $I_{\max K}=e_KT_0/R_K$ is the maximum operating current at τ; $I_{\max H}=e_HT/R_H$ is the maximum operating current at τ=0; e_H, e_K is the thermo emf coefficient of a thermoelement branch, respectively, at the beginning and at the end of the cooling process, V/K; R_H, R_K is the electrical resistance a thermoelement branch at the beginning and at the end of the cooling process, Ohm.

Under condition of equality of currents at the beginning and end of a cooling process:

$$I=B_HI_{\max H}=B_KI_{\max K}, \quad (2)$$

T_0 is the temperature of the heat-absorbing weld joint at the end of the cooling process, K; T is the temperature of the heat-absorbing weld joint at the beginning of the cooling process, K, τ=0; $\Theta=\Delta T/T_{\max}$ is the relative temperature difference; $\Delta T=T-T_0$ is the temperature difference in TED, K; $\Delta T_{\max}=0.5\,\bar{z}_K T_0^2$ is the maximum temperature difference, K;

$\bar{z}_K$ is the average value for the efficiency of a thermoelectric material in the module at the end of the cooling process, 1/K; I is the working current magnitude, A; $K_K = \bar{æ}_K/(l/S)$ is the heat transfer coefficient, W/K; $\bar{æ}_K$ is the average thermal conductivity coefficient, W/cm·K.

$\sum_i m_i C_i$ is the total magnitude of the product of heat capacity and the mass of components of CTE at the specified geometry of thermoelements branches l/S=10 cm^{-1}.

The number n of elements can be determined from the ratio:

$$n = \frac{Q_0}{I^2_{\max K} R_K \left(2B_K - B_K^2 - \Theta\right)}, \qquad (3)$$

where Q_0 is the thermal load magnitude, W.

Power consumption W_K of TED can be determined from expression:

$$W_K = 2nI^2_{\max K} R_K B_K \left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right). \qquad (4)$$

Voltage drop U:

$$U_K = W_K/I. \qquad (5)$$

Refrigeration coefficient E can be calculated from formula:

$$E = Q_0/W_K. \qquad (6)$$

Relative failure intensity λ/λ_0 and the probability of non-failure operation P can be determined from expressions [13]:

$$\lambda/\lambda_0 = nB_K^2\left(\Theta + C_K\right)\frac{\left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}K_{T_1};$$

$$P = e^{-\lambda t} = \exp(-\lambda t), \qquad (7)$$

where λ_0 is the rated failure rate, 1/h, obtained experimentally by calculation for the generally accepted manufacturing technology;

$$C_K = \frac{Q_0}{nI^2_{\max K} R_K}$$

is the relative heat load; K_{T1} is the meaningful temperature coefficient.

The expressions given above provide an opportunity to analyze the dynamics of TED and to predict reliability indicators at the predefined geometry of thermoelements' branches.

5. Analysis of temporal and reliability indicators of the model for various current operation modes

5. 1. Mode $Q_{0\max}$

Results of calculation of the basic parameters, taking into consideration the temperature dependence [2] of the time required to enter a stationary working mode and the reliability indicators for mode $Q_{0\max}$ (B_K=1.0; B_H=B_K($I_{\max K}$/$I_{\max H}$) at T=300 K, l/S=10 cm^{-1}; ΔT=5; 10; 20; 30; 40; 50; 60 K; $\sum_i m_i C_i = 175\cdot10^{-4}$ J/K and at various thermal load Q_0, are given in Table 1.

Table 1

Calculation of basic parameters under mode $Q_{0\max}$ at T=300 K, l/S=10 cm^{-1}, mode $Q_{0\max}$, $m_0C_0 \to 0$, $\sum_i m_i C_i$=175·10^{-4} J/K; K_K=15.6·10^{-4} W/KK; $I_{\max H}$=5.4 A

Q_0, W	n, pcs.	W, W	U, V	E	I, A	τ, s	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
ΔT=5 K, $\Delta T_{\max}$=104.4 K; T_0=295 K; Θ=0.048; R_H=11.1·10^{-3} Ohm; R_K=11·10^{-3} Ohm; $I_{\max K}$=5.36 A; B_H=0.993; B_K=1.0									
0.5	1.66	1.07	0.20				1.66	5.0	0.99950
1.0	3.3	2.1	0.40				3.3	10.0	0.9990
2.0	6.6	4.3	0.80				6.6	20.0	0.9980
5.0	16.5	10.7	2.0	0.47	5.36	0.5	16.6	49.8	0.9950
7.0	23.1	14.9	2.8				23.2	69.7	0.9930
10.0	33.0	21.3	4.0				33.2	99.6	0.9900
20.0	66.0	42.6	8.0				66.4	200	0.9802
ΔT=10 K, $\Delta T_{\max}$=100.5 K; T_0=290 K; Θ=0.10; R_H=11.1·10^{-3} Ohm; R_K=10.9·10^{-3} Ohm; $I_{\max K}$=5.32 A; B_H=0.985; B_K=1.0									
0.5	1.8	1.15	0.22				1.8	5.4	0.99946
1.0	3.6	2.30	0.43				3.6	10.8	0.99892
2.0	7.2	4.6	0.86				7.2	21.6	0.9978
5.0	18.0	11.5	2.16	0.43	5.32	1.0	18.0	54.0	0.9946
7.0	25.2	16.1	3.0				25.2	75.6	0.9925
10.0	36.0	23.0	4.30				36.0	108.0	0.9893
20.0	72.0	46.0	8.6				72.0	216.0	0.9786
ΔT=20 K, $\Delta T_{\max}$=93.7 K; T_0=280 K; Θ=0.213; R_H=11.1·10^{-3} Ohm; R_K=10.64·10^{-3} Ohm; $I_{\max K}$=5.24 A; B_H=0.970; B_K=1.0									
0.5	2.2	1.38	0.26				2.2	6.6	0.99934
1.0	4.4	2.75	0.52				4.4	13.2	0.9987
2.0	8.8	5.5	1.0				8.8	26.4	0.9974
5.0	22.0	13.8	2.60	0.36	5.24	2.3	22.0	66.0	0.9934
7.0	31.0	19.3	3.67				31.0	92.4	0.9908
10.0	44.0	27.5	5.2				44.0	132.0	0.9869
20.0	88.0	55.0	10.5				88.0	264.0	0.9739
ΔT=30 K, $\Delta T_{\max}$=86.8 K; T_0=270 K; Θ=0.346; R_H=11.1·10^{-3} Ohm; R_K=10.2·10^{-3} Ohm; $I_{\max K}$=5.19 A; B_H=0.961; B_K=1.0									
0.5	2.8	1.71	0.33				2.83	8.5	0.99915
1.0	5.6	3.42	0.66				5.66	17.0	0.99830
2.0	11.2	6.84	1.32				11.3	34.0	0.99660
5.0	28.0	17.1	3.30	0.29	5.19	4.0	28.3	84.9	0.99154
7.0	39.2	23.9	4.61				39.6	118.9	0.9882
10.0	56.0	34.2	6.6				56.6	169.8	0.9832
20.0	112	68.4	13.2				113.2	340.0	0.9665
ΔT=40 K, $\Delta T_{\max}$=79.8 K; T_0=260 K; Θ=0.50; R_H=11.1·10^{-3} Ohm; R_K=10.1·10^{-3} Ohm; $I_{\max K}$=5.02 A; B_H=0.93; B_K=1.0									
0.5	3.9	2.30	0.46				4.0	12	0.99988
1.0	7.8	4.60	0.91				8.0	24	0.9976
2.0	15.6	9.20	1.82				16.0	48	0.9952
5.0	39.0	22.9	4.55	0.22	5.02	6.4	40	120	0.9881
7.0	54.6	32.1	6.40				56.0	168	0.9833
10.0	78.0	45.8	9.10				80.0	240	0.9763
20.0	156.0	91.6	18.2				160.0	480	0.9531
ΔT=50 K, $\Delta T_{\max}$=73.4 K; T_0=250 K; Θ=0.68; R_H=11.1·10^{-3} Ohm; R_K=9.8·10^{-3} Ohm; $I_{\max K}$=4.9 A; B_H=0.907; B_K=1.0									
0.5	6.6	3.72	0.76				6.8	20.4	0.9980
1.0	13.2	7.44	1.52				13.6	40.8	0.99592
2.0	26.4	14.9	3.04				27.2	81.6	0.9919
5.0	66.0	37.2	7.60	0.234	4.9	10.0	68.0	204.0	0.9798
7.0	92.4	52.1	10.6				95.2	285.6	0.9718
10.0	132	74.4	15.2				136	408	0.9600
20.0	264	149	30.4				272	816	0.9216
ΔT=60 K, $\Delta T_{\max}$=66.8 K; T_0=240 K; Θ=0.90; R_H=11.1·10^{-3} Ohm; R_K=9.62·10^{-3} Ohm; $I_{\max K}$=4.74 A; B_H=0.88; B_K=1.0									
0.5	23.1	12.5	2.64				23.9	717	0.9929
1.0	46.2	25	5.30				47.8	143.4	0.9858
2.0	92.4	509	10.6				95.6	287	0.9717
5.0	231	125	26.4	0.040	4.74	19.0	239	717	0.9308
7.0	323	175	37.0				335	1000	0.9045
10.0	462	250	52.8				478	1434	0.8664
20.0	924	500	106.0				956	2870	0.7507

