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INFLUENCE OF THE MEAN VOLUMETRIC TEMPERATURE OF A THERMOELEMENT ON RELIABILITY INDICATORS AND THE DYNAMICS OF A COOLER

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Розглянуто вплив середньооб'ємної температури гілки термоелементу на основні параметри, показники надійності і динаміку функціонування термоелектричного охолоджувача при різних перепадах температури при заданому тепловому навантаженні, геометрії гілок термоелементів для характерних струмових режимів роботи. Показано, що середня температура термоелементу, яка є опорною точкою при розрахунку енергетичних показників термоелектричного охолоджувача, може бути використана тільки для розрахунків в стаціонарному режимі роботи. Використання її в динамічному режимі призводить до значних похибок. Обґрунтовано, що для динамічного режиму такою опорною точкою може служити середньооб'ємна температура термоелектричної гілки. Визначено співвідношення для оцінки среднеоб'ємної температури в залежності від відносного робочого струму. Проаналізовано зв'язки среднеоб'ємної температури термоелемента, часу виходу на стаціонарний режим, необхідну кількість термоелементів, відмінності між среднеоб'ємної і середньою температурою, холодильного коефіцієнта в залежності від відносного робочого струму. Показано, що з ростом среднеоб'ємної температури при заданому струмовому режимі роботи і перепаді температури, що перевищує 40 K, величина робочого струму, кількість термоелементів, потужність споживання, інтенсивність відмов і постійна часу зменшується, а холодильний коефіцієнт зростає. Час виходу на стаціонарний режим при переході від режиму мінімуму інтенсивності відмов в режим максимальної холодопродуктивності, знижується на 5 %, а інтенсивність відмов зростає на 16 %.

Практична значимість проведених досліджень полягає як у підвищенні якості проектування охолоджувачів, так і виборі необхідних режимів термоелектричної системи забезпечення теплових режимів електронної апаратури в залежності від значимості динамічних або критеріїв управління по надійності

Ключові слова: гілка термоелементі, середньооб'ємна температура, показники надійності, динаміка охолоджувача

1. Introduction

When designing thermo-electric cooling devices (TED), it is necessary to take into consideration a temperature dependence of parameters for the branches of thermo-elements [1]. This circumstance is caused by the fact that the material of branches is semiconductors of different conductivity, parameters of which directly depend on temperature and the formation of temperature difference is the basic function of a thermo-electric cooler. The use of the mean temperature equal to half of the temperature difference at the ends of the thermo-element branches is possible only for a stationary mode, when temperature data are unchanged. In the dynamic mode, the mean temperature cannot serve as a reliable indicator and will lead to incorrect results of calculation of energy, dynamic and some reliability indicators of TED.

This defines the relevance of analysis into possibilities to use the mean volumetric thermo-element temperature as the basic point for calculations when designing thermo-electric coolers that operate in a dynamic mode.

2. Literature review and problem statement

Paper [2] shows the results of simulation of thermo-electric cooling devices, in which it was shown that the analytical model of thermo-electric devices enhances the design quality of thermo-electric systems ensuring thermal modes. The issues related to the influence on the parameters of the cooler of the thermo-electric branch as the main active element of the thermo-electric cooler remained unresolved. The variant of a solution to this task can be the representation of the thermo-element as a heat source [3], which makes it possible to describe the temperature distribution on the electrodes of a thermo-electric cooler in a stationary mode. Paper [4] dealt with one of the aspect of the problem, associated with enhancing efficiency of thermo-electric materials. The mathematical model, which enabled numerical modeling of thermo-electric sources in the differential mode with the possibility of taking into consideration temperature dependences of the properties of semiconductor materials, was developed. Further development of the research was creation of the gradient model of heat distribution in a thermo-element [5], which describes the dynamic processes in the thermoelectric cooler. However, the temperature of the thermo-element branch, which is the basis for calculation of energy indicators and structural parameters, in these works was represented as the average between the temperatures of hot and cold ends of the thermo-element, which is fair only for a stationary mode.

