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Method of reliability control of thermoelectric systems to ensure thermal regimes

Vladimir P. Zaykov[1)]
ORCID: https://orcid.org/0000-0002-4078-3519; gradan@i.ua. Scopus Author ID: 57192640250
Vladimir I. Mescheryakov[2)]
ORCID: https://orcid.org/0000–0003–0499–827X; gradan@ua.fm. Scopus Author ID: 57192640885
Andrey S. Ustenko[2)]
ORCID: https://orcid.org/0000-0002-0546-7019; uas059877@gmail.com
[1)] Research Institute STORM, 27, Tereshkova Str. Odessa, 65076, Ukraine
[2)] State Environmental University, 15, Lvivska Str. Odessa, 65026, Ukraine

ABSTRACT

The paper presents the results of research of controllability of the thermoelectric system for ensuring thermal modes of electronic equipment, including a regulator, a cooler, and a component of excess heat removal to the environment. It is shown that for the use of methods of optimization of automatic control systems it is necessary to study the transfer and dynamic characteristics of the object - thermoelectric cooling device with one input and one output. The mathematical model of the thermoelectric cooler of the system of providing thermal modes of a given design is presented, which takes into account the influence of the conditions of interaction of the heat sink with the medium on the main significant parameters, reliability indicators, dynamic and energy characteristics of the single stage cooler. The model is created for the operating range of cooling, level of thermal load, geometry of thermocouple branches, different temperature of the medium, for the characteristic thermal regime of maximum cooling capacity. The results of calculations of the main significant parameters, reliability indicators, dynamic and energy characteristics of the cooler for different medium temperature in the operating temperature range and variation of conditions of heat exchange of the heat sink with the medium are given. It is shown that as the intensity of heat exchange of the heat sink with the medium increases, the temperature difference between the heat sink and the medium decreases. This makes it possible to significantly reduce the relative failure rate, increase the probability of failure-free operation of the thermoelectric cooler and control the reliability indicators of the device of a given design during operation.

Keywords: System of thermal modes provision; mathematical model; dynamic characteristics; reliability performance; control

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INTRODUCTION

Thermal management systems (TMS) of heat-loaded elements and processor units are a necessary component of onboard information structures. From the reliability point of view, the fuel element and the heat extraction system are included in series and the resulting probability of failure-free operation is equal to the product of their probabilities. Hence the requirement to the probability of failure-free operation of the cooler – its reliability index should be not less than the index of the heat-loaded element. Since the reliability indices of semiconductor components significantly depend on temperature, this requirement is very strict in relation to cooling devices. Among the most rational and perspective TMS for thermal stabilization of electronic equipment are: forced air or liquid cooling. Thermoelectric coolers (TEC) are the most promising in terms of mass-size characteristics, reliability and dynamics. In addition, they are the most suitable for controlling the cooling capacity according to the following parameters: lag time, time constant, and transfer coefficient (operating current – temperature difference). In accordance with the theory of automatic control, this allows us to consider the thermal management system as a SISO-system, which has one input and one output. Since this dependence is nonlinear for thermal power plants, the study of the control object from the point of view of reliability and controllability indicators is important.

LITERATURE REVIEW

Systems for ensuring thermal conditions of electronic equipment have become widespread in products with strict requirements for mass and dimensional characteristics [1]. This is largely satisfied by coolers operating on the Peltier effect [2]. Analyzing the TEC as a control object from the point of view of automatic control theory allows us to consider the TEC and the controller as a SISO-system [3]. These systems find application for controlling separate objects with one input and one output [4, 5], which satisfies the TEC – operating current and temperature difference. At the same time, the reliability of this system has not been practically considered, and for thermal system it seems to be important [6]. The comparison of TECs was carried out on the allocated characteristics on the basis of modeling [7] studies and on qualitative results of passing accelerated tests [8]. It is shown in [9, 10] that taking into account such design peculiarities of TECs as a large number of single-type thermoelements and their sequential connection allowed to obtain mathematical models of TECs with exponential distribution. Further studies are aimed at revealing the analytical relationship of reliability indicators with structural [11], mechanical parameters [12], and manufacturing technology [13], and energy effects [14]. The issues of TEC dynamics are considered in [15, 16]. However, these works did not consider the issues of TEC dynamics, which are important for the cooler-regulator complex. In [17, 18], the results of investigation of the relationship between the dynamics of a thermoelectric cooler and reliability indices at variation of geometry of thermoelements and modes of operation are presented. In [19] the task of reducing the inertia of the cooler and its dependence on the design and loading characteristics is considered. In [20] the possibilities of controlling the operating modes of the cooler by complex indices are presented. However, the above studies are oriented mainly to the design stage, when there is an opportunity to influence the design of the power plant. At the same time, at creation of controlled systems for providing thermal modes there arises a necessity in reliability-oriented control of already existing coolers. The relevance of such studies, especially in case of limited terms of creation of systems with thermoelectric TMSs, does not cause doubts.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this paper is to enable the management of the reliability performance of a thermoelectric cooler during operation.

In order to achieve this goal, the following tasks need to be solved:

1. To develop a model of thermoelectric cooler for operation with variable load this provides the possibility of reliability indices control.
2. To carry out analysis of relation of control action on TEC with reliability indices.

CONTROL OF A HEAT-LOADED OBJECT

Provision of the thermal regime of a heat-loaded element implies extraction of excess heat to a level sufficient to achieve its required level of reliability. Depending on the tasks to be solved, the temperature difference between the object and the environment $(T - T_C)$ can be achieved passively by heat conduction or actively by cold generation. The second approach is more appropriate to the control task and can be realized on thermoelectric coolers. In this case, the most important control characteristics are the lag time, time constant and transfer function.

