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# STUDYING THE INFLUENCE OF THE THERMOELECTRIC MATERIALS PARAMETERS ON THE DYNAMICS OF SINGLE-CASCADE COOLING DEVICES

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*Розглянуто зв'язок варіантів сполучень параметрів первинних термоелектричних матеріалів однакової ефективності на динаміку функціонування однокаскадного термоелектричного охолоджувача. Варіанти відрізняються коефіцієнтами термоЕДС, електропровідності і теплопровідності. Дослідження проведені в робочому діапазоні перепадів температур, номінальному тепловому навантаженні при заданій геометрії гілок термоелементів.*

*Аналіз проведено для характерних струмових режимів функціонування: максимальної холодопродуктивності  $Q_{0max}$ , максимальної холодопродуктивності при заданому струмі  $(Q_0/I)_{max}$ , максимального холодильного коефіцієнта  $(Q_0/P)_{max}$ , мінімальної інтенсивності відмов  $\lambda_{min}$ .*

*Виявлено взаємозв'язок динаміки охолоджувача з основними параметрами і показниками надійності для різних струмових режимів роботи. Показана можливість зменшення часу виходу на стаціонарний режим роботи для варіанту з підвищеною електропровідністю матеріалу на 9–10 % у порівнянні з базовим варіантом, що засновано на усереднених електрофізичних параметрах. Максимальний час виходу на стаціонарний режим досягається в режимі максимальної холодопродуктивності.*

*Економічна доцільність використання первинних матеріалів з підвищеною електропровідністю полягає не тільки у покращенні характеристик динаміки і надійності. При проектуванні термоелектричних охолоджувачів також досягається зниження вартості охолоджувача за рахунок використання матеріалів, які відносилися до некондиційних.*

*При раціональному проектуванні термоелектричних охолоджувачів для систем забезпечення теплових режимів електронної апаратури враховується комплект заборонних вимог. До них відносяться енергоспоживання, маса і габаритні розміри, швидкодія, показники надійності та інші, які є суперечливими по суті. Запропонований вибір компромісних варіантів струмових режимів роботи для різних умов експлуатації дозволяє вести оптимізоване проектування теплонавантаженої апаратури*

*Ключові слова: охолоджувач, термоелектричний матеріал, сполучення параметрів, електропровідність, динамічні характеристики, показники надійності*

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## 1. Introduction

The operational dynamics of thermoelectric cooling devices (TEDs) are inextricably linked to the quality of the starting thermoelectric materials and, first of all, their efficiency. As the efficiency of the source materials improves, the time to enter a stationary mode of operation is reduced. As evidenced by the world practice of thermoelectric engineering, it is not possible to significantly improve the efficiency of thermoelectric materials at present. The issue relates to the fact that the creation of new materials with higher efficiency does not automatically improve the quality of thermoelectric coolers as the mechanical strength and thermal conductivity of the thermoelements' material can neutralize the results obtained. The relevance of improving the dynamic characteristics in the application of industrially

produced materials, for which the technology of cooler fabrication has been tested and the climatic and mechanical tests have been performed, is beyond any doubt.

## 2. Literature review and problem statement

Paper [1] shows that the systems that enable thermal modes are an integral part of thermally-loaded electronic equipment without which its operation is impossible. However, there are unresolved issues related to the consideration of differences in the heat output of components of the equipment. For concentrated heat sources, such as semiconductor lasers or intense radiation receivers, the requirements to the reliability of tools that enable their thermal modes to become similar to the thermally-loaded elements [2]. The reason is that from the

point of view of the theory of reliability, they are enabled consistently and a minimum of failure rate is achieved with equal reliability indicators. It was this approach that made it possible to distinguish thermoelectric coolers as the most promising ones in comparison with compression ones, including their mass-size, dynamic, and operational characteristics [3]. The optimization of the energy interaction between a cooled object and thermal modes is considered in work [4]. The study was conducted only for the static modes of operation and the requirements for stricter operating conditions for on-board systems required further research to improve reliability indicators [5]. One of the most important structural parameters that affect the reliability indicators of thermoelectric coolers is the variation of geometric parameters and the structural integrity of thermoelectric modules, which was addressed in [6]. The dynamic indicators were not considered because thermoelectric coolers have a significant advantage compared to air and liquid cooling systems. The modern approach to the systems that enable the thermal modes implies the inclusion of a thermoelectric cooler in the feedback chain of a temperature control system, so its dynamic characteristics become significant. At the same time, it is known that tests of thermoelectric coolers for operational reliability are carried out in a cyclical mode of heating and cooling [7]. A given mode, which makes it possible to reduce the mean time between failures by an order of magnitude, should become a working mode of thermoelectric modules, albeit in a softer manner. The link between dynamic characteristics and reliability indicators is a fundamental problem, and the need to improve the dynamics of a thermoelectric cooler included in the control chain is obvious. Studying the dynamic characteristics and the connection with reliability indicators were addressed in work [8]. It considers the issues related to decreasing the time to enter a stationary mode by a cooler depending on temperature changes and the current modes of operation. However, the impact on the dynamics and reliability indicators exerted by the coolers' structural parameters remained unsolved. Further research was aimed at analyzing the effect of the structural parameters of thermoelements in the range of working temperature changes and the current modes of operation on the time constant of the cooler and reliability indicators [9]. However, the issues related to the connection between the thermal-physical parameters of thermoelements and the inertia of a thermoelectric cooler remained unsolved. A previous study tackled the effect of the physical parameters of a thermoelectric material of thermoelements on reliability indicators [10]; the possibility of the effective impact of these parameters on the performance indicators of the cooler was shown. Since reliability indicators and dynamic performance are in direct contradiction, the challenge is to find a trade-off between improving the dynamic characteristics and the acceptable reliability indicators that satisfy a specific task.

### 3. The aim and objectives of the study

The aim of this work is to study the effect of the combination of parameters of a thermoelectric material of the same efficiency on the operational dynamics of single-cascade cooling devices.

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

- to investigate a dynamic model of a thermoelectric cooling device for different variants of combinations of the parameters of the original materials of thermoelements;

- to analyze the dynamic characteristics and reliability indicators for the main current modes of thermoelectric coolers.

### 4. A dynamic model of a thermoelectric cooler in terms of the efficiency of thermoelectric materials

The rated spread of parameters for the branches of thermoelements, used in the manufacture of unified thermoelectric modules, lies within the following limits of average values: the thermoEMF ratio –  $\bar{e} = 220 - 180$  mcV/K, electrical conductivity –  $\bar{\sigma} = 800 - 1200$  S/cm at the original materials' efficiency  $\dot{z} = 2.4 \cdot 10^{-3}$  1/K at  $T = 300$  K.

At the same time, as experience has shown, a possible range of change in the parameters in the manufacture of thermoelectric materials is much wider and can be within  $\bar{e} = 250 - 165$   $\mu$ V/K,  $\bar{\sigma} = 550 - 1500$  S/cm at  $T = 300$  K.

Materials with such boundary parameters were considered substandard and were not used in the manufacture of modules.

Let us consider the possible (experimentally obtained for the conditions of mass production) variants of the combination of parameters of the source materials in a module at  $T = 300$  K,  $\dot{z} = 2.4 \cdot 10^{-3}$  1/K,  $l/S = 10$  cm<sup>-1</sup>,  $\Delta T = 0$ , given in Table 1, for the purpose of their potential use.

Table 1

Variants of the combinations of parameters for the original thermoelectric materials

Combination variant No.	$\bar{e}$ , mcV/K	$\bar{\sigma}$ , S/cm	$\bar{z} \cdot 10^3$ , W/cm <sup>3</sup> ·K	$\bar{e}^2 \bar{\sigma} \cdot 10^4$ , W/K <sup>2</sup> cm	$\beta = \bar{e}^2 \bar{\sigma} T_0^2 S / e$ , W
1	250	550	14.3	0.344	0.310
2	210	800	14.7	0.353	0.318
3	200	900	15.0	0.360	0.325
4	180	1,200	16.0	0.390	0.351
5	165	1,500	17.0	0.410	0.370

Using  $\bar{e}$  and  $\bar{\sigma}$  as the basic important parameters of thermoelectric materials gives quite complete information about the cooling capabilities of modules assembled on their basis.

Consider the model of the relationship between the main characteristics, the indicators of reliability and operational dynamics of a single-cascade TED with the original material parameters  $\bar{e}$  and  $\bar{\sigma}$ .

Paper [8] reported the ratios for determining the time to enter a stationary mode of operation  $\tau$ ; the authors comprehensively described the impact of the structural and technological elements (STE) on the basic TED parameters for the geometry of thermoelements branches  $l/S = 10$  cm<sup>-1</sup>. We shall use the ratio to determine the time to enter a stationary mode of operation  $\tau$  depending on the relative working current  $B_K$ :

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

where

$$\gamma = \frac{I_{\max H}^2 R_H}{I_{\max K}^2 R_K}$$

where  $I_{\max H}$ ,  $R_H$  are, respectively, the maximum working current, A, and the electrical resistance of a thermoelement branch, Ohm, at the beginning of the cooling process at  $\tau=0$ ;

$I_{\max K}$ ,  $R_K$  are, respectively, the maximum working current, A, and the electrical resistance of a thermoelement branch, Ohm, at the end of the cooling process  $\tau$ ;

$e_H$ ,  $e_K$  are, respectively, the thermoEMF factor of a thermoelement branch at the beginning and end of the cooling process, V/K;

$B_H=I/I_{\max H}$  is, respectively, the relative working current at  $\tau=0$ ;

$B_K=I/I_{\max K}$  is, respectively, the relative working current at  $\tau$ ;

if the currents are equal at the beginning and end of the cooling process:

$$I=B_H I_{\max H}=B_K I_{\max K}; \tag{2}$$

$T_0$  is the temperature of heat-absorbing welding joint at the end of the cooling process, K;

$T$  is the temperature of heat-absorbing welding joint at the beginning of the cooling process, K;

$\Theta=\Delta T/T_{\max}$  is the relative temperature difference;

$\Delta T=T-T_0$  is the relative difference in a TED temperature, K;

$\Delta T_{\max} = 0,5\bar{z}T_0^2$  is the maximum temperature difference, K;

$\bar{z}$  is the averaged value of the thermoelectric material efficiency in a module, 1/K;

$I$  is the magnitude of working current, A;

$K_K = \bar{\alpha}_K / (l / S)$  is the heat transfer factor, W/K;

$\bar{\alpha}_K$  is the averaged thermal conductivity ratio, W/(cm·K);

$$\sum_i m_i C_i = 175 \cdot 10^{-4} \text{ J/K}$$

is the total magnitude of the product of heat intensity by the mass of STE components at the predefined geometry of thermoelement branches  $l/S=10 \text{ cm}^{-1}$ .

