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Method for increasing the dynamic characteristics of thermoelectric coolers

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ABSTRACT

The influence of the efficiency of the initial thermoelectric materials on the dynamics of the functioning of the thermoelectric cooling device for various characteristic current modes of operation in the range of operating temperature drops and heat load at a given geometry of thermoelement legs is considered. The parameters of thermoelectric materials of thermoelements are conventionally divided into three groups: used for batch production, laboratory research and maximum values. The criterion for choosing the operating mode of the thermoelectric cooler takes into account the mutual influence and weight of each of the limiting factors. Since the design conditions can be very diverse, simultaneously varying several limiting factors (constructive, energy and reliability), you can choose the most rational mode of operation. The analysis was carried out for typical current modes of operation of thermoelectric coolers: maximum cooling capacity, maximum cooling capacity at a given current, maximum coefficient of performance, minimum failure rate. It is shown that with an increase in the efficiency of the initial thermoelectric materials, the time for reaching the stationary operating mode of the thermoelectric cooler, the required number of thermoelements, and the maximum temperature difference increase. A method is proposed for reducing the time constant of thermoelectric coolers due to the revealed relationship between the efficiency of thermoelectric materials and the dynamic characteristics of thermoelements. It is shown that an increase in the dynamic characteristics of thermoelectric coolers is achieved without changing the design documentation, manufacturing technology and additional climatic and mechanical testing of products.

Keywords: Thermoelectric materials; efficiency; dynamic characteristics; operating modes; reliability indicators

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INTRODUCTION

The process of improving modern electronic equipment is characterized by an increase in its complexity, a high density of integration of the element base. One of the main requirements for its design is to ensure a high level of reliability [1]. The experience in the development of systems for ensuring thermal conditions allows choosing the thermoelectric cooling method as one of the most rational and promising ones. Its main advantage over other cooling methods is high reliability, small overall dimensions, ease of control and speed.

These advantages are inherently a consequence of the solid state nature of such coolers. An increase in the reliability of thermoelectric cooling devices (TEC) is inextricably linked with an increase in the quality of the initial thermoelectric materials and, first of all, with their efficiency [2]. When designing a TEC, in a number of cases, one of the main requirements is to provide a given time for reaching a stationary mode of operation and the possibility of its reduction [3]. Therefore, the determination of the dynamic characteristics of the TEC in relation to the efficiency of the starting materials seems to be relevant.

LITERATURE REVIEW

In work [4, 5], the design of systems for providing thermal regimes of equipment is considered, based on the thermodynamic analysis of the object and the cooler to optimize their energy interaction. The tightening of requirements for the development and analysis of thermoelectric modules to improve the service life required additional research [6, 7]. An increase in reliability indicators made it necessary to carry out studies of the structural integrity of thermoelectric modules and changing geometry, the results of which are given in [8, 9]. The most difficult mode from the point of view of reliability is the pulsed mode of operation of a thermoelectric cooler in the construction of cooling equipment, the study of which is devoted to work [10, 11]. When thermoelectric systems are included in the control circuit, designed to provide thermal modes of heat-loaded elements of on-board equipment, the requirements for dynamic characteristics are constantly increasing, which required research on ways to increase the speed of TEC [12]. In [13], the issues of determining the time of the thermoelectric cooler reaching the stationary mode as the main dynamic parameter of control systems are investigated. Further studies are devoted to the influence of the geometry of thermoelements

[14] and energy modes of operation [15] with the dynamics and reliability indicators of a thermoelectric cooler. The problem lies in the contradiction of the dynamic characteristics to the reliability indicators, since an increase in the values of temperature gradients at the junction of thermoelements and electrodes of the thermoelectric power plant leads to an increase in mechanical stresses, cracking of the material. The effect of material efficiency on cooler dynamics has not been considered.

PURPOSE AND OBJECTIVES OF THE RESEARCH

The aim of the work is to analyze the influence of the efficiency of thermoelectric materials in the range of industrial use on the dynamics of functioning of a single-stage thermoelectric cooling device.

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

1. To develop a mathematical model of the relationship between the efficiency of thermoelement materials with dynamic characteristics and indicators of cooler reliability in the operating range of currents and temperatures.

2. Conduct an analysis of the model to identify the effect of the efficiency of materials on the time to reach the stationary mode of thermoelements and indicators of reliability, energy and design indicators of the cooler for various operating modes and temperature drops.

DYNAMIC MODEL OF THERMOELECTRIC COOLER

The studies were carried out for the following averaged values of the thermoelectric figure of merit of starting materials ż commercially available modules at various values of the operating temperature drop ΔT from 40 to 60 K, thermal load Q_0 = 2.0 W and geometry of thermoelement legs l/S = 10 cm^{-1} and various current operating modes at T = 300 K:

ż = 2.4 · 10^{-3} 1/K, ΔT = 65 K (for batch production conditions);

ż = 2.6 · 10^{-3} 1/K, ΔT = 68 K (for laboratory conditions);

ż = 2.75 · 10^{-3} 1/K, ΔT = 72 K (maximum value).

In [8], relations were obtained for determining the time of reaching a stationary operating mode, where the influence of structural and technological elements on the main parameters of a TEC for the geometry of thermoelement legs l/S = 10 cm^{-1} is described in sufficient detail. We will use the relation to determine the time of reaching the stationary operating mode depending on the relative operating current B

$$\tau = \frac{\sum_i m_i C_i}{K_К\left(1+2B_К\dfrac{\Delta T_{max}}{T_0}\right)} \ln \frac{\gamma B_Н\left(2-B_Н\right)}{2B_К - B_К^2 - \Theta}, \qquad (1)$$

where: $\gamma = \dfrac{I_{max\,Н}^2 R_Н}{I_{max\,К}^2 R_К}$,

$\sum_i m_i C_i$ = 175·10^{-4} J/K − is the total value of the product of heat capacity and mass of constituent structural technological elements for a given geometry of thermoelement legs l/S = 10 $см^{-1}$;

$I_{max\,Н}$, $R_Н$ − respectively, the maximum operating current, A, and the electrical resistance of the thermoelement leg, Ohm, at the beginning of the cooling process at τ = 0;

$I_{maxК}$, $R_К$ − respectively, the maximum operating current, A, and the electrical resistance of the thermoelement leg, Ohm, at the end of the cooling process τ;

$B_Н = I/I_{maxН}$ − relative operating current at τ= 0;

$B_К = I/I_{maxК}$ – relative operating current at τ;

I – is the value of the operating current, A;

$I_{maxН} = e_Н T/R_Н$ – maximum operating current, A, at τ = 0;

$I_{maxК} = e_К T_0/R_К$ – maximum operating current, A, at τ;

$e_Н$, $e_К$ – respectively, the thermoEMF coefficient of the thermoelement leg at the beginning and at the end of the cooling process, V/K;

T_0 – temperature of the heat-absorbing junction at the end of the cooling process, K;

T – is the temperature of the heat-absorbing junction at the beginning of the cooling process, K;

$\Theta = \Delta T/T_{max}$ – relative temperature drop;

$\Delta T = T - T_0$ – is the temperature drop of the TEC, K;

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

ż – is the average value of the efficiency of the thermoelectric material in the module, 1/К;

$K_К = \bar{æ}_К/(l/S)$ – heat transfer coefficient, W/K;

$\bar{æ}_К$ – averaged coefficient of thermal conductivity, W/(cm·K).

