1. Introduction

Determining the time that it takes for a thermoelectric cooling device (TED) to enter a stationary working mode over the preset temperature range is an interesting task. This is related to the fact that dynamic indicators for the means that enable heat regimes of thermally loaded elements largely define both functional and reliable capabilities of critical
systems. In this case, only the mass and specific heat of an object are typically accounted for in the process of entering the mode. At the same time, experience has shown that there is a need to additionally take into consideration the heat capacity and mass of structural and technological elements, as well as current operating mode. In terms of operational control, of special interest is the current mode, and in terms of strategic control – the effect of heat capacity on the dynamic characteristics of a thermoelectric cooling device.

Thus, it is a relevant task to create a controllable dynamic system to monitor temperature at a thermally loaded element.

2. Literature review and problem statement

The issues of enabling thermal modes are integral part of the development of radio electronic equipment whose elements operate under thermally loaded modes [1]. Comparative analysis of compression and solid-state coolers [2] reveals that in terms of weight and dimensions, performance and reliability, thermoelectric coolers have a clear advantage [3]. Improved reliability indicators when designing thermoelectric coolers are achieved by taking into consideration the influence of thermal-physical, electrical properties, chemical activity of the thermoelements’ materials when interacting with external environment [4]. Creation of new materials with enhanced thermoelectric efficiency [5] gives rise to new challenges associated with the growing influence of contact resistances, heat conductivity of thermal elements, linear expansion of thermoelement contact with electrode. Specification of requirements to thermoelectric coolers for cooling capacity, energy indicators, weight and dimensions, resulted in the variety of thermoelectric modules [6]. Since such an integrated indicator as reliability depends on the design and manufacturing technology, there are developed methods to investigate indicators of reliability over the entire life cycle, starting at the design stage all the way to operation of thermoelectric coolers [7].

For the on-board systems, the most important is the influence of mechanical and thermal loads. The effect of impact and harmonic mechanical load on the cooler is strengthened by the fact that lower temperatures lead to the worsening of plasticity of the thermoelement soldering with the electrode, and to the increased fragility of a thermoelectric material [8]. Heat load increases temperature gradients, which can lead to the cracking of places where dissimilar materials are connected [9].

Under the non-stationary heat flows, control over coolers for deviation is ineffective. Working out a temperature deviation at the receiving element starts only after the temperature wave reaches the sensor of a thermal control system [10]. Working out a thermal perturbation by the cooler, which is typically described by integrating link, includes the lag time in the process of transition into a stationary mode, during which temperature of the thermally loaded element may exceed maximum permissible temperature. Proactive control implies launching a cooler prior to the moment when the heat wave reaches the cooler, therefore, it employs more complex algorithms to ing out a thermal perturbation by the cooler, which is typically

\[ \sum m_i C_i = m_{Cu} C_{Cu} + m_{Ce} C_{Ce} + m_{Ni} C_{Ni} + m_{Cu} \tau_{Cu} C_{Cu} + m_{Ce} \tau_{Ce} C_{Ce} = 175 \times 10^{-3} \text{ J/K.} \]

The aim of present study is to reduce the time it takes for a thermoelectric cooler to enter a stationary regime by taking into consideration the impact of structural and technological elements of the cooler, as well as operational modes.

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

- to develop a dynamic model of TED that would account for the structural and technological elements of the cooler;
- to perform a reliability-oriented analysis of the model in order to estimate a possibility to control the time it takes for TED to enter a stationary regime.

3. The aim and objectives of the study

The structural and technological elements on the heat absorbing junction of TED include:

- copper switching plates;
- a layer of soldering and a nickel coating;
- ceramic plate and a metallization layer in line with the switching circuit of thermoelements branches;
- a diffusion layer of a semiconductor material.

The following has to be taken into consideration:

- condition of the thermoelectric material surface, which is related to the technology of processing and storage conditions [8, 9];
- the depth of copper atoms migration in a thermoelectric material.

The thickness of a diffusion layer of the thermoelectric material, a contact area “metal-semiconductor” can be adopted equal to 100–150 μm. We used an aluminum plate with a mass of 1 gram as the object to be cooled. Indicative data on mass and heat capacity of structural and technological elements of TED are given in Table 1. When calculating the volume, for the geometry of thermoelements \( l/S = 10 \text{ cm} \), we used dimensions of the branch cross-section equal to 2×2 mm at height \( l = 4 \text{ mm} \).

The total magnitude of heat capacity and the mass of TED components can be represented in the form:

4. Development of dynamic model of TED taking into consideration its structural and technological elements

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The total magnitude of heat capacity and the mass of TED components can be represented in the form:

\[ \sum m_i C_i = m_{Cu} C_{Cu} + m_{Ce} C_{Ce} + m_{Ni} C_{Ni} + m_{Cu} \tau_{Cu} C_{Cu} + m_{Ce} \tau_{Ce} C_{Ce} = 175 \times 10^{-3} \text{ J/K.} \]

We shall consider the process of cooling an object in time \( \tau \), which is determined by the current mode selected, the magnitude of thermal load \( Q_0 \), branch geometry of the cooling thermoelement \( l/S \), taking into consideration the temperature dependence of parameters of a thermoelectric material in the module (Fig. 1), as well as specific heat capacity \( C \) and thermal diffusivity \( \alpha \) (Fig. 2). The dependence of total heat capacity and the mass of structural elements on the geometry of TED branches \( l/S \) is shown in Fig. 3. The temperature of heat emitting junctions is accepted to be constant and equal to \( T = 300 \text{ K} \) due to intensive heat exchange.
Parameters and indicators of structural and technological elements of the cooler