Taking into consideration the substantially higher performance of thermo-electric coolers compared with compression machines, the problems of the improvement of TED performance were virtually not considered [6]. Miniaturization of thermo-loaded elements resulted in increased thermal power density, which is necessary to discharge by the system of ensuring thermal modes. Maintenance of thermal modes of the elements with pulse release or absorption of heat suggests a reduction of discharge time, which requires a decrease in time constant of a thermo-electric cooler [7]. However, the problems related to the influence of temperature change on reliability indicators of a thermo-electric cooler remained outside the scope of consideration, because switching modes are used for accelerated testing of products for reliability [8] and cause the cracking of welding joints of thermo-elements and more rapid breakage of a cooler. Simultaneous improvement of dynamic characteristics of a thermo-electric cooler and reliability indicators is a challenge, so the research related to the search for compromise solutions is necessary.

An attempt at such research was undertaken in paper [8], which dealt with the problems of reducing time constant of a thermo-electric cooler and corresponding reliability indicators depending on the influence of technological structural elements of a device. The issues related to the influence of temperature of the thermo-element branch on dynamic characteristics and reliability indicators remained unresolved.

3. The aim and objectives of the study

The aim of this research is to identify the influence of the mean volumetric temperature on the thermo-element on the dynamic and reliability indicators of a single-stage thermo-electric cooler in the operating temperature range.

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

– to develop a model of relationship between the mean volumetric temperature of a thermo-element branch and structural and energy indicators for TED;

– to perform an analysis of reliability and dynamic indicators of a single-stage thermo-electric cooler.

4. Development of the model of relationship between the mean volumetric temperature of the branch and structural and energy indicators

The thermo-element branch can be represented in the form of a rod, in which the model of temperature distribution t by coordinate x by time τ is represented in the form [10]:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2}\right), \tag{1}$$

where a of the coefficient of thermal conductivity.

The restrictions of this model are described as:

1) boundary condition of the fist kind , when the temperature of the body surface at any moment of time is assigned;

2) boundary condition of the third kind, when the ambient temperature is known and convective exchange occurs on the body of the surface.

Structurally, thermo-elements when a volumetric TED production technology is used are located with air gaps, thermal conductivity of which differs from thermal conductivity of the thermo-element's junction with heat-receiving electrodes by orders of magnitude, that is why heat loss through the air layer can be neglected. For planar technologies of TED, this assumption is not correct. In this work, the thermo-element used in manufacturing coolers made by volumetric technology is considered. The problems of this type are solved using the Fourier method by representing the equation (1) as the product of two functions, each of which depends on one variable $t(x,\tau) = T(\tau)\cdot T(x)$ [10]. Then (1) is represented in the form:

$$\frac{T^{'}}{T} = a\frac{X^{''}}{X}. \tag{2}$$

Exponential dependence

$$T = C\exp\left\{-an^2\tau\right\}$$

is the solution to the left-hand side, and harmonic dependence $X = C_1\cos nx + C_2\sin nx.$ is the solution to the right part. Analysis of these expressions shows that the mean temperature of the thermo-element branch depends on time, which is why it cannot be the reference point when determining energy indicators of TED.

The concept of the "mean volumetric temperature", determined as [10], is introduced for a rod with height l at the symmetrical temperature distribution:

$$\bar{t}(\tau) = \frac{2}{l}\int_0^{l/2} t(x,\tau)\mathrm{d}x, \tag{3}$$

and relative mean volume temperature

$$\bar{\Theta}(\tau)=\frac{2}{l}\int_0^{l/2}\Theta(x,\tau)\mathrm{d}x. \qquad (4)$$

In this case, if the initial temperature of the body is constant and equal to t_H, the amount of heat, released by a body when it is cooled from t_H to the mean volumetric temperature $\bar{t}$, is equal to

$$Q_V=c\rho V(t_H-\bar{t}), \qquad (5)$$

where c is the specific thermal capacity, ρ is the density, V is the volume.

Therefore, the mean volumetric temperature of the branches of thermo-elements serves as a reference point for the connection with energy (amount of heat and currents) indicators and structural (material density and volume) parameters of TED.