With equal currents at the beginning and at the end of the cooling process

$$I = B_Н I_{maxН} = B_К I_{maxК}. \qquad (2)$$

The number of thermoelements n can be determined from the ratio

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

where: Q_0 is the value of the heat load, W.

Power consumption W_K TEC can be determined from the expression:

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

Voltage drops

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

The coefficient of performance E can be calculated using the formula

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

The relative value of the failure rate λ/λ_0 can be determined by the formula [2]

$$\lambda/\lambda_0 = nB_K^2\left(\Theta + C_K\right)\frac{\left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2} K_{T_1}; \quad (7)$$

where: $C_K = \frac{Q_0}{nI^2_{\max K} R_K}$ – relative heat load;

K_{T1} – significant coefficient of lowered temperature [2].

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

$$P = \exp(-\lambda t), \quad (8)$$

where t is the assigned resource, h.

DYNAMIC MODEL ANALYSIS

1. Q_{0max} mode

The results of calculating the main parameters taking into account the temperature dependence, the time to reach the stationary operating mode and the reliability indicators for the Q_{0max} mode (B_K = 1,0) and for various temperature drops ΔT are given in Table. 1.

Analysis of the calculation results given in Table. 1 showed that with an increase in the efficiency of the thermoelectric material in the module ż in the range (2.4-2.75) · 10^{-3} 1/K at T = 300 K for various temperature drops ΔT in the Q_{0max} mode:

− the maximum temperature drops increases by an average of 17 %;

− the maximum operating current Imax and the value of the operating current I increase by 19% on average, the relative temperature drop by an average of 13 % decreases (Fig. 1);

− the number of thermoelements n decreases:
ΔT = 40 K by 29 %;
ΔT = 50 K by 39 %;
ΔT = 60 K by 64 %;

– the refrigerating coefficient E increases:
ΔT = 40 K by 13 %;
ΔT = 50 K by 30 %;
ΔT = 60 K by 125 %;

– the relative value of the failure rate λ / λ0 decreases: at ΔT = 40 K by 29 %; at ΔT = 50 K by 40 %; at ΔT = 60 K by 64 %;

Table 1. **Results of calculating the main parameters for mode Q_{0max}:**
B_K = 1.0; T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1}; R_H = 11.1·10^{-3} Ohm; I_{maxH} = 5.4 A

ż·10^3, 1/K	R_K·10^3, Ohm	I_{max}=I, A	ΔT_{max}, K	Θ	τ, s	W	n, it.	W, W	U, V	E	γ	λ / λ_0	λ·10^8, 1/h	P
ΔT = 40 K; T_0 = 260 K														
2.4	10.1	5.02	79.8	0.50	6.3	0.984	15.7	9.23	1.84	0.217	1.272	16.0	48.1	0.9952
2.6	9.52	5.38	86.2	0.46	5.8	0.921	13.5	8.6	1.60	0.233	1.30	13.8	41.4	0.9959
2.75	8.93	5.97	91.9	0.435	5.0	0.894	11.1	8.1	1.36	0.246	1.335	11.3	34.0	0.9966
ΔT = 50 K; T_0 = 250 K														
2.4	9.85	4.87	73.1	0.68	10.2	0.902	27.1	15.2	3.10	0.132	1.386	27.9	83.6	0.9917
2.6	9.43	5.20	79.1	0.632	8.8	0.892	21.3	13.1	2.51	0.153	1.408	24.8	65.3	0.9935
2.75	8.62	5.86	85.0	0.588	7.3	0.861	16.4	11.7	2.0	0.172	1.435	16.8	50.3	0.9950
ΔT = 60 K; T_0 = 240 K														
2.4	9.43	4.81	66.8	0.898	18.3	0.891	90.0	49.1	10.2	0.041	1.483	93.2	279.5	0.9724
2.6	9.09	5.10	72.3	0.830	14.6	0.873	49.8	29.4	5.77	0.068	1.519	51.5	154.6	0.9847
2.75	8.47	5.67	77.8	0.771	11.6	0.849	32.1	21.8	3.84	0.092	1.56	33.2	99.7	0.9900

Source: **compiled by the author**

– the probability of failure-free operation P increases;

– the time of reaching the stationary mode τ decreases (Fig. 2): at ΔT = 40 K by 21 %; at ΔT = 50 K by 28 %; at ΔT = 60 K by 37 %.

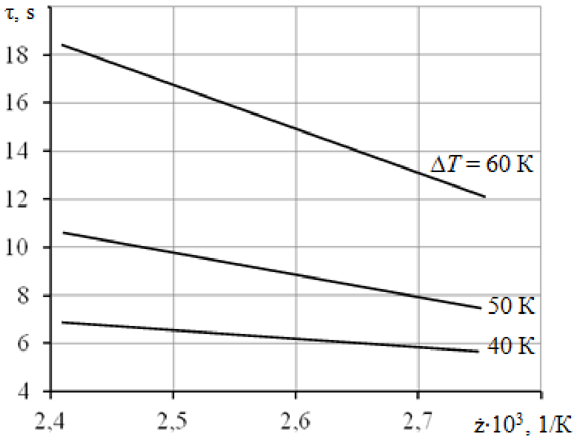

Fig. 1. **Dependence of the operating current I (solid lines) and the relative temperature difference Θ (dashed lines) of a single-stage TEC on the efficiency of the thermoelectric material ż for various temperature drops ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1}**

***Source:* compiled by the author**

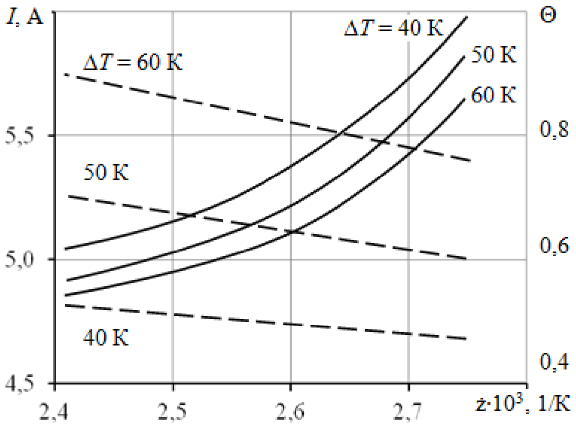

Fig. 2. **Dependence of the time of reaching the stationary operating mode of a single-stage TEC on the efficiency of the thermoelectric material ż for various temperature drops ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the Q_{0max} mode**

***Source:* compiled by the author**

At a given efficiency of the thermoelectric material in the module ż with an increase in the temperature difference ΔT, the time to reach the stationary mode increases. For example, with ż = 2.5 · 10^{-3} 1/K:

τ_1 = 6.0 s at ΔT = 40 K;

τ_2 = 9.3 s at ΔT = 50 K;

τ_3 = 16.2 s at ΔT = 60 K.