The number of thermoelements  $n$  can be determined from ratio

$$n = \frac{Q_0}{I_{\max K}^2 R_K (2B_K - B_K^2 - \Theta)} = \frac{Q_0}{\beta (2B_K - B_K^2 - \Theta)}, \tag{3}$$

where  $Q_0$  is the magnitude of heat load, W;  $\beta = I_{\max K}^2 R_K$  is the maximum power of thermoelectric cooling.

The power of consumption  $W_K$  by a TED can be determined from expression:

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

Voltage drop is

$$U_K = W_K / I. \tag{5}$$

Refrigerating factor  $E$  can be determined from formula

$$E = Q_0 / W_K. \tag{6}$$

The relative failure rate  $\lambda/\lambda_0$  can be determined from formula [10]:

$$\lambda/\lambda_0 = nB_K^2 (\Theta + C_K) \frac{\left( B_K + \frac{\Delta T_{\max}}{T_0} \Theta \right)^2}{\left( 1 + \frac{\Delta T_{\max}}{T_0} \Theta \right)^2} K_{T_i}, \tag{7}$$

where  $C_K = \frac{Q_0}{nI_{\max K}^2 R_K}$  is the relative heat load;  $K_{T_i}$  is the significant lower temperature factor;  $\lambda_0=3 \cdot 10^{-8} \text{ 1/h}$  is the rated failure rate.

The probability of a failure-free operation  $P$  by a TED can be determined from expression

$$P = \exp(-\lambda t), \tag{8}$$

where  $t=10^4 \text{ h}$  is the designated resource.

We calculate the dynamics of the main parameters and reliability indicators of a single-cascade TED for different variants of the combinations of the source material parameters (1) to (5) and the current modes of operation from  $Q_{0\max}$  to  $\lambda_{\min}$ .

## 5. Analysis of the dynamic model

### 5.1. Mode $Q_{0\max}$

The results of calculating the basic parameters taking into consideration the temperature dependence, reliability indicators, operational dynamics of a single-cascade TED for variants of the combination of the source material parameters (1) to (5) are given in Table 2. Calculations were performed at  $T=300 \text{ K}$ , temperature variations from 10 to 60 K, heat load  $Q_0=2.0 \text{ W}$ ,  $l/S=10 \text{ cm}^{-1}$ ,  $\sum_i m_i C_i = 175 \cdot 10^{-4} \text{ J/K}$ ,  $\lambda_0 = 3 \cdot 10^{-8} \text{ 1/h}$ ,  $t=10^4 \text{ h}$ .

Analysis of the results of calculating the main parameters, reliability indicators and the operational dynamics of a single-cascade TED for different variants of the combinations of the source material parameters (1) to (5), given in Table 2, has shown that an increase in the temperature difference  $\Delta T$  leads to the following:

- the magnitude of refrigerating capacity per thermoelement  $Q_0/n$  is reduced for the assigned variant of the combination of the original material parameters (1) to (5). The largest increase in  $Q_0/n$  is observed at  $\Delta T=10 \text{ K}$  (Fig. 1) and is 19.2 % for variant 5 compared to variant 1 and 69 % for variant 5 compared to traditional variant 3;

- the magnitude of the maximum temperature difference  $\Delta T_{\max}$  decreases and does not depend on the combination of the original material parameters (1) to (5);

- the number of thermoelements  $n$  increases for all combination variants (1) to (5). At a predetermined temperature difference  $\Delta T$ , for example,  $\Delta T=40 \text{ K}$ ,  $n$  is reduced from variant 1 to variant 5 by 13.6 %, and from variant 3 to variant 5 – by 7 %;

- the magnitude of the relative temperature difference  $\Theta$  is increasing and does not depend on the combination of the original material parameters (1) to (5);

- the magnitude of the maximum working current  $I_{\max K}$  is reduced for different combination variants (1) to (5);

- the magnitude of the refrigerating factor  $E$  decreases and does not depend on the combination of the source material parameters (1) to (5);

- the magnitude of the working current  $I$  decreases for all variants of the combination of the original material parameters (1) to (5) (Fig. 2); at the assigned temperature

change, for example,  $\Delta T=40$  K, the magnitude of the working current  $I$  increases from variant 1 to variant 5 by 73 %;

– the magnitude of the relative working current  $B_K=1.0$  remains almost unchanged under a  $Q_{0max}$  mode and does not depend on the variant of the combination of the source material parameters (1) to (5), while  $B_H$  decreases;

– the failure rate  $\lambda/\lambda_0$  increases for all variants of the combination of the source material parameters (1) to (5); at the assigned temperature change, for example,  $\Delta T=40$  K, the failure rate  $\lambda/\lambda_0$  decreases for the variant of combination 5, compared to variant 1, by 13.9 %, and, compared to 3, by 10.6 %;

– the probability of failure-free operation  $P$  is reduced for all variants of the combination of the original material parameters (1) to (5); at the assigned temperature difference, for example,  $\Delta T=40$  K, the probability of failure-free operation  $P$  increases from the variant of combination 1 to variant 5;

– the time to enter a stationary mode  $\tau$  is increased (Fig. 3) for all variants of the combination of the original material parameters (1) to (5); at the assigned temperature change, for example,  $\Delta T=40$  K, the time to enter a stationary mode  $\tau$  is reduced for the variant of combination 5, compared to variant 1, by 13 %, and, compared to 3, by 7.7 %;

– the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_5)/\tau_1$  % – pos. 1 for the variant of combination 5, compared to variant 1,  $\Delta\tau/\tau=(\tau_3-\tau_5)/\tau_3$  % – pos. 2 for the variant of combination 5, compared to variant 3, decreases (Fig. 4);

– the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_4)/\tau_1$  % – pos. 1 for the variant of combination 4, compared to variant 1, and  $\Delta\tau/\tau=(\tau_3-\tau_4)/\tau_3$  % – pos. 2, compared to variant 3, decreases (Fig. 5); at the assigned temperature change, for example,  $\Delta T=40$  K, the magnitude  $\Delta\tau/\tau$  is reduced for the variant of combination 4, compared to variant 1, by 9 %, and, compared to 3, by 3 %.

Table 2

Mode  $Q_{0max}$ ;  $B_K=1.0$ ;  $T=300$  K;  $Q_0=2.0$  W;  $I/S=10$  cm<sup>-1</sup>;  $\sum_i m_i C_i = 175 \cdot 10^{-4}$  J/K

Variant No.	$R_H \cdot 10^3$ , Ohm	$I_{maxH}$ , A	$R_K \cdot 10^3$ , Ohm	$I_{maxK}$ , A	$B_H$	$Q_0/n$ , W/pc.	$I$ , A	$\tau$ , s	$n$ , pc.	$K \cdot 10^3$ , W/K	$U$ , V	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ , 1/h	$P$
$\Delta T=10$ K; $T_0=290$ K; $\Delta T_{max}=104.7$ K; $\Theta=0.0955$ ; $W=4.57$ W; $E=0.438$ ; $K_f=1.01$ ; $\gamma=1.062$														
1	18.18	4.125	17.9	4.03	0.977	0.263	4.03	1.14	7.6	1.44	1.13	7.7	23.0	0.99770
2	12.5	5.04	12.27	4.94	0.98	0.270	4.94	1.09	7.4	1.48	0.93	7.5	22.4	0.9978
3	11.1	5.5	11.0	5.35	0.97	0.286	5.35	1.07	7.0	1.56	0.85	7.1	21.2	0.9979
4	8.33	6.48	8.2	6.33	0.977	0.299	6.33	1.015	6.7	1.63	0.72	6.8	20.3	0.9980
5	6.67	7.42	6.54	7.27	0.980	0.313	7.27	0.95	6.4	1.71	0.63	6.5	19.4	0.9981
$\Delta T=20$ K; $T_0=280$ K; $\Delta T_{max}=93.7$ K; $\Theta=0.213$ ; $W=5.43$ W; $E=0.37$ ; $K_f=1.011$ ; $\gamma=1.14$														
1	18.18	4.125	17.2	4.0	0.97	0.217	4.0	2.6	9.2	1.46	1.35	9.3	27.9	0.9972
2	12.5	5.04	11.9	4.87	0.966	0.222	4.87	2.55	9.0	1.50	1.12	9.1	27.3	0.9973
3	11.1	5.5	10.64	5.26	0.956	0.233	5.26	2.5	8.6	1.55	1.03	8.7	26.1	0.9974
4	8.33	6.48	8.13	6.13	0.946	0.241	6.13	2.4	8.3	1.63	0.89	8.4	25.2	0.9975
5	6.67	7.42	6.49	7.03	0.947	0.253	7.03	2.2	7.9	1.71	0.77	8.0	24.0	0.9976
$\Delta T=30$ K; $T_0=270$ K; $\Delta T_{max}=86.8$ K; $\Theta=0.346$ ; $W=6.8$ W; $E=0.294$ ; $K_f=1.016$ ; $\gamma=1.21$														
1	18.18	4.125	17.0	3.86	0.936	0.165	3.86	4.5	12.1	1.47	1.76	12.3	36.9	0.99632
2	12.5	5.04	11.6	4.77	0.946	0.172	4.77	4.25	11.6	1.52	1.42	11.8	35.4	0.99647
3	11.1	5.5	10.42	5.16	0.938	0.182	5.16	4.09	11.0	1.59	1.31	11.2	33.6	0.99665
4	8.33	6.48	7.94	5.98	0.923	0.185	5.98	4.0	10.8	1.64	1.14	11.0	33.0	0.99670
5	6.67	7.42	6.41	6.86	0.925	0.198	6.86	3.78	10.1	1.74	0.986	10.3	30.9	0.99691
$\Delta T=40$ K; $T_0=260$ K; $\Delta T_{max}=79.8$ K; $\Theta=0.50$ ; $W=9.25$ W; $E=0.216$ ; $K_f=1.022$ ; $\gamma=1.32$														
1	18.18	4.125	16.4	3.80	0.921	0.118	3.80	6.9	16.9	1.49	2.43	17.3	51.8	0.9948
2	12.5	5.04	11.4	4.65	0.923	0.123	4.65	6.7	16.3	1.53	2.0	16.7	50.0	0.9950
3	11.1	5.5	10.0	5.04	0.916	0.127	5.04	6.5	15.7	1.60	1.83	16.0	48.1	0.9952
4	8.33	6.48	7.75	5.84	0.901	0.132	5.84	6.3	15.1	1.65	1.58	15.4	46.3	0.9954
5	6.67	7.42	6.33	6.57	0.885	0.137	6.57	6.0	14.6	1.75	1.40	14.9	44.8	0.9955
$\Delta T=50$ K; $T_0=250$ K; $\Delta T_{max}=73.1$ K; $\Theta=0.684$ ; $W=15.2$ W; $E=0.132$ ; $K_f=1.028$ ; $\gamma=1.42$														
1	18.18	4.125	15.6	3.77	0.914	0.070	3.77	10.8	28.5	1.51	4.0	29.3	87.9	0.9912
2	12.5	5.04	11.0	4.52	0.897	0.071	4.52	10.7	28.2	1.54	3.36	29.0	87.0	0.9913
3	11.1	5.5	9.8	4.90	0.891	0.074	4.90	10.4	26.9	1.61	3.10	27.7	83.0	0.9917
4	8.33	6.48	7.69	5.62	0.867	0.077	5.62	10.0	26.0	1.66	2.70	26.7	80.2	0.9920
5	6.67	7.42	6.17	6.44	0.868	0.081	6.44	9.47	24.7	1.75	2.35	25.4	76.2	0.9924
$\Delta T=60$ K; $T_0=240$ K; $\Delta T_{max}=66.8$ K; $\Theta=0.898$ ; $W=49.1$ W; $E=0.0407$ ; $K_f=1.035$ ; $\gamma=1.53$														
1	18.18	4.125	15.4	3.62	0.878	0.0206	3.62	19.9	97.2	1.52	13.6	100.6	301.8	0.9703
2	12.5	5.04	10.75	4.40	0.873	0.0212	4.40	19.4	94.2	1.56	11.2	97.5	292.5	0.9712
3	11.1	5.5	9.85	4.70	0.855	0.0222	4.70	18.6	90.1	1.63	10.4	92.4	277.0	0.9727
4	8.33	6.48	7.52	5.46	0.843	0.0229	5.46	18.2	87.5	1.67	9.0	90.6	271.7	0.9732
5	6.67	7.42	6.13	6.19	0.834	0.0240	6.19	17.3	83.5	1.75	7.9	86.4	259.3	0.9744