An increase in the temperature difference ΔT at $m_0C_0 \to 0$, where C_0 is the heat capacity of the object, leads to:

– an increase in the time required to enter a stationary working mode τ (Fig. 1, point 1) that does not depend on heat load Q_0;

– a decrease in the magnitude of working current I (Fig. 2, point 1) that does not depend on heat load Q_0;

– a decrease in refrigeration coefficient E (Fig. 3, point 1) that does not depend on heat load Q_0;

– an increase in voltage drop U for different heat load Q_0 (Fig. 4); the voltage drop increases with an increase in the heat load;

– a decrease in the number of thermoelements n for different heat load Q_0 (Fig. 5);

– an increase in failure rate λ/λ_0 for different heat load Q_0 (Fig. 6); the failure rate increases with an increase in the heat load;

– a decrease in failure-free operation probability P for different heat load Q_0 (Fig. 7);

– the failure-free operation probability decreases with an increase in the heat load.

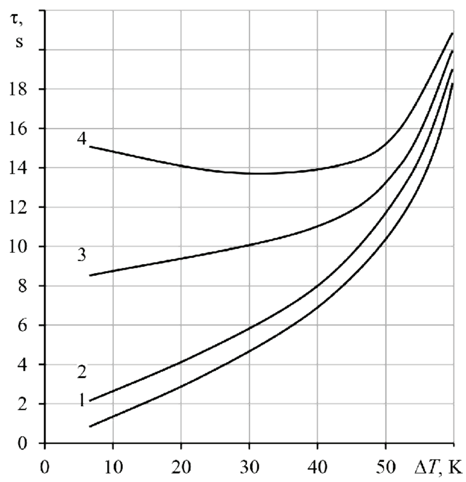

Fig. 1. Dependence of time required to enter a stationary working mode τ_0 by a single-stage TED on temperature difference ΔT for different modes of operation at $m_0C_0 \to 0$, T=300 K, l/S=10 cm^{-1}; $\sum_i m_iC_i = 175\cdot10^{-4}$ J/K: 1 – mode Q_{0max}; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}

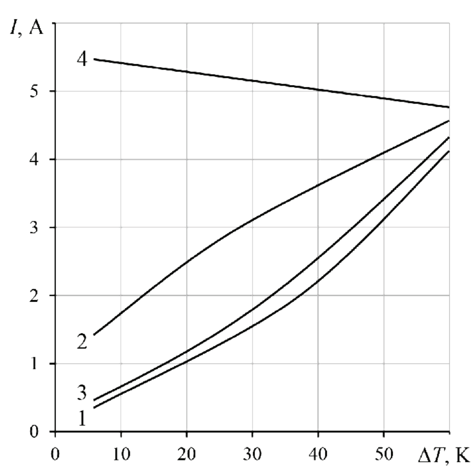

Fig. 2. Dependence of magnitude of the working current I in a single-stage TED on temperature difference ΔT for different modes of operation at T=300 K, l/S=10 cm^{-1}: 1 – mode Q_{0max}; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}

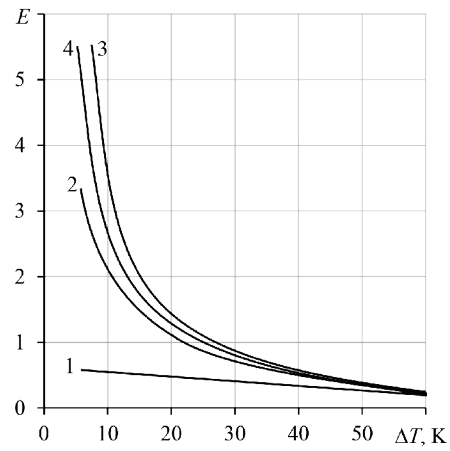

Fig. 3. Dependence of refrigeration coefficient E of a single-stage TED on temperature difference ΔT for different modes of operation at T=300 K, l/S=10 cm^{-1}: 1 – mode Q_{0max}; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}

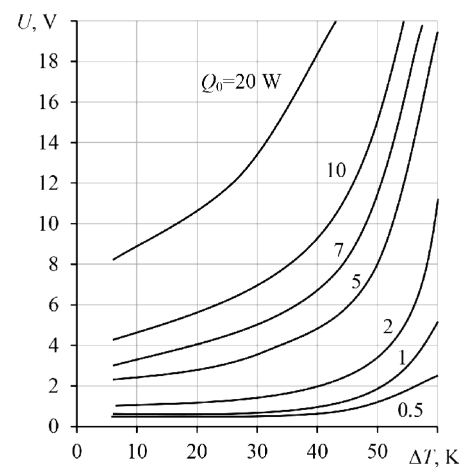

Fig. 4. Dependence of voltage drop U in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0

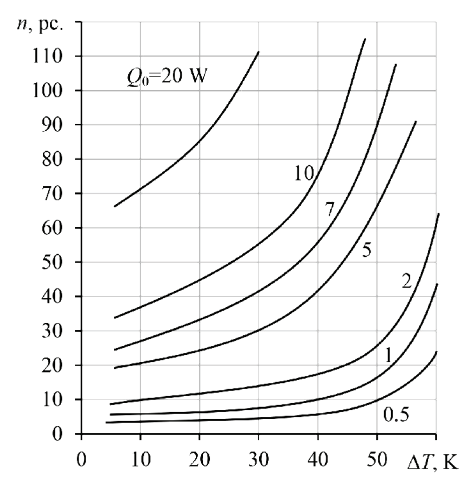

Fig. 5. Dependence of thermoelements number n in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode Q_{0max}