With increasing temperature difference ΔT for different efficiency of thermoelectric material in module ż:

− the time of reaching the stationary operating mode τ increases (Fig. 3); at a given temperature difference ΔT, with an increase in efficiency, the time to reach a stationary mode of operation decreases τ ;

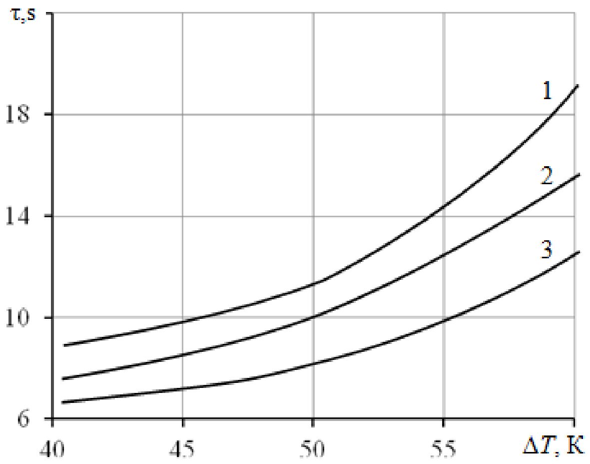

Fig. 3. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the temperature drop ΔT at T = 300 K, Q_0 = 2.0 W, l/S = 10 cm^{-1} in Q_{0max} mode for different efficiency of thermoelectric material: 1 – ż = 2.4 · 10^{-3} 1/K; 2 – ż = 2.6 · 10^{-3} 1/K; 3 – ż = 2.75 · 10^{-3} 1/K at 300 K**

***Source:* compiled by the author**

− the relative value of the time to reach the stationary mode of operation increases $\frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_3}{\tau_1}$ – pos. 1 and $\frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_2}{\tau_1}$ – pos. 2 in Fig. 4. So, for example, at ΔT = 50 K Δτ/τ = 14 % for pos. 1 and $\Delta\tau/\tau$ = 28 % for pos. 2. This leads to

a) with an increase in the efficiency of the thermoelectric material in the module ż from 2.4·10^{-3} to 2.6·10^{-3} 1/K, the time to reach the stationary mode of operation can be reduced by 14 % at ΔT = 50 K;

b) with an increase in the efficiency of the thermoelectric material in the module ż from 2.4·10^{-3} to 2.75·10^{-3} 1/K, the time to reach the stationary mode of operation can be reduced by 28 % at ΔT = 50 K.

Let us consider the coefficient $K_\tau = \frac{\Delta\tau / \tau}{\Delta\dot{z} / \dot{z}}$ reflecting the relationship between the relative change in the time of reaching the stationary operating mode $\Delta\tau/\tau$ and the thermoelectric efficiency Δż/ż.

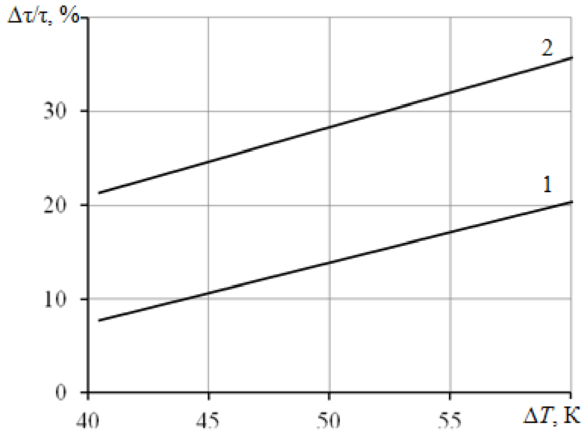

Fig. 4. **Dependence of the relative value of the time of reaching the stationary operating mode $\Delta\tau/\tau$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the Q_{0max} mode for different efficiency of thermoelectric material:**

1 – $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_3}{\tau_1}$; 2 – $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_2}{\tau_1}$, $\dot{z}_1 = 2.4\cdot10^{-3}$ 1/K;

2 – $\dot{z}_2 = 2.6\cdot10^{-3}$ 1/K; 3 – $\dot{z}_3 = 2.75\cdot10^{-3}$ 1/K at 300 K

***Source:* compiled by the author**

With an increase in the temperature difference ΔT, the *Kτ* coefficient increases (Fig. 5, item 1) for the Q_{0max} mode.

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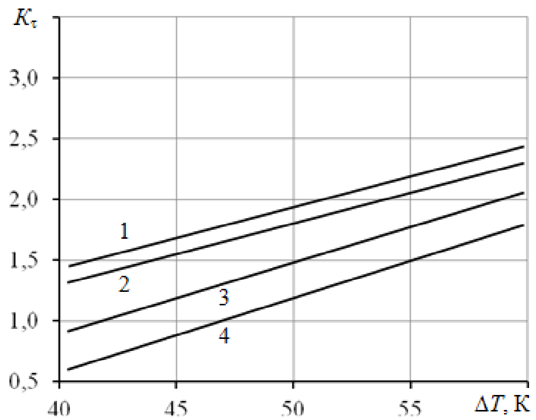

Fig. 5. **Dependence of the coefficient $K_\tau=\frac{\Delta\tau/\tau}{\Delta\dot{z}/\dot{z}}$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} for different operating modes: 1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}**

***Source:* compiled by the author**

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time of reaching the stationary operating mode τ by 1.4 % for the Q_{0max} mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time to reach the stationary operating mode τ by 1.9% for the Q_{0max} mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material ż by 1 % allows to reduce the time to reach the stationary operating mode τ by 2.4 % for the $Q0_{max}$ mode.

Let us consider a coefficient $K_\lambda=\frac{\Delta\lambda/\lambda}{\Delta\dot{z}/\dot{z}}$ reflecting the relationship between the relative change in the failure rate Δλ/λ and thermoelectric efficiency Δż/ż.

With an increase in the temperature difference ΔT, the K_λ coefficient increases (Fig. 6, item 1) for the Q_{0max} mode, i.e. an increase in the thermoelectric efficiency of the starting materials in the module leads to a decrease in the relative failure rate λ/λ_0.

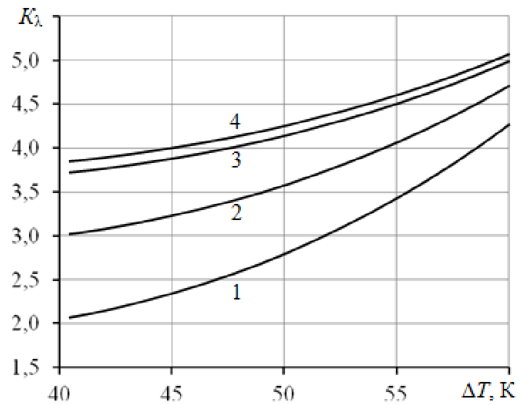

Fig. 6. **Dependence of the coefficient $K_\lambda=\frac{\Delta\lambda/\lambda}{\Delta\dot{z}/\dot{z}}$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} for different operating modes: 1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}**

***Source:* compiled by the author**

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 1.9 % for the Q_{0max} mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material

$\dot{z}$ by 1% makes it possible to reduce the relative failure rate λ/λ_0 by 2.7 % for the Q_{0max} mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material $\dot{z}$ by 1% makes it possible to reduce the relative failure rate λ/λ_0 by 4.1 % for the Q_{0max} mode.

Let us consider the coefficient $K_E = \frac{\Delta E / E}{\Delta \dot{z} / \dot{z}}$ reflecting the relationship between the relative change in the coefficient of performance ΔE/E and thermoelectric efficiency $\Delta\dot{z}/\dot{z}$.