Let us consider nonlinear temperature distribution along the thermo-element branch $T(x)=T$ at $x=0$ and $T(x)=T_0$ at $x=l$, which can be represented in the form [1]:

$$\tilde{T}=\frac{1}{l}\int_0^l\left\{T+\frac{\Delta T_{\max}}{l}x\left[B^2\left(1-\frac{x}{l}\right)-\theta\right]\right\}\mathrm{d}x, \qquad (6)$$

where $B=I/I_{\max}$ is the relative operating current, A; I is the magnitude of operating current, A; $I_{\max}=\bar{e}T/R$ is the maximum operating current, A; T_0 is the temperature of the heat absorbing welding joint, K; $\bar{e}$ is the averaged value of thermal EMF of the thermo-element branch, V/K; $R=l/(\bar{\sigma}S)$ is the electrical resistance of the thermo-element branch, Ohm; $\bar{\sigma}$ is the averaged value of electric conductivity of the thermo-element branch, Cm/cm; l, S are, relatively, height, cm, and area, cm^2, of the cross-section of the thermo-element branch;

$$\Delta T_{\max}=0{,}5\bar{z}T_0^2$$

is the maximal difference of the temperatures, K; $\bar{z}$ is the average value of effectiveness of thermo-electric material in module, 1/K; $\Theta=(T-T_0)/\Delta T_{\max}$ is the maximum difference of temperatures.

By integrating expression (6), using the Newton-Leibniz formula, we will obtain the ratio to determine the mean volumetric temperature in the simple form:

$$\tilde{T}=\frac{T+T_0}{2}+\frac{B^2I_{\max}^2R}{12K}, \qquad (7)$$

where $K=\frac{\text{æ}S}{l}$ is the thermal conductivity coefficient, W/K; æ is the averaged value of thermal conductivity coefficient, W/(cm·K).

Ratio (7) can be represented as:

$$\tilde{T}=\frac{T_0+T}{2}+\frac{B^2\Delta T_{\max}}{6}. \qquad (8)$$

In accordance with [9], the time for entering a stationary operation mode τ can be determined from the expression

$$\tau=\frac{\sum_i m_iC_i}{K_K\left(1+2B_K\frac{\Delta T_{\max}}{T_0}\right)}\ln\frac{\gamma B_H(2-B_H)}{2B_K-B_K^2-\Theta}, \qquad (9)$$

where

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

$I_{\max H}=e_HT/R_H$ is the maximum operating current at the beginning of the cooling process at $\tau=0$, A; $I_{\max K}=e_KT_0/R_K$ is the maximum operating current at the end of the cooling process, A; $\bar{e}_H$, $\bar{e}_K$ are, respectively, coefficient of thermo-EMF of the thermo-element branch at the beginning and at the end of the cooling process, V/K; R_H, R_K are, respectively, electric resistance of the thermo-element branch at the beginning and at the end of the cooling process, Om; $B_H=I/I_{\max H}$ is the relative operating current at the beginning of the cooling process at $\tau=0$; $B_K=I/I_{\max K}$ is the relative operating current at the end of the cooling process; $\sum_i m_iC_i$ is the total magnitude of the product of thermal capacity and the weight of the structural and technological elements (STE) of the TED.

At constant magnitude of operating current I at the beginning and at the end of the cooling process, it can be written as

$$I=B_H\,I_{\max H}=B_K\,I_{\max K}. \qquad (10)$$

The number of thermo-elements n can be determined from ratio

$$n=\frac{Q_0}{I_{\max K}^2R_K\left(2B_K-B_K^2-\Theta\right)}, \qquad (11)$$

where Q_0 is the thermal load, W. Consumption power W of TED can be determined from expression

$$W=2nI_{\max K}^2R_KB_K\left(B_K+\frac{\Delta T_{\max}}{T_0}\Theta\right). \qquad (12)$$

Voltage drop U_K can be determined from ratio

$$U_K=W_K/I. \qquad (13)$$

Cooling factor E can be calculated from formula

$$E=Q_0/W_K. \qquad (14)$$

Failure rate λ/λ_0 can be determined from expression [1]

$$\lambda/\lambda_0=nB_K^2(\Theta+C)\frac{\left(B_K+\frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1+\frac{\Delta T_{\max}}{T_0}\Theta\right)^2}K_{T_1}, \qquad (15)$$

where

$$C=\frac{Q_0}{nI_{\max K}^2R_K}$$

is the relative thermal load; K_{T1} is the significant temperature coefficient.

The probability of failure-free operation P of the TED can be determined from expression:

$$P=\exp[-\lambda t], \qquad (16)$$

where t is the assigned resource, h.

5. Analysis of energy, structural, reliability and dynamic indicators of the model of a single-stage cooler

The results of calculation of the main parameters, indicators of reliability and dynamics of operation of TED in the cooling mode for temperature differences ΔT=20; 40; 50; 60 K, thermal load Q_0=5.5 W, l/S=10 cm^{-1} and for various current operation modes are given in Table 1.