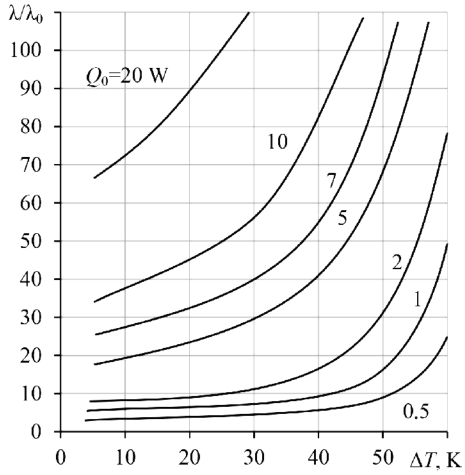

Fig. 6. Dependence of failure rate λ/λ_0 in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $Q_{0\max}$

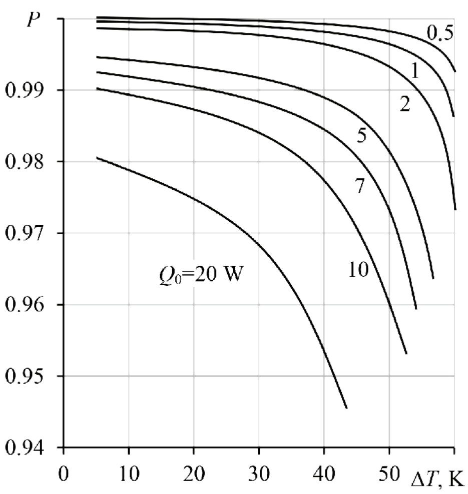

Fig. 7. Dependence of failure-free operation probability P for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $Q_{0\max}$

5. 2. Mode $(Q_0/I)_{\max}$

Results of calculation of the basic parameters, taking into consideration temperature dependence [2] of the time required to enter a stationary working mode and reliability indicators for mode $(Q_0/I)_{\max}$ ($B_K=\sqrt{\Theta}$; $B_H=B_K I_{\max K}/I_{\max H}$) at T=300 K, l/S=10; ΔT_1=5; 10; 20; 30; 40; 50; 60 K; $\sum_i m_i C_i=175\cdot10^{-4}$ J/K and at different heat load Q_0 are given in Table 2.

An increase in temperature difference ΔT at $m_0C_0\to0$ leads to:

– an increase in the time required to enter a stationary mode τ (Fig. 1, point 2) that does not depend on heat load Q_0;

– a decrease in the magnitude of working current I (Fig. 2, point 2) that does not depend on heat load Q_0;

– a decrease in refrigeration coefficient E (Fig. 3, point 2) that does not depend on heat load Q_0;

– an increase in voltage drop U (Fig. 8) for different heat load Q_0; the voltage drop increases with an increase in the heat load;

– the functional dependence of thermoelements number $n=f(\Delta T)$ has a minimum at ΔT=20 K for different heat load Q_0 (Fig. 9); the number of thermoelements increases with an increase in the heat load;

– an increase in failure rate λ/λ_0 for different heat load Q_0 (Fig. 10); the failure rate increases with an increase in the heat load;

– a decrease in failure-free operation probability P for different heat load Q_0 (Fig. 11);

– the failure-free operation probability decreases with an increase in the heat load.

Table 2

Calculation of basic parameters under mode $(Q_0/I)_{\max}$ at T=300 K, l/S=10, mode$(Q_0/I)_{\max}$, $m_0C_0\to0$, $\sum_i m_iC_i=175\cdot10^{-4}$ J/K; $I_{\max H}$=5.4 A

Q_0, W	n, pcs.	W, W	U, V	E	I, A	τ, s	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
1	2	3	4	5	6	7	8	9	10
ΔT=5 K, $\Delta T_{\max}$=104.4 K; T_0=295 K; Θ=0.048; R_H=11.1·10^{-3} Ohm; R_K=11·10^{-3} Ohm; $I_{\max K}$=5.36 A; B_H=0.220; B_K=0.222									
0.5	4.6	0.15	0.13				0.0046	0.0138	0.9999986
1.0	9.2	0.30	0.26				0.0092	0.0276	0.9999972
2.0	18.4	0.61	0.52				0.0184	0.0552	0.9999945
5.0	46.0	1.52	1.30	3.3	1.19	1.45	0.046	0.138	0.999986
7.0	64.4	2.13	1.82				0.0644	0.1932	0.999981
10.0	92.0	3.04	2.60				0.092	0.276	0.999972
20.0	184.0	6.1	5.20				0.184	0.552	0.999945
ΔT=10 K, $\Delta T_{\max}$=100.5 K; T_0=290 K; Θ=0.10; R_H=11.1·10^{-3} Ohm; R_K=10.9·10^{-3} Ohm; $I_{\max K}$=5.32 A; B_H=0.311; B_K=0.316									
0.5	3.8	0.26	0.16				0.023	0.069	0.9999931
1.0	7.6	0.52	0.31				0.046	0.138	0.999986
2.0	15.2	1.04	0.62				0.092	0.276	0.999972
5.0	38.0	2.60	1.55	1.92	1.68	2.30	0.23	0.69	0.999931
7.0	53.2	3.64	2.17				0.322	0.966	0.99990
10.0	76.0	5.20	3.10				0.46	1.38	0.99986
20.0	152.0	10.4	6.20				0.92	2.76	0.99972
ΔT=20 K, $\Delta T_{\max}$=93.7 K; T_0=280 K; Θ=0.213; R_H=11.1·10^{-3} Ohm; R_K=10.64·10^{-3} Ohm; $I_{\max K}$=5.24 A; B_H=0.445; B_K=0.462									
0.5	3.4	0.489	0.20				0.129	0.388	0.999961
1.0	6.8	0.980	0.40				0.259	0.776	0.999922
2.0	13.6	1.96	0.80				0.518	1.55	0.999845
5.0	34.0	4.89	2.0	1.02	2.42	3.8	1.30	3.90	0.99961
7.0	47.6	6.85	2.80				1.81	5.44	0.99945
10.0	68.0	9.78	4.0				2.59	7.77	0.99922
20.0	136.0	19.6	8.0				5.18	15.5	0.99845
ΔT=30 K, $\Delta T_{\max}$=86.8 K; T_0=270 K; Θ=0.346; R_H=11.1·10^{-3} Ohm; R_K=10.2·10^{-3} Ohm; $I_{\max K}$=5.19 A; B_H=0.565; B_K=0.588									
0.5	3.8	0.86	0.28				0.436	1.81	0.99987
1.0	7.6	1.72	0.56				0.872	2.62	0.99974
2.0	15.2	3.43	1.12				1.74	5.23	0.99948
5.0	38.0	8.58	2.80	0.58	3.05	5.5	4.36	13.1	0.9987
7.0	53.2	12.0	3.92				6.10	18.3	0.9982
10.0	76.0	17.2	5.60				8.70	26.2	0.9974
20.0	152	34.4	11.2				17.4	52.2	0.9948
ΔT=40 K, $\Delta T_{\max}$=79.8 K; T_0=260 K; Θ=0.50; R_H=11.1·10^{-3} Ohm; R_K=10.1·10^{-3} Ohm; $I_{\max K}$=5.02 A; B_H=0.657; B_K=0.707									
0.5	4.7	1.46	0.41				1.23	3.69	0.99963
1.0	9.4	2.92	0.82				2.46	7.38	0.99926
2.0	18.8	5.84	1.64				4.92	14.8	0.9985
5.0	47.0	14.6	4.1	0.34	3.55	7.7	12.3	36.9	0.9963
7.0	65.8	20.4	5.74				17.2	51.7	0.9948
10.0	94.0	29.2	8.20				24.6	73.8	0.9926
20.0	188	58.4	16.4				49.2	147.6	0.9853