With an increase in the temperature difference ΔT, the coefficient K_E increases (Fig. 7, pos. 1) for the Q_{0max} mode, i.e. an increase in the thermoelectric efficiency of the starting materials in the module leads to an increase in the coefficient of efficiency E.

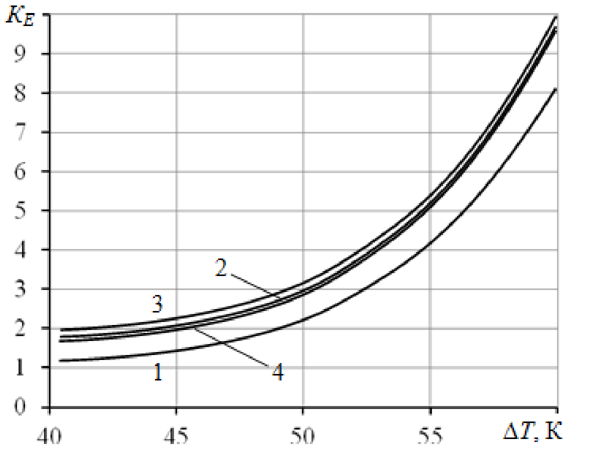

Fig. 7. **Dependence of the coefficient $K_E = \frac{\Delta E / E}{\Delta \dot{z} / \dot{z}}$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} for different operating modes: 1 – Q_{0max} mode; 2 – mode $(Q_0/I)_{max}$; 3 – mode $(Q_0/I^2)_{max}$; 4 – mode λ_{min}**

***Source:* compiled by the author**

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material $\dot{z}$ by 1 % allows increasing the refrigerating coefficient E by 0.9 % for the Q_{0max} mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material $\dot{z}$ by 1% allows increasing the refrigerating coefficient E by 2 % for the Q_{0max} mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material $\dot{z}$ by 1 % allows increasing the refrigerating coefficient E by 8 % for the Q_{0max} mode.

Thus, an increase in the efficiency of the initial thermoelectric materials in the module by 1 % for the Q_{0max} mode, depending on the temperature difference ΔT:

– the time of reaching the stationary operating mode τ decreases by 1.4-2.4 %;

– the relative failure rate λ/λ_0 decreases by 1.9-4.1%;

– the refrigerating coefficient E increases by 1-8 %.

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

The results of calculating the main parameters taking into account the temperature dependence, the time to reach the stationary operating mode and the reliability indicators for the mode $(Q_0/I)_{max}$ and for various temperature drops ΔT are given in Table. 2.

Analysis of the calculation results given in Table 2, showed that with an increase in the efficiency of the thermoelectric material in the module $\dot{z}$ for different temperature drops ΔT in the mode (Q_0/I) max, the tendency of changes in the main parameters, such as the maximum temperature difference ΔT_{max}, maximum operating current I_{max}, relative temperature difference Θ, the number of thermoelements n remains unchanged. Next, we will consider in detail the dynamics of the TEC functioning in the mode $(Q_0/I)_{max}$.

The time for reaching the stationary regime τ decreases (Fig. 8):

at ΔT = 40 K by 19 %;
at ΔT = 50 K by 26 %;
at ΔT = 60 K by 35 %.

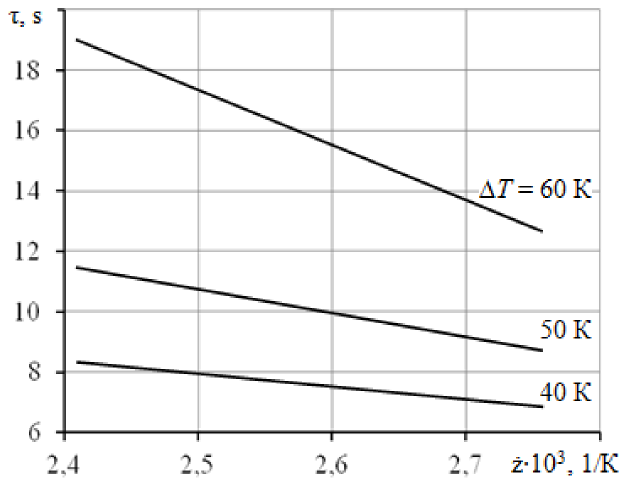

Fig. 8. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the efficiency of the thermoelectric material $\dot{z}$ for various temperature drops ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I)_{max}$**

***Source:* compiled by the author**

With an increase in the temperature difference ΔT, the time to reach the stationary mode increases (Fig. 9).

Table 2. **Results of calculating the main parameters for mode $(Q_0/I)_{max}$:**
T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1}; R_H = 11.1·10^{-3} Ohm; I_{maxH} = 5.4 A

$\dot{z}$·10^3, 1/K	R_K·10^3, Ohm	I_{max}, I, A	ΔT_{max}, K	Θ	τ , s	B_K, B_H	n, it.	W, W	U, V	E	γ	λ / λ$_0$	λ·10^8, 1/h	P
ΔT = 40 K; T_0 = 260 K														
2.4	10.1	5.02 3.55	79.8	0.50	7.8	0.707 0.645	19.0	5.9	1.66	0.34	1.32	4.94	14.8	0.9985
.,6	9.52	5.38 3.66	86.2	0.46	6.9	0.68 0.67	16.7	5.2	1.43	0.38	1.22	3.72	1.,2	0.9989
2.75	8.93	5.97 3.94	91.9	0.435	6.3	0.66 0.59	14.0	4.8	1.21	0.42	1.335	2.73	8.2	0.9992
ΔT = 50 K; T_0 = 250 K														
2.4	9.85	4.87 4.0	73.1	0.68	11.3	0.83 0.73	30.0	11.9	3.0	0.168	1.437	14.9	44.8	0.9955
2.6	9.43	5.20 4.13	79.1	0.63	9.9	0.795 0.708	24.0	9.7	2.35	0.206	1.408	10.3	30.8	0.9969
2.75	8.62	5.86 4.49	85.0	0.59	8.4	0.767 0.67	18.9	8.3	1.85	0.241	1.435	7.0	21.0	0.9979
ΔT = 60 K; T_0 = 240 K														
2,4	9.43	4.81 4.56	66.8	0.90	19.0	0.95 0.83	92.6	45.9	10.1	0.044	1.539	79.3	237.8	0.9765
2.6	9.09	5.10 4.65	72.3	0.83	15.2	0.911 0.80	52.2	26.1	5.6	0.077	1.52	38.4	115.1	0.9886
2.75	8.47	5.67 5.0	77.8	0.77	1.,3	0.88 0.745	34.3	18.5	3.7	0.108	1.56	22.0	66.0	0.9934

Source: **compiled by the author**

For different efficiency of thermoelectric material in module ż, the relative value of the time of reaching the stationary operating mode $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_3}{\tau_1}$ – pos. 1 and $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_2}{\tau_1}$ – pos. 2 in Fig. 10.