If we abstract from the specific problem, we obtain an information SISO control system, which has one input and one output and perturbation, one task and one controller. If there is a model of the object, the system of providing thermal modes is replaced by an information model, through which signals are transmitted, but not the actual flows themselves.

An ideal PID controller is described by the expression [3]:

$$u(t) = Ke(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}, \quad (1)$$

where u is control; e is mismatch signal.

If in the first approximation the cooler is represented by a model of a first-order inertial link with a lag

$$W_0 = \frac{k_o}{T_o s + 1} e^{-\tau_o s}, \quad (2)$$

then it is possible to study the quality of transients of the thermal control system. The procedure of controller synthesis allows finding a compromise between robustness and speed of transients both on perturbation and on setpoint.

However, this should be preceded by the development of a reliability-oriented model of the thermoelectric cooler and its analysis.

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DEVELOPMENT OF A THERMOELECTRIC COOLER MODEL

When building reliable TMS, one of the key problems is the necessity of estimation and forecasting of FTE reliability indicators, as well as searching for ways to improve and control them in real time.

When operating the structure of the object consisting of a TEC and a heat sink with forced air cooling, which is used to dissipate thermal power into the environment, it is possible to use different modes of operation of the fan (air flow rate $G = Var$). With increasing air flow rate G of the fan increases the velocity of air flow V in the live section of the heat sink of a given design, which leads to an increase in the heat transfer coefficient α. This allows reducing the temperature drop $(T - T_c)$ at a given design of heat sink.

Let us consider the construction of the model in the process of operation of thermal power plant in the characteristic mode of maximum cooling capacity $Q_{0\max}$ at $(T - T_c)$ = 10K. It means that the number n of thermocouples temperature cooling T_0, heat load Q_0, geometry of branches of thermo-couples (ratio l/S), surface area of the heat sink in the range F of temperature change of the medium is set T_c.

Let's consider the influence of conditions of heat exchange of the heat sink with the medium on the main significant parameters, reliability indicators, dynamic and energy characteristics of the single-cascade fuel-electric power plant.

To calculate the main parameters, reliability indices, and dynamics of single-stage fuel and energy units, we use the following relations [17]:

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

where Q_0 is value of heat load; W – or dissipation power of the cooling object; $I_{\max} = \frac{\bar{e}_K T_o}{R_K}$ is maximum operating current, A; $\bar{e}_K$ is average value of the coefficient of thermal TEC of the thermocouple branch at the end of the cooling process, V/K; T_0 is temperature of the heat-absorbing junction, K; $R_K = \frac{l}{\bar{\sigma} S}$ is electrical resistance of the thermocouple branch at the end of the cooling process, Ohm; l, S are respectively, height and cross-sectional area of the thermocouple branch;

$\bar{\sigma}_K$ is average value of electrical conductivity of the thermocouple branch, S/sm; $B_K = I/I_{\max K}$ is relative operating current at the end of the cooling process; I is operating current value, A; $\Theta = \frac{T - T_0}{\Delta T_{\max}}$ is relative temperature difference; T is temperature of the heat-generating junction, K; $\Delta T_{\max} = 0{,}5 \bar{z} T_0^2$ is maximum temperature difference, K; $\bar{z}$ is average value of initial thermoelectric materials in the module, 1/K.

The reliability of the consumption of the TEC W_K can be determined from the expression [18]:

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

Voltage drop U_K

$$U_K = \frac{W_K}{I}. \qquad (5)$$

The refrigeration coefficient E can be determined from the expression

$$E = \frac{Q_0}{W}. \qquad (6)$$

The relative failure rate λ/λ_0 can be determined from the relationship [18]

$$\frac{\lambda}{\lambda_0} = nB^2(\Theta + c)\frac{\left(B_K + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2}{\left(1 + \frac{\Delta T_{\max}}{T_0}\Theta\right)^2} K_T, \qquad (7)$$

where $c = \frac{Q_0}{nI^2_{\max} R}$ is relative thermal load; λ_0 =3 10^{-8}1/h is nominal failure rate; K_T is significant coefficient of reduced temperatures [17].

The probability P of failure-free operation of the thermal power plant can be determined from the expression:

$$P = \exp[-\lambda t], \tag{8}$$

where $t = 10^4$h is the assigned resource.

The formula for determining the time of steady-state operation can be presented in the form [19]:

$$\tau = \frac{m_0 c_0 + n\sum_i m_i c_i}{nK(1 + 2B_K \frac{\Delta T_{\max}}{T_0})} \ln \frac{\gamma B_H (2 - B_H)}{eB_K - B_K^2 - \Theta}, \tag{9}$$

where $\gamma = \frac{I^2_{\max H} R_H}{I^2_{\max K} R_K}$; $m_0 c_0$ is product of mass by heat capacity of the cooling object. In our case $m_0 c_0 \to 0$ (no object); $\sum_i m_i c_i$ is the total value of the product of heat capacity and mass of the constituent structural and technological elements on the heat-absorbing layer of the module at a given l/S.

Index H means the initial moment of time.

Index K means the final moment of time.

$$B_H = \frac{I}{I_{\max H}}, \tag{10}$$

$I_{\max H} = \frac{\bar{e}_H T}{R_H}$ is maximum operating current at the beginning of the cooling process, A.