| Elements of design and technology | Width, mm | Volume, cm³ | Density of material, p. g/cm³ | Mass, m, g | Specific heat capacity, Cₚ, J/(g·K) | mC, J/K | Note |
|-----------------------------------|-----------|-------------|-------------------------------|-----------|-------------------------------------|---------|------|
| Thermoelectric material Bi₂Te₃   | 0.1       | 2×2×0.1–4×10⁻³ | 7.8                           | 31.2×10⁻⁴ | 0.31                                | 19.3×10⁻⁴ | mₚCₚ |
| Antidiffusion nickel-based coating| 0.025     | 2×2×0.025×10⁻³ | 8.1                           | 8.1×10⁻⁴  | 0.427                               | 13.8×10⁻⁴ | mₚCₚ |
| Solder                            | 0.1       | 2×2×0.1–4×10⁻³ | 9.6                           | 38.4×10⁻⁴ | 0.126                               | 9.7×10⁻⁴  | mₚCₚ |
| Switching plate, copper           | 0.2       | 2×2×0.2×8×10⁻³ | 9.0                           | 72×10⁻⁴   | 0.389                               | 58.1×10⁻⁴ | mₚCₚ |
| Ceramic plate                     | 0.3       | 2×2×0.3×12×10⁻³ | 1.84                          | 22×10⁻⁴   | 1.674                               | 73.7×10⁻⁴ | mₚCₚ |
| Object to be cooled (Al)          | –         | –           | 2.7                           | 8.1×10⁻⁴  | 0.894                               | 0.894    | mₚCₚ |

Thermal balance conditions on the heat emitting junctions of TED can be written in the form

\[-(mₚCₚ + n\sum mₚC_i)\int T₀ = nI_{_{max}}^{2}R(2B – B – Θ)ΔT₁, (2)\]

where \(mₚCₚ\) are, respectively, the mass and specific heat capacity of the cooled object; \(I_{_{max}}\) is the maximum operating current; \(R\) are, respectively, the averaged value of coefficient of thermoEMF, V/K, and electrical resistance of the thermoelement branch, Ohm; \(B = I/I_{_{max}}\) is the relative operating current; \(I\) is the working current magnitude; \(A\); \(T₀\) is the temperature of a heat absorbing junction, K; \(Θ = \Delta T₁/T_{_{max}}\) is the relative difference in temperature; \(ΔT_{_{max}} = 0.5T_{₀}^{2}\) is the maximum temperature difference, K; \(ΔT₁\) is the averaged value of the efficiency of thermoelectric material in module 1/K; \(ΔT₁\) is the difference in temperature at TED, K; \(n\) is the number of thermoelements, pcs.

By solving differential equation (2) under initial conditions \(τ = 0; \, T = T₀\), we shall obtain

\[\tau = \frac{mₚCₚ + n\sum mₚC_i}{nK₁(1 + 2B\frac{ΔT_{_{max}}}{T₀})}\ln \left(\frac{B_i(2B – Bₜ)}{2B₂ – B₂ – Θ}\right)\]

where \(K₁\) is the heat transfer coefficient, \(K₁ = \frac{S}{l}, \, W/K;\)

\[γ = \frac{I_{_{max}}Rₙ}{I_{_{max}}R₀}\]

\(I_{_{max}},\, R₀\) are, respectively, the maximum operating current and electrical resistance of the thermoelement branch at the beginning of the cooling process at \(τ = 0;\)

\(I_{_{max}},\, R₁\) are, respectively, the maximum operating current and electrical resistance of the thermoelement branch at the end of the process of cooling; \(θ\) is the coefficient of thermal conductivity.

This formula represents an analytical dependence of the time required to enter a stationary mode on the current operating mode (the magnitude of relative current \(B\), heat load \(Q₀\) (number of thermoelements \(n\)), taking into consideration both the mass and the heat capacity of the cooled object \(mₚCₚ\), and the structural and technological elements of TED at a preset temperature difference \(ΔT₀\).

Given that \(B₁ = I/I_{_{max}},\, B₂ = I/I_{_{max}},\) we shall write:

\[-\text{for mode } Q_{0_{max}}\]

\[I = I_{_{max}},\, B₁ = I_{_{max}}/I_{_{max}},\, B₂ = 1.0;\]

\(4\)
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Expression (8) describes the relationship for various current operating modes and heat load for the assigned temperature difference, taking into consideration the mass and specific heat capacity of structural and technological elements of TED.

## 5. Analysis of temporal and reliability indicators of the model for different operation modes of TED

The results of calculation of basic parameters and the time required for TED to enter a stationary mode, parameters of reliability for current modes of operation $Q_{\text{max}}$, $(Q_0/I)_{\text{max}}$, $E_{\text{max}}$ and $\lambda_{\text{min}}$ at $T=300 \text{ K}$; $\Delta T=40 \text{ K}$; $S=10 \text{ cm}^2$; $m_{\text{Al}}=1 \text{ g}$; $C_{\text{Al}}=0.894 \text{ J/(g-K)}$ and $\sum m_\text{C}_i = 175 \cdot 10^{-4} \text{ J/K}$ are given in Table 2. Here $t_0$ is the time required to enter a stationary mode, calculated with respect to the mass and heat capacity of the object, $\tau^*$ with respect to the mass and heat capacity, of both the object and the elements of TED design.