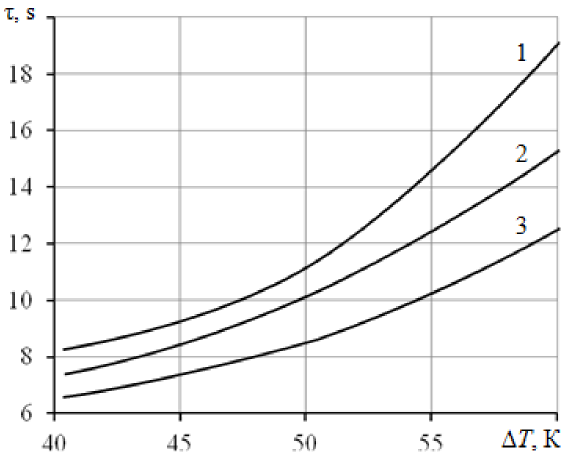

Fig. 9. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the temperature drop ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I)_{max}$ for different efficiency of thermoelectric material:**
1 – ż = 2.4·10^{-3} 1/K; 2 – ż = 2.6 · 10^{-3} 1/K;
3 – ż = 2.75 · 10^{-3} 1/K at 300 K
Source: **compiled by the author**

With an increase in the efficiency of the thermoelectric material in the module ż from 2.4·10^{-3} to 2.6·10^{-3} 1/K, the time to reach the stationary operating mode τ can be reduced by 13 % at ΔT = 50 K (Fig. 10, item 2).

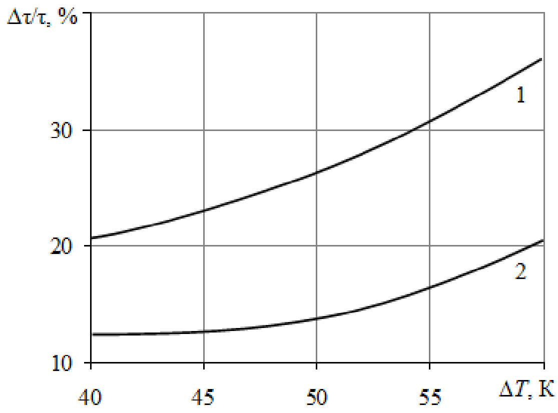

Fig. 10. **Dependence of the relative value of the time of reaching the stationary operating mode $\Delta\tau/\tau$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I)_{max}$ for different efficiency of thermoelectric material:**
$1-\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_3}{\tau_1}$; $2-\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_2}{\tau_1}$,
$\dot{z}_1$ = 2.4 · 10^{-3} 1/K; 2 – $\dot{z}_2$ = 2.6 · 10^{-3} 1/K;
3 – $\dot{z}_3$ = 2.75 · 10^{-3} 1/K at 300 K
Source: **compiled by the author**

With an increase in the efficiency of thermoelectric materials in the module by 1%, the time of reaching the stationary operation mode decreases by 1.3-2.3 % for the mode $(Q_0/I)_{max}$, depending on the temperature difference ΔT (Fig. 5, item 2).

With an increase in the temperature difference ΔT, the K_τ coefficient increases (Fig. 5, item 2).

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time of reaching the stationary operating mode τ by 1.3% for the $(Q_0/I)_{max}$ mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time to reach the stationary operating mode τ by 1.7 % for the $(Q_0/I)_{max}$ mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of the thermoelectric material ż by 1 % makes it possible to reduce the time to reach the stationary operating mode τ by 2.3% for the $(Q_0/I)_{max}$ mode.

With an increase in the temperature difference ΔT, the K_λ coefficient increases (Fig. 6, item 2), i.e., an increase in the thermoelectric efficiency of the starting materials in the module leads to a decrease in the relative failure rate λ/λ_0.

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 2.9 % for the $(Q_0/I)_{max}$ mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1% makes it possible to reduce the relative failure rate λ/λ_0 by 3.5 % for the $(Q_0/I)_{max}$ mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 4.7 % for the mode $(Q_0/I)_{max}$.

With an increase in the temperature difference ΔT, the K_E coefficient increases (Fig. 7, item 2) for the $(Q_0/I)_{max}$ mode, i.e., an increase in the thermoelectric efficiency of the starting materials in the module leads to an increase in the coefficient of efficiency *E*.

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % allows increasing the refrigerating coefficient *E* by 1.5 % for the $(Q_0/I)_{max}$ mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1% makes it possible to increase the refrigerating coefficient *E* by 2.9 % for the mode $(Q_0/I)_{max}$;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material ż by 1 % allows increasing the refrigerating coefficient *E* by 9.4 % for the mode $(Q_0/I)_{max}$.

Thus, with an increase in the efficiency of the initial thermoelectric materials in the module by 1% for the mode (Q_0/I) max, depending on the temperature difference ΔT:

– the time to reach the stationary operating mode is reduced by 1.3-2.3 %;

− the relative failure rate λ / λ decreases by 2.9-4.7 %;

− the refrigerating coefficient E increases by 1.5-9.4 %.

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

The results of calculating the main parameters taking into account the temperature dependence, the time to reach the stationary operating mode and the reliability indicators for the mode (Q_0/I^2) max and for various temperature drops ΔT are given in Table 3.

Analysis of the calculation results given in Table 3, showed that with an increase in the efficiency of the thermoelectric material in the module ż for various temperature drops ΔT in the mode $(Q_0/I^2)_{max}$, the tendency of changes in the main parameters remains unchanged. Next, we will consider in detail the dynamics of the TEC functioning in the mode $(Q_0/I^2)_{max}$.

Increasing the efficiency of the thermoelectric material in the module ż for various temperature drops ΔT in the mode $(Q_0/I^2)_{max}$:

– the time to reach the stationary mode decreases (Fig. 11):

ΔT = 40 K by 13 %;
ΔT = 50 K by 20.6 %;
ΔT = 60 K by 30.8 %.

With an increase in the temperature difference ΔT, the time to reach the stationary mode increases (Fig. 12). For a given efficiency of the thermoelectric material in the module ż, the relative value of the time to reach the stationary mode of operation increases $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_3}{\tau_1}$ – pos. 1 and $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_2}{\tau_1}$ – pos. 2 in Fig. 13.

With an increase in the efficiency of the thermoelectric material in the module ż from $2.4\cdot10^{-3}$ to $2.6\cdot10^{-3}$ 1/K, the time to reach the stationary mode of operation can be reduced by 9.6% at ΔT = 50 K (Fig. 13, item 2).

Table 3. **Results of calculating the main parameters for mode $(Q_0/I^2)_{max}$: T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1}; R_H = 11.1·10^{-3} Ohm; I_{maxH} = 5.5 A**

$\dot{z}\cdot10^3$, 1/K	$R_K\cdot10^3$, Ohm	I_{max}, I, A	ΔT_{max}, K	Θ	τ, s	B_K, B_H	n, it.	W, W	U, V	E	γ	λ / λ_0	$\lambda\cdot10^8$, 1/h	P
ΔT = 40 K; T_0 = 260 K														
2.4	10.1	5.02 2.54	79.8	0.50	10.9	0.50 0.456	31.4	5.2	2.1	0.382		1.94	5.8	0.99942
2.6	9.52	5.38 2.49	86.2	0.46	10.3	0.46 0.454	29.1	4.6	1.8	0.436		1.31	3.92	0.99961
2.75	8.93	5.97 2.60	91.9	0.435	9.5	0.435 0.389	25.5	4.15	1.6	0.48		0.87	2.62	0.99974
ΔT = 50 K; T_0 = 250 K														
2.4	9.85	4.87 3.33	73.1	0.68	13.6	0.68 0.61	39.6	11.17	3.35	0.18		9.26	27.8	0.9972
2.6	9.43	5.20 3.29	79.1	0.63	12.3	0.63 0.56	33.8	9.10	2.76	0.22		5.76	17.3	0.9983
2.75	8.62	5.86 3.45	85.0	0.588	10.8	0.588 0.516	27.9	7.65	2.22	0.26		3.53	10.6	0.9989
ΔT = 60 K; T_0 = 240 K														
2.4	9.43	4.81 4.32	66.8	0.898	19.8	0.898 0.785	99.6	44.9	10.4	0.045		69.4	208	0.9794
2.6	9.09	5.10 4.23	72.3	0.83	16.5	0.83 0.725	60.0	25.4	6.0	0.079		31.0	93	0.9907
2.75	8.47	5.67 4.37	77.8	0.77	13.7	0.77 0.65	41.5	17.7	4.1	0.113		16.1	48.4	0.9952