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

$$I = B_K I_{\max K} = B_H I_{\max H} \tag{11}$$

The voltage drop U on the TEC can be written in the following form

$$U = 2nI_{\max K} R_k (B + \frac{\Delta T_{\max}}{T_o} \Theta). \tag{12}$$

The amount of energy N given can be written as a ratio:

$$N = W\tau\ . \tag{13}$$

The required heat dissipation capacity of the heat sink αF can be represented in the form:

$$\alpha F = \frac{Q}{T - T_c}, \tag{14}$$

αF is thermal conductivity of the heat sink, T_c is medium temperature, K.

The results of calculations of the main significant parameters, reliability indicators, dynamic and energy characteristics of the TMS using a single-cascade TEC in the mode $Q_{0\max}$ under the variation of the conditions of heat exchange with the medium of the heat sink at a given cooling temperature level T_0 =260K, thermal load Q_0 =2.0 W, geometry of the branches of thermocouples $l/S = 10$, the surface area F of the radiator $A = \frac{\lambda^{T-T_c=10K}}{\lambda^{T-T_c=Var}}$, for different temperature of the medium T_c, are shown in Table 1.

ANALYSIS OF THE MODEL

As the temperature $(T - T_c)$ differential between the heat sink T and the medium decreases T_c for a given limiting temperature level T_0 =260K, thermal load Q_0 =2.0 W, thermocouple branch geometry l/S =10 and medium temperature T_c variation from T_c=290K to T_c=320K in the mode $Q_{0\max}$ at $(T - T_c)$=10K:

– the relative temperature Θ difference decreases (Fig. 1) for different temperature T_c. As the medium temperature T_c increases, the relative temperature difference Θ increases for a fixed temperature difference Θ;

– relative operating current B decreases (Fig. 2) for different medium temperature T_c. As the medium temperature B increases, the relative operating current remains constant at a fixed value of $(T - T_c)$;

– the value of operating current I decreases (Fig. 3) for different medium temperature T_c. As the medium temperature increases T_c, the operating current I decreases insignificantly at a fixed value of $(T - T_c)$;

– number of thermocouples n (Fig. 4) remains constant for different medium temperature T_c. As the medium temperature T_c increases, the number of thermocouples n increases for a fixed temperature difference $(T - T_c)$;

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– cooling coefficient E increases (Fig. 5) for different medium temperature T_c. As the medium temperature T_c increases, the refrigeration coefficient E decreases for a fixed temperature difference $(T - T_c)$;

Table 1. **Results of calculations of main parameters at** T_0 **=260K;** $l/S = 10$ **;** Q_0 **=2.0 W at** $(T - T_c)$ **=10K**

T_c	$T - T_c$	Θ	B	I	W	E	U	Q_0/n	τ	N	αF	α	A	λ/λ_0	$\lambda \cdot 10^8$	P
290	n =15.7 pcs F =373 sm²															
	10	0.50	1.0	5.0	9.2	0.22	1.8	0.127	6.5	60	1.1	30	1.0	16	48	0.9952
	7.0	0.46	0.81	4.1	6.2	0.32	1.5		6.5	41	1.1	32	2.2	7.2	21	0.9978
	5.0	0.44	0.76	3.8	5.4	0.37	1.4		6.4	35	1.4	40	3.0	5.4	16	0.9984
	3.0	0.42	0.72	3.7	4.9	0.41	1.3		6.3	31	2.3	60	3.6	4.4	13	0.9987
	2.0	0.40	0.70	3.5	4.6	0.44	1.3		6.2	29	3.3	90	4.1	3.9	11	0.9988
	0.0	0.38	0.66	3.3	4.0	0.50	1.2		5.9	24	-	-	5.5	2.9	8.7	0.9991
300	n =20.5 pcs F =490 sm²															
	10	0.62	1.0	5.0	12.6	0.16	2.5	0.097	9.0	113	1.4	30	1.0	21	63	0.9937
	7.0	0.59	0.82	4.1	8.6	0.23	2.1		9.0	77	1.5	31	2.1	9.8	29	0.9971
	5.0	0.56	0.77	3.8	7.5	0.27	2.0		9.0	66	1.9	39	2.8	7.5	22	0.9978
	3.0	0.54	0.73	3.6	6.7	0.30	1.9		8.7	59	2.9	60	3.5	6.0	18	0.9982
	2.0	0.53	0.70	3.5	6.3	0.32	1.8		8.6	54	4.1	85	4.1	5.1	15	0.9985
	0.0	0.50	0.66	3.3	5.6	0.36	1.7		8.4	47	-	-	5.3	4.0	12	0.9988
310	n =30.8 pcs F =700 sm²															
	10	0.74	1.0	4.9	19.2	0.10	3.9	0.065	12.2	234	2.1	30	1.0	31.5	94	0.9906
	7.0	0.70	0.80	4.0	12.8	0.16	3.2		12.4	159	2.1	31	2.3	13.7	41	0.9959
	5.0	0.68	0.77	3.8	11.7	0.17	3.1		12.1	142	2.7	39	2.8	11.3	34	0.9966
	3.0	0.66	0.70	3.5	10.0	0.20	2.9		12.3	123	4.0	57	4.0	7.9	23	0.9976
	2.0	0.65	0.68	3.4	9.6	0.21	2.8		12.2	117	5.8	83	4.4	7.1	21	0.9979
	0.0	0.62	0.65	3.2	8.6	0.23	2.7		12.1	104	-	-	5.5	5.7	17	0.9983
320	n =57.5 pcs F =1300 sm²															
	10	0.86	1.0	4.86	37.0	0.05	7.6	0.035	16.6	616	3.9	30	1.0	59	176	0.9826
	7.0	9.83	0.82	4.0	25.6	0.07	6.4		17.2	440	3.9	31	2.2	27.4	82	0.9918
	5.0	0.80	0.76	3.7	22.2	0.09	6.0		17.5	388	4.8	37	2.9	20.5	61	0.9939
	3.0	0.78	0.71	3.5	19.8	0.10	5.7		17.4	345	7.3	56	3.7	16.1	48	0.9952
	2.0	0.77	0.69	3.4	18.7	0.11	5.5		17.4	326	10	80	4.2	14.2	43	0.9957
	0.0	0.74	0.65	3.2	16.9	0.11	5.2		17.5	295	-	-	5.2	11.4	34	0.9966