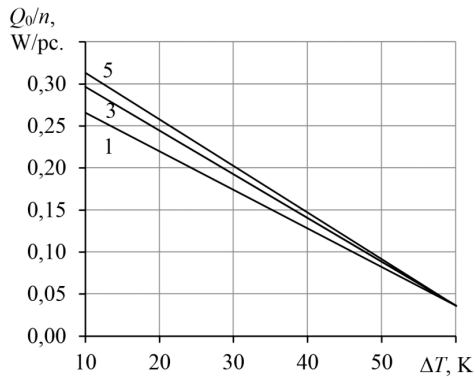


Fig. 1. Dependence of refrigerating capacity per a single thermal element  $Q_0/n$  of the single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$  under a  $Q_{0max}$  mode

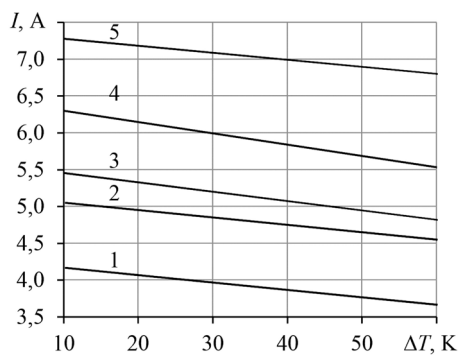


Fig. 2. Dependence of the magnitude of working current  $I$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$  under a  $Q_{0max}$  mode

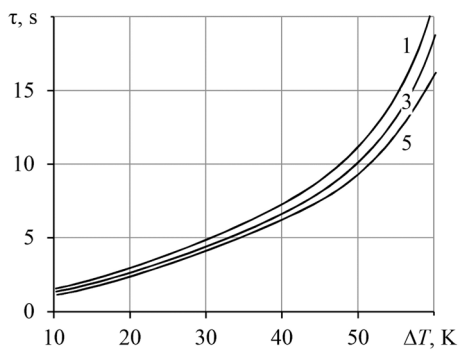


Fig. 3. Dependence of the time to enter a stationary mode  $\tau$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$  under a  $Q_{0max}$  mode

Thus, we have established the relationship between the operational dynamics of a single-cascade TED and the basic parameters and reliability indicators under a  $Q_{0max}$ : at  $T=300$  K;  $Q_0=2.0$  W;  $l/S=10$  cm $^{-1}$ .

The minimum time to enter a stationary mode of operation  $\tau_{min}$  is provided by the variant of the combination of parameters 5 of the source material and is, at  $\Delta T=40$  K,  $\tau_{min}=6$  s.

The lowest failure rate  $\lambda/\lambda_0$  and, accordingly, the largest probability of failure-free operation  $P$ , are provided by the

variant of combining the parameters 5 of the source material and are  $\lambda/\lambda_0=44.8$ ;  $P=0.9955$ .

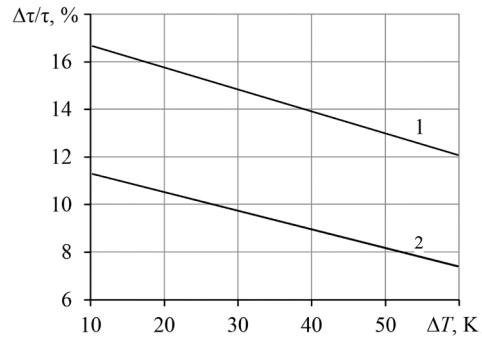


Fig. 4. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$  under a  $Q_{0max}$  mode:

$$1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_5}{\tau_1}; \quad 2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_5}{\tau_3}$$

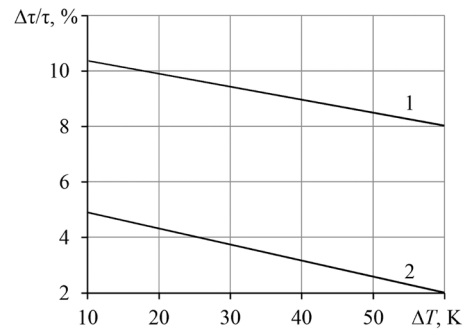


Fig. 5. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$  under a  $Q_{0max}$  mode:

$$1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_4}{\tau_1}; \quad 2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_4}{\tau_3}$$

The minimum number of thermoelements  $n$  is provided by the variant of the combination of parameters 5 of the source material and is  $n=14.6$  pcs. This is achieved at  $\Delta T=40$  K, refrigeration factor  $E=0.216$ , the magnitude of working current  $I=6.6$ , the maximum working current  $I_{max}=6.6$  A, and voltage drop  $U=1.4$  V.

Thus, the choice of the variant of the combination of parameters 5 with the increased electrical conductivity of the source material is the most appropriate when constructing the thermoelectric systems to enable the electronic equipment thermal mode.

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

The results of calculating the basic parameters taking into consideration the temperature dependence, reliability indicators, operational dynamics of a single-cascade TED for different variants of the combination of the original material parameters (1) to (5) are given in Table 3. Calculations were performed at  $T=300$  K, temperature difference  $\Delta T$  from 10 to 60 K, heat load  $Q_0=2.0$  W,  $l/S=10$  cm $^{-1}$ ,  $\sum_i m_i C_i = 175 \cdot 10^{-4}$  J/K,  $\lambda_0=3 \cdot 10^{-8}$  1/h,  $t=10^4$  h.

Table 3

Mode ( $Q_0/\Lambda$ )<sub>max</sub>;  $T=300$  K;  $Q_0=2.0$  W;  $l/S=10$  cm<sup>-1</sup>;  $\sum_i m_i C_i = 175 \cdot 10^{-4}$  J/K

