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# On the importance of thermal resistances of the cooling system when choosing a thermoelectric module

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Calculations and analysis of the energy characteristics of the cooling and thermal control system are carried out, taking into account the operating characteristics of the thermoelectric module, thermal resistances of heat supply and removal devices, and parameters of the cooled object. The cooling efficiency is compared when using two serial thermoelectric modules with different power. It is shown that a significant factor affecting the efficiency of cooling is the thermal resistance of the devices for supplying and removing heat. Criteria are defined that allow choosing a thermoelectric module for a cooling and thermal control system.

**Keywords:** thermoelectric cooling system, heat exchanger, coefficient of performance, cooling capacity.

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## Introduction

Currently, Peltier elements are widely used in various practical applications [1–6]. Thermoelectric systems have relatively low efficiency [7–9], so it is important to choose the optimal design that ensures maximum process characteristics. Thermoelectric cooling and temperature control systems (TECTC) are used to provide the required temperature conditions for both micro-objects and large-volume refrigerating chambers. The thermoelectric module (TEM), which is a heat pump, produces a negative temperature drop on its sides, carrying out heat transfer from its cold side to the hot side. The efficiency of the TECTC is determined by the parameters of the TEM, as well as the magnitude and ratio of internal and external heat losses. The first type of loss is caused primarily by the reverse heat flow through the material of the thermoelements. The magnitude of these losses depends on the design and parameters of the TEM, as a result, it is reflected in the performance characteristics of the manufacturer. The second type refers to losses on the thermal resistances of heat supply and removal devices, as well as on all thermal contacts. Temperature differences on the thermal resistances of heat exchange devices refer to irreversible losses that reduce the energy efficiency of TECTC. In general, the efficiency of the cooling process depends on the overall design of the TECTC, the parameters of the heat exchange devices, the performance characteristics of the TEM and its operating mode.

Currently, a large range of TEMs is produced with significantly varying specifications and parameters. Choosing the optimal TEM is quite a difficult task, since it depends on a whole set of initial parameters TECTC. The impact of thermal resistances of heat supply and heat removal devices, the parameters of TEM and the cooled object (CO) on the energy characteristics of TECTC is investigated in this paper for justifying the choice of TEM.

## 1. Diagram of the thermoelectric cooling system

The general scheme of the TECTC and the characteristic temperature distribution in it are shown in Fig. 1. TECTC is designed to maintain the set temperature $T_1$ of the base of the cooled object *1*, which is characterized by the heat dissipation capacity $Q$. Cooled objects can be of different types: heat-loaded electronics elements [10], refrigerating chamber volume [11], biological objects [12,13], etc. The heat from the CO to the cold side of the TEM is supplied using a heat supply device (HSD) *2*, which together with the adjacent thermal contacts (CO−HSD and HSD−TEM) is integrally characterized by thermal resistance $R_T$. A plate heat exchanger [11], a heat distributor [14], etc. can act as an HSD. In the simplest case, when the CO is installed directly on the cold side of the TEM, $R_T$ is equal to the thermal resistance of the thermal contact of the CO−TEM. The thermoelectric module *3* should divert thermal power from the CO $Q$, providing a given temperature drop $\Delta T_0 = T_1 - T_0$. The main characteristics of the TEM are the maximum values of the cooling capacity $Q_{\max}$, the temperature difference between its hot and cold sides $\Delta T_{\mathrm{TEM}} = T_3 - T_2$ and its own energy consumption $W$. The heat removal device (HRD) *4* transfers heat from the hot side of the TEM to the environment or heat carrier, which have a temperature of $T_0$. The most common HRD in the form of air and liquid heat exchangers, the heat transfer efficiency of HRD taking into account thermal contacts, is characterized by a total thermal resistance of $R_S$.

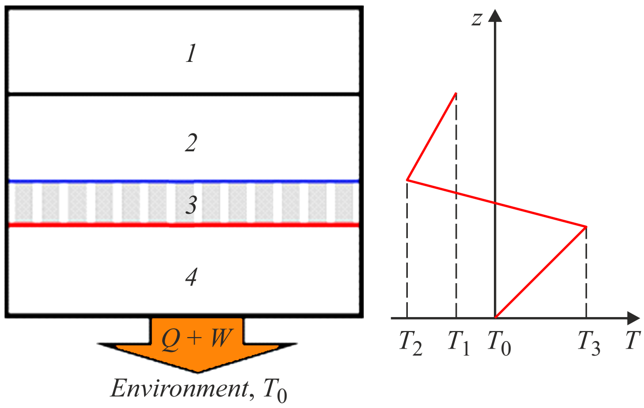


**Figure 1.** Scheme and characteristic temperature distribution in the TECTC: *1* — cooled object, *2* — heat supply device, *3* — thermoelectric module, *4* — heat removal device.