Source: **compiled by the authors**

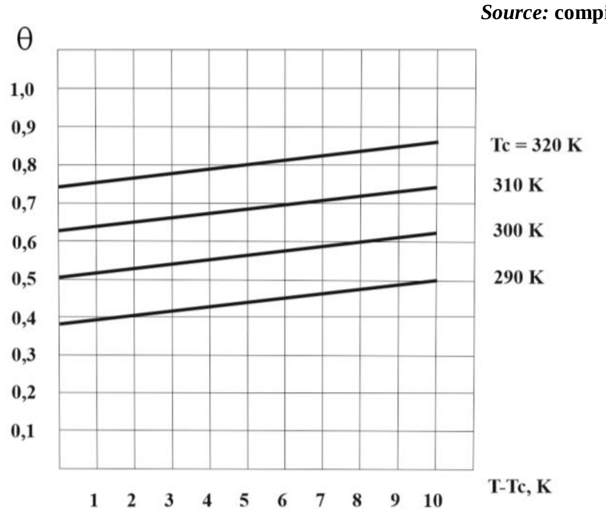

Fig. 1. **Dependence of the relative temperature difference** Θ **of a single-cascade TEC on the temperature difference** $(T - T_c)$

Source: **compiled by the authors**

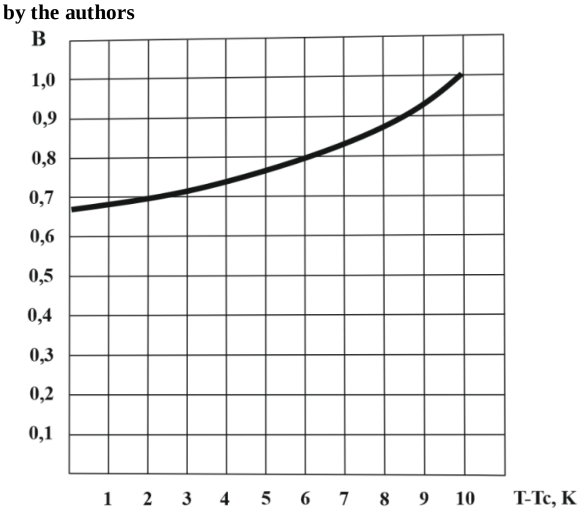

Fig. 2. **Dependence of relative operating current** B **of a single-stage TEC on the temperature difference** $(T - T_c)$

Source: **compiled by the authors**

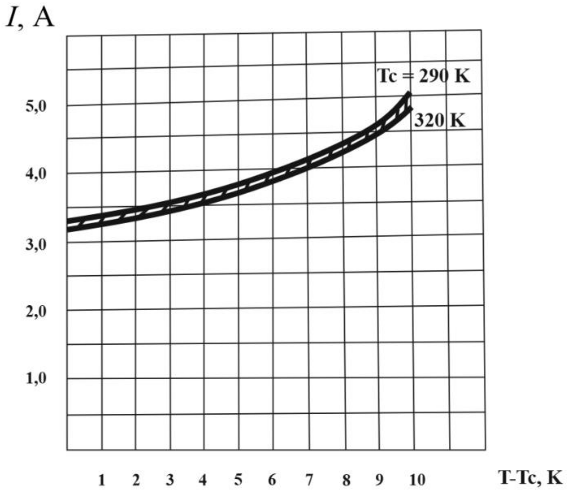

Fig. 3. **Dependence of the operating current value I of a single-stage TEC on the temperature difference $(T - T_C)$**

***Source*: compiled by the authors**

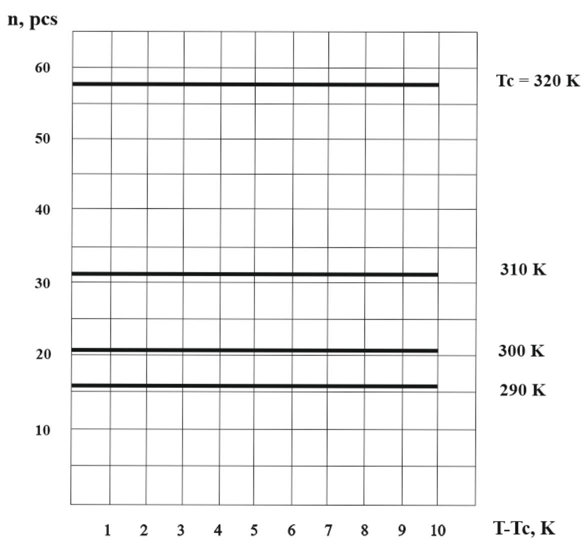

Fig. 4. **Dependence of the number of thermocouples n of a single-cascade TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

– the voltage drop U decreases (Fig. 6) for different medium temperature T_C. As the medium temperature T_C increases, the voltage drop U increases for a fixed temperature difference $(T - T_C)$;