Continuation of Table 2

1	2	3	4	5	6	7	8	9	10
ΔT=50 K, ΔT_{max}=73.4 K; T_0=250 K; Θ=0.68; R_H=11.1·10^{-3} Ohm; R_K=9.8·10^{-3} Ohm; I_{maxK}=4.9 A; B_H=0.748; B_K=0.825									
0.5	7.3	2.90	0.72				3.6	10.8	0.9989
1.0	14.6	5.80	1.44				7.2	21.6	0.9978
2.0	29.2	11.6	2.88				14.4	43.2	0.9957
5.0	73.0	29.0	7.20	0.17	4.0	11.0	36.0	108	0.9893
7.0	102	40.6	10.0				50.4	151	0.9850
10.0	146	58.0	14.4				72.0	216	0.9786
20.0	292	116	28.8				144	432	0.9577
ΔT=60 K, ΔT_{max}=66.8 K; T_0=240 K; Θ=0.90; R_H=11.1·10^{-3} Ohm; R_K=9.62·10^{-3} Ohm; I_{maxK}=4.74 A; B_H=0.833; B_K=0.949									
0.5	23.6	11.63	2.58				20.2	60.5	0.9940
1.0	47.2	23.3	5.16				40.4	121.2	0.9880
2.0	94.4	46.6	10.3				80.8	242	0.9760
5.0	236	116.5	25.8	0.043	4.5	19.1	202	606	0.9412
7.0	330	263	36.1				283	848	0.9187
10.0	472	233	51.6				404	1212	0.8859
20.0	944	466	103.2				808	2424	0.7847

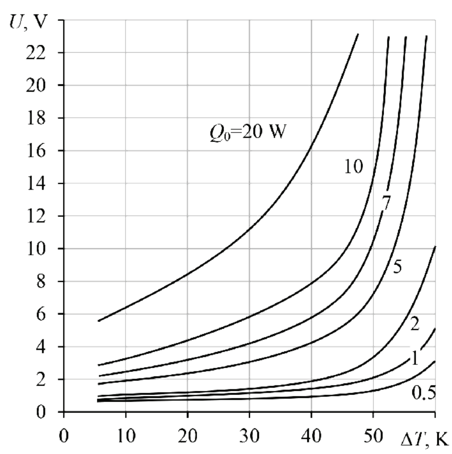

Fig. 8. Dependence of voltage drop U in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I)_{max}$

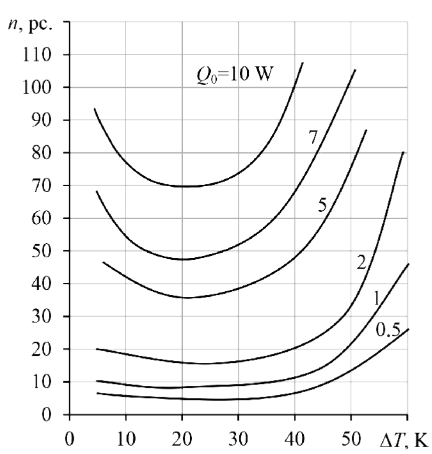

Fig. 9. Dependence of thermoelements number n in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I)_{max}$

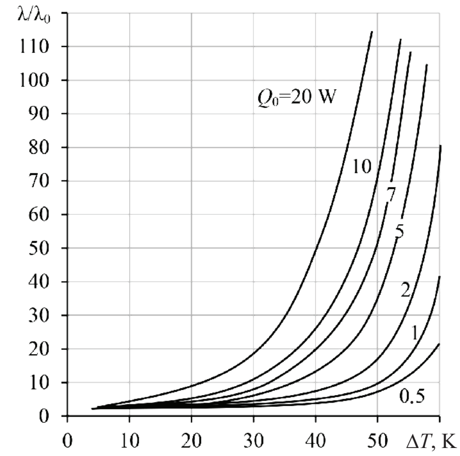

Fig. 10. Dependence of failure rate λ/λ_0 for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I)_{max}$

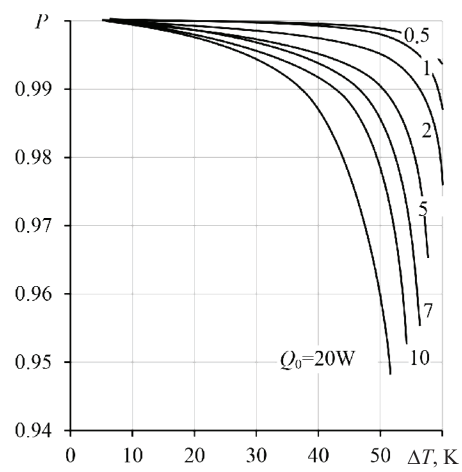

Fig. 11. Dependence of the failure-free operation probability P for a single-stage TED temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I)_{max}$

5. 3. Mode $(Q_0/I^2)_{max}$

Results of calculation of the basic parameters and the time required for reliability indicators to enter a stationary working mode for regime $(Q_0/I^2)_{max}$ ($B_K=\Theta$; $B_H=B_K I_{maxK}/I_{maxH}$) at T=300 K, l/S=10; ΔT=5; 10; 20; 30; 40; 50; 60 K; $\sum_i m_i C_i = 175\cdot10^{-4}$ J/K and different heat load Q_0 are given in Table 3.

An increase in temperature difference ΔT at $m_0C_0\to0$ leads to:

– an increase in the time required to enter a stationary mode τ (Fig. 1, point 3) that does not depend on heat load Q_0;

– a decrease in the magnitude of working current I (Fig. 2, point 3) that does not depend on heat load Q_0;

– a decrease in the refrigeration coefficient E (Fig. 3, point 3) that does not depend on heat load Q_0;

– an increase in voltage drop U (Fig. 12) for different heat load Q_0; the voltage drop increases with an increase in the heat load Q_0;

– the functional dependence of the thermoelements number $n=f(\Delta T)$ has a minimum at ΔT=35 K for different heat load Q_0 (Fig. 13); the number of thermoelements grow with an increase in the heat load;

– an increase in the failure rate λ/λ_0 for different heat load Q_0 (Fig. 14); the failure rate grows with an increase in the heat load;

– a decrease in the failure-free operation probability P for different heat load Q_0 (Fig. 15);

– the failure-free operation probability decreases with an increase in the heat load.

Table 3

Calculation of basic parameters under mode $(Q_0/I^2)_{max}$ at T=300 K, l/S=10, regime $(Q_0/I^2)_{max}$, $m_0C_0 \to 0$, $\sum_i m_iC_i = 175 \cdot 10^{-4}$ J/K; I_{maxH}=5.4 A