Source: **compiled by the author**

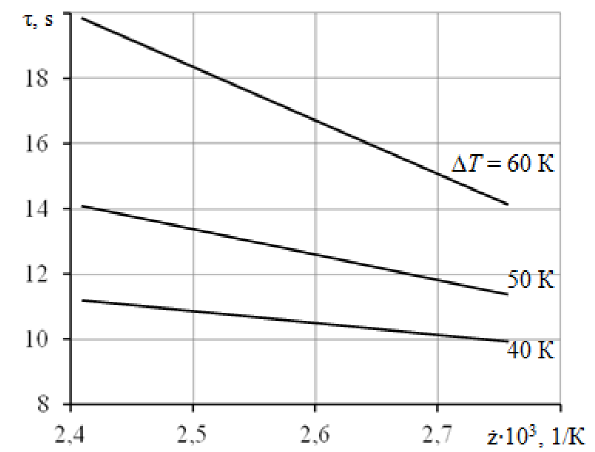

Fig. 11. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the efficiency of the thermoelectric material ż for various temperature drops ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I^2)_{max}$**

Source: **compiled by the author**

With an increase in the efficiency of the thermoelectric material in the module ż from 2.4·10^{-3} to 2.75·10^{-3} 1/K, the time to reach the stationary mode of operation can be reduced by 20.6 % at ΔT = 50 K (Fig. 13, item 1). With an increase in the efficiency of the initial thermoelectric materials in the module by 1 %, the time to reach the stationary mode decreases by 0.8-2 % (Fig. 5, item 3).

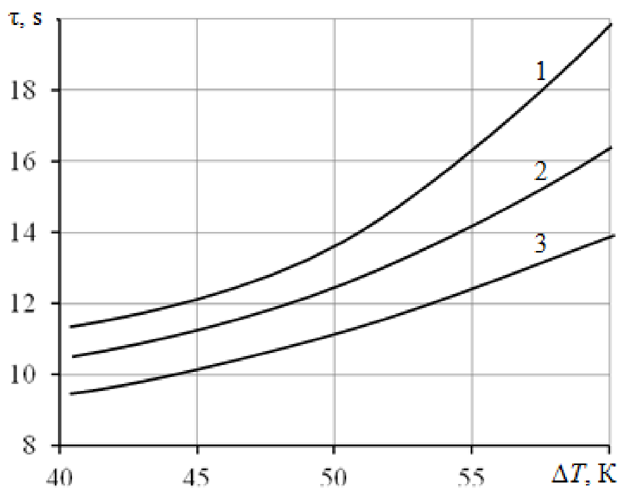

Fig. 12. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I^2)_{max}$ for different efficiency of thermoelectric material:**
1 – ż = 2.4·10^{-3} 1/K; 2 – ż = 2.6·10^{-3} 1/K; 3 – ż = 2.75·10^{-3} 1/K at 300 K

Source: **compiled by the author**

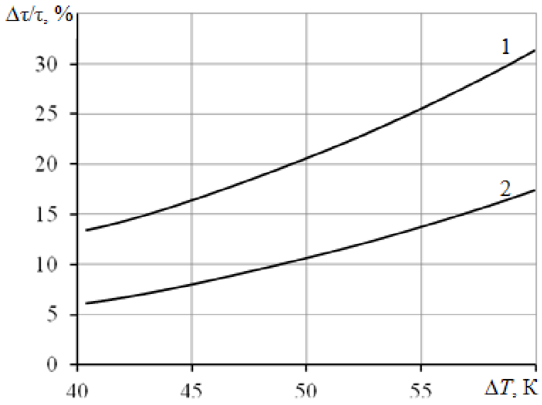

Fig. 13. **Dependence of the relative value of the time of reaching the stationary operating mode $\Delta\tau / \tau$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode $(Q_0/I^2)_{max}$ for different efficiency of thermoelectric material:**

$$1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_3}{\tau_1};\ 2 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_2}{\tau_1},$$

$\dot{z}_1 = 2.4 \cdot 10^{-3}$ 1/K; 2 – $\dot{z}_2 = 2.6 \cdot 10^{-3}$ 1/K; 3 – $\dot{z}_3 = 2.75 \cdot 10^{-3}$ 1/K at 300 K

***Source:* compiled by the author**

With an increase in the temperature difference ΔT, the K_τ coefficient increases (Fig. 5, item 3).

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of the thermoelectric material ż by 1 % allows to reduce the time to reach the stationary operating mode by 0.85 % for the $(Q_0/I^2)_{max}$ mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % allows reducing the time to reach a stationary operating mode by 1.4 % for the $(Q_0/I^2)_{max}$ mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of thermoelectric material ż by 1 % allows reducing the time to reach a stationary operating mode by 2.0 % for the mode $(Q_0/I^2)_{max}$.

With an increase in the temperature difference ΔT, the K_λ coefficient increases (Fig. 6, item 3), i.e., an increase in the thermoelectric efficiency of the starting materials in the module leads to a decrease in the relative failure rate λ/λ_0.

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 3.6 % for the mode $(Q_0/I^2)_{max}$;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 4.2 % for the mode $(Q_0/I^2)_{max}$;

− for a temperature difference ΔT = 60 K an increase in the efficiency of thermoelectric material ż by 1 % allows reducing the relative failure rate λ/λ_0 by 5 % for the mode $(Q_0/I^2)_{max}$.

With an increase in the temperature difference ΔT, the K_E coefficient increases (Fig. 7, item 3) for the mode $(Q_0/I^2)_{max}$, i.e. an increase in the thermoelectric efficiency of the starting materials in the module leads to an increase in the coefficient of efficiency E.

It should be noted that:

– for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % allows increasing the refrigerating coefficient *E* by 1.7 % for the mode $(Q_0/I^2)_{max}$;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % allows increasing the refrigerating coefficient *E* by 3 % for the mode $(Q_0/I^2)_{max}$;

– for a temperature difference ΔT = 60 K growth the efficiency of thermoelectric material ż by 1 % allows to increase the refrigerating coefficient *E* by 10 % for the mode $(Q_0/I^2)_{max}$.

Thus, with an increase in the efficiency of thermoelectric materials in the module by 1 % for the mode $(Q_0/I^2)_{max}$, depending on the temperature difference ΔT:

− the time to reach the stationary operating mode is reduced τ by 1-2 %;

− the relative failure rate λ/λ_0 decreases by 3.6-5 %;

− the refrigerating coefficient E increases by 1.7-10 %.

4. Mode λ_{min}

The results of calculating the main parameters taking into account the temperature dependence, the time to reach the stationary operating mode and the reliability indicators for the λ_{min} mode and for various temperature drops ΔT are given in Table. 4.