### Table 2

| Mode of operation | $Q_0$, A | $n$, pcs. | $t_0$, s | $\tau^*$, W | $B_1/B_2$ | $I$, A | $W$, W | $E$, V | $U$, V | $\lambda_{\text{I0}}$, $\lambda \cdot 10^8$, 1/h | $P$ |
|-------------------|---------|---------|-------|---------|---------|------|------|------|------|------------------|-------|
| $Q_{\text{max}}$ | 0.3     | 2.3     | 137   | 143.3   | 0.93/1.0 | 5.02 | 1.39 | 0.216 | 0.274 | 2.35 | 7.05 | 0.99930 |
|                   | 0.5     | 3.9     | 90.9  | 96.8    |         |      | 2.30 | 0.216 | 0.46  | 4.0  | 12.0 | 0.99888 |
|                   | 1.0     | 7.8     | 45.0  | 51.8    |         |      | 4.53 | 0.216 | 0.903 | 8.0  | 24.0 | 0.9976 |
|                   | 1.5     | 11.7    | 30.0  | 36.8    |         |      | 6.83 | 0.216 | 1.37  | 12.0 | 36.0 | 0.9964 |
|                   | 2.0     | 15.6    | 22.4  | 29.4    |         |      | 9.10 | 0.216 | 1.81  | 16.0 | 48.0 | 0.9952 |
|                   | 3.0     | 23.4    | 15.0  | 21.9    |         |      | 13.6 | 0.216 | 2.71  | 23.9 | 71.7 | 0.9929 |
|                   | 5.0     | 39.0    | 9.0   | 15.9    |         |      | 22.7 | 0.216 | 4.52  | 40   | 120  | 0.9881 |
|                   | 10.0    | 78.0    | 4.5   | 11.3    |         |      | 45.4 | 0.216 | 9.0   | 79.7 | 239.1 | 0.9764 |
| $Q_0/I_{\text{max}}$ | 0.3     | 2.8     | 144   | 152.3   | 0.66/0.707 | 3.55 | 0.88 | 0.34  | 0.25  | 0.73 | 2.19 | 0.99978 |
|                   | 0.5     | 4.7     | 86.7  | 94.7    |         |      | 1.44 | 0.347 | 0.41  | 1.23 | 3.68 | 0.99963 |
|                   | 1.0     | 9.4     | 43.4  | 51.3    |         |      | 2.88 | 0.347 | 0.81  | 2.45 | 7.36 | 0.99926 |
|                   | 1.5     | 14.1    | 28.9  | 36.9    |         |      | 4.40 | 0.347 | 1.23  | 3.68 | 11.0 | 0.9989 |
|                   | 2.0     | 18.8    | 21.7  | 29.6    |         |      | 5.88 | 0.347 | 1.66  | 4.9  | 14.7 | 0.9985 |
|                   | 3.0     | 28.2    | 14.4  | 22.3    |         |      | 8.80 | 0.347 | 2.46  | 7.35 | 22.0 | 0.9978 |
|                   | 5.0     | 47.0    | 8.6   | 16.7    |         |      | 14.7 | 0.347 | 4.1   | 12.3 | 36.8 | 0.9963 |
|                   | 10.0    | 94.0    | 4.3   | 12.2    |         |      | 28.8 | 0.347 | 8.1   | 24.5 | 73.5 | 0.9926 |
| $E_{\text{max}}$ | 0.5     | 6.6     | 77.3  | 87.2    | 0.47/0.50 | 2.76 | 1.10 | 0.460 | 0.40  | 0.607 | 1.82 | 0.00081 |
|                   | 1.0     | 13.0    | 38.6  | 48.6    |         |      | 2.20 | 0.460 | 0.80  | 1.20 | 3.6  | 0.99964 |
|                   | 1.5     | 19.5    | 25.7  | 33.7    |         |      | 3.30 | 0.460 | 1.20  | 1.82 | 5.46 | 0.99946 |
|                   | 2.0     | 26.0    | 19.3  | 29.3    |         |      | 4.40 | 0.460 | 1.60  | 2.42 | 7.26 | 0.99928 |
|                   | 3.0     | 39.0    | 12.9  | 22.8    |         |      | 6.60 | 0.460 | 2.40  | 3.64 | 10.9 | 0.9989 |
|                   | 5.0     | 65.0    | 7.7   | 17.7    |         |      | 11.0 | 0.460 | 4.0   | 6.0  | 18.0 | 0.9982 |
|                   | 10.0    | 130     | 3.9   | 13.8    |         |      | 22.0 | 0.460 | 8.0   | 12.0 | 36.0 | 0.9964 |
| $\lambda_{\text{min}}$ | 0.3     | 6.9     | 101   | 114.3   | 0.40/0.425 | 2.13 | 0.88 | 0.347 | 0.41  | 0.215 | 0.64 | 0.99936 |
|                   | 0.5     | 11.6    | 61.3  | 75.0    |         |      | 1.40 | 0.347 | 0.68  | 0.361 | 1.28 | 0.99892 |
|                   | 1.0     | 23.2    | 30.6  | 44.4    |         |      | 2.88 | 0.347 | 1.36  | 0.722 | 2.17 | 0.99780 |
|                   | 1.5     | 34.8    | 20.4  | 34.3    |         |      | 4.32 | 0.347 | 2.03  | 1.07 | 3.22 | 0.99968 |
|                   | 2.0     | 46.4    | 15.3  | 29.2    |         |      | 5.76 | 0.347 | 2.70  | 1.43 | 4.33 | 0.99957 |
|                   | 3.0     | 99.6    | 10.2  | 24.0    |         |      | 8.64 | 0.347 | 4.06  | 2.16 | 6.48 | 0.99935 |
|                   | 5.0     | 116     | 6.1   | 20.0    |         |      | 14.4 | 0.347 | 6.80  | 3.61 | 10.8 | 0.9989 |
|                   | 10.0    | 232     | 3.0   | 17.0    |         |      | 28.8 | 0.347 | 13.5  | 7.22 | 21.7 | 0.99783 |
Data in Fig. 4–7 show that an increase in heat load $Q_0$ (the number of thermoelements $n$ in TED) at the assigned temperature difference $\Delta T$ for various current modes of operation leads to the following:

- the time required to enter a stationary mode $\tau$ reduces;
- the number of thermoelements $n$ increases;
- voltage drop $U$ grows.

An analysis of data given reveals that the time required to enter a mode $\tau'$ increases compared to $\tau_0$. For example, at thermal load $Q_0=5.0$ W:

- under mode $Q_{0\text{max}}$ $\tau_0=9.0$ s; $\tau'=15.9$ s, that is, it is increased by 77%;
- under mode $(Q_0/I)_{\text{max}}$ $\tau_0=8.6$ s; $\tau'=16.7$ s, that is, it is increased by 94%;
- under mode $E_{\text{max}}$ $\tau_0=7.7$ s; $\tau'=17.7$ s, that is, it is increased by 130%;
- under mode $\lambda_{\text{min}}$ $\tau_0=6.1$ s; $\tau'=20$ s, that is, it is increased by 228%.

Fig. 4 shows that the greatest difference between the magnitudes of $\tau'$ and $\tau_0$ is observed under a $\lambda_{\text{min}}$ mode.