Variant No.	$R_H \cdot 10^3$ , Ohm	$I_{maxH}$ , A	$R_K \cdot 10^3$ , Ohm	$I_{maxK}$ , A	$B_H$	$Q_0/n$ , W/pc.	$I$ , A	$\tau$ , s	$n$ , pc.	$U$ , V	$K \cdot 10^3$ , W/K	$\lambda/\lambda_0$	$\lambda \cdot 10^8$ , 1/h	$P$
$\Delta T=10$ K; $T_0=290$ K; $\Delta T_{max}=104.7$ K; $\Theta=0.0955$ ; $W=0.995$ W; $E=2.0$ ; $B_K=0.309$ ; $K_T=1.01$ ; $\gamma=1.06$														
1	18.18	4.125	17.9	4.03	0.302	0.124	1.245	2.44	16.1	0.80	1.44	0.089	0.27	0.999973
2	12.5	5.04	12.27	4.94	0.303	0.128	1.53	2.36	15.6	0.65	1.48	0.087	0.26	0.999974
3	11.1	5.5	11.0	5.35	0.300	0.134	1.65	2.22	14.9	0.60	1.56	0.083	0.25	0.999975
4	8.33	6.48	8.2	6.33	0.302	0.140	1.96	2.16	14.3	0.51	1.63	0.078	0.24	0.999976
5	6.67	7.42	6.54	7.27	0.303	0.147	2.25	2.06	13.6	0.44	1.71	0.075	0.22	0.999978
$\Delta T=20$ K; $T_0=280$ K; $\Delta T_{max}=93.7$ K; $\Theta=0.213$ ; $W=1.97$ W; $E=1.01$ ; $B_K=0.462$ ; $K_T=1.01$ ; $\gamma=1.124$														
1	18.18	4.125	17.2	4.0	0.446	0.136	1.84	4.2	14.7	1.07	1.46	0.488	1.465	0.999854
2	12.5	5.04	11.9	4.87	0.446	0.141	2.25	4.0	14.2	0.876	1.50	0.54	1.62	0.999840
3	11.1	5.5	10.64	5.26	0.441	0.147	2.43	3.9	13.6	0.810	1.57	0.52	1.55	0.999850
4	8.33	6.48	8.13	6.13	0.437	0.153	2.83	3.7	13.1	0.70	1.63	0.50	1.50	0.999851
5	6.67	7.42	6.49	7.03	0.438	0.160	3.25	3.55	12.5	0.61	1.71	0.475	1.43	0.999860
$\Delta T=30$ K; $T_0=270$ K; $\Delta T_{max}=86.8$ K; $\Theta=0.346$ ; $W=3.4$ W; $E=0.588$ ; $B_K=0.588$ ; $K_T=1.016$ ; $\gamma=1.221$														
1	18.18	4.125	17.0	3.86	0.550	0.123	2.27	6.0	16.3	1.49	1.47	1.88	5.65	0.999435
2	12.5	5.04	11.6	4.77	0.557	0.127	2.80	5.8	15.7	1.22	1.52	1.81	5.43	0.999457
3	11.1	5.5	10.42	5.16	0.552	0.134	3.0	5.5	14.9	1.13	1.59	1.72	5.15	0.999485
4	8.33	6.48	7.94	5.98	0.543	0.137	3.52	5.4	14.6	0.97	1.64	1.69	5.06	0.999494
5	6.67	7.42	6.41	6.86	0.544	0.146	4.0	5.0	13.7	0.85	1.74	1.59	4.76	0.999524
$\Delta T=40$ K; $T_0=260$ K; $\Delta T_{max}=79.8$ K; $\Theta=0.50$ ; $W=5.89$ W; $E=0.34$ ; $B_K=0.707$ ; $K_T=1.022$ ; $\gamma=1.306$														
1	18.18	4.125	16.4	3.80	0.651	0.098	2.7	8.3	20.4	2.19	1.49	5.3	15.9	0.99841
2	12.5	5.04	11.4	4.65	0.652	0.102	3.3	8.0	19.7	1.79	1.53	5.1	15.3	0.99847
3	11.1	5.5	10.0	5.04	0.648	0.105	3.6	7.8	19.0	1.65	1.60	4.9	14.8	0.9985
4	8.33	6.48	7.75	5.84	0.637	0.109	4.1	7.5	18.3	1.43	1.65	4.76	14.3	0.9986
5	6.67	7.42	6.33	6.57	0.626	0.113	4.6	7.1	17.7	1.27	1.75	4.6	13.8	0.99862
$\Delta T=50$ K; $T_0=250$ K; $\Delta T_{max}=73.1$ K; $\Theta=0.684$ ; $W=11.82$ W; $E=0.169$ ; $B_K=0.827$ ; $K_T=1.028$ ; $\gamma=1.395$														
1	18.18	4.125	15.6	3.77	0.756	0.0635	3.12	12.2	31.5	3.8	1.51	15.7	47.1	0.9953
2	12.5	5.04	11.0	4.52	0.742	0.0643	3.7	11.7	31.1	3.2	1.54	15.5	46.5	0.99536
3	11.1	5.5	9.8	4.90	0.737	0.0673	4.1	11.3	29.7	2.9	1.61	14.8	44.4	0.99557
4	8.33	6.48	7.69	5.62	0.717	0.0694	4.65	10.9	28.8	2.6	1.66	14.3	43.0	0.99571
5	6.67	7.42	6.17	6.44	0.718	0.0733	5.3	10.3	27.3	2.2	1.75	13.6	40.7	0.99594
$\Delta T=60$ K; $T_0=240$ K; $\Delta T_{max}=66.8$ K; $\Theta=0.898$ ; $W=45.9$ W; $E=0.0436$ ; $B_K=0.948$ ; $K_T=1.035$ ; $\gamma=1.533$														
1	18.18	4.125	15.4	3.62	0.832	0.020	3.4	20.4	100.1	13.4	1.52	85.3	256	0.9747
2	12.5	5.04	10.75	4.40	0.827	0.0206	4.2	19.8	97.0	11.0	1.56	82.6	248	0.9755
3	11.1	5.5	9.85	4.70	0.810	0.0216	4.45	19.0	92.8	10.3	1.63	79.0	237	0.97658
4	8.33	6.48	7.52	5.46	0.800	0.0222	5.2	18.6	90.1	8.9	1.67	76.7	230	0.97724
5	6.67	7.42	6.13	6.19	0.790	0.0233	5.9	17.7	86.0	7.8	1.75	73.2	220	0.9783

Our analysis of the results of calculating the basic parameters, reliability indicators, and the operational dynamics of a single-cascade TED for different variants of the combination of the original material parameters (1) to (5), given in Table 3, has revealed that the increase in temperature difference  $\Delta T$  leads to the following:

– the functional dependence  $Q_0/n=f(\Delta T)$  has a maximum at  $\Delta T=20$  K (Fig. 6). The highest refrigerating capacity per thermoelement  $Q_0/n$  is observed for variant 5, under which  $Q_0/n$  increases for variant 5, compared to variant 1, by 17.6 %, and, for variant 5 compared to 3, by 8.1 %;

– the functional dependence of the number of thermoelements  $n=f(\Delta T)$  has a flat minimum for  $\Delta T=20$  K; at the predetermined temperature change, for example,  $\Delta T=40$  K, the number of thermoelements  $n$  decreases from variant 1 to variant 5 by 13.2 %, and, from variant 3 to variant 5, by 6.8 %;

– the relative working current  $B_K$  and  $B_H$  increases at the beginning and end of the cooling mode;  $B_K$  does not depend

on the variant of the combination of the original material parameters (1) to (5), while  $B_H$  decreases;

– the magnitude of the working current  $I$  increases (Fig. 7) for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature change, for example,  $\Delta T=40$  K, the magnitude of the working current  $I$  increases from variant 1 to variant 5 by 70 %, and, by 28 %, from variant 3 to variant 5;

– the magnitude of the voltage drop  $U$  increases; for all variants of the combinations of the original material parameters (1) to (5). At the predefined temperature difference, for example,  $\Delta T=40$  K, the magnitude of the voltage drop  $U$  decreases, for the variant of combination 5, compared to 1, by 42 %, and, compared to 3, by 23 %;

– the failure rate  $\lambda/\lambda_0$  increases for all variants of the combination of the source material parameters (1) to (5); at the assigned temperature change, for example,  $\Delta T=40$  K, the failure rate  $\lambda/\lambda_0$  decreases for the variant of combination 5, compared to variant 1, by 13.2 %, and, to 3, by 6.1 %;

– the probability of failure-free operation  $P$  is reduced; at the assigned temperature change, for example,  $\Delta T=40$  K, the probability of failure-free operation  $P$  increases from the variant of combination 1 to variant 5;

– the time to enter a stationary mode  $\tau$  is increased (Fig. 8) for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature change, for example,  $\Delta T=40$  K, the time to enter a stationary mode  $\tau$  is reduced for variant 5, compared to 1, by 14.5 %, and, compared to 3, by 9 %;

– the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_5)/\tau_1$  % – pos. 1 for variant 5, compared to 1,  $\Delta\tau/\tau=(\tau_3-\tau_5)/\tau_3$  % – pos. 2 for variant 5, compared to 3, decreases (Fig. 9);

– the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_4)/\tau_1$  % – pos. 1 for variant 4, compared to 1, and 1, and  $\Delta\tau/\tau=(\tau_3-\tau_4)/\tau_3$  % – pos. 2, compared to 3, decreases (Fig. 10). At the assigned temperature difference, for example,  $\Delta T=40$  K, the magnitude  $\Delta\tau/\tau$  is reduced for the variant of combination 4, compared to variant 1, by 9 %, and, compared to 3, by 3 %.

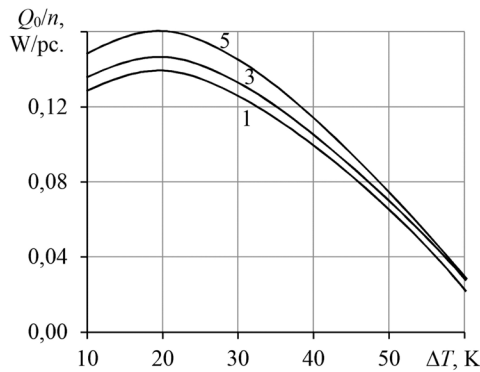


Fig. 6. Dependence of refrigerating capacity per thermoelement  $Q_0/n$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $(Q_0/I)_{max}$  mode

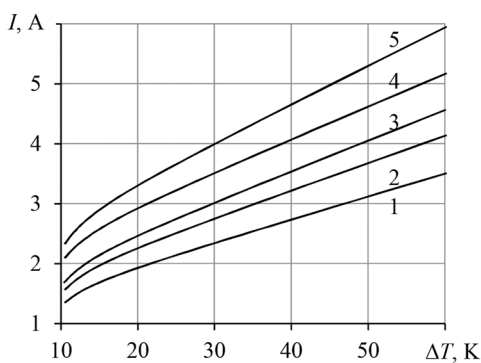


Fig. 7. Dependence of the magnitude of working current  $I$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $(Q_0/I)_{max}$  mode

Thus, we have established the relationship between the operational dynamics of a single-cascade TED and the basic parameters and reliability indicators under a  $(Q_0/I)_{max}$  mode: at  $T=300$  K;  $Q_0=2.0$  W;  $l/S=10$  cm<sup>-1</sup>.