– cold-productivity per one element Q_0/n (Fig. 7) remains constant for different medium temperature T_C. As the medium temperature T_C increases, the cooling capacity per element decreases Q_0/n;

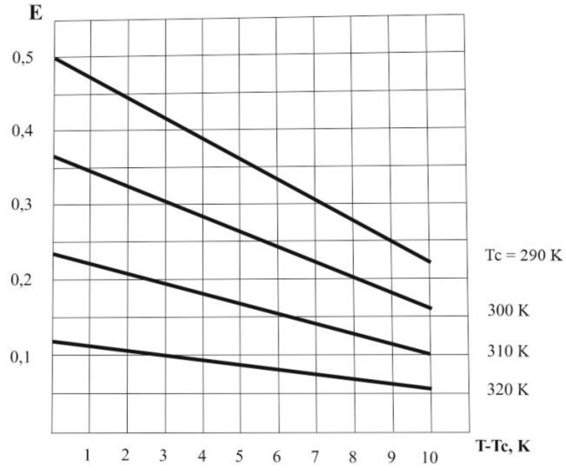

Fig. 5. **Dependence of the refrigeration coefficient of a single-cascade TEC on the temperature drop $(T - T_C)$**

***Source:* compiled by the authors**

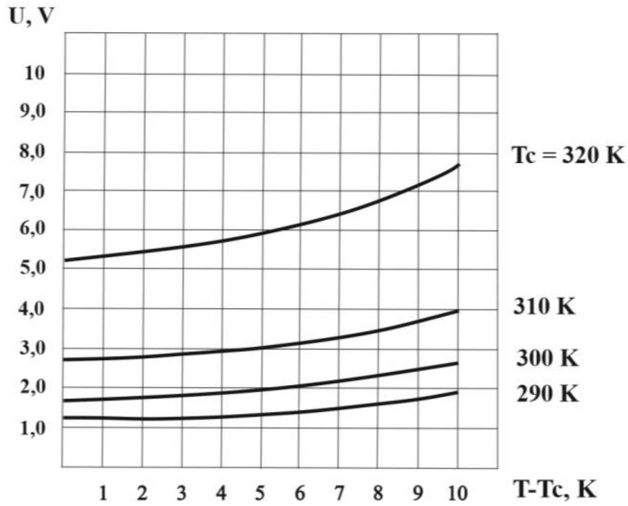

*Fig. 6***. Dependence of voltage drop U of single-stage TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

– time of reaching the stationary mode τ of operation (Fig. 8) for different medium temperature T_C remains practically constant. With the increase of the medium temperature T_C, the time of reaching the steady-state mode of operation remains practically constant. With the increase of the medium temperature, the time τ to reach the steady-state operating mode increases.

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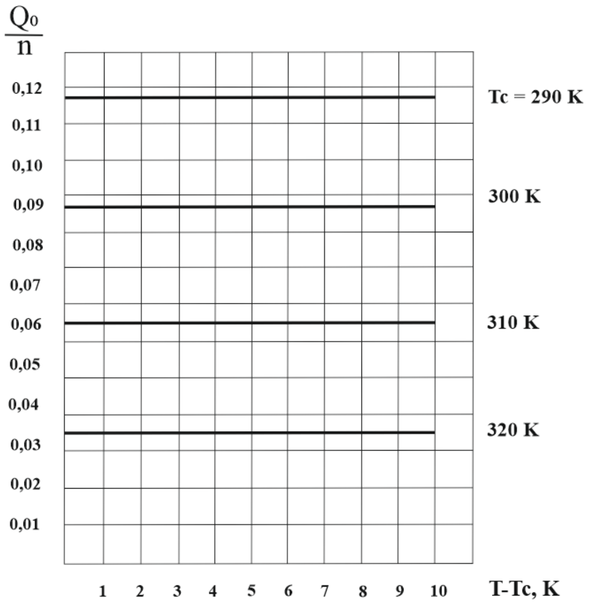

Fig. 7. **Dependence of the cooling capacity per one thermocouple Q_0/n of a single-cascade TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

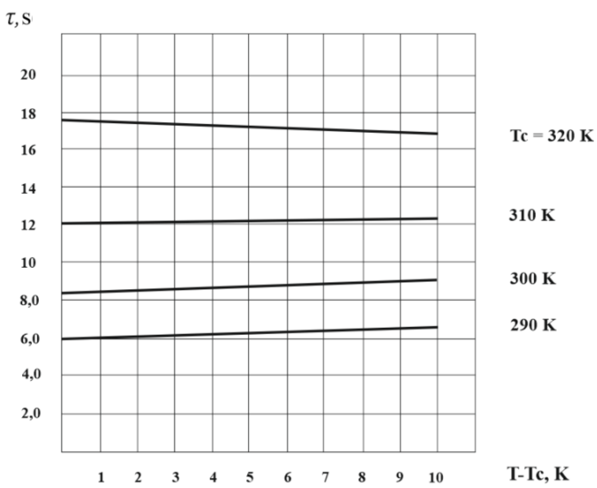

Fig. 8. **Dependence of time to reach the steady-state mode of operation τ of a single-cascade TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

– the amount of expended energy N decreases (Fig. 9) for different medium temperature T_C. As the medium temperature T_C increases, the amount of expended energy N increases for a fixed temperature difference $(T - T_C)$;