At an increase in relative operating current B for various temperature differences ΔT at Q_0=5.5 W:

– the mean volumetric temperature increases and in mode $Q_{0\max}$ reaches its maximum value $\tilde{T} = 305{,}6$ K at ΔT=20 K (Fig. 1);

– the time for entering a stationary operation mode τ (Fig. 2) decreases. At an increase in temperature difference ΔT, the time for entering a stationary mode τ increases; the longest time for entering the stationary operation mode τ=18.7 is reached at ΔT=60 K without respect to overheating, whereas it decreases up to=17.8 s with respect to overheating;

– the number of thermo-elements n decreases (Fig. 3). At an increase in temperature difference, the number of thermo-elements n increases and in mode Q_{omax} reaches maximum of n=249.5 pieces at ΔT=60 K, while with respect to overheating it decreases up to n=208.2 pieces (that is the number of thermo-elements can be reduced by 16.5 %);

– the relative magnitude of failure rate λ/λ_0 increases (Fig. 4). At an increase in temperature difference ΔT, failure rate increases at assigned B; in mode Q_{omax} for ΔT=60 K, failure rate λ/λ_0=258 without respect to overheating, while with respect to overheating it decreases up to λ/λ_0=215,5, that is by 16.5 %;

– the probability of failure-free operation P decreases (Fig. 5). At an increase in temperature difference, the probability failure-free operation decreased at assigned B; with respect to overheating, the probability of failure-free operation P increases.

Table 1

T=300 K; R_H=11.1·10^{-3} Ohm; $I_{\max H}$=5.51 A; l/S=10 cm^{-1}; $\sum_i m_i C_i = 175\cdot 10^{-4}$ J/K; Q_0=5.5 W

Operation mode	V_K	Θ	τ, s	I, A	n	W, W	E	U, V	B_H	$\tilde{T}$, K	λ/λ_0	$\lambda\cdot10^8$, 1/h	P
ΔT=20 K													
Q_{omax}	1.0	0.213	2.57	5.24	23.9	15.0	0.368	2.85	0.951	290	24.2	72.6	0.9928
	1.0*	0.213	2.57	5.10	24.0	15.0	0.367	2.94	0.926	305.6	24.3	72.8	0.99275
$(Q_0/I)_{\max}$	0.462	0.213	4.0	2.43	37.8	5.43	1.01	2.24	0.439	290	1.43	4.3	0.99957
	0.462*	0.213	3.94	2.43	37.5	5.43	1.01	2.23	0.441	293.3	1.42	4.26	0.999574
$(Q_0/I^2)_{\max}$	0.213	0.213	9.0	1.12	112.3	3.96	1.39	3.53	0.203	290	0.137	0.412	0.999959
	0.213*	0.213	9.0	1.12	112.3	3.96	1.39	3.53	0.203	290.7	0.137	0.412	0.999959
$\lambda_{\min}$	0.16	0.213	14.0	0.84	231.3	5.0	1.1	5.93	0.152	290	0.082	0.245	0.9999755
	0.16*	0.213	14.0	0.84	231.3	5.0	1.1	5.93	0.152	290.4	0.082	0.245	0.9999755
ΔT=40 K													
Q_{omax}	1.0	0.503	6.6	5.04	43.6	25.6	0.215	5.08	0.915	280	44.6	133.7	0.9867
	1.0*	0.498	6.5	4.90	42.5	25.0	0.22	5.10	0.890	293.3	43.4	130.2	0.9871
$(Q_0/I)_{\max}$	0.709	0.503	7.90	3.57	53.5	16.36	0.336	4.58	0.650	280	13.8	41.5	0.9959
	0.705*	0.498	7.82	3.48	52.0	16.0	0.335	4.60	0.630	286.7	13.4	40.2	0.9960
$(Q_0/I^2)_{\max}$	0.501	0.501	11.0	2.53	86.8	14.5	0.38	5.73	0.460	280	5.39	16.2	0.9984
	0.50*	0.50	11.07	2.50	86.3	14.4	0.382	5.77	0.450	283.3	5.32	16.0	0.9984
$\lambda_{\min}$	0.42	0.501	14.0	2.12	133.2	16.3	0.337	7.70	0.380	280	3.94	11.8	0.99880
	0.42*	0.50	14.1	2.11	132.1	16.2	0.34	7.70	0.380	282.3	3.92	11.8	0.9988
ΔT=50 K													
Q_{omax}	1.0	0.684	10.4	4.90	74.0	41.7	0.132	8.5	0.890	275	76.1	228.2	0.9774
	1.0*	0.672	10.1	4.75	71.3	40.3	0.137	8.;8	0.860	287.2	73.3	220	0.9782
$(Q_0/I)_{\max}$	0.827	0.684	11.4	4.05	81.7	32.6	0.169	8.05	0.740	275	40.7	122.2	0.9879
	0.821*	0.675	11.1	3.94	80	31.6	0.174	8.0	0.720	283.3	38.9	116.7	0.9884
$(Q_0/I^2)_{\max}$	0.684	0.684	13.5	3.35	108	30.7	0.179	9.2	0.610	275	25.3	76.0	0.9924
	0.675*	0.675	13.3	3.26	106	27.4	0.20	8.4	0.590	280.7	23.8	71.3	0.9929
$\lambda_{\min}$	0.620	0.684	15.3	3.04	136	32.5	0.169	10.7	0.550	275	21.7	65.2	0.9935
	0.61*	0.678	15.1	2.96	138	32.1	0.171	10.9	0.540	279.7	20.5	61.4	0.9939
ΔT=60 K													
Q_{omax}	1.0	0.898	18.73	4.74	249.5	135	0.041	28.5	0.860	270	258	775	0.92545
	1.0*	0.878	17.8	4.63	208.2	112.3	0.049	24.3	0.840	181.1	215.5	646.5	0.9374
$(Q_0/I)_{\max}$	0.948	0.898	19.2	4.49	256.3	126	0.0437	28.1	0.820	270	218.5	655.4	0.9366
	0.939*	0.882	18.4	4.37	222	107.2	0.0513	24.5	0.790	280	182.4	547.2	0.94675
$(Q_0/I^2)_{\max}$	0.898	0.898	20.0	4.26	276.6	123.4	0.0416	29.0	0.770	270	192.6	578	0.94384
	0.882*	0.882	19.3	4.10	244.0	105.3	0.0522	25.7	0.750	279	158.8	476.5	0.95374
$\lambda_{\min}$	0.871	0.898	20.6	4.13	298	125.9	0.0437	30.5	0.750	270	185	554.9	0.9460
	0.856*	0.882	19.88	4.0	261.6	107.1	0.0513	26.8	0.720	278.4	151.5	454.5	0.95556