## 2. Thermal resistance of heat exchangers

One of the main initial parameters in the calculation of the characteristics of the TECTC are the values of $R_S$ and $R_T$, the value of which is determined by the thermal resistances of the HSD, HRD and thermal contacts. As a rule, a variety of heat exchangers are used in the design of HSD and HRD, of which two most common types can be distinguished: air and liquid. The value of the thermal resistance of heat exchangers can be determined from the calculation of [11], experiment [15] or obtained from the manufacturer's information. Let's estimate the possible ranges of thermal resistance values for air and liquid heat exchangers.

The thermal resistance of standard air heat exchangers with a fan (coolers) for computer processors usually lies in the range of 0.3–0.5 K/W, the best samples using heat pipes can reach 0.1 K/W and even lower. At the same time, as a rule, an increase in the efficiency of coolers is accompanied by an increase in weight, size and price. Heat tubes and thermosiphons allow efficient heat transfer between the relatively small side surface of the TEM and the fins of the heat exchanger, significantly developing the heat exchange surface. The experimental study [16] showed that the use of a thermosiphon in the HSD improved the thermal resistance between the cold side of the TEM and the CO by 37%, and the refrigeration coefficient increased by 32%.

The heat in liquid heat exchangers is transferred to the flow of liquid, the movement of which is provided by a pump, so they are more complex and expensive. Liquid cooling is superior to air cooling in efficiency, since the heat exchange coefficient of a liquid with a solid surface can be 100 or more times higher than the same parameter for air. The calculated value of the thermal resistance of a liquid heat exchanger for a thermoelectric cooling unit was 0.03 K/W [11]. It should be noted that in some systems, further heat removal from the liquid into the environment is eventually carried out by a cooler. In this case, the heat transfer device will have a lower overall thermal resistance only if an efficient air heat exchanger is used. This condition is usually fulfilled due to the fact that the air heat exchanger is located remotely from the heat source, while having a more developed heat exchange surface and better conditions for heat exchange with the environment.

If the dimensions of the TEM and the CO do not match a heat distributor which usually has the form of a rectangular plate made of a material with high thermal conductivity is installed to reduce the heterogeneity of the temperature and heat flux fields between the CO and the TEM. The thermal resistance of the heat distributing plate increases with decreasing CO dimensions, for a copper heat distributor $40 \times 40$ mm, its minimum thermal resistance is approximately 0.03 K/W at the size of CO $22.5 \times 22.5$ mm [14].

The value of the thermal resistance of thermal contacts depends on the thermal conductivity of the filler, the thickness and the area of the gap. The thermal conductivity of industrial thermal pastes is in the range 0.5–6 W/(m·K). When using a standard thermal paste KPT-8 with a thermal conductivity coefficient $\lambda = 0.85$ W/(m·K), the thermal resistance value $R = \delta/(\lambda S)$ for the layer thickness $\delta = 0.1-0.2$ mm and the contact area $S = 40 \times 40$ mm will be 0.074–0.15 K/W. The value of $R$ can be significantly reduced when using solder contacts; for example, the low-temperature solder POSV-50 (Rose alloy) has $\lambda = 16$ W/(m·K).

## 3. Calculation and analysis of the characteristics of the thermoelectric cooling system

The development of the TECTC is based on the fulfillment of the main task, namely, ensuring the required temperature drop at a given heat dissipation capacity of the CO. This condition determines the design of HSD and HRD, as well as the choice of TEM. Along with this, an important task in the development of TECTC is to achieve maximum energy efficiency of the cooling process. The energy efficiency of a separate TEM is described by the well-known characteristic COP (coefficient of performance), equal to the ratio of its cooling capacity to the electrical power consumed by it. The COP corresponds to the ideal case when the processes of heat supply to the cold side and heat removal from the hot side of the TEM occur without external heat losses. In a real TECTC, which has heat losses in HSD and HRD, the efficiency of operation is described by the refrigeration coefficient, which is determined similarly to the ideal case $\varepsilon = Q/W$. At the same time, the compensation of heat losses in the TECTC requires a higher value of $W$ to ensure the set values of $\Delta T_0$ and $Q$, so the value of $\varepsilon$ for the TECTC is always lower than the COP for a separate TEM.

The calculation of the energy characteristics of the TECTC was carried out for a stationary process using a ratio linking the total temperature difference with temperature differences on individual elements of the TECTC:

$$\Delta T_0 = R_T Q - \Delta T_{\mathrm{TEM}}(I, Q) + R_s[Q + U(I, Q)I], \quad (1)$$

where $U, I$ is the voltage and current of the TEM power supply. The first term in the right part of the formula (1) describes the temperature difference in the HSD, the second determines the temperature difference between the hot and cold sides of the TEM, the third — the temperature difference in the HRD. The operating characteristics of the thermoelectric module $Q(\Delta T_{\mathrm{TEM}})$ and $U(\Delta T_{\mathrm{TEM}})$ are the initial data for determining the dependencies $U(I, Q)$ and $\Delta T_{\mathrm{TEM}}(I, Q)$ using interpolation polynomials, the calculation method of these dependencies is given in [17]. Numerical solution of a nonlinear algebraic system of equations for the given values $R_S$, $R_T$, $\Delta T_0$ and $I$ allows calculating the energy characteristics of $Q$, $W$ and $\varepsilon$.