With a decrease in the time required to enter stationary mode $\tau$, the intensity of failures $\lambda/\lambda_0$ increases for different modes of operation (Fig. 9, $a$ – for modes $Q_{0\text{max}}$ and $(Q_0/I)_{\text{max}}$, Fig. 9, $b$ – for modes $E_{\text{max}}$ and $\lambda_{\text{min}}$) – due to the increase in the number of thermoelements $n$ in TED.

An analysis of the results of estimating the temporal process of TED entering a stationary mode of operation makes it possible to consider the relation between the mass and heat capacity of the object ($m_0C_0$) and the mass and heat capacity of structural elements at the heat absorbing junction of TED ($\sum_i m_iC_i$). The relation can be written in the form:

$$\frac{m_0C_0}{n\sum_i m_iC_it_0} = f.$$
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Fig. 8. Dependence of relative magnitude of the time required for a single-stage TED to enter a stationary mode on thermal load at $T=300$ K; $\Delta T=40$ K; $l/S=10$ cm$^{-1}$ for different modes of operation

A possible range of change in the magnitude $f$ can be represented as follows:

a) $f>>1$, that is, the mass and heat capacity of the object $m_iC_i$ are much larger than the mass and heat capacity of structural and technological elements of TED. In this case, the relative magnitude of the time required to enter a stationary mode $\tau/\tau_0 \geq 1.5$. The time required for TED to enter a stationary mode with respect to the mass and heat capacity of structural and technological elements exceeds the time required to enter a stationary mode with respect to the mass and heat capacity of the object by not larger than 50%;

b) $1.5 \geq f \geq 0.75$, that is, there is an approximate match between the mass and heat capacity of the object, and the mass and heat capacity of structural and technological elements of TED. In this case, the magnitude $\tau/\tau_0$ is in the range of $2.2 \geq \tau/\tau_0 \geq 1.7$, that is, the time required to enter a stationary mode with respect to the mass and heat capacity of structural and technological elements may exceed the time required to enter a stationary mode without taking them into consideration by the magnitude of 70 to 120%;

c) $f<<1$, that is, the mass and heat capacity of the object are much smaller than the mass and heat capacity of structural and technological elements. In this case, the magnitude $\tau/\tau_0 \geq 2.2$, that is, the time required to enter a stationary mode with respect to the mass and heat capacity of structural and technological elements is much longer, by 2–10 times, than the time required to enter a stationary mode without taking them into consideration.

Dependence of relative magnitude of the time required for a single-stage TED to enter a stationary mode $\tau/\tau_0$ on the magnitude of $f$ at $T=300$ K; $\Delta T=40$ K; $l/S=10$ cm$^{-1}$ is shown in Fig. 10. It should be noted that a given dependence applies to all the considered modes of operation.

In accordance with expression (8), we shall estimate the temperature of a heat-absorbing junction $T_0$ and other basic parameters for a single-stage TED for the operation modes $Q_{0\text{max}}$, $(Q_0/I)_{\text{max}}$, $E_{\text{max}}$ and $\lambda_{\text{min}}$. Initial conditions: $T=300$ K; $\Delta T=40$ K; $l/S=10$ cm$^{-1}$ with and without taking into consideration the mass and heat capacity of TED structural and technological elements for various thermal load $Q_0$. Calculated data are given in Tables 3–6, where $T_0$, $\Delta T_{\text{max}}$, $\Theta$, $\lambda/\lambda_0$ and $P$ are those without taking into consideration the structural and technological elements; $T'_0$, $\Delta T'_{\text{max}}$, $\Theta'$, $(\lambda/\lambda')$ and $P'$ are those taking into consideration the structural and technological elements.
### Table 3

| $Q_0$, W | $T_0$, K | $T_0'$, K | $t$, s | $n$, pc. | $\Delta T_{\text{max}}$ | $\Delta T_{\text{max}}'$, K | $\Theta$ | $\Theta'$ | $\lambda \cdot \lambda_0$ | $\lambda \cdot 10^4$, 1/h | $P$ | $\lambda_0 / \lambda_0' Y$ | $\lambda' \cdot 10^4$, 1/h | $P'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 293.2 | 293.6 | 10 | 103.0 | 103.4 | 0.068 | 0.062 | 2.23 | 6.7 | 0.99933 | 2.21 | 6.62 | 0.99934 |
| | 287.4 | 288.2 | 20 | 99.1 | 99.7 | 0.127 | 0.118 | 2.48 | 7.44 | 0.99925 | 2.44 | 7.33 | 0.999267 |
| | 277.4 | 278.7 | 40 | 92.0 | 92.8 | 0.246 | 0.229 | 2.96 | 8.89 | 0.999111 | 2.90 | 8.70 | 0.99913 |
| | 269.4 | 271.0 | 60 | 3.9 | 86.4 | 87.4 | 0.334 | 0.332 | 3.40 | 10.2 | 0.99898 | 3.32 | 9.95 | 0.9999 |
| | 263.7 | 264.7 | 80 | 82.0 | 83.0 | 0.431 | 0.425 | 3.80 | 11.4 | 0.99886 | 3.70 | 11.09 | 0.99889 |
| | 260.3 | 262.9 | 90 | 80 | 81.0 | 0.496 | 0.469 | 4.0 | 12.0 | 0.99880 | 3.87 | 11.6 | 0.99884 |
| | 257.8 | 259.6 | 95 | 78.1 | 79.2 | 0.54 | 0.509 | 4.165 | 12.5 | 0.99875 | 4.04 | 12.12 | 0.99879 |
| 1.0 | 287.0 | 288.6 | 10 | 98.8 | 100.0 | 0.132 | 0.114 | 5.0 | 15.0 | 0.9985 | 4.86 | 14.6 | 0.99854 |
| | 276.7 | 279.2 | 20 | 91.9 | 93.5 | 0.254 | 0.222 | 6.0 | 18.0 | 0.9982 | 5.7 | 17.2 | 0.99828 |
| | 261.7 | 263.2 | 40 | 80.9 | 83.0 | 0.471 | 0.419 | 7.76 | 23.3 | 0.9977 | 7.35 | 22.0 | 0.9978 |
| | 256.6 | 260.0 | 50 | 77.4 | 79.8 | 0.56 | 0.501 | 8.49 | 25.5 | 0.99745 | 8.0 | 24.0 | 0.9976 |
| | 250.6 | 244 | 84 | 79.5 | – | 0.508 | – | 8.08 | 24.2 | 0.99738 | – | – | – |
| 1.5 | 281.6 | 284.6 | 10 | 94.8 | 96.8 | 0.194 | 0.159 | 8.26 | 24.8 | 0.9975 | 7.84 | 23.5 | 0.99765 |
| | 268.5 | 272.8 | 20 | 85.8 | 88.6 | 0.367 | 0.307 | 10.4 | 31.1 | 0.9969 | 9.65 | 29.0 | 0.9971 |
| | 261.4 | 263.9 | 30 | 80.6 | 82.1 | 0.479 | 0.44 | 11.62 | 34.85 | 0.99652 | 11.16 | 33.47 | 0.9967 |
| | 259.8 | 31 | 79.6 | – | 0.504 | – | 12.05 | 36.2 | 0.9964 | – | – | – |
| | – | 259.7 | 36 | – | 79.6 | – | 0.506 | – | – | – | 12.1 | 36.2 | 0.9964 |