*Note: * – data were obtained taking into consideration overheating*

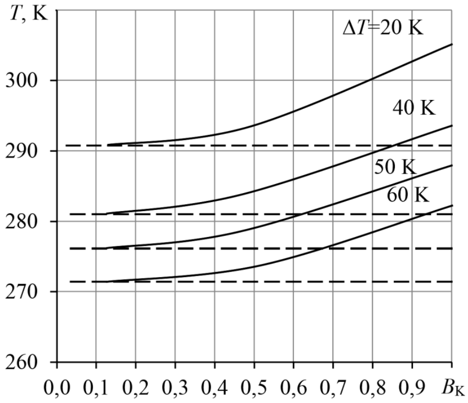


Fig. 1. Dependence of mean volumetric temperature $\tilde{T}$ of s single-stage TED on relative operating current B_K for various temperature differences ΔT at T=300 K, l/S= 10 cm^{-1}; Q_0=5.5 W: *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

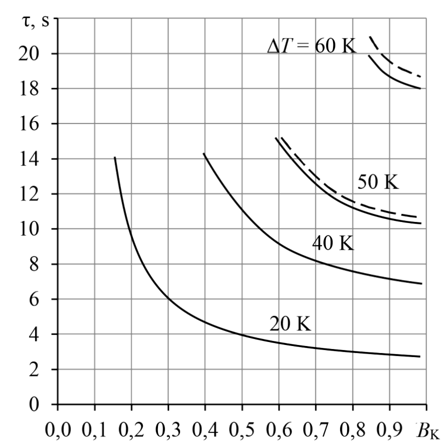


Fig. 2. Dependence of time for entering a stationary mode τ of a single-stage TED on relative operating current B_K for various temperature differences at ΔT at T=300 K, l/S=10 cm^{-1}; Q_0=5.5 W: *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