Analysis of the calculation results given in Table. 4, showed that with an increase in the efficiency of the thermoelectric material in the module ż for various temperature drops ΔT in the λ_{min} mode, the tendency for the main parameters to change remains unchanged. Next, we will consider in detail the dynamics of the TEC functioning in the λ_{min} mode.

Increasing the efficiency of thermoelectric material in module ż for various temperature drops ΔT in the λ_{min} mode:

– the time to reach the stationary mode decreases (Fig. 14):

at ΔT = 40 K by 8 %;
at ΔT = 50 K by 15.6 %;
at ΔT = 60 K by 26 %.

Table 4. **Results of calculating the main parameters for mode λ_{min}:**
T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1}; R_H = 11.1·10^{-3} Ohm; I_{maxH} = 5.5 A

$\dot{z}\cdot10^3$, 1/K	$R_K\cdot10^3$, Ohm	I_{max}, I, A	ΔT_{max}, K	Θ	τ, s	B_K, B_H	n, it.	W, W	U, V	E	γ	λ / λ$_0$	λ·10^8, 1/h	P
ΔT = 40 K; T_0 = 260 K														
2.4	10.1	5.02 2.13	79.8	0.50	13.7	0.425 0.387	46.5	5.83	2.74	0.343	1.319	1.45	4.34	0.99957
2,6	9.52	5.38 2.04	86.2	0.46	13.8	0.38 0.37	47.8	5.34	2.62	0.375	1.22	0.93	2.78	0.99972
2.75	8.93	5.97 2.13	91.9	0.435	12.6	0.357 0.319	41.3	4.78	2.24	0.418	1.335	0.615	1.84	0.99982
ΔT = 50 K; T_0 = 250 K														
2.4	9.85	4.87 2.995	73.1	0.68	15.4	0.615 0.545	51.0	11.9	3.97	0.168	1.437	7.76	23.3	0.99767
2.6	9.43	5.20 2.89	79.1	0.63	14.6	0.556 0.495	45.9	9.87	3.41	0.203	1.41	4.68	14.0	0.9986
2.75	8.62	5.86 3.0	85.0	0.588	13.0	0.512 0.449	38.8	8.4	2.8	0.239	1.435	2.8	8.42	0.99916
ΔT = 60 K; T_0 = 240 K														
2.4	9.43	4.81 4.19	66.8	0.898	20.4	0.871 0.762	107.8	46.0	11.0	0.044	1.539	67.0	201	0.9800
2.6	9.09	5.10 4.0	72.3	0.83	17.4	0.79 0.69	67.1	26.0	6.51	0.077	1.52	28.7	86	0.9914
2.75	8.47	5.67 4.068	77.8	0.77	15.0	0.717 0.609	49.3	18.6	4.56	0.108	1.56	14.4	43.3	0.9957

Source: **compiled by the author**

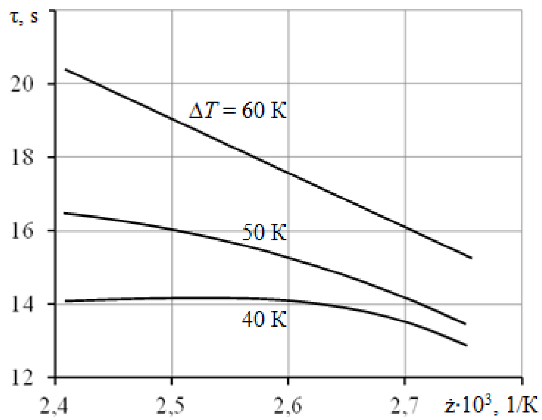

Fig. 14. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the efficiency of thermoelectric material ż for various temperature drops ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the mode λ_{min}**
Source: **compiled by the author**

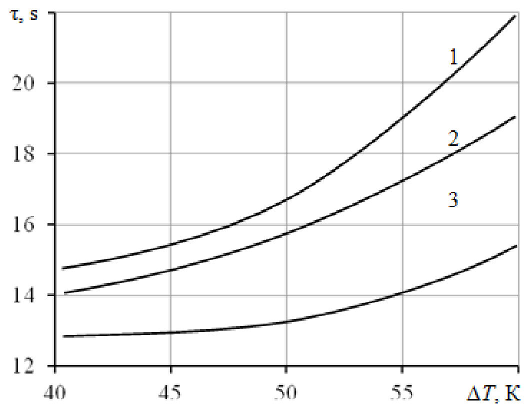

Fig. 15. **Dependence of the time of reaching the stationary mode of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the λ_{min} mode for different efficiency of thermoelectric material: 1 – ż = 2.4·10^{-3} 1/K; 2 – ż = 2.6·10^{-3} 1/K; 3 – ż = 2.75·10^{-3} 1/K at 300 K**
Source: **compiled by the author**

With an increase in the temperature difference ΔT, the time to reach the stationary mode increases (Fig. 15).

For a given efficiency of the thermoelectric material in the module ż, the relative value of the time to reach the stationary operating mode – $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_3}{\tau_1}$ pos. 1 and $\frac{\Delta\tau}{\tau}=\frac{\tau_1-\tau_2}{\tau_1}$ – pos. 2 in Fig. 16.

With an increase in the efficiency of the thermoelectric material in the module ż from 2.4 · 10^{-3} to 2.6 · 10^{-3} 1/K, the time to reach the stationary mode τ of operation can be reduced by 5.2 % at ΔT = 50 K (Fig. 16, item 2).

With an increase in the efficiency of the thermoelectric material in the module ż from 2.4 · 10^{-3} to 2.75 · 10^{-3} 1/K, the time to reach the stationary mode τ of operation can be reduced by 15.6 % at ΔT = 50 K (Fig. 16, item 1).

With an increase in the efficiency of thermoelectric materials in the module by 1%, the time of reaching the stationary operation mode decreases by 0.55–1.8 % for the λ_{min} mode, depending on the temperature difference ΔT (Fig. 5, item 4).

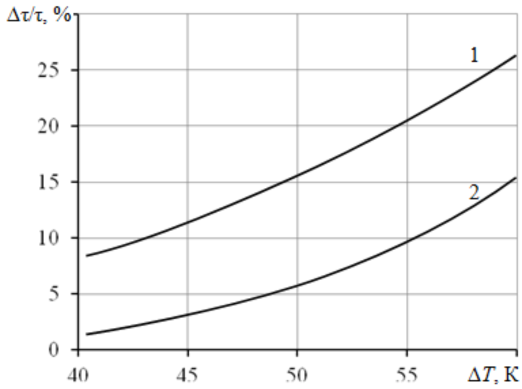

Fig. 16. **Dependence of the relative value of the time of reaching the stationary operating mode $\Delta\tau/\tau$ of a single-stage TEC on the temperature difference ΔT at T = 300 K; Q_0 = 2.0 W; l/S = 10 cm^{-1} in the λ_{min} mode for different efficiency of thermoelectric material:**

$$1 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_3}{\tau_1};\ 2 - \frac{\Delta\tau}{\tau} = \frac{\tau_1 - \tau_2}{\tau_1},$$

$\dot{z}_1 = 2.4 \cdot 10^{-3}$ 1/K; 2 – $\dot{z}_2 = 2.6 \cdot 10^{-3}$ 1/K; 3 – $\dot{z}_3 = 2.75 \cdot 10^{-3}$ 1/K at 300 K

***Source:* compiled by the author**

With an increase in the temperature difference ΔT, the K_τ coefficient increases (Fig. 5, item 4).