Q_0, W	n, pcs.	W, W	U, V	E	I, A	τ, s	λ/λ_0	$\lambda \cdot 10^8$, 1/h	P
1	2	3	4	5	6	7	8	9	10
ΔT=5 K, ΔT_{max}=104.4 K; T_0=295 K; Θ=0.048; R_H=11.1·10^{-3} Ohm; R_K=11·10^{-3} Ohm; I_{maxK}=5.36 A; B_H=0.0476; B_K=0.048									
0.5	34.6	0.068	0.26				0.000030	0.00009	~1.0
1.0	69.2	0.136	0.53				0.00006	0.00018	~1.0
2.0	138	0.272	1.06				0.00012	0.00036	~1.0
5.0	346	0.68	2.65	7.35	0.257	8.0	0.00030	0.0009	~1.0
7.0	484	0.952	3.71				0.00042	0.00126	0.99999987
10.0	692	1.36	5.3				0.00060	0.0018	0.99999982
20.0	1384	2.72	10.6				0.0012	0.0036	0.99999964
ΔT=10 K, ΔT_{max}=100.5 K; T_0=290 K; Θ=0.10; R_H=11.1·10^{-3} Ohm; R_K=10.9·10^{-3} Ohm; I_{maxK}=5.32 A; B_H=0.0981; B_K=0.10									
0.5	18.0	0.15	0.28				0.00058	0.00174	0.99999983
1.0	36.0	0.30	0.56				0.00116	0.0035	0.99999965
2.0	72.0	0.60	1.12				0.00232	0.0070	0.99999930
5.0	180	1.50	2.8	3.33	0.53	8.2	0.0058	0.0174	0.9999983
7.0	252	2.10	3.92				0.0081	0.024	0.9999975
10.0	360	3.0	5.60				0.00116	0.035	0.9999966
20.0	720	6.0	11.2				0.0232	0.070	0.9999930
ΔT=20 K, ΔT_{max}=93.7 K; T_0=280 K; Θ=0.213; R_H=11.1·10^{-3} Ohm; R_K=10.64·10^{-3} Ohm; I_{maxK}=5.24 A; B_H=0.207; B_K=0.213									
0.5	1.02	0.362	0.32				0.0125	0.0373	0.9999963
1.0	20.4	0.724	0.65				0.025	0.075	0.9999925
2.0	40.8	1.43	1.30				0.050	0.15	0.999985
5.0	102.0	3.62	3.25	1.38	1.12	8.8	0.125	0.375	0.999965
7.0	143	5.10	4.52				0.175	0.525	0.999948
10.0	104	7.24	6.50				0.250	0.75	0.999925
20.0	408	14.5	13.0				0.50	1.50	0.99985
ΔT=30 K, ΔT_{max}=86.8 K; T_0=270 K; Θ=0.346; R_H=11.1·10^{-3} Ohm; R_K=10.2·10^{-3} Ohm; I_{maxK}=5.19 A; B_H=0.333; B_K=0.346									
0.5	8.05	0.70	0.39				0.095	0.285	0.999972
1.0	16.1	1.40	0.78				0.19	0.570	0.999943
2.0	32.3	2.80	1.56				0.38	1.14	0.99989
5.0	80.5	7.0	3.90	0.714	1.80	9.45	0.95	2.85	0.99972
7.0	113	9.8	5.46				1.33	4.0	0.99960
10.0	161	14.0	7.80				1.90	5.70	0.99943
20.0	322	28.0	15.6				3.80	11.7	0.9989
ΔT=40 K, ΔT_{max}=79.8 K; T_0=260 K; Θ=0.50; R_H=11.1·10^{-3} Ohm; R_K=10.1·10^{-3} Ohm; I_{maxK}=5.02 A; B_H=0.465; B_K=0.5									
0.5	7.9	1.32	0.52				0.488	1.46	0.999854
1.0	15.8	2.64	1.04				0.976	2.93	0.99971
2.0	31.6	5.30	2.08				1.95	5.85	0.99941
5.0	79.0	13.2	5.20	0.38	2.51	11.0	4.88	14.6	0.99854
7.0	111	18.5	7.3				6.83	20.5	0.9980
10.0	158	25.4	10.4				9.76	29.3	0.9971
20.0	316	52.8	20.8				19.5	58.5	0.9942

Continuation of Table 3

1	2	3	4	5	6	7	8	9	10
ΔT=50 K, ΔT_{max}=73.4 K; T_0=250 K; Θ=0.68; R_H=11.1·10^{-3} Ohm; R_K=9.8·10^{-3} Ohm; I_{maxK}=4.9 A; B_H=0.617; B_K=0.68									
0.5	9.7	2.72	0.82				2.22	6.67	0.99933
1.0	19.4	5.44	1.64				4.44	13.3	0.99867
2.0	38.8	10.9	3.28				8.90	26.7	0.9973
5.0	97.0	27.2	8.20	0.183	3.33	13.4	22.2	66.7	0.9934
7.0	136	38.1	11.5				31.1	93.2	0.9907
10.0	194	54.4	16.4				44.4	133	0.9868
20.0	388	109	32.8				89.0	267	0.9737
ΔT=60 K, ΔT_{max}=66.8 K; T_0=240 K; Θ=0.90; R_H=11.1·10^{-3} Ohm; R_K=9.62·10^{-3} Ohm; I_{maxK}=4.74 A; B_H=0.791; B_K=0.90									
0.5	25.1	11.2	2.62				17.5	52.6	0.99475
1.0	50.2	22.4	5.24				35.0	105	0.9895
2.0	100	44.8	10.4				70.0	210	0.9792
5.0	251	112	26.2	0.045	4.27	20.4	175.0	525	0.9489
7.0	351	157	36.7				245.0	735	0.9291
10.0	502	224	52.4				350	1,050	0.900
20.0	1,000	448	104				700	2,100	0.810

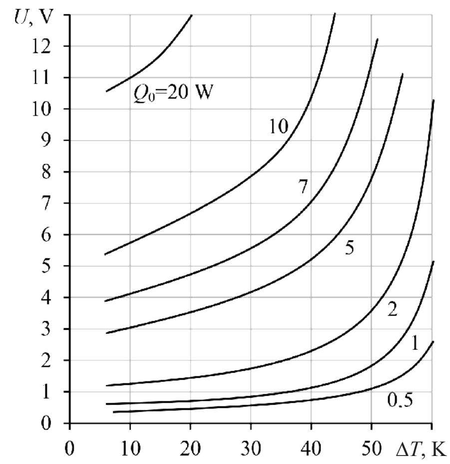

Fig. 12. Dependence of voltage drop U in a single-stage TED on temperature difference ΔT at T=300 K, l/S= 10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I^2)_{max}$

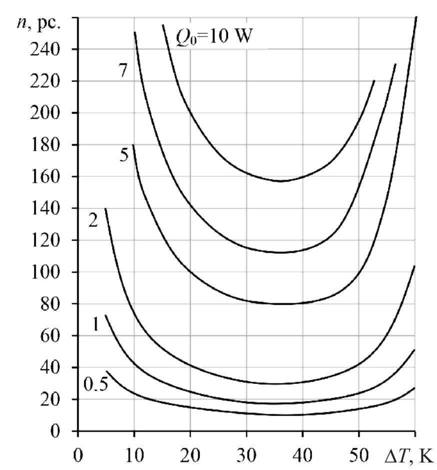

Fig. 13. Dependence of thermoelements number n in a single-stage TED on temperature difference ΔT at T=300 K, l/S= 10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I^2)_{max}$

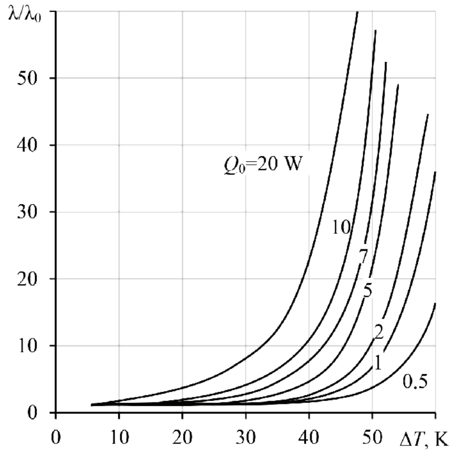

Fig. 14. Dependence of failure rate λ/λ_0 for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I^2)_{max}$

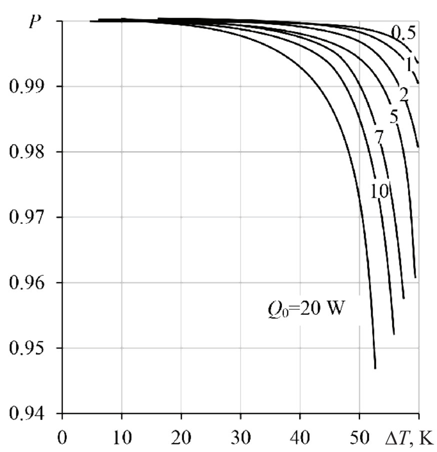

Fig. 15. Dependence of failure-free operation probability P for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode $(Q_0/I^2)_{max}$

5. 4. Mode λ_{min}

Results of calculation of the basic parameters and the time required for the reliability indicators to enter a stationary working mode for regime λ_{min} ($B_K=\eta\Theta$, where η is the correction factor [13]; $B_H=B_K(I_{\max K}/I_{\max H})$) at T=300 K, l/S=10; ΔT=5; 10; 20; 30; 40; 50; 60 K; $\sum_i m_iC_i=175\cdot10^{-4}$ J/K and different heat load Q_0 are given in Table 4.