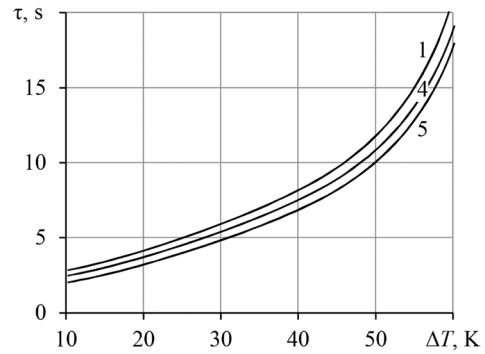


Fig. 8. Dependence of the time to enter a stationary mode  $\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $(Q_0/I)_{max}$  mode

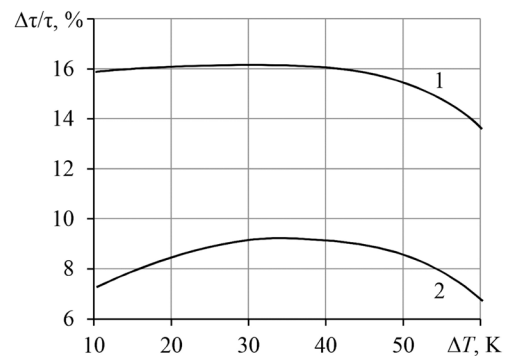


Fig. 9. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters (5 compared to 1 and 3) at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $(Q_0/I)_{max}$  mode: 1 –  $\frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_5}{\tau_1}$ ; 2 –  $\frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_5}{\tau_3}$

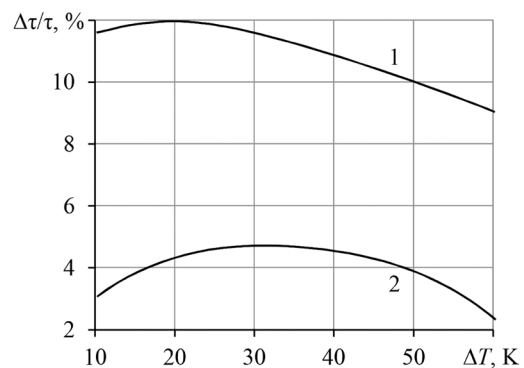


Fig. 10. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters (4 compared to 1 and 3) at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $(Q_0/I)_{max}$  mode:

$$1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_4}{\tau_1}; \quad 2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_4}{\tau_3}$$

The minimum time to enter a stationary mode of operation  $\tau_{min}$  is provided by the variant of the combination

of parameters 5 of the source material and is, at  $\Delta T=40$  K,  $\tau_{\min}=7$  s.

The lowest failure rate  $\lambda/\lambda_0$  is provided by the variant of the combination of parameters 5 of the source material and is  $\lambda/\lambda_0=13.8$ .

The number of thermoelements  $n$ , provided by the variant of combination 5 of the parameters of the source material is,  $\Delta T=40$  K,  $n=17.7$  pcs. at refrigerating factor  $E=0.34$ , the magnitude of working current  $I=4.6$  A, the maximum working current  $I_{\max}=6.57$  A, and a drop in voltage  $U=1.27$  V.

Therefore, the choice of the variant of the combination of parameters 4, 5 with increased electrical conductivity of the source material is the most appropriate.

### 5.3. Mode $(Q_0/I^2)_{\max}$

The results of calculating the basic parameters taking into consideration the temperature dependence, the time to enter a stationary mode, reliability indicators for the  $(Q_0/I^2)_{\max}$  mode and for different temperature difference  $\Delta T$  are given in Table 4.

Table 4

Mode  $(Q_0/I^2)_{\max}$ ;  $T=300$  K;  $Q_0=2.0$  W;  $l/S=10$  cm<sup>-1</sup>;  $\sum_i m_i C_i = 175 \cdot 10^{-4}$  J/K

Variant No.	$R_H \cdot 10^3$ , Ohm	$I_{\max H}$ , A	$R_K \cdot 10^3$ , Ohm	$I_{\max K}$ , A	$B_H$	$Q_0/n$ , W/pc.	$I$ , A	$\tau$ , s	$n$ , pc.	$K \cdot 10^3$ , W/K	$\gamma$	$U$ , V	$\lambda/\lambda_0$	$P$
$\Delta T=10$ K; $T_0=290$ K; $\Delta T_{\max}=104.7$ K; $\Theta=0.0955$ ; $W=0.514$ W; $E=3.48$ ; $B_K=0.0955$ ; $K_T=1.01$														
1	18.18	4.125	17.9	4.03	0.0933	0.025	0.385	8.9	79.6	1.44	1.064	1.49	0.0021	0.99999937
2	12.5	5.04	12.27	4.94	0.0937	0.0259	0.472	8.7	77.3	1.48	1.060	1.22	0.00205	0.99999939
3	11.1	5.5	11.0	5.35	0.0929	0.0272	0.511	8.2	73.5	1.56	1.066	1.12	0.00195	0.99999942
4	8.33	6.48	8.2	6.33	0.0933	0.0284	0.605	7.9	70.5	1.63	1.065	0.95	0.00187	0.99999944
5	6.67	7.42	6.54	7.27	0.0935	0.0298	0.694	7.5	67.0	1.71	1.062	0.83	0.00177	0.99999947
$\Delta T=20$ K; $T_0=280$ K; $\Delta T_{\max}=93.7$ K; $\Theta=0.213$ ; $W=1.44$ W; $E=1.39$ ; $B_K=0.213$ ; $K_T=1.01$														
1	18.18	4.125	17.2	4.0	0.206	0.0458	0.848	9.6	43.7	1.46	1.133	1.70	0.0535	0.999984
2	12.5	5.04	11.9	4.87	0.206	0.0473	1.04	9.3	42.3	1.50	1.125	1.39	0.0508	0.999985
3	11.1	5.5	10.64	5.26	0.204	0.0494	1.12	9.0	40.5	1.57	1.142	1.28	0.0486	0.9999855
4	8.33	6.48	8.13	6.13	0.201	0.0512	1.30	8.5	39.1	1.63	1.145	1.10	0.047	0.999986
5	6.67	7.42	6.49	7.03	0.202	0.0538	1.50	8.2	37.2	1.71	1.145	0.96	0.0446	0.999987
$\Delta T=30$ K; $T_0=270$ K; $\Delta T_{\max}=86.8$ K; $\Theta=0.346$ ; $W=2.79$ W; $E=0.717$ ; $B_K=0.346$ ; $K_T=1.016$														
1	9.18	4.125	17.0	3.86	0.324	0.0573	1.34	10.5	34.9	1.47	1.221	2.08	0.412	0.99988
2	12.5	5.04	11.6	4.77	0.327	0.0597	1.65	10.0	33.5	1.52	1.20	1.69	0.395	0.999881
3	11.1	5.5	10.42	5.16	0.325	0.0627	1.79	9.6	31.9	1.59	1.21	1.56	0.376	0.999887
4	8.33	6.48	7.94	5.98	0.319	0.0643	2.07	9.37	31.1	1.64	1.232	1.35	0.367	0.99989
5	6.67	7.42	6.41	6.86	0.320	0.0682	2.37	8.70	29.3	1.74	1.217	1.18	0.346	0.999896
$\Delta T=40$ K; $T_0=260$ K; $\Delta T_{\max}=79.8$ K; $\Theta=0.50$ ; $W=5.24$ W; $E=0.382$ ; $B_K=0.50$ ; $K_T=1.022$														
1	18.18	4.125	16.4	3.80	0.461	0.0592	1.90	11.8	33.8	1.49	1.306	2.76	2.08	0.99938
2	12.5	5.04	11.4	4.65	0.461	0.0613	2.33	11.4	32.6	1.53	1.293	2.25	2.0	0.99940
3	11.1	5.5	10.0	5.04	0.458	0.0635	2.52	11.0	31.5	1.60	1.322	2.08	1.93	0.99942
4	8.33	6.48	7.75	5.84	0.451	0.0660	2.92	10.6	30.3	1.65	1.323	1.80	1.86	0.99944
5	6.67	7.42	6.33	6.57	0.443	0.0683	3.29	10.0	29.3	1.75	1.344	1.59	1.80	0.99946
$\Delta T=50$ K; $T_0=250$ K; $\Delta T_{\max}=73.1$ K; $\Theta=0.684$ ; $W=11.2$ W; $E=0.179$ ; $B_K=0.684$ ; $K_T=1.028$														
1	18.18	4.125	15.6	3.77	0.625	0.048	2.58	14.2	41.7	1.51	1.395	4.32	9.77	0.9971
2	12.5	5.04	11.0	4.52	0.613	0.0485	3.10	14.0	41.2	1.54	1.413	3.62	9.65	0.9971
3	11.1	5.5	9.8	4.90	0.609	0.510	3.35	13.4	39.3	1.61	1.427	3.33	9.20	0.9972
4	8.33	6.48	7.69	5.62	0.593	0.525	3.84	12.9	38.1	1.66	1.440	2.91	8.92	0.9973
5	6.67	7.42	6.17	6.44	0.594	0.552	4.40	12.3	36.2	1.75	1.435	2.54	8.48	0.9975
$\Delta T=60$ K; $T_0=240$ K; $\Delta T_{\max}=66.8$ K; $\Theta=0.898$ ; $W=44.9$ W; $E=0.045$ ; $B_K=0.898$ ; $K_T=1.035$														
1	18.18	4.125	15.4	3.62	0.788	0.0186	3.25	21.2	107.7	1.52	1.532	13.8	75.1	0.9777
2	12.5	5.04	10.75	4.40	0.784	0.0191	3.95	20.7	104.5	1.56	1.526	11.4	72.9	0.9784
3	11.1	5.5	9.85	4.70	0.767	0.020	4.22	19.7	100	1.63	1.543	10.6	69.8	0.9793
4	8.33	6.48	7.52	5.46	0.756	0.0206	4.95	19.3	97.0	1.67	1.56	9.2	67.7	0.97989
5	6.67	7.42	6.13	6.19	0.749	0.0217	5.56	18.4	92.1	1.75	1.563	8.0	64.3	0.9809



Our analysis of the results of calculating the basic parameters, reliability indicators, and the operational dynamics of a single-cascade TED for different variants of the combination of the original material parameters (1) to (5), given in Table 4, has revealed that the increase in temperature difference  $\Delta T$  leads to the following:

- the functional dependence  $Q_0/n=f(\Delta T)$  has a maximum for  $\Delta T=40$  K (Fig. 11). The highest refrigerating capacity per thermoelement  $Q_0/n$  is observed for variant 5, under which  $Q_0/n$  increases for variant 5, compared to variant 1, by 15.4 %, and, for variant 5, compared to 3, by 7.6 %;

- the relative working current  $B_K$  and  $B_H$  increases at the beginning and end of the cooling mode;  $B_K$  does not depend on the variant of the combination of the original material parameters (1) to (5), while  $B_H$  decreases;

- the magnitude of the working current  $I$  (Fig. 12) increases for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature change, for example,  $\Delta T=40$  K, the magnitude of working current  $I$  increases from variant 1 to variant 5 by 73 %, and by 30 % from variant 3 to 5;