### Table 4

| $Q_0$, W | $t$, s | $T_0$, K | $T_0'$, K | $n$, pc. | $\Delta T_{\text{max}}$ | $\Delta T_{\text{max}}'$, K | $\Theta$ | $\Theta'$ | $\lambda \cdot \lambda_0$ | $\lambda \cdot 10^4$, 1/h | $P$ | $(\lambda_0 / \lambda_0') Y$ | $\lambda' \cdot 10^4$, 1/h | $P'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 10 | 292.6 | 293.2 | 0.727 | 0.702 | 0.072 | 0.066 | 0.587 | 1.76 | 0.999824 | 0.579 | 1.74 | 0.99983 |
| | 20 | 286 | 287.1 | 98.2 | 98.9 | 0.143 | 0.130 | 0.69 | 2.07 | 0.99979 | 0.672 | 2.02 | 0.99978 |
| | 40 | 275.1 | 276.7 | 90.4 | 91.5 | 0.275 | 0.253 | 0.882 | 2.65 | 0.99974 | 0.853 | 2.56 | 0.99974 |
| | 60 | 267.9 | 268.4 | 85.4 | 85.7 | 0.376 | 0.369 | 1.04 | 3.12 | 0.99969 | 1.025 | 3.08 | 0.99969 |
| | 80 | 259.7 | 261.8 | 79.6 | 80.9 | 0.506 | 0.472 | 1.22 | 3.67 | 0.99963 | 1.175 | 3.52 | 0.99964 |
| | 85 | 260.4 | – | 80.0 | – | 0.495 | – | – | – | 1.205 | 3.62 | 0.99964 |
| 1.0 | 10 | 286 | 288 | 98.2 | 99.5 | 0.143 | 0.12 | 1.38 | 4.14 | 0.99959 | 1.32 | 3.95 | 0.9995 |
| | 20 | 275.1 | 278.2 | 90.4 | 92.5 | 0.275 | 0.236 | 1.76 | 5.29 | 0.99947 | 1.65 | 4.96 | 0.9995 |
| | 40 | 259.7 | 263.7 | 78.6 | 82.4 | 0.506 | 0.44 | 2.44 | 7.32 | 0.99927 | 2.25 | 6.74 | 0.99933 |
| | 46 | 260.4 | – | 80.0 | – | 0.495 | – | – | – | 2.42 | 7.25 | 0.999275 |
| 1.5 | 10 | 280.2 | 283.9 | 93.8 | 96.3 | 0.211 | 0.167 | 2.37 | 7.1 | 0.99929 | 2.18 | 6.54 | 0.99935 |
| | 20 | 267 | 271.8 | 84.8 | 87.9 | 0.389 | 0.321 | 3.18 | 9.53 | 0.99905 | 2.87 | 8.6 | 0.99914 |
| | 30 | 256.9 | 262.7 | 77.5 | 81.8 | 0.556 | 0.456 | 3.94 | 11.83 | 0.99882 | 3.475 | 10.4 | 0.99896 |
| | 33 | 259.7 | – | 79.6 | – | 0.506 | – | – | – | 3.70 | 11.1 | 0.99889 |
Fig. 11–14 show the time-temperature dependences of a heat-absorbing junction $T_0$ and failure rate $\lambda/\lambda_0$ of a single-stage TED for different modes of operation and varying heat load $Q_0$ at $T=300$ K; $\Delta T=40$ K; $B_1=0.40; B_2=0.425; k=2.155$ A; $l/s=10$ cm$^{-1}$; $C=0.17$ J/(g-K)

| $\lambda_{\text{min}}$ T=300 K; ΔT=40 K; $B_1=0.40; B_2=0.425; k=2.155$ A; $l/s=10$ cm$^{-1}$; $C=0.17$ J/(g-K) |
|---|---|---|---|---|---|---|---|---|---|
| $Q_0$, W | $T_0$, K | $T_0^*$, K | $n$, pc. | $\Delta T_{\text{max}}, K$ | $\Delta T^*_{\text{max}}, K$ | $\Theta$ | $\Theta^*$ | $\lambda/\lambda_0$ | $\lambda \cdot 10^6$, 1/h | $P$ | $(\lambda/\lambda_0)^2$ | $\lambda^* \cdot 10^6$, 1/h | $P^*$ |
| 10 | 288 | 290 | 0.5 | 99.5 | 99.0 | 0.121 | 0.099 | 0.123 | 0.368 | 0.999963 | 0.111 | 0.334 | 0.999967 |
| 20 | 278.7 | 281.9 | 0.5 | 92.8 | 95.0 | 0.23 | 0.19 | 0.182 | 0.546 | 0.999945 | 0.16 | 0.48 | 0.999952 |
| 40 | 266.1 | 270.0 | 0.5 | 83.9 | 86.4 | 0.404 | 0.347 | 0.293 | 0.878 | 0.999912 | 0.255 | 0.764 | 0.999924 |
| 60 | 258.5 | 262.2 | 0.5 | 78.9 | 81.1 | 0.526 | 0.466 | 0.375 | 1.125 | 0.999887 | 0.334 | 1.0 | 0.99990 |
| 10 | 278.7 | 284.2 | 1.0 | 92.8 | 96.9 | 0.23 | 0.163 | 0.364 | 1.092 | 0.999889 | 0.291 | 0.874 | 0.999913 |
| 20 | 266.1 | 273.1 | 1.0 | 83.9 | 88.4 | 0.404 | 0.304 | 0.588 | 1.76 | 0.999882 | 0.457 | 1.37 | 0.99986 |
| 30 | 258.6 | 265.4 | 1.0 | 78.9 | 83.5 | 0.525 | 0.414 | 0.75 | 2.25 | 0.999775 | 0.436 | 1.31 | 0.99987 |
| 40 | 260 | 260 | 1.0 | 79.8 | 79.8 | 0.5 | 0.495 | - | - | - | - | - | - |
| 1.5 | 271.6 | 280.5 | 1.5 | 88.5 | 94.0 | 0.321 | 0.207 | 0.721 | 2.16 | 0.999784 | 0.543 | 1.54 | 0.99985 |
| 20 | 258.5 | 268.2 | 1.5 | 78.9 | 85.6 | 0.526 | 0.371 | 1.14 | 3.41 | 0.999664 | 0.814 | 2.44 | 0.99976 |
| 29 | 260 | 260 | 1.5 | 80.0 | 80.0 | 0.494 | - | - | - | - | - | - |