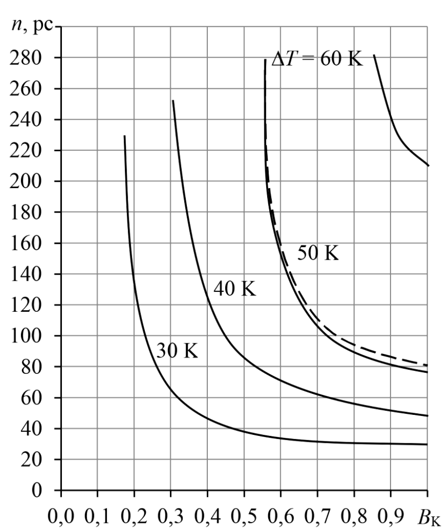


Fig. 3. Dependence of the number of thermo-elements n of a single-stage operating current B_K for various temperature differences ΔT at T=300 K, l/S=10 cm^{-1}; Q_0=5.5 W: *continuous lines* – with respect to overheating; *dashed lines* – without respect to overheating

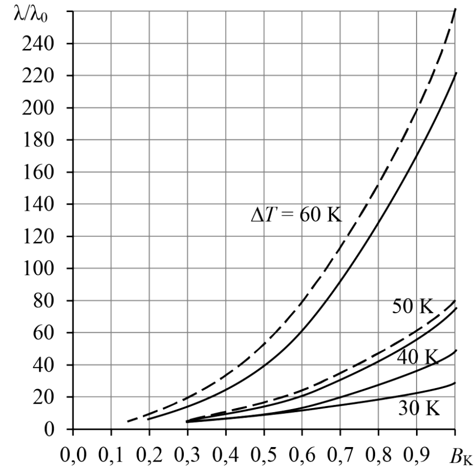


Fig. 4. Dependence of failure rate λ/λ_0 of single-stage TED on relative operating current B_K for various temperature differences ΔT at T=300 K, l/S=10 cm^{-1}; Q_0=5.5 W: *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

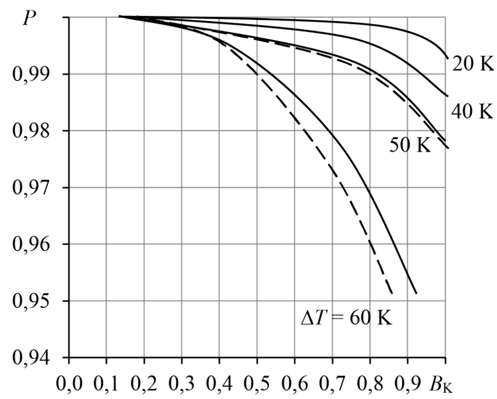


Fig. 5. Dependence of probability of failure-free operation P of single-stage TED on relative operating current B_K for various temperature differences ΔT at T=300 K, l/S=10 cm^{-1}; Q_0=5.5 W: *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

At an increase in temperature difference ΔT for various current operation modes:

– temperature difference

$$\Delta\tilde{T} = \tilde{T} - \bar{T}$$

increases (Fig. 6) for operation mode $(Q_0/I)_{max}$, $(Q_0/I^2)_{max}$ and λ_{min} and decreases for mode Q_{omax}; at the assigned temperature difference, magnitude $\Delta\tilde{T}$ increases from mode λ_{min} to mode Q_{0max};

– operating current I (Fig. 7) increases for operation modes $(Q_0/I)_{max}$, $(Q_0/I^2)_{max}$ and λ_{min} and decreases for mode Q_{0max}; at the assigned temperature difference, the magnitude of operating current increases from mode λ_{min} to mode Q_{0max};

– cooling coefficient E decreases (Fig. 8); at the assigned temperature difference, cooling coefficient increases from mode Q_{0max} to mode $(Q_0/I^2)_{max}$; at temperature differences close to maximum ($\Delta T \rightarrow \Delta T_{max}$), cooling coefficient is virtually the same for all operation modes; with respect to the thermo-element branch, cooling coefficient E=0.049, that is by 16 % higher that without respect to it in mode Q_{0max} at ΔT=40 K.