- the functional dependence of the number of thermoelements  $n=f(\Delta T)$  has a minimum for  $\Delta T=40$  K. At the assigned temperature difference, for example,  $\Delta T=40$  K, the number of thermoelements  $n$  decreases from variant 1 to variant 5 by 13.3 %, and, from variant 3 to variant 5, by 7 %;

- the magnitude of refrigerating factor  $E$  decreases and does not depend on the variant of the combination of the source material parameters (1) to (5);

- the magnitude of voltage drop  $U$  increases; at the assigned temperature change, for example,  $\Delta T=40$  K, the magnitude of voltage drop  $U$  decreases for the variant of combination 5, compared to variant 1, by 42 %, and, to 3, by 23.6 %;

- the failure rate  $\lambda/\lambda_0$  increases for all variants of the combination of the source material parameters (1) to (5). At the assigned temperature change, for example,  $\Delta T=40$  K, the failure rate  $\lambda/\lambda_0$  decreases for the variant of combination 5, compared to 1, by 13.5 %, and, to 3, by 6.7 %;

- the probability of failure-free operation  $P$  is reduced; at the assigned temperature difference, for example,  $\Delta T=40$  K, the probability of failure-free operation  $P$  increases from the variant of combination 1 to variant 5;

- the time to enter a stationary mode  $\tau$  is increased (Fig. 13) for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature difference, for example,  $\Delta T=40$  K, the time to enter a stationary mode  $\tau$  is reduced for variant 5, compared to 1, by 15.3 %, and, to 3, by 9.1 %;

- the relative magnitude of the time to enter a stationary mode of operation  $\Delta\tau/\tau$  decreases for different variants of combinations 1 –  $\Delta\tau/\tau=(\tau_1-\tau_5)/\tau_1$  % and 2 –  $\Delta\tau/\tau=(\tau_3-\tau_5)/\tau_3$  % (Fig. 14);

- the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_4)/\tau_1$  % – pos. 1 for variant 4, compared to 1, and  $\Delta\tau/\tau=(\tau_3-\tau_4)/\tau_3$  % – pos. 2, compared to 3, decreases (Fig. 15). At the assigned temperature difference, for example,  $\Delta T=40$  K, the magnitude  $\Delta\tau/\tau$  is reduced for the variant of combination 4, compared to variant 1, by 10 %, and, to 3, by 3.5 %.

Thus, we have established the relationship between the operational dynamics of a single-cascade TED and the main parameters and reliability indicators under a  $(Q_0/I^2)_{max}$  mode at  $T=300$  K;  $Q_0=2.0$  W;  $I/S=10$  cm<sup>-1</sup>.

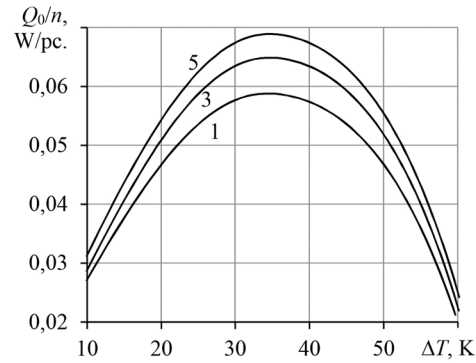


Fig. 11. Dependence of refrigerating capacity per thermoelement  $Q_0/n$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $I/S=10$  cm<sup>-1</sup> under a  $(Q_0/I^2)_{max}$  mode

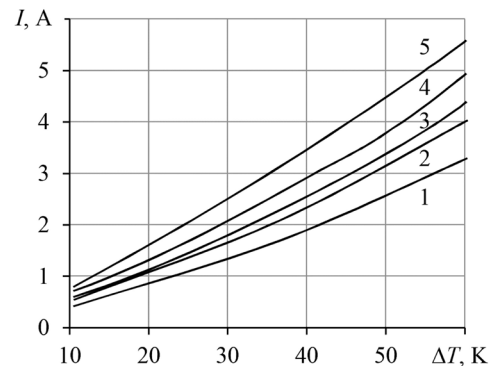


Fig. 12. Dependence of the magnitude of working current  $I$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $I/S=10$  cm<sup>-1</sup> under a  $(Q_0/I^2)_{max}$  mode

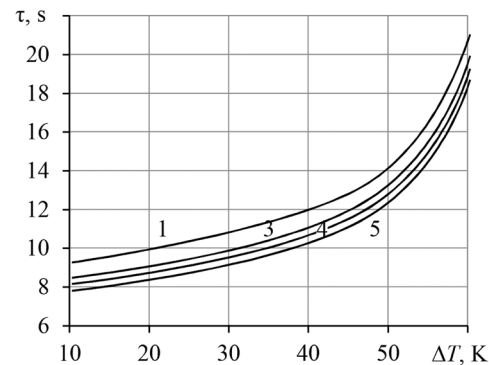


Fig. 13. Dependence of the time to enter a stationary mode  $\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $I/S=10$  cm<sup>-1</sup> under a  $(Q_0/I^2)_{max}$  mode

The lowest time to enter a stationary mode of operation  $\tau_{min}$  is provided by the variant of the combination of parameters 5 of the source material and is, at  $\Delta T=40$  K,  $\tau_{min}=10$  s.

The lowest failure rate  $\lambda/\lambda_0$  and, therefore, the highest probability of failure-free operation  $P$  is provided by the

variant of the combination of parameters 5 of the source material and is  $\lambda/\lambda_0=1.8$ ;  $P=0.99946$  at  $\Delta T=40$  K.

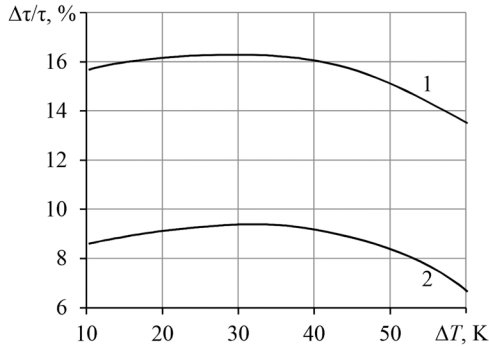


Fig. 14. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters (5 compared to 1 and 3) at  $T=300$  K,  $Q_0=2.0$  W,  $I/S=10$  cm<sup>-1</sup>

under a  $(Q_0/\beta)_{\max}$  mode:  $1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_5}{\tau_1}$ ;  $2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_5}{\tau_3}$

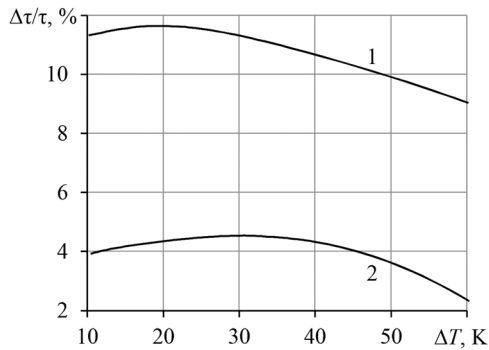


Fig. 15. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters (4 compared to 1 and 3) at  $T=300$  K,  $Q_0=2.0$  W,  $I/S=10$  cm<sup>-1</sup>

under a  $(Q_0/I^2)_{\max}$  mode:  $1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_4}{\tau_1}$ ;  $2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_4}{\tau_3}$

The number of thermoelements  $n$ , provided by the combination of parameters 5 of the source material, is  $n=29.3$  pcs. The calculations were performed for  $\Delta T=40$  K at refrigerating factor  $E=0.38$ , the magnitude of working current  $I=3.3$  A, the maximum working current  $I_{\max}=6.67$  A, and the drop in voltage  $U=1.6$  V.

Thus, the choice of the variant of the combination of parameters 4, 5 with increased electrical conductivity of the source material is the most appropriate.

#### 5. 4. Mode $\lambda_{\min}$

The results of calculating the basic parameters taking into consideration the temperature dependence, the time to enter a stationary mode, reliability indicators for the  $\lambda_{\min}$  mode and for different temperature change  $\Delta T$  are given in Table 5.

Our analysis of the results of calculating the basic parameters, reliability indicators, and the operational dy-

namics of a single-cascade TED for different variants of the combination of the original material parameters (1) to (5), given in Table 5, has revealed that the increase in temperature difference  $\Delta T$  leads to the following:

- the functional dependence  $Q_0/n=f(\Delta T)$  has a maximum for  $\Delta T=40$  K (Fig. 16). The highest refrigerating capacity per thermoelement  $Q_0/n$  is observed for variant 5, and is, at  $\Delta T=40$  K,  $Q_0/n=0,0463$ , that is, it is larger by 15.8 % compared to variant 1, and, compared to 3, by 7.7 %.

- the relative working current  $B_K$  and  $B_H$  increases at the beginning and end of the cooling mode;  $B_K$  does not depend on the variant of the combination of the original material parameters (1) to (5), while  $B_H$  decreases;

- the magnitude of the working current  $I$  (Fig. 17) increases for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature difference, for example,  $\Delta T=40$  K, the magnitude of working current  $I$  increases from variant 1 to variant 5 by 72 %, and by 32 % from variant 3 to 5;

- the functional dependence of the number of thermoelements  $n=f(\Delta T)$  has a minimum for  $\Delta T=40$  K. At the assigned temperature difference, for example,  $\Delta T=40$  K, the number of thermoelements  $n$  decreases from variant 1 to variant 5 by 13.63 %, and, from variant 3 to variant 5, by 7.1 %;

- the magnitude of refrigerating factor  $E$  decreases and does not depend on the variant of the combination of the source material parameters (1) to (5);

- the magnitude of voltage drop  $U$  increases; at the assigned temperature change, for example,  $\Delta T=40$  K, the magnitude of voltage drop  $U$  decreases for the variant of combination 5, compared to variant 1, by 42 %, and, compared to 3, by 23.5 %;

- the failure rate  $\lambda/\lambda_0$  increases for all variants of the combination of the source material parameters (1) to (5). At the assigned temperature change, for example,  $\Delta T=40$  K, the failure rate  $\lambda/\lambda_0$  increases, compared to the variant of combination 5, compared to 1, by 14.1 %, and, to 3, by 7.6 %;

- the probability of failure-free operation  $P$  failure is reduced; at the assigned temperature change, for example,  $\Delta T=40$  K, the probability of failure-free operation  $P$  increases from the variant of combination 1 to variant 5;

- the time to enter a stationary mode  $\tau$  is increased (Fig. 18) for all variants of the combination of the original material parameters (1) to (5). At the assigned temperature difference, for example,  $\Delta T=40$  K, the time to enter a stationary mode  $\tau$  is reduced, for variant 5 compared to 1, by 15 %, compared to 3, by 9.4 %. For the variant of combination 4, compared to variant 1, by 9.5 %, and, compared to 3, by 3.6 %;

- the relative magnitude of the time to enter a stationary mode of operation  $\Delta\tau/\tau$  decreases for different variants of combinations 1 -  $\Delta\tau/\tau=(\tau_1-\tau_5)/\tau_1$  % and 2 -  $\Delta\tau/\tau=(\tau_3-\tau_5)/\tau_3$  % (Fig. 19);

- the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau=(\tau_1-\tau_4)/\tau_1$  % - pos. 1 for the variant of combination of 4, compared to 1, and  $\Delta\tau/\tau=(\tau_3-\tau_4)/\tau_3$  % - pos. 2, compared to 3, decreases (Fig. 19). At the assigned temperature difference, for example,  $\Delta T=40$  K, the magnitude  $\Delta\tau/\tau$  is reduced for the variant of combination of 4, compared to variant 1, by 9.5 %, and, to 3, by 3.5 %.