Thus, for example, at equal thermal load $Q_0=0.5$ W the time to reach the set temperature of $T_0=260$ K at $T=300$ K and the mass and heat capacity of the object $m\rho_0=0.894$ J/K is:

- under mode $Q_{\text{max}} (B_1=0.93; B_2=1.0; n=1); \tau_0=90$ s; with respect to the mass and heat capacity of TED ST $\tau^*=95$ s, the time required to enter a preset mode increased by 5.5% at the same failure rate $\lambda/\lambda_0$:

- under mode $Q_{\text{th}} (B_1=0.66; B_2=0.71; n=4.7); \tau_0=80$ s, $\tau^*=85$ s, the time required to enter a preset mode increased by 6.3% at $\lambda/\lambda_0=1.22$;

- under mode $E_{\text{max}} (B_1=0.47; B_2=0.50; n=6.5); \tau_0=70$ s, $\tau^*=80$ s, the time required to enter a preset mode increased by 14% at $\lambda/\lambda_0=0.6$;

- under mode $\lambda_{\text{min}} (B_1=0.40; B_2=0.425; n=11.5); \tau_0=57$ s, $\tau^*=66$ s, the time required to enter a preset mode increased by 14% at $\lambda/\lambda_0=0.36$. 

...
An analysis of the estimation data reveals that the $\lambda_{\text{min}}$ mode ensures minimum time required to enter a stationary mode at minimal failure rate $\lambda/\lambda_0$ for a varying heat load $Q_0$.

At a thermal load of $Q_0=1$ W, the time to reach the preset temperature $T_0=260$ K at $T=300$ K with a mass and heat capacity of the object of $m_0C_0=0.894$ J/K is:

- under mode $Q_{0,\text{max}}$ ($B_1=0.93$; $B_2=1.0$; $n=7.8$): $t_0=44$ s; $\tau'=50$ s, that is, the time required to enter a mode increased by 13.6 % at $\lambda/\lambda_0=8$;
- under mode $Q_{0,1,\text{max}}$ ($B_1=0.66$; $B_2=0.71$; $n=9.4$): $t_0=40$ s; $\tau'=46$ s, that is, the time required to enter a mode increased by 15 % at $\lambda/\lambda_0=2.4$;
- under mode $E_{\text{max}}$ ($B_1=0.47$; $B_2=0.50$; $n=13$): $t_0=37$ s; $\tau'=44$ s, that is, the time required to enter a mode increased by 19 % at $\lambda/\lambda_0=1.2$;
- under mode $\lambda_{\text{min}}$ ($B_1=0.40$; $B_2=0.425$; $n=23$): $t_0=29$ s; $\tau'=40$ s, that is, the time required to enter a mode increased by 38 % at $\lambda/\lambda_0=0.72$.

At thermal load $Q_0=1.5$ W, the time to reach the preset temperature $T_0=260$ K at $T=300$ K, with a mass and heat capacity of the object of $m_0C_0=0.894$ J/K, is:

- under mode $Q_{0,\text{max}}$ ($B_1=0.93$; $B_2=1.0$; $n=11.7$): $t_0=31$ s; $\tau'=36$ s, that is, the time required to enter a mode increased by 16.1 % at $\lambda/\lambda_0=12$;
- under mode $Q_{0,1,\text{max}}$ ($B_1=0.66$; $B_2=0.71$; $n=14.1$): $t_0=26$ s; $\tau'=33$ s, that is, the time required to enter a mode increased by 27 % at $\lambda/\lambda_0=3.8$;
- under mode $E_{\text{max}}$ ($B_1=0.47$; $B_2=0.50$; $n=19.5$): $t_0=24$ s; $\tau'=32$ s, that is, the time required to enter a mode increased by 33 % at $\lambda/\lambda_0=1.8$;
- under mode $\lambda_{\text{min}}$ ($B_1=0.40$; $B_2=0.425$; $n=34.5$): $t_0=19$ s; $\tau'=29$ s, that is, the time required to enter a mode increased by 53 % at $\lambda/\lambda_0=1.1$.

Fig. 15 shows the dependence of relative magnitude of the time required to enter a stationary mode $\beta=(\tau'-\tau_0)/\tau_0$ and relative magnitude of the failure rate $\lambda/\lambda_0$ of a single-stage TED on the magnitude of heat load $Q_0$ for different modes of operation at $T=300$ K; $\Delta T=40$ K; $I=10$ cm$^{-1}$.

It follows from Fig. 15 that with a growth of thermal load $Q_0$ for different modes of operation and the preset cooling temperature level $T_0=260$ K and the geometry of thermoelement branches $I/S$ at $T=300$ K:
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- the magnitude of relative time required to enter a stationary mode $\beta$ increases, with the greatest magnitude $\beta$ observed under the mode of $\lambda_{\min}$;
- the magnitude of relative failure rate $\lambda/\lambda_0$ increases, with the largest magnitude of failure rate $\lambda/\lambda_0$ observed under the mode of $Q_{\max}$, and the lowest is under the mode of $\lambda_{\min}$.