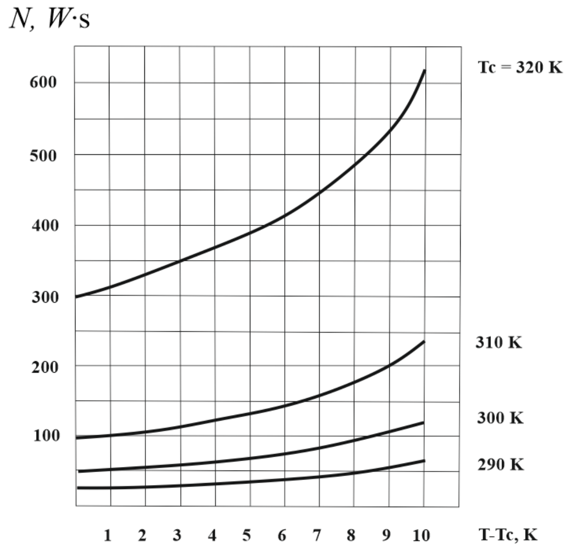

Fig. 9. **Dependence of the amount of expended energy N of a single-cascade TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

– the relative intensity of failures λ/λ_0 decreases (Fig. 10) for different medium temperature T_C. As the medium temperature T_C increases, the relative failure rate λ/λ_0 increases for a fixed temperature difference $(T - T_C)$;

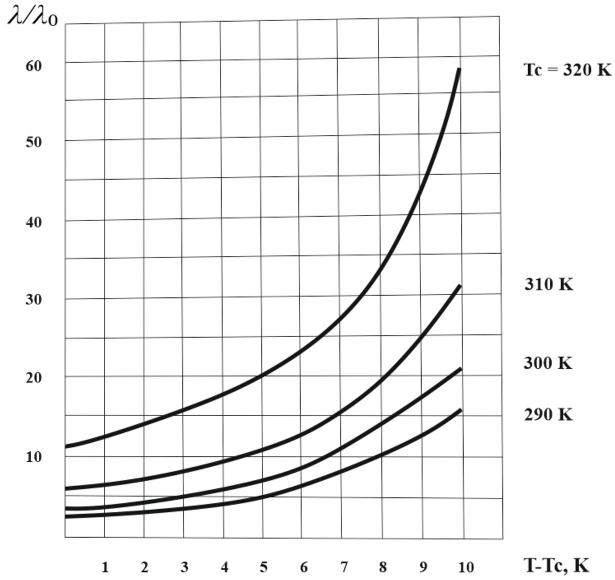

Fig. 10. **Dependence of relative intensity of failures λ/λ_0 of a single-cascade TEC on the temperature difference $(T - T_C)$**

***Source:* compiled by the authors**

– the probability of failure-free operation P increases (Fig. 11) for different medium temperature T_C. As the medium temperature T_C increases, the probability of operation T_C at a fixed temperature difference $(T - T_C)$ decreases;

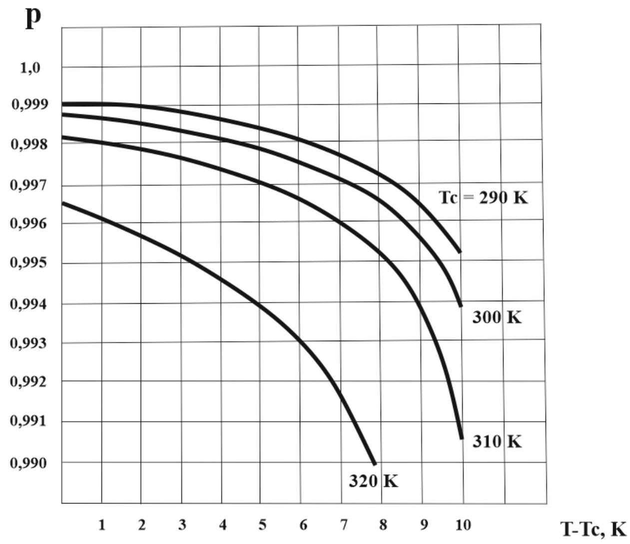

Fig. 11. **Dependence of probability P of failure-free operation of single-cascade TEC on the temperature difference $(T - T_C)$**
Source: **compiled by the authors**

– the ratio of failure intensity at $(T - T_C)$=10K to failure intensity at $(T - T_C)$=Var<10K (Fig. 12) from temperature difference increases $(T - T_C)$. As the medium temperature T_C increases, the ratio A remains almost constant;

– the heat dissipation capacity of the heat sink αF increases (Fig. 13) for different medium temperature T_C. The heat dissipation capacity of the heat sink T_C at fixed temperature difference αF increases with increasing of the medium temperature $(T - T_C)$.

DISCUSSION OF ANALYSIS RESULTS

Analysis of the research results showed that as the temperature differential $(T - T_C)$ decreased from $(T - T_C)$=10K to $(T - T_C)$=2K at a cooling temperature level T_0=260K, thermal load Q_0 =2.0W, thermocouple branch geometry λ / λ_0 =10 in the mode $Q_{0\max}$:

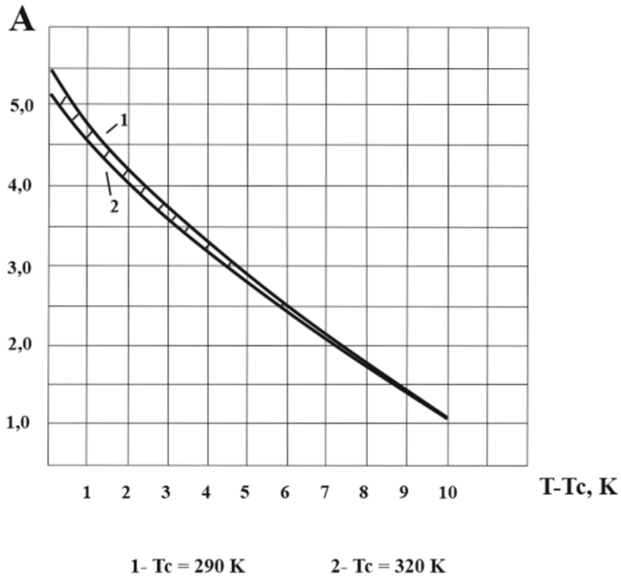

Fig. 12. **Dependence of the ratio of failure intensities A of a single-cascade TEC on the temperature difference $(T - T_C)$**
Source: **compiled by the authors**