Table 5

Mode  $\lambda_{\min}$ ;  $T=300\text{ K}$ ;  $Q_0=2.0\text{ W}$ ;  $l/S=10\text{ cm}^{-1}$ ;  $\sum_i m_i C_i = 175 \cdot 10^{-4}\text{ J/K}$

Variant No.	$R_H \cdot 10^3$ , Ohm	$I_{\max H}$ , A	$R_K \cdot 10^3$ , Ohm	$I_{\max K}$ , A	$B_H$	$Q_0/n$ , W/pc.	$I$ , A	$\tau$ , s	$n$ , pc.	$K \cdot 10^3$ , W/K	$\gamma$	$U$ , V	$\lambda/\lambda_0$	$P$
$\Delta T=10\text{ K}$ ; $T_0=290\text{ K}$ ; $\Delta T_{\max}=104.7\text{ K}$ ; $\Theta=0.0955$ ; $W=0.72\text{ W}$ ; $E=2.77$ ; $B_K=0.071$ ; $K_T=1.01$														
1	18.18	4.125	17.9	4.03	0.0690	0.012	0.285	14.2	166	1.44	1.064	2.53	0.0012	0.99999964
2	12.5	5.04	12.27	4.94	0.0696	0.0124	0.351	13.8	161	1.48	1.060	2.06	0.0035	0.99999895
3	11.1	5.5	11.0	5.35	0.0691	0.0131	0.380	13.1	153	1.56	1.066	1.90	0.0033	0.9999990
4	8.33	6.48	8.2	6.33	0.0694	0.0136	0.449	12.6	147	1.63	1.065	1.61	0.00316	0.99999905
5	6.67	7.42	6.54	7.27	0.0696	0.0144	0.516	12.0	139	1.71	1.062	1.40	0.0030	0.99999910
$\Delta T=20\text{ K}$ ; $T_0=280\text{ K}$ ; $\Delta T_{\max}=93.7\text{ K}$ ; $\Theta=0.213$ ; $W=1.746\text{ W}$ ; $E=1.145$ ; $B_K=0.164$ ; $K_T=1.01$														
1	18.18	4.125	17.2	4.0	0.158	0.0240	0.653	14.3	73.2	1.46	1.133	2.67	0.0326	0.9999902
2	12.5	5.04	11.9	4.87	0.158	0.0248	0.80	13.8	80.5	1.50	1.125	2.18	0.0315	0.9999905
3	11.1	5.5	10.64	5.26	0.157	0.0259	0.86	13.3	77.2	1.57	1.142	2.02	0.0302	0.9999909
4	8.33	6.48	8.13	6.13	0.155	0.0269	1.0	12.7	74.4	1.63	1.145	1.75	0.0292	0.9999913
5	6.67	7.42	6.49	7.03	0.155	0.0282	1.15	12.1	70.9	1.71	1.145	1.52	0.0277	0.9999917
$\Delta T=30\text{ K}$ ; $T_0=270\text{ K}$ ; $\Delta T_{\max}=86.8\text{ K}$ ; $\Theta=0.346$ ; $W=3.27\text{ W}$ ; $E=0.612$ ; $B_K=0.277$ ; $K_T=1.016$														
1	18.18	4.125	17.0	3.86	0.259	0.0333	1.07	14.5	60.1	1.47	1.221	3.0	0.272	0.999918
2	12.5	5.04	11.6	4.77	0.262	0.0347	1.32	13.9	57.7	1.52	1.20	2.48	0.261	0.999922
3	11.1	5.5	10.42	5.16	0.260	0.0346	1.43	13.4	54.9	1.59	1.21	2.29	0.248	0.9999255
4	8.33	6.48	7.94	5.98	0.256	0.0373	1.66	13.0	53.6	1.64	1.232	1.97	0.242	0.999927
5	6.67	7.42	6.41	6.86	0.256	0.0396	1.90	12.1	50.5	1.74	1.217	1.72	0.228	0.999932
$\Delta T=40\text{ K}$ ; $T_0=260\text{ K}$ ; $\Delta T_{\max}=79.8\text{ K}$ ; $\Theta=0.50$ ; $W=5.84\text{ W}$ ; $E=0.342$ ; $B_K=0.425$ ; $K_T=1.022$														
1	18.18	4.125	16.4	3.80	0.3915	0.040	1.62	14.7	50	1.49	1.306	3.61	1.56	0.99953
2	12.5	5.04	11.4	4.65	0.392	0.0416	1.98	14.2	48.1	1.53	1.293	2.94	1.50	0.99955
3	11.1	5.5	10.0	5.04	0.389	0.0430	2.14	13.8	46.5	1.60	1.322	2.72	1.45	0.999565
4	8.33	6.48	7.75	5.84	0.383	0.0447	2.48	13.3	44.7	1.65	1.323	2.35	1.39	0.99958
5	6.67	7.42	6.33	6.57	0.376	0.0463	2.79	12.5	43.2	1.75	1.344	2.08	1.34	0.99960
$\Delta T=50\text{ K}$ ; $T_0=250\text{ K}$ ; $\Delta T_{\max}=73.1\text{ K}$ ; $\Theta=0.684$ ; $W=11.9\text{ W}$ ; $E=0.168$ ; $B_K=0.616$ ; $K_T=1.028$														
1	18.18	4.125	15.6	3.77	0.563	0.0374	2.32	16.2	53.5	1.51	1.395	5.13	8.2	0.99754
2	12.5	5.04	11.0	4.52	0.552	0.0379	2.78	15.9	52.8	1.54	1.413	4.28	8.1	0.9976
3	11.1	5.5	9.8	4.90	0.549	0.0397	3.02	15.3	50.4	1.61	1.427	3.94	7.72	0.9977
4	8.33	6.48	7.69	5.62	0.534	0.0409	3.46	14.8	48.9	1.66	1.440	3.44	7.49	0.99775
5	6.67	7.42	6.17	6.44	0.535	0.0431	3.97	14.0	46.4	1.75	1.445	3.0	7.1	0.9979
$\Delta T=60\text{ K}$ ; $T_0=240\text{ K}$ ; $\Delta T_{\max}=66.8\text{ K}$ ; $\Theta=0.898$ ; $W=45.8\text{ W}$ ; $E=0.0437$ ; $B_K=0.871$ ; $K_T=1.035$														
1	18.18	4.125	15.4	3.62	0.764	0.0172	3.15	21.9	116	1.52	1.532	14.5	72.0	0.9786
2	12.5	5.04	10.75	4.40	0.760	0.0178	3.83	21.3	112.5	1.56	1.526	12.0	69.8	0.9793
3	11.1	5.5	9.85	4.70	0.744	0.0186	4.09	20.3	107.6	1.63	1.543	11.2	66.8	0.9802
4	8.33	6.48	7.52	5.46	0.734	0.0191	4.76	20.0	104.5	1.67	1.56	9.62	64.9	0.9807
5	6.67	7.42	6.13	6.19	0.727	0.0200	5.39	19.0	99.7	1.75	1.563	8.5	61.9	0.9816

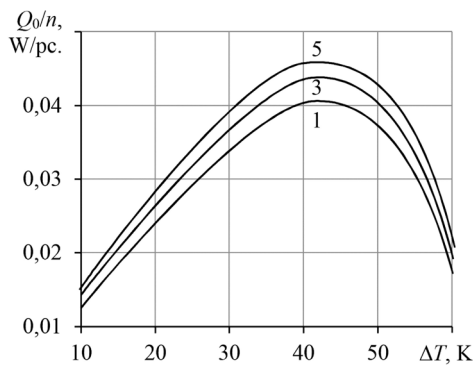


Fig. 16. Dependence of refrigerating capacity per thermoelement  $Q_0/n$  of a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300\text{ K}$ ,  $Q_0=2.0\text{ W}$ ,  $l/S=10\text{ cm}^{-1}$  under a  $\lambda_{\min}$  mode

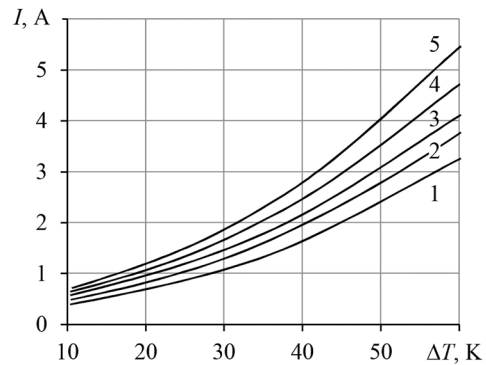


Fig. 17. Dependence of the magnitude of working current  $I$  in a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300\text{ K}$ ,  $Q_0=2.0\text{ W}$ ,  $l/S=10\text{ cm}^{-1}$  under a  $\lambda_{\min}$  mode