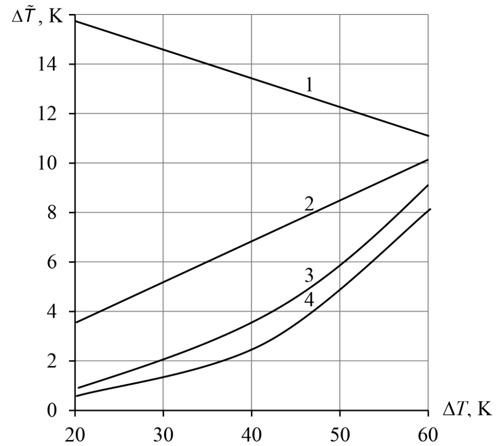
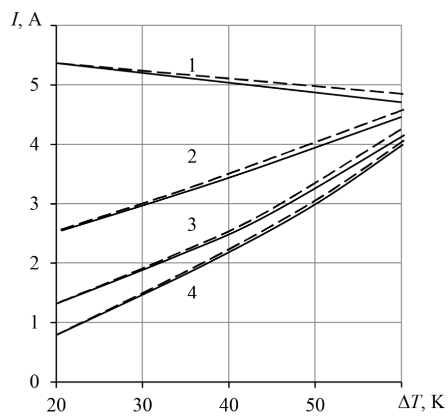


Fig. 6. Dependence of temperature difference between mean volumetric and mean temperature $\Delta\tilde{T}=\tilde{T}-\bar{T}$ of single-stage TED on temperature difference ΔT for various operation modes at T=300 K, I/S=10 cm^{-1}; Q_0=5.5 W:
1 – mode $Q_{0\max}$; 2 – mode $(Q_0/I)_{\max}$; 3 – mode $(Q_0/I^2)_{\max}$;
4 – mode $\lambda_{\min}$



Fog. 7. Dependence of magnitude of operating current I of single-stage TED on temperature difference ΔT for different operation modes at T=300 K, I/S=10 cm^{-1}; Q_0=5.5 W:
1 – mode $Q_{0\max}$; 2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$;
continuous lines – with respect to overheating;
dashed line – without respect to overheating

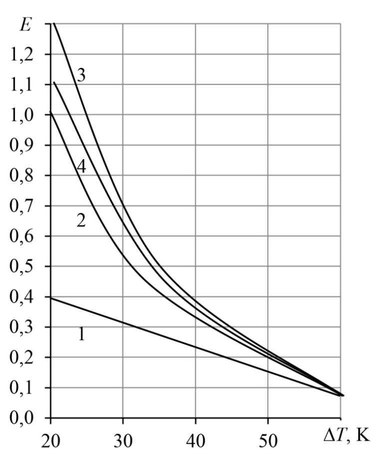


Fig. 8. Dependence of cooling coefficient E of single-stage TED on temperature difference ΔT for different operation modes T=300 K, I/S=10 cm^{-1}; Q_0=5.5 W: 1 – mode $Q_{0\max}$;
2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

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

The analysis that we present shows:

– the time for entering a stationary mode τ increases (Fig. 9); at the assigned temperature difference, the time for entering a stationary mode decreases from mode $\lambda_{\min}$ to mode $Q_{0\max}$; the shortest time for entering a stationary mode is ensured in mode $Q_{0\max}$; with respect to overheating the thermo-element branch, the time for entering a stationary mode τ=17.8 s, that is, 5 % lower that without respect to it in mode $Q_{0\max}$ at ΔT=60 K;

– the relative magnitude of failure rate λ/λ_0 increases (Fig. 10); at the assigned difference, failure rate decreases from mode $Q_{0\max}$ to mode $\lambda_{\min}$ and is minimum in mode $\lambda_{\min}$; with respect to overheating of thermo-element branch, failure rate λ/λ_0=215 in comparison with λ/λ_0=258 without respect to overheating, that is, less by 16.7 %, at ΔT=60 K in mode $Q_{0\max}$;

– probability of failure-free operation P decreases (Fig. 11); at the assigned temperature difference, probability of failure-free operation increases from mode $Q_{0\max}$ to mode $\lambda_{\min}$, which ensures the maximum of probability of failure-free operation P more, thus, for example, for ΔT=50 K, P=0.9782 with respect to overheating and P=0.9774 without respect to overheating in mode $Q_{0\max}$.