With the increasing number of thermoelements $n$ for a preset heat load $Q_0$ and temperature difference $\Delta T$ (Fig. 16):
- relative operating current $B$ and the magnitude of operating current $I$ decrease;
- voltage drop $U$ grows;
- functional dependence of cooling coefficient $E=\varphi(n)$ has a maximum;
- the time required to enter a stationary mode $t_0$ and $\tau'$ is reduced; the time required to enter a stationary mode $\tau'$, taking into consideration the structural and technological elements, increases compared to $t_0$; for example, at $n=25$ pcs, $\tau'=61$ s; $t_0=41$ s, that is, $\tau'$ increases by 53 % (Fig. 17);

We shall consider a possibility of reducing the time required for a single-stage TED to enter a stationary mode by increasing the number of thermoelements $n$ for a preset heat load $Q_0$ and temperature difference $\Delta T$: at $T=300$ K; $\Delta T=40$ K; $I/\varphi=10$ cm$^{-1}$; $Q_0=0.5$ W; $\lambda_0=3\times10^{-8}$ 1/h for different modes of operation

Results of the calculations are given in Table 7.

![Fig. 15. Dependence of relative magnitudes of the failure rate $\lambda/\lambda_0$ and the time required to enter a stationary mode $\beta=(\tau'-\tau_0)/\tau_0$ of a single-stage TED on thermal load $Q_0$ at $T=300$ K; $\Delta T=40$ K; $I/\varphi=10$ cm$^{-1}$; $Q_0=0.5$ W; $\lambda_0=3\times10^{-8}$ 1/h for different modes of operation](image)

![Fig. 16. Dependences of parameters $B$, $I$, $E$, $U$ of a single-stage TED on the number of thermoelements $n$ at $T=300$ K; $\Delta T=40$ K; $I/\varphi=10$ cm$^{-1}$; $Q_0=0.5$ W](image)

| Mode of operation | $B_1/B_2$ | $I$, A | $U$, V | $E$, W | $W$, W | $n$, pcs | $t_0$, s | $\tau'$, s | $\beta$, % | $\lambda/\lambda_0$ | $\lambda\cdot10^{6}$, 1/h | $P$ |
|-------------------|-----------|--------|-------|--------|--------|---------|--------|---------|----------|----------------|----------------|--------|
| $Q_{\max}$        | 0.93/1.0  | 5.02   | 0.46  | 0.217  | 2.30   | 3.9     | 83.0   | 89.5    | 7.6      | 4.0           | 12.0           | 0.9988 | |
| $B_2$             | 0.80/0.86 | 4.32   | 0.42  | 0.275  | 1.82   | 4.1     | 84.9   | 91.7    | 8.0      | 3.245         | 7.0            | 0.9993 | |
| $B_3$             | 0.72/0.77 | 3.87   | 0.41  | 0.313  | 1.60   | 4.4     | 85.0   | 92.4    | 8.7      | 1.62          | 4.86           | 0.9995 | |
| $I_{\min}$        | 0.66/0.71 | 3.55   | 0.41  | 0.340  | 1.46   | 4.7     | 84.1   | 91.8    | 9.1      | 1.23          | 3.70           | 0.9996 | |
| $B_4$             | 0.62/0.67 | 3.38   | 0.42  | 0.352  | 1.42   | 5.0     | 83.7   | 91.9    | 9.8      | 1.06          | 3.19           | 0.9996 | |
| $B_5$             | 0.56/0.60 | 3.0    | 0.45  | 0.374  | 1.34   | 5.8     | 80.4   | 89.5    | 11.4     | 0.765         | 2.30           | 0.9997 | |
| $F_{\max}$        | 0.51/0.55 | 2.76   | 0.47  | 0.385  | 1.30   | 6.6     | 75.4   | 85.2    | 12.9     | 0.61          | 1.82           | 0.9998 | |
| $(Q_0/F)_{\max}$ | 0.47/0.50 | 2.51   | 0.53  | 0.379  | 1.32   | 7.9     | 72.4   | 83.5    | 15.3     | 0.486         | 1.46           | 0.9998 | |
| $E_{\min}$        | 0.44/0.47 | 2.36   | 0.57  | 0.372  | 1.345  | 90.0    | 68.7   | 81.0    | 18.0     | 0.428         | 1.28           | 0.9997 | |
| $E_{\min}$        | 0.39/0.42 | 2.11   | 0.57  | 0.339  | 1.475  | 12.0    | 60.6   | 74.8    | 23.4     | 0.356         | 1.07           | 0.9999 | |
| $\lambda_{\min}$  | 0.37/0.40 | 2.0    | 0.79  | 0.316  | 1.58   | 14.0    | 56.3   | 71.6    | 27.2     | 0.330         | 0.990          | 0.99901 | |
| $\lambda_{\min}$  | 0.35/0.38 | 1.92   | 0.92  | 0.284  | 1.76   | 17.0    | 51.0   | 67.7    | 33.0     | 0.334         | 1.0            | 0.99990 | |
| $L_{\max}$        | 0.32/0.35 | 1.76   | 1.30  | 0.22   | 2.28   | 23.3    | 41.0   | 61.0    | 49.5     | 0.35          | 1.05          | 0.999895 | |
| $L_{\max}$        | 0.31/0.33 | 1.66   | 1.88  | 0.16   | 3.13   | 38.4    | 31.7   | 55.5    | 75.0     | 0.415         | 1.245         | 0.999875 | |
| $L_{\max}$        | 0.30/0.32 | 1.61   | 2.61  | 0.12   | 4.18   | 54.0    | 25.0   | 51.5    | 106      | 0.51          | 1.53         | 0.99985 | |
| $L_{\max}$        | 0.29/0.312 | 1.57  | 3.40  | 0.0936 | 5.34   | 72.0    | 21.0   | 50.7    | 141      | 0.62          | 1.85         | 0.99982 |
Fig. 17. Dependence of the time required for TED to enter a stationary mode ($\tau_0$, $\tau'$ are, respectively, without and with taking into consideration $\sum m_i C_i$) of single-stage TED on the number of thermoelements $n$ at $T=300$ K; $\Delta T=40$ K; $I/S=10$ cm$^{-1}$; $Q_0=0.5$ W.