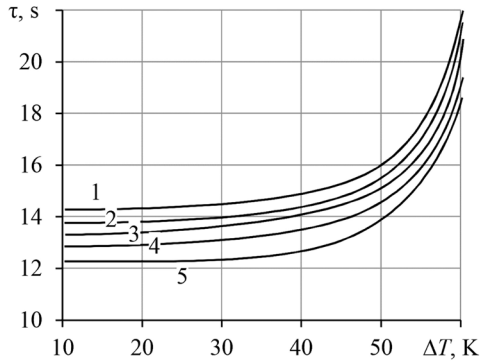


Fig. 18. Dependence of the time to enter a stationary mode  $\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $\lambda_{\min}$  mode

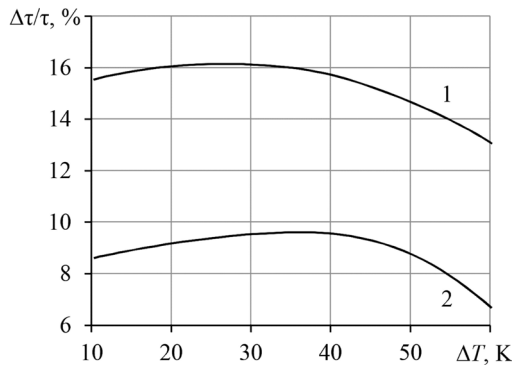


Fig. 19. Dependence of the relative magnitude of the time to enter a stationary mode  $\Delta\tau/\tau$  by a single-cascade TED on temperature difference  $\Delta T$  for different variants of the combination of the original material parameters (5 compared to 1 and 3) at  $T=300$  K,  $Q_0=2.0$  W,  $l/S=10$  cm<sup>-1</sup> under a  $\lambda_{\min}$  mode:  $1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_5}{\tau_1}$ ;  $2 - \frac{\Delta\tau}{\tau} = \frac{\tau_3 - \tau_5}{\tau_3}$

Thus, we have established the relationship between the operational dynamics of a single-cascade TED and the main parameters and reliability indicators under a  $\lambda_{\min}$  mode: at  $T=300$  K;  $Q_0=2.0$  W;  $l/S=10$  cm<sup>-1</sup>.

The shortest time to enter a stationary mode of operation  $\tau_{\min}$  is provided by the variant of the combination of parameters 5 of the source material and is, at  $\Delta T=40$  K,  $\tau_{\min}=12.5$  s.

The smallest failure rate  $\lambda/\lambda_0$  and the highest probability of failure-free operation  $P$  are provided by the variant of the combination of parameters 5 of the source material and are  $\lambda/\lambda_0=1.3$ ;  $P=0.99960$  at  $\Delta T=40$  K.

The number of thermoelements  $n$ , provided by the variant of the combination of parameters 5 of the source material, is  $n=43.2$  pcs. The calculations were performed for  $\Delta T=40$  K at refrigerating factor  $E=0.34$ , the magnitude of working current  $I=2.8$  A, the maximum working current  $I_{\max}=6.57$  A and the drop in voltage  $U=2.1$  V.

Thus, the choice of the variant of the combination of parameters 4, 5 with increased electrical conductivity of the source material is the most appropriate.

## 6. Discussion of results of analyzing the impact of combinations of the starting materials parameters of equal efficiency on the operational dynamics of single-cascade cooling devices

We have analyzed the dynamic model of the operation of a single-cascade TED, made from different source materials with the variants of the combination of parameters (1) to (5), given in Table 1, with the same efficiency of the original materials  $\bar{z}=2,410^{-3}$  1/K. The study was performed at  $T=300$  K, thermal load  $Q_0=2.0$  W in the range of temperature difference  $\Delta T$  from 10 to 60 K and the geometry of the thermoelement branches  $l/S=10$  cm<sup>-1</sup>. The model takes into consideration the peculiarity of the thermoelectric principle of cooling implying that the refrigerating factor approaches a maximum when the efficiency of thermoelectric material is striving for infinity. And since the efficiency of existing thermoelectric materials is limited and it is not possible to achieve its significant improvement, an attempt has been made to investigate the impact of the components of efficiency: thermoEMF, electrical conductivity, and thermal conductivity. It follows from Table 1 that at unchanged efficiency electrical conductivity has the greatest variability.

We have established the relationship between the operational dynamics of a single-cascade TED and the basic parameters and reliability indicators for different current modes of operation. The model (1) illustrates an analytical connection of the time to enter a stationary mode on the ratio of the allocated heating capacity at the resistances of thermoelements made from materials with the electrical conductivity given in Table 1. Our analysis of this dependence has shown that an increase in electrical conductivity can reduce the time to enter a stationary mode.

The possibility of reducing the time to enter a stationary mode of operation  $\tau$  has been shown. Thus, for the variant of combination 4, 5 for materials with high electrical conductivity, compared to variant 3 of materials of medium electrical conductivity, the decrease amounted to 9–10 %. And for the material of variant 1 with low electric conductivity, the gain reaches 16 %.

The data obtained make it possible, at the constant efficiency of the thermoelements' material, to choose the variant of combining the original material parameters with increased electrical conductivity (variants 4, 5).

The minimum time to enter a stationary mode of operation  $\lambda_{\min}$  is provided under a  $Q_{0\max}$  mode, which follows from the given analysis of Tables 2, 3, 4, 5. For the variant of combination 5 and the current modes of operation  $\lambda_{\min}$ ,  $(Q_0/I^2)_{\max}$ ,  $(Q_0/I)_{\max}$ ,  $Q_{0\max}$ ,  $\lambda_{\min}$ ,  $(Q_0/I^2)_{\max}$ ,  $(Q_0/I)_{\max}$ ,  $Q_{0\max}$ , the values of  $\lambda_{\min}$  are 12.5 s, 10 s, 7 s, 6 s, respectively.

The practical importance of our research is related to the possibility to improve the dynamic characteristics of thermoelectric coolers without changing the design documentation, manufacturing technology, materials used, conducting additional mechanical and climatic tests. In addition, thermoelectric materials whose parameters go beyond Table 1 were considered substandard and rejected. The results obtained make it possible to expand the limits of applicability of thermoelectric materials by taking into consideration their electrical conductivity.

Improving the dynamic characteristics of thermoelectric coolers causes additional thermal stresses, which

reduces the reliability of products, so it is proposed to control changes in the relative reliability indicators  $\lambda/\lambda_0$  (Tables 2–5). This compromise approach makes it possible to assess the achievable time to enter a stationary mode at acceptable indicators of reliability of the thermoelectric system that enables thermal modes. By using the choice of current modes of operation for different operating conditions, it is possible to optimize the design of heat-loaded elements of electronic equipment involving thermoelectric coolers.

In this work, we have analyzed only the influence of electrical conductivity as one of the most variable components in the expression of thermoelectric material effectiveness. At the same time, thermoEMF and thermal conductivity contribute to  $\tau_{\min}$  and  $\lambda/\lambda_0$ , both independently and in conjunc-

tion with electrical conductivity, which could be addressed in further research.

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## 7. Conclusions

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1. Choosing materials with enhanced electrical conductivity from the most used thermoelectrics based on the solid solutions of bismuth telluride  $\text{Bi}_2\text{Te}_3$ - $\text{Bi}_2\text{Se}_3$  and  $\text{Bi}_2\text{Te}_3$ - $\text{Sb}_2\text{Te}_3$  makes it possible to improve the dynamic characteristics of thermoelectric coolers by 9–10 %.

2. The minimal inertia (6 s) of thermoelectric coolers, all other things being equal, is achieved under the mode of maximum refrigerating capacity and differs significantly from the mode of a minimal failure rate (12.5 s).

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## References

1. Shalumova, N. A., Shalumov, A. S., Martynov, O. Yu., Bagayeva, T. A. (2011). Analysis and provision of thermal characteristics of radioelectronic facilities using the subsystem ASONIKA-T. *Advances in modern radio electronics*, 1, 42–49.
2. Sootsman, J. R., Chung, D. Y., Kanatzidis, M. G. (2009). New and Old Concepts in Thermoelectric Materials. *Angewandte Chemie International Edition*, 48 (46), 8616–8639. doi: <https://doi.org/10.1002/anie.200900598>
3. Choi, H.-S., Seo, W.-S., Choi, D.-K. (2011). Prediction of reliability on thermoelectric module through accelerated life test and Physics-of-failure. *Electronic Materials Letters*, 7 (3), 271–275. doi: <https://doi.org/10.1007/s13391-011-0917-x>
4. Eslami, M., Tajeddini, F., Etaati, N. (2018). Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers. *Energy Conversion and Management*, 174, 417–429. doi: <https://doi.org/10.1016/j.enconman.2018.08.045>
5. Bakhtiaryfard, L., Chen, Y. S. (2014). Design and Analysis of a Thermoelectric Module to Improve the Operational Life. *Advances in Mechanical Engineering*, 7 (1), 152419. doi: <https://doi.org/10.1155/2014/152419>
6. Erturun, U., Mossi, K. (2012). A Feasibility Investigation on Improving Structural Integrity of Thermoelectric Modules With Varying Geometry. Volume 2: Mechanics and Behavior of Active Materials; Integrated System Design and Implementation; Bio-Inspired Materials and Systems; Energy Harvesting. doi: <https://doi.org/10.1115/smasis2012-8247>
7. Manikandan, S., Kaushik, S. C., Yang, R. (2017). Modified pulse operation of thermoelectric coolers for building cooling applications. *Energy Conversion and Management*, 140, 145–156. doi: <https://doi.org/10.1016/j.enconman.2017.03.003>
8. Zaykov, V., Mescheryakov, V., Zhuravlov, Y. (2017). Analysis of the possibility to control the inertia of the thermoelectric cooler. *Eastern-European Journal of Enterprise Technologies*, 6 (8 (90)), 17–24. doi: <https://doi.org/10.15587/1729-4061.2017.116005>
9. Zaykov, V., Mescheryakov, V., Zhuravlov, Y., Mescheryakov, D. (2018). Analysis of dynamics and prediction of reliability indicators of a cooling thermoelement with the predefined geometry of branches. *Eastern-European Journal of Enterprise Technologies*, 5 (8 (95)), 41–51. doi: <https://doi.org/10.15587/1729-4061.2018.123890>
10. Zaikov, V., Meshcheryakov, V., Zhuravlov, Y. (2015). Selection of parameters combination of thermoelectric materials for development of high-reliability coolers. *Eastern-European Journal of Enterprise Technologies*, 3 (8 (75)), 4–14. doi: <https://doi.org/10.15587/1729-4061.2015.42474>