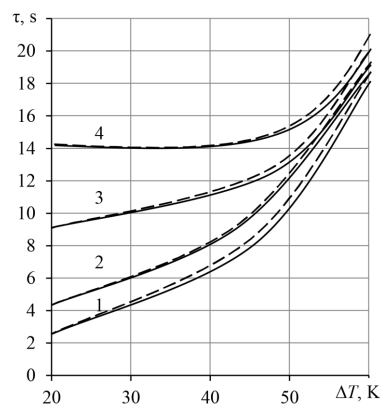


Fig. 9. Dependence of time for entering a stationary mode τ of TED on temperature difference ΔT for various operation modes at T=300 K, I/S=10 cm^{-1}; Q_0=5.5 W:
1 – mode $Q_{0\max}$; 2 – mode $(Q_0/I)_{\max}$; 3 – mode $(Q_0/I^2)_{\max}$;
4 – mode $\lambda_{\min}$; *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

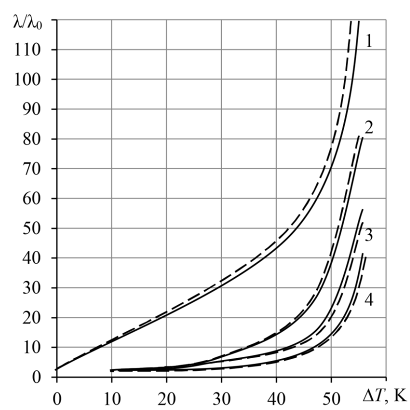


Fig. 10. Dependence of relative magnitude of failure rate λ/λ_0 of single-stage TED on temperature difference ΔT at T=300 K, I/S=10 cm^{-1}; Q_0=5.5 W: 1 – mode $Q_{0\max}$;
2 – $(Q_0/I)_{\max}$; 3 – $(Q_0/I^2)_{\max}$; 4 – $\lambda_{\min}$

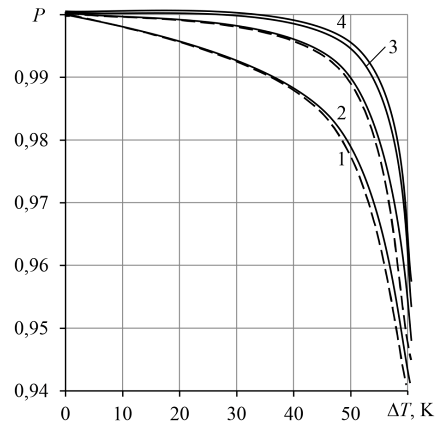


Fig. 11. Dependence of probability of failure-free operation P of single-stage TED on temperature difference ΔT at T=300 K, l/S=10 cm^{-1}; Q_0=5.5 W: 1 – mode $Q_{0\max}$; 2 – mode $(Q_0/I)_{\max}$; 3 – mode $(Q_0/I^2)_{\max}$; 4 – mode $\lambda_{\min}$ *continuous lines* – with respect to overheating; *dashed line* – without respect to overheating

An analysis of the shown graphic dependences of the time of a thermo-electric cooler entering a stationary mode, failure rate and the probability of failure-free operation reveals that during designing the TED, it is necessary to take into consideration the influence of mean volumetric temperature on the basic parameters, reliability indicators and dynamics of operation.

The advantage of using the mean volumetric temperature of the thermo-element branch, unlike the arithmetic mean, is caused by the fact that energy indicators are associated with design parameters of TED irrespective of time, which makes it possible to use it as basic for the calculation of dynamic operation modes of the product. Restrictions laid down in the model imply uniformity of geometry and thermo-physical parameters of the material of a thermo-element, which is true for most practical purposes of manufacturing thermo-electric coolers. To create homogeneous temperature field or thermal fields of the assigned configuration based on thermo-electric coolers, e. g. for calibration of infrared multi-element radiation receivers, the used restrictions may turn out to be unacceptable. More detailed studies of the influence of variations in the geometry of branches of thermo-elements, homogeneity of material, thickness of welding joint with electrodes, reciprocal influence of thermocouples, etc. will be required.

7. Conclusions

1. The model of relationship of the mean volumetric temperature of the thermo-element branch and relative operating current for different operating temperature differences and operation modes at an assigned geometry of thermo-element branches was developed and it was shown that taking into consideration of thermo-element overheating helps to decrease calculation errors by 3–5 %.

2. We performed an analysis that takes into consideration the mean volumetric temperature of the thermo-element branches, which reveals the possibility of decreasing the number of thermo-elements by up to 16 %, time for entering a stationary operation mode of a cooler by up to 5 %, relative failure rate by up to 16 %, depending on the relative operating current and temperature difference.

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