Fig. 18. Dependence of relative magnitudes of failure rate $\lambda/\lambda_0$ and the time required to enter a stationary mode $\beta=(\tau'-\tau_0)/\tau_0$ of a single-stage TED on the number of thermoelements $n$ at $T=300$ K; $\Delta T=40$ K; $I/S=10$ cm$^{-1}$; $Q_0=0.5$ W; $\lambda_0=3\times10^{-8}$ 1/h.

It should be noted that with an increase in the relative working current $B$ for a preset heat load $Q_0=0.5$ W and a temperature difference $\Delta T=40$ K:

- the magnitude of operating current $I$ increases;
- the magnitudes of voltage drop $U$ and the number of thermoelements $n$ decrease;
- functional dependence of the cooling coefficient $E=f(n)$ has a maximum at current under the mode of $E_{max}$ (Fig. 19);

Fig. 19. Dependence of the magnitude of working current $I$, cooling coefficient $E$, the number of thermoelements $n$ and voltage drop $U$ of a single-stage TED on the relative working current $B_0$ for different modes of operation at $T=300$ K; $Q_0=0.5$ W; $\Delta T=40$ K; $I/S=10$ cm$^{-1}$.

- failure rate $\lambda/\lambda_0$ grows;
- relative magnitude $\beta$ decreases (Fig. 20);
- functional dependence of the time required to enter a stationary mode without taking into consideration the structural and technological elements $\tau_0$ and taking into consideration the structural and technological elements $\tau'$ has a flat maximum at $B=0.8$ (Fig. 21).

Fig. 20. Dependence of failure rate $\lambda/\lambda_0$ and the magnitude of $\beta$ for a single-stage TED on relative working current $B_2$ for different modes of operation at $T=300$ K; $Q_0=0.5$ W; $\Delta T=40$ K; $I/S=10$ cm$^{-1}$.

Fig. 21. Dependence of the time required for a single-stage TED to enter a stationary mode $\tau'$ and $\tau_0$ on the relative working current $B_2$ for different modes of operation $T=300$ K; $Q_0=0.5$ W; $\Delta T=40$ K; $I/S=10$ cm$^{-1}$.

Thus, it is possible, given the preset value of the time required to enter a stationary mode $\tau$, to determine graphically the magnitude of relative working current $B$ for the assigned temperature difference $\Delta T$ and the magnitude of thermal load $Q_0$ (Fig. 21).

6. Discussion of results of analysis of the time required to enter a stationary mode, energy and reliability indicators of a single-stage TED

The analytical expressions obtained allow us to determine:

- the time required to enter a stationary mode taking into consideration structural and technological elements on
the heat-absorbing junctions of a single-stage TED for different modes of operation $Q_{0\text{max}}$ (where $Q_0$ is the heat load, $E_{\text{max}}$ is the magnitude of working current $I$) grows; 
- voltage drop $U$ and the number of thermoelements $n$ decrease; 
- functional dependence of the cooling coefficient $E=\frac{f(B)}{\lambda}$ has a maximum at $B=0.55$ (the $E_{\text{max}}$ mode); 
- failure rate $\lambda/\lambda_0$ grows, therefore, the probability of failure-free operation $P$ decreases; 
- the relative magnitude of $\beta$ decreases; 
- the time required to enter stationary mode $\tau_0$ and $\tau'$ increases, both with and without taking into consideration the structural and technological elements.

There is a flat maximum of dependence $\tau=\frac{f(B)}{\lambda}$ for the $E_{\text{max}}$ mode.

The results obtained could form the basis for the development of control algorithms over dynamic characteristics of single-stage thermoelectric coolers during work with a nonstationary thermal load for the criterion of minimum relative failure rate.

### 7. Conclusions

1. We have developed an analytical model for the relation between a cooling time of a single-stage thermoelectric cooler with different modes of operation, heat load in the range of working temperature difference, taking into consideration the impact of structural and technological components of the device.

2. The results of analysis of dynamic characteristics, energy and reliability indicators of a single-stage TED showed the possibility to control the time required to enter a stationary mode. Structural control, enabled by selecting the number and geometry of TED thermoelements, and the mass and heat capacity of the load makes it possible to reduce the time required for TED to enter a stationary mode by up to 2.5 times. Operational control, executed by changing working current of the cooler, makes it possible to reduce the time required to enter a stationary mode by up to 3 times.

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1. Introduction

The construction and reconstruction of high-pressure waterworks sets a number of scientific and engineering tasks that require a new approach to their solution. One of them is to design reliable and economical culverts, able to work both in the construction and operational periods, making it possible to combine the spillway and energy flow channels. Damping of the excess energy of idle flows is one of the most important tasks when creating hydraulic spillway systems. The choice of the method for damping the kinetic energy of the flow significantly affects the overall layout of the hydraulic engineering structure.

This task becomes the most urgent in the transition to the construction of high-pressure hydraulic systems, which requires studying the phenomena associated with high-speed water flows, their interaction and the development of fundamentally new designs of spillway structures. The hydraulic sections that are used to solve the problems of transit water flows through such structures have been developed. When designing spillways in high-pressure waterworks, it is necessary to take into account the features of the interaction of high-speed flows with solid boundaries and the air environment. It is essential to ensure ventilation in the case of gravity and partial pressure in closed conduits, as well as take into account other phenomena of hydraulic nature. The resulting hydrodynamic loads under these phenomena are transferred to the building structures, and they must be taken into account in the design, construction and operation of spillway systems.

One of the promising areas for solving these and a number of other problems is the use of swirling water flows in hydrotechnical facilities. The so-called counter-vortex flows of liquid and gas and consideration of the prospects for their practical application have been studied at Moscow State University of Civil Engineering (MGSU, Russia) for several years.