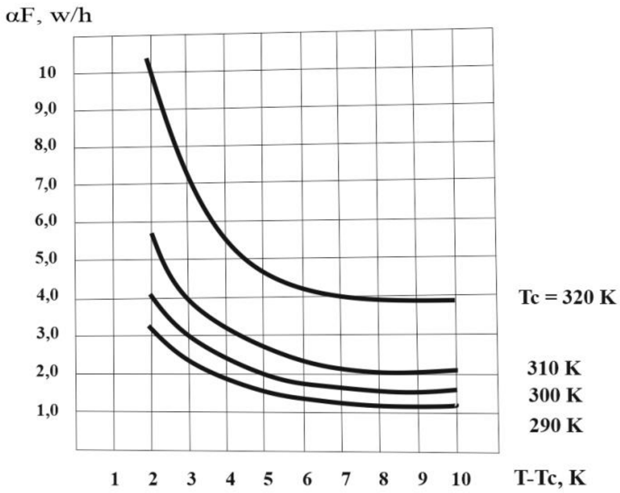

Fig. 13. **Dependence of heat dissipation capacity of the heat sink αF of a single-cascade TEC on the temperature difference $(T - T_C)$**
Source: **compiled by the authors**

Decreases:
relative temperature difference Θ:
– from Θ=0.50 to Θ=0.40, i.e. by 20 % at T_C=290K;
– from Θ=0.62 to Θ=0.53, i.e. by 14.5 % at T_C=300K;
– from Θ=0.74to Θ=0.65, i.e. by 12 % at T_C=310K;

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– from Θ =0.86to Θ =0.77, i.e. by 10 % at T_C =320K;
relative operating current B:
– from B =1.0 to B =0.70, i.e. by 30 % at T_C =290K;
– from B =1.0 to B =0.70, i.e. by 30 % at T_C =300K;
– from B =1.0 to B =0.68, i.e. by 32 % at T_C =310K;
– from B =1.0 to B =0.69, i.e. by 34 % at T_C =320K;
operating current I :
– from I =5.0A to I =3.5A, i.e. by 31 % at T_C =290K;
– from I =5.0A to I =3.5A, i.e. by 30 % at T_C =300K;
– from I =4.9A to I =3.4A, i.e. by 31 % at – T_C =310K;
– from I =4.86A to I =3.54, i.e. by 30 % at – T_C =320K;
voltage drop U :
– from U =1.8V to U =1.3V, i.e. by 28 % at T_C =290K;
– from U =2.5V to U =1.8V, i.e. by 28 % at T_C =300K;
– from U =3.9V to U =2.8V, i.e. by 28 % at T_C =310K;
– from U =7.6V to U =5.5V, i.e. by 27 % at T_C =320K;
time to reach steady-state operation τ :
–from τ =6.5 s to τ =6.2 s, i.e. by 4.6 % at T_C =290K;
– from τ =9.0 s to τ =8.6 s, i.e. by 4.4 % at T_C =300K;
– from τ =12 s to τ =12.2 s, i.e. by 0.0% at T_C =310K;
– from τ =16.6s to τ =17.5s, i.e. by 5.4% at T_C =320K;
energy input N :
– from N =60 Ws to N =29 Ws, i.e. 2.0 times at T_C =290K;
– from N =113 Ws to N =54 Ws, i.e. 2.1 times at T_C =300K;
– from N =234 Ws to N =117 Ws, i.e. 2.0 times at T_C =310K;
– from N =616 Ws to N =326 Ws, i.e. в 1.9 times at T_C =320K;
relative failure rate λ/λ_0 :
– from λ/λ_0 =16.0 to λ/λ_0 =3.9, i.e. 4.1 times at T_C =290K;
– from λ/λ_0 =21.0 to λ/λ_0 =5.1, i.e. 4.1 times at T_C =300K;
– from λ/λ_0 =31.5 to λ/λ_0 =7.1, i.e. 4.4 times at T_C =310K;
– from λ/λ_0 =59 to λ/λ_0 =14.2, i.e. 4.2 times at T_C =320K;

increases:

cooling coefficient E :
– from E =0.22 to E =0.44, i.e. 2.0 times at T_C =290K;
– from E =0.06 to E =0.22, i.e. 2.0 times at T_C =300K;
– from E =0.10 to E =0.21, i.e. 2.1 times at T_C =310K;
– from E =0.054 to E =0.11, i.e. 2.04 times at T_C =320K;
heat dissipation capacity of the radiator αF :
– from αF =1.1 W/K to αF =3.3 W/K, i.e. 3.0 times at T_C =290K;
– from αF =1.46 W/K to αF =4.15 W/K, i.e. 2.8 times at T_C =300K;
– from αF =2.1 W/K to αF =5.8 W/K, i.e. 2.8 times at T_C =310K;
– from αF =3.9 W/K to αF =3.3 W/K, i.e. 10.4 times at T_C =320K;
probability of failure P :
– from P =0.9952 to P =0.9988 at T_C =290K;
– from P =0.9937 to P =0.9985 at T_C =300K;
– from P =0.9906 to P =0.9979 at T_C =310K;
– from P =0.9826 to P =0.9957 at T_C =320K.