An increase in temperature difference ΔT at $m_0C_0\to0$ leads to:

– the functional dependence $\tau=f(\Delta T)$ has a minimum at ΔT=30 K (Fig. 1, point 3) that does not depend on heat load Q_0;

– an increase in working current I (Fig. 1, point 4) that does not depend on heat load Q_0;

– a decrease in refrigeration coefficient E (Fig. 3, point 4) that does not depend on heat load Q_0;

– an increase in voltage drop U (Fig. 16) for different heat load Q_0; the voltage drop increases with an increase in the heat load;

– the functional dependence of thermoelements number $n=f(\Delta T)$ has a minimum at ΔT=40 K (Fig. 17) for different heat load Q_0 (Fig. 13); the number of thermoelements grows with an increase in the heat load;

– an increase in failure rate λ/λ_0 for different heat load Q_0 (Fig. 18); the failure rate increases with an increase in heat load;

– a decrease in failure-free operation probability P for different heat load Q_0 (Fig. 19);

– the failure-free operation probability decreases with an increase in heat load.

Table 4

Calculation of basic parameters under mode λ_{min} at T=300 K, l/S=10, mode λ_{min}, $m_0C_0\to0$, $\sum_i m_iC_i=175\cdot10^{-4}$ J/K; $I_{\max H}$=5.4 A

Q_0, W	n, pcs.	W, W	U, V	E	I, A	τ, s	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
1	2	3	4	5	6	7	8	9	10
ΔT=5 K, ΔT_{max}=104.4 K; T_0=295 K; Θ=0.048; $R_H=11.1\cdot10^{-3}$ Ohm; $R_K=11\cdot10^{-3}$ Ohm; $I_{\max K}$=5.36 A; B_H=0.033; B_K=0.034									
0.5	84.0	0.092	0.50				0.000016	0.000049	→1.0
1.0	168	0.123	1.0				0.000032	0.000097	→1.0
2.0	336	0.246	2.0				0.000065	0.00019	→1.0
5.0	840	0.615	5.0	5.5	0.18	14.0	0.00016	0.00049	→1.0
7.0	1176	0.861	7.0				0.00023	0.00068	→1.0
10.0	1680	1.23	10.0				0.00032	0.00097	→1.0
20.0	3360	2.46	20.0				0.00065	0.0019	0.99999983
ΔT=10 K, ΔT_{max}=100.5 K; T_0=290 K; Θ=0.10; $R_H=11.1\cdot10^{-3}$ Ohm; $R_K=10.9\cdot10^{-3}$ Ohm; $I_{\max K}$=5.32 A; B_H=0.070; B_K=0.071									
0.5	43.8	0.20	0.54				0.00044	0.00133	0.99999987
1.0	87.6	0.41	1.08				0.00089	0.0027	0.99999973
2.0	175	0.812	2.16				0.0018	0.0053	0.99999947
5.0	438	2.0	5.4	2.46	0.38	14.5	0.0044	0.0133	0.9999987
7.0	613	2.84	7.56				0.0062	0.0186	0.9999981
10.0	876	4.1	10.8				0.0089	0.0266	0.9999973
20.0	1752	8.1	21.6				0.0177	0.053	0.9999947
ΔT=20 K, ΔT_{max}=93.7 K; T_0=280 K; Θ=0.213; $R_H=11.1\cdot10^{-3}$ Ohm; $R_K=10.64\cdot10^{-3}$ Ohm; $I_{\max K}$=5.24 A; B_H=0.155; B_K=0.16									
0.5	21.0	0.45	0.54				0.0073	0.022	0.9999978
1.0	42.0	0.904	1.08				0.0147	0.044	0.9999956
2.0	84.0	1.80	2.16				0.029	0.0882	0.0000012
5.0	210	2.26	5.40	1.11	0.84	13.8	0.0735	0.220	0.999978
7.0	294	3.16	7.56				0.103	0.31	0.999970
10.0	420	4.52	10.8				0.147	0.441	0.999956
20.0	840	9.0	21.6				0.294	0.882	0.999912
ΔT=30 K, ΔT_{max}=86.8 K; T_0=270 K; Θ=0.346; $R_H=11.1\cdot10^{-3}$ Ohm; $R_K=10.2\cdot10^{-3}$ Ohm; $I_{\max K}$=5.19 A; B_H=0.267; B_K=0.28									
0.5	13.4	0.806	0.56				0.065	0.192	0.999981
1.0	26.8	1.61	1.12				0.128	0.383	0.999961
2.0	53.6	3.22	2.24				0.256	0.768	0.999923
5.0	134	8.05	5.6	0.62	1.44	13.3	0.64	1.92	0.99981
7.0	188	11.3	7.84				0.90	2.90	0.99973
10.0	268	16.1	11.2				1.28	3.84	0.99962
20.0	536	32.2	22.4				2.56	7.68	0.99923
ΔT=40 K, ΔT_{max}=79.8 K; T_0=260 K; Θ=0.50; $R_H=11.1\cdot10^{-3}$ Ohm; $R_K=10.1\cdot10^{-3}$ Ohm; $I_{\max K}$=5.02 A; B_H=0.39; B_K=0.42									
0.5	12.0	1.48	0.709				0.356	1.07	0.99989
1.0	24.0	2.95	1.40				0.712	2.14	0.99979
2.0	48.0	5.90	2.80				1.42	4.27	0.99957
5.0	120	14.8	7.0	0.34	2.11	14.0	3.56	10.7	0.99893
7.0	168	20.7	9.8				5.0	15.0	0.9985
10.0	240	29.5	14.0				7.12	21.4	0.9979
20.0	480	59.0	28.0				14.2	42.7	0.9957

Continuation of Table 4

1	2	3	4	5	6	7	8	9	10
ΔT=50 K, ΔT_{max}=73.4 K; T_0=250 K; Θ=0.68; R_H=11.1·10^{-3} Ohm; R_K=9.8·10^{-3} Ohm; I_{maxK}=4.9 A; B_H=0.555; B_K=0.61									
0.5	12.6	2.92	0.97				1.85	5.56	0.99944
1.0	25.2	5.84	1.94				3.70	11.1	0.9989
2.0	50.4	11.7	3.90				7.4	22.2	0.9978
5.0	126	29.2	9.70	0.17	3.0	15.2	18.5	55.5	0.9945
7.0	176	40.9	13.6				25.9	77.7	0.9923
10.0	252	58.4	19.4				37.0	111.0	0.9890
20.0	504	117	38.8				74.0	222.0	0.9780
ΔT=60 K, ΔT_{max}=66.8 K; T_0=240 K; Θ=0.90; R_H=11.1·10^{-3} Ohm; R_K=9.62·10^{-3} Ohm; I_{maxK}=4.74 A; B_H=0.76; B_K=0.87									
0.5	27.9	11.77	2.87				17.3	51.8	0.9948
1.0	55.8	23.5	5.74				34.6	103.8	0.9897
2.0	111.6	47.0	11.5				69.2	207.6	0.97945
5.0	279	117.5	28.7	0.042	4.10	21.0	173.0	519.0	0.9494
7.0	391	164.5	40.2				242.0	727	0.930
10.0	558	235	57.4				346	1,038	0.9014
20.0	1,116	470	114.8				692	2,076	0.8125