It should be noted that:

– for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time to reach the stationary operating mode by 0.5 % for the λ_{min} mode;

– for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the time to reach the stationary operating mode τ by 1.05 % for the λ_{min} mode;

– for a temperature difference ΔT = 60 K, an increase in the efficiency of a thermoelectric material ż by 1 % makes it possible to reduce the time to reach a stationary operating mode τ by 1.7% for a λ_{min} mode.

With an increase in the temperature difference ΔT, the K_λ coefficient increases (Fig. 6, pos. 4), i.e., an increase in the thermoelectric efficiency of the starting materials in the module leads to a decrease in the relative failure rate λ/λ_0.

It should be noted that:

− for a temperature difference ΔT = 40 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 3.8 % for the λ_{min} mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 4.3 % for the λ_{min} mode;

− for a temperature difference ΔT = 60 K, an increase in the efficiency of a thermoelectric material ż by 1 % makes it possible to reduce the relative failure rate λ/λ_0 by 5.1 % for the λ_{min} mode.

With an increase in the temperature drop ΔT, the K_E coefficient increases (Fig. 7, item 4) for the λ_{min} mode, i.e., an increase in the thermoelectric efficiency of the starting materials in the module leads to an increase in the coefficient of efficiency E.

It should be noted that:

– for a temperature difference ΔT = 40 K, an increase in the efficiency of the thermoelectric material ż by 1 % allows an increase in the refrigerating coefficient E by 1.4 % for the λ_{min} mode;

− for a temperature difference ΔT = 50 K, an increase in the efficiency of a thermoelectric material ż by 1 % makes it possible to increase the refrigerating coefficient E by 2.8 % for the λ_{min} mode;

– for a temperature difference ΔT = 60 K, an increase in the efficiency of a thermoelectric material ż by 1 % makes it possible to increase the refrigerating coefficient E by 9.6 % for the λ_{min} mode.

Thus, with an increase in the efficiency of the initial thermoelectric materials in the module by 1 % for the λ_{min} mode, depending on the temperature difference ΔT:

− the time to reach the stationary operating τ mode is reduced by 0.5-1.7 %;

− the relative failure rate λ/λ_0 decreases by 3.8-5.1 %;

− the refrigerating coefficient E increases by 1.4-9.6 %.

DISCUSSION OF RESEARCH RESULTS

The studies have shown that an increase in the efficiency of a thermoelectric material in a module ż from $2.4 \cdot 10^{-3}$ to $2.75 \cdot 10^{-3}$ 1/K at T = 300 K allows, depending on the temperature difference ΔT, in the range of 40-60 K:

– increase the maximum temperature difference ΔT_{max} to 17 %;

– reduce the relative temperature difference Θ by 13-14 %;

− reduce the number of thermoelements n in the thermoelectric power plant:

by 29-64 % in Q_{0max} mode;
by 26-63 % in the $(Q_0/I)_{max}$ mode;
by 19-55 % in the $(Q_0/I^2)_{max}$ mode;
by 11-54 % in the λ_{min} mode;

− increase the coefficient of performance E:
by 13-125 % in Q_{0max} mode;
by 22-145 % in the $(Q_0/I)_{max}$ mode;
by 26-153 % in the $(Q_0/I^2)_{max}$ mode;
by 22-148 % in the λ_{min} mode;
− reduce the relative value of the failure rate λ/λ_0:
by 29-64 % in Q_{0max} mode;
by 45-72 % in the $(Q_0/I)_{max}$ mode;
by 55-77 % in the $(Q_0/I^2)_{max}$ mode;
by 58-79 % in the λ_{min} mode;
− increase the probability of no-failure operation P;
− reduce the time to reach the stationary τ mode:
by 21-37 % in Q_{0max} mode;
by 19-35 % in the Q_{0max} mode;
by 13-31 % in the $(Q_0/I^2)_{max}$ mode;
by 8-26 % in the λ_{min} mode.

Thus, with an increase in the efficiency of the initial thermoelectric materials in the module by 1%:

− the time of reaching the stationary regime τ decreases from 0.6 to 2.5 %;

− the relative value of the failure rate λ/λ_0 decreases from 1.9 to 5.1 %;

– the refrigerating coefficient E increases from 0.9 to 10 %.

The criterion for choosing the operating mode of the TEC can be either one- or multifactorial. However, in most cases it is necessary to take into account the mutual influence and weight of each of the limiting factors. Since the design conditions can be very diverse, simultaneously varying several limiting factors (n, I, E, λ/λ_0, T), you can choose the most rational operating mode.

CONCLUSIONS

1. A mathematical model has been developed that connects a complex of parameters significant for control with design parameters, reliability indicators and dynamics of a thermoelectric cooling device. A method is proposed for reducing the time constant of thermoelectric coolers due to the revealed relationship between the efficiency of thermoelectric materials and the dynamic characteristics of thermoelements.

2. The analysis of the dynamic model in the standard current modes of operation of the thermoelectric cooler in the range of operating temperature drops has been carried out. The extrema of the dependences are determined, which contribute to the identification of a compromise between the reliability and the dynamics of the operation of the device. It is shown that an increase in the dynamic characteristics of thermoelectric coolers is achieved without changing the design documentation, manufacturing technology and additional climatic and mechanical testing of products.

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Метод підвищення динамічних характеристик термоелектричних охолоджувачів

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АНОТАЦІЯ

Розглянуто вплив ефективності первинних термоелектричних матеріалів на динаміку функціонування термоелектричного охолоджуючого пристрою для різних характерних струмових режимів роботи у діапазоні робочих перепадів температур і теплового навантаження при заданій геометрії гілок термоелементів. Параметри термоелектричних матеріалів умовно розділені на три групи: які використовуються для серійного виробництва, лабораторних досліджень і максимальні значення. Критерії вибору режиму роботи термоелектричного охолоджувача враховує взаємний вплив і вагомість кожного з обмежувальних факторів. Оскільки умови проектування можуть бути вельми різнорідними, змінюючи одночасно декількома обмежуючими факторами (конструктивними, енергетичними і надійності) можна вибрати найбільш раціональний режим роботи. Аналіз проведено для типових струмових режимів функціонування термоелектричних охолоджувачів: максимальної холодопродуктивності, максимальної холодопродуктивності при заданому струмі, максимального холодильного коефіцієнту, мінімальної інтенсивності відмов. Показано, що з ростом ефективності первинних термоелектричних матеріалів зменшується час виходу на стаціонарний режим роботи термоелектричного охолоджувача, необхідна кількість термоелементів і зростає максимальний перепад температур. Запропоновано спосіб зниження постійної часу термоелектричних охолоджувачів за рахунок виявленого зв’язку ефективності термоелектричних матеріалів з динамічними характеристиками термоелементів. Показано, що підвищення динамічних характеристик термоелектричних охолоджувачів досягається без зміни проектної документації, технології виготовлення і додаткового проведення кліматичних і механічних випробування виробів.

Ключові слова: термоелектричні матеріали; ефективність; динамічні характеристики; режими роботи; показники надійності

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