Thus, along with the known method of increasing the reliability of fuel and energy units [20], the possibility of a systematic approach to increasing the levels of reliability indicators of fuel and energy units in TMS of a given design during operation is considered.

CONCLUSIONS

1. The mathematical model of the heat extraction object of the system of providing thermal modes in the mode of maximum cooling capacity for different temperature of the medium is developed, which takes into account the interactions of the component of heat removal to the external

environment, reliability indicators, dynamic and energy characteristics of the thermoelectric cooler.

2. Analyses of the research results have shown the possibilities of controlling:

2.1) by increasing the air flow of the external environment significantly reduce the dependence on the temperature of the environment and the relative intensity of failures up to 4.4 times, the value of the operating current up to 30 %, the time to reach steady-state operation up to 5 %, the amount of expended energy up to 2 times;

2.2) increase of the refrigeration coefficient up to 2 times, probability of failure-free operation from 0.9952 to 0.9988 at the medium temperature of 290K at constant cold-productivity per one thermocouple for different medium temperature.

3. Thus, by varying the temperature difference and the value of operating current, it is possible to significantly increase the reliability indices of a given design and thus to control the reliability indices of TMC during operation.

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Метод управління надійністю термоелектричних систем забезпечення теплових режимів

Зайков Володимир Петрович[1)]
ORCID: http://orcid.org/0000-0002-4078-3519; gradan@i.ua. Scopus Author ID: 57192640250
Мещеряков Володимир Іванович[2)]
ORCID: http://orcid.org/0000–0003–0499–827X; gradan@ua.fm. Scopus Author ID: 57192640885
Устенко Андрій Сергійович[2)]
ORCID: http://orcid.org/0000-0001-7342-1031; ivanovich1zh@gmail.com
[1)] Науково-дослідницький інститут ШТОРМ, вул. Терешкової, 27. Одеса, 65076, Україна
[2)] Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна

АНОТАЦІЯ

У роботі представлено результати дослідження процесом управління термоелектричною системою забезпечення тепловим режимом електронної апаратури, що включає регулятор, охолоджувач, складову відведення надлишку тепла в навколишнє середовище. Показано, що для використання методів оптимізації автоматичних SISO-систем регулювання необхідне дослідження передавальних і динамічних характеристик об'єкта - термоелектричного охолоджувального пристрою з одним входом і одним виходом. Представлено математичну модель термоелектричного охолоджувача системи забезпечення теплових режимів заданої конструкції, яка враховує вплив умов взаємодії тепловідвідного радіатора із середовищем на основні значущі параметри, показники надійності, динамічні та енергетичні характеристики однокаскадного охолоджувача. Модель створено для робочого діапазону охолодження, рівня теплового навантаження, геометрії гілок термоелементів, різної температури середовища, для характерного теплового режиму максимальної холодопродуктивності. Наведено результати розрахунків основних значущих параметрів, показників надійності, динамічних та енергетичних характеристик охолоджувача для різної температури середовища в робочому діапазоні температур і варіації умов теплообміну тепловідвідного радіатора із середовищем. Показано, що зі зростанням інтенсивності теплообміну тепловідвідного радіатора із середовищем, зменшується різниця температур між тепловідводом і середовищем. Це дає змогу значно зменшити відносну інтенсивність відмов, підвищити ймовірність безвідмовної роботи термоелектричного охолоджувача та керувати показниками надійності пристрою заданої конструкції в процесі експлуатації.

Ключові слова: системи забезпечення теплових режимів; математична модель; динамічні характеристики; показники надійності; управління

ABOUT THE AUTHORS

Vladimir P. Zaykov - PhD, Head of Sector Research Institute “STORM”. 27, Tereshkova Str. Odessa, 65076, Ukraine
ORCID: http://orcid.org/0000-0002-4078-3519; gradan@i.ua. Scopus Author ID: 57192640250
***Research field*:** Reliability and dynamic descriptions of thermo-electric cooling devices; design, planning of the systems of providing of the thermal modes of electronic apparatus

Зайков Володимир Петрович - кандидат технічних наук, начальник сектору науково-дослідного інституту «ШТОРМ», вул. Терешкової 27. Одеса, 65076, Україна

Vladimir I. Mescheryakov - Doctor of Engineering Sciences, Professor, Head of Department of Informatics. State Environmental University, 15, Lvivska Str. Odessa, 65026, Ukraine
ORCID: http://orcid.org/0000-0003-0499-827X; gradan@ua.fm. Scopus Author ID: 57192640885
***Research field*:** Reliability and dynamic descriptions of thermo-electric cooling devices; design of power processes; biotechnical informative systems

Мещеряков Володимир Іванович - доктор технічних наук, зав. кафедри Інформатики. Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна

Andrii S. Ustenko - Graduate student. State Environmental University, 15, Lvivska Str. Odessa, 65026, Ukraine
ORCID: http://orcid.org/0000-0002-0546-7019; uas059877@gmail.com
***Research field*:** Reliability and dynamic descriptions of thermo-electric cooling devices; planning of the systems of providing of the thermal modes of electronic apparatus

Устенко Андрій Сергійович - аспірант кафедры Автоматизованих систем моніторингу навколишнього середовища та інформатики. Одеський державний екологічний університет, вул. Львівська, 15. Одеса, 65026, Україна

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