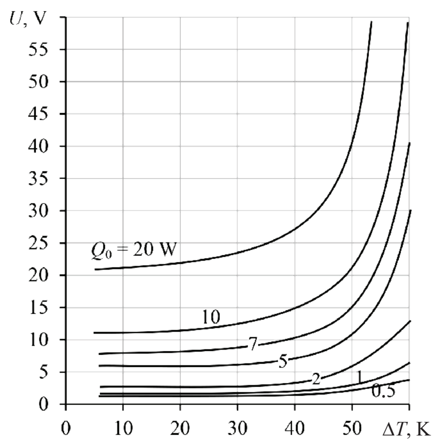

Fig. 16. Dependence of voltage drop U in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode λ_{min}

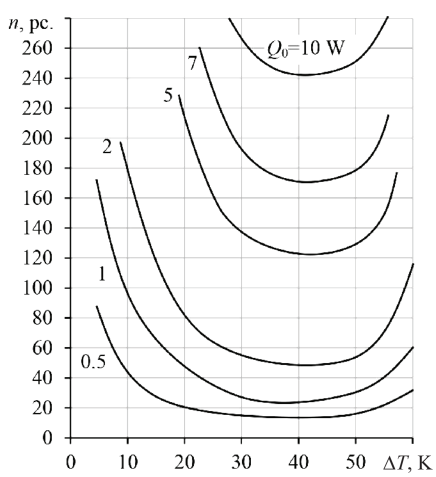

Fig. 17. Dependence of thermoelements number n in a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode λ_{min}

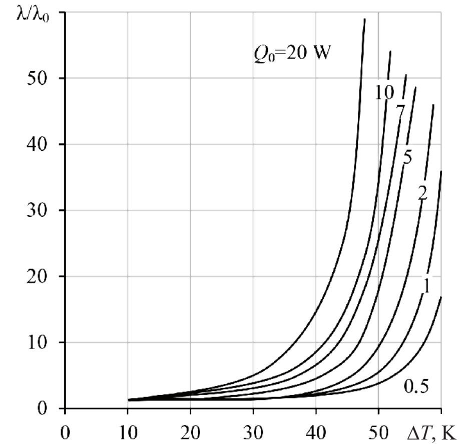

Fig. 18. Dependence of failure rate λ/λ_0 for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode λ_{min}

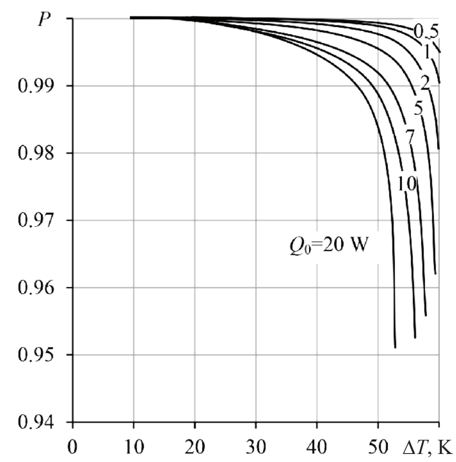

Fig. 19. Dependence of failure-free operation probability P for a single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1} for different heat load Q_0 under mode λ_{min}

6. Discussion of results of analyzing the time required for a single-stage TED to enter a stationary mode

To run a comparative analysis of the basic parameters, indicators of reliability, and the time required to enter a stationary working mode for various current regimes, we shall employ calculations data given in Table 5 at temperature difference ΔT=40 K, heat load Q_0=1.0 W, and the geometry of thermoelements' branches l/S=10 cm^{-1}.

Table 5

Comparative analysis of basic parameters, indicators of reliability, and the time required to enter a stationary working mode for various current regimes of TED

Mode of operation	B_H	B_K	τ, s	I, A	n, pcs.	U, V	W, W	E	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
Q_{0max}	0.930	1.0	6.4	5.0	7.8	0.91	4.6	0.22	8.0	24.0	0.9976
$(Q_0/I)_{max}$	0.657	0.71	7.7	3.55	9.4	0.82	2.92	0.34	2.46	7.40	0.99926
$(Q_0/I)^2_{max}$	0.465	0.50	11.0	2.51	15.8	1.04	2.64	0.38	0.976	2.93	0.99971
λ_{min}	0.390	0.42	14.0	2.11	24.0	1.40	2.95	0.34	0.71	2.14	0.99979

An analysis of calculation results reveals that an increase in relative working current B_K leads to:

– a decrease in time required to enter a stationary working mode τ from $\tau=14.0$ s under mode λ_{min} to $\tau=6.4$ s under mode Q_{0max} by 2.2 times (Fig. 20, point 1);

– a decrease in the number of thermoelements n from $n=24$ pcs. under mode λ_{min} to $n=7.8$ pcs. under regime Q_{0max}, that is by 3 times (Fig. 20, point 2);

– an increase in the magnitude of working current I from $I=2{,}11$ A under mode λ_{min} to $I=5.0$ A under mode Q_{0max}, that is by 2.4 times (Fig. 20, point 3);

– the functional dependence of refrigeration coefficient $E=f(B)$ has a maximum at $B=0.5$ (Fig. 20, point 4);

– a decrease in voltage drop U from $U=1.4$ V under mode λ_{min} to $U=0.91$ V under mode Q_{0max}, that is by 35 %;

– an increase in failure rate λ/λ_0 from $\lambda/\lambda_0=0.71$ under mode λ_{min} to $\lambda/\lambda_0=8.0$ under mode Q_{0max}, that is by 11 times (Fig. 21, point 2);

– a decrease in failure-free operation probability P from $P=0.99920$ under mode λ_{min} to $P=0.9927$ under mode Q_{0max} (Fig. 21, point 2).

Within the framework of the adopted model, the estimation of the time required by a thermoelectric device itself to enter a stationary working mode, as well as the basic parameters and indicators of reliability for different modes of operation in a range of working temperature differences at the predefined geometry of thermoelements branches $l/S=10$, is as follows:

– from $\tau=0.5$ s at $\Delta T=5$ K to $\tau=19$ s at $\Delta T=60$ K under mode Q_{0max};

– from $\tau=1.45$ s at $\Delta T=5$ K to $\tau=19.1$ s at $\Delta T=60$ K under mode $(Q_0/I)_{max}$;

– from $\tau=8.0$ s at $\Delta T=5$ K to $\tau=20.4$ s at $\Delta T=60$ K under mode $(Q_0/I)^2{}_{max}$;

– from $\tau=14$ s at $\Delta T=5$ K to $\tau=21.0$ s at $\Delta T=60$ K under mode λ_{min}.

Comparative analysis of the basic parameters, indicators of reliability, and dynamical characteristics allows us to choose compromise solutions when designing TED, taking into consideration the weight of each of the constraints.

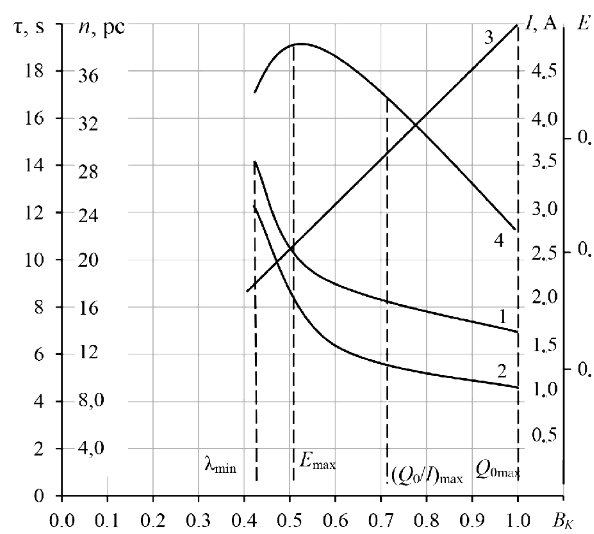

Fig. 20. Dependence of time required to enter a stationary working mode τ, number of thermoelements n, magnitude of operating current I and refrigeration coefficient E of a single-stage TED on relative working current B $T=300$ K, $\Delta T=40$ K; $Q_0=1$ W; $l/S=10$ cm^{-1}: 1 – $\tau=f(B)$; 2 – $n=f(B)$; 3 – $I=f(B)$; 4 – $E=f(B)$

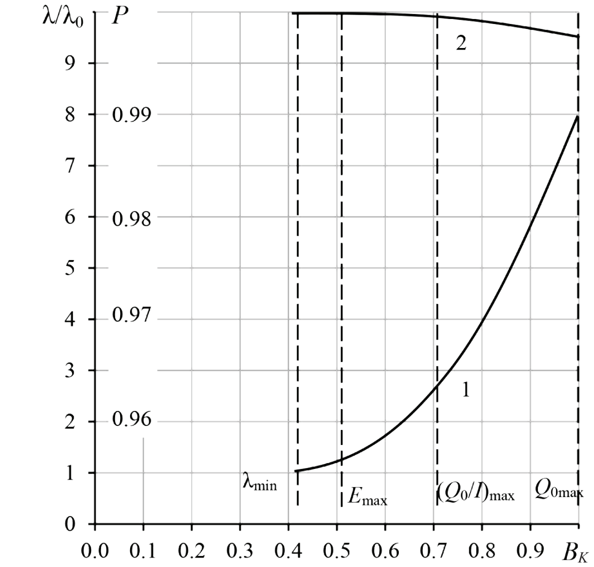

Fig. 21. Dependence of failure rate λ/λ_0 and failure-free operation probability P for a single-stage TED on relative working current B at $T=300$ K, $\Delta T=40$ K; $Q_0=1$ W; $l/S=10$ cm^{-1}; $\lambda_0=3\cdot10^{-8}$ 1/h; $t=10^4$ h: 1 – $\lambda/\lambda_0=f(B)$; 2 – $P=f(B)$

The results obtained suggest that the dynamical characteristics of TED could be controlled through the variation of current regime. An increase in the working current simultaneously with an increase in the rate of a transition process lead to an increase in mechanical stresses due to temperature gradients of linear expansion of dissimilar materials of the thermoelement and the substrate. The result is a deterioration of reliability indicators of coolers. The difference in relative values for the growth in performance and a decrease in reliability indicators shows the need for an external control over current regimes of TED depending on the instantaneous spectrum of heat load frequencies. That would allow for TED operation under the modes of maximum currents at worse indicators of reliability only in the regions of the highest frequencies of the heat load, passing subsequently over to modes with lower currents and higher reliability indicators. The absence of such results prevented setting a task to control indicators of reliability in the control analogs of thermoelectric devices that ensure thermal modes of radio electronic equipment, thereby making it the task for further research.

7. Conclusions

At the predefined geometry of thermoelements and the absence of objects to cool by a thermoelectric cooler:

– the time required to enter a stationary mode does not depend on the number of thermoelements, it is slightly different at the maximum temperature difference, and in a transition from the mode of operation at minimum failure rate λ_{min} to the mode of maximum cooling capacity Q_{0max}, it reduces by 2.2 times;

– under a dynamical load of TED, the mode Q_{0max}, in order to ensure the minimum duration of the transition process, must be as short as possible, because, when compared to the mode λ_{min}, relative failure rate increases almost by an order of magnitude.

References

1. Analysis and provision of thermal characteristics of radioelectronic facilities using the subsystem ASONIKA-T / Shalumova N. A., Shalumov A. S., Martynov O. Yu., Bagayeva T. A. // Advances in modern radio electronics. 2011. Issue 1. P. 42–49.
2. Perspectives on thermoelectrics: from fundamentals to device applications / Zebarjadi M., Esfarjani K., Dresselhaus M. S., Ren Z. F., Chen G. // Energy & Environmental Science. 2012. Vol. 5, Issue 1. P. 5147–5162. doi: https://doi.org/10.1039/c1ee02497c
3. System problems of reliability, quality, mathematical modeling and intelligent technologies in innovative projects / Kofanov Yu. N. et. al. Moscow: HRU HES, 2014. 532 p.
4. Ndao S., Peles Y., Jensen M. K. Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies // International Journal of Heat and Mass Transfer. 2009. Vol. 52, Issue 19-20. P. 4317–4326. doi: https://doi.org/10.1016/j.ijheatmasstransfer.2009.03.069
5. Thermoelectric modules market. Analytical review. RosBussinessConsalting, 2009. 92 p.
6. Sootsman J. R., Chung D. Y., Kanatzidis M. G. New and Old Concepts in Thermoelectric Materials // Angewandte Chemie International Edition. 2009. Vol. 48, Issue 46. P. 8616–8639. doi: https://doi.org/10.1002/anie.200900598
7. Materials, Preparation, and Characterization in Thermoelectrics. Vol. 1 / D. M. Rowe (Ed.). 1-st ed. Boca Raton: CRC Press, 2012. 544 p.
8. Approach on thermoelectricity reliability of board-level backplane based on the orthogonal experiment design / Zhang L., Wu Z., Xu X., Xu H., Wu Y., Li P., Yang P. // International Journal of Materials and Structural Integrity. 2010. Vol. 4, Issue 2/3/4. P. 170. doi: https://doi.org/10.1504/ijmsi.2010.035205
9. Choi H.-S., Seo W.-S., Choi D.-K. Prediction of reliability on thermoelectric module through accelerated life test and Physics-of-failure // Electronic Materials Letters. 2011. Vol. 7, Issue 3. P. 271–275. doi: https://doi.org/10.1007/s13391-011-0917-x
10. Wereszczak A. A., Wang H. Thermoelectric Mechanical Reliability // Vehicle Technologies Annual Merit Reviewand Peer Evaluation Meeting. Arlington, 2011. P. 18.
11. Singh R. Experimental Characterization of Thin Film Thermoelectric Materials and Film Deposition VIA Molecular Beam Epitaxial. University of California, 2008. 54 p.
12. Zaykov V., Mescheryakov V., Zhuravlov Y. Analysis of the possibility to control the inertia of the thermoelectric cooler // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 6, Issue 8 (90). P. 17–24. doi: https://doi.org/10.15587/1729-4061.2017.116005
13. Zaykov V. P., Kinshova L. A., Moiseev V. F. Prediction of reliability on thermoelectric cooling devices. Kn. 1 Single-stage devices. Odessa: Politehperiodika, 2009. 120 p.