The choice of the optimal TEM is based on the analysis of the dependences of energy characteristics on the parameters of TEM and CO, thermal resistances of heat supply and heat removal devices. The most efficient is such a TEM, which, at a given heat dissipation capacity of the CO, provides the required temperature difference between the CO and the environment and has the highest refrigeration coefficient. We will conduct such a comparative analysis using the example of two serial TEMs with the same side surface area $40 \times 40$ mm. Standard TEM „S–199–14–11" has maximum values of cooling capacity $Q = 124.2$ W (for $\Delta T_{\mathrm{TEM}} = 0$) and temperature drop $\Delta T_{\mathrm{TEM}} = 72.5$ K (for $Q = 0$) at current $I_{\max} = 7.9$ A and voltage $U_{\max} = 25.3$ V [18]. High-power TEM „D–200–14–06" provides at $I_{\max} = 15.1$ and $U_{\max} = 25.3$ V cooling capacity by 92% above $Q = 238.3$ W, but at a lower by 3.5% value $\Delta T_{\mathrm{TEM}} = 70$ K [19]. According to the manufacturer, such TEMs are designed for applications requiring high performance, where it is necessary to remove a large amount of heat [20].

Energy characteristics of TECTC for TEM „S–199–14–11" and values $R_T = 0.3$ K/W, $R_S = 0.3$ K/W are shown in Fig. 2 and 3, the curves show their corresponding values $\Delta T_0$ in degrees Celsius. The cooling capacity dependencies $Q(I)$ have maxima, the values of which decrease with an increase in the absolute value of the temperature difference $\Delta T_0$. The values of $Q$, below the maximum, correspond to two values of the current strength. So, for the level $Q = 20$ W, indicated by a horizontal dashed line, they are approximately equal to 2.5 A (marked by a vertical dashed line) and 6 A. It is obvious that a more efficient operation mode of the TECTC is provided with a lower current value, since the TEM's own energy consumption in this case is much lower.

The graphs of the refrigeration coefficient in Fig. 3 also have maxima depending on the temperature difference $\Delta T_0$, the values of which are indicated in degrees Celsius on the corresponding curves. In contrast to the dependencies $Q(I)$ in Fig. 2, the current values corresponding to the maxima of the graphs $\varepsilon(I)$ have a significant dependence on $\Delta T_0$.

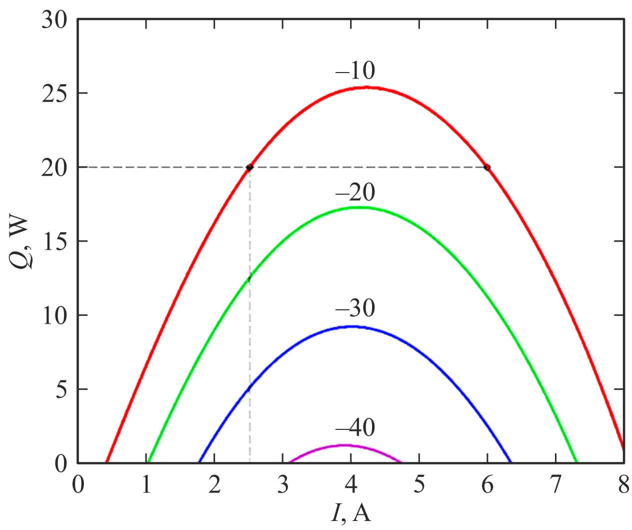


**Figure 2.** The dependence of the cooling capacity on the current at different values of the temperature difference $\Delta T_0$, indicated on the corresponding curves in degrees.

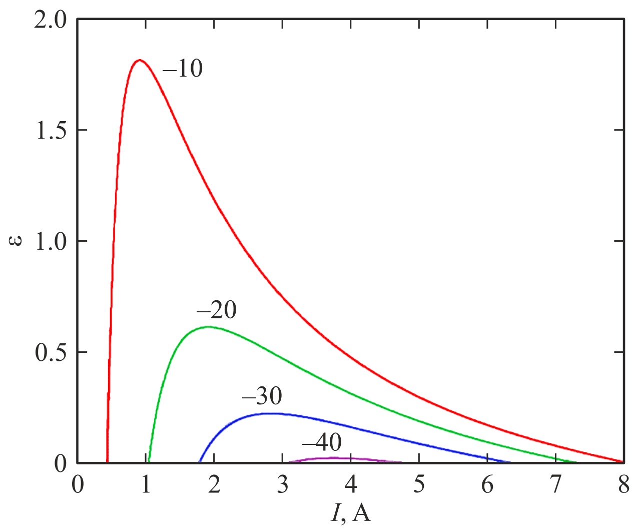


**Figure 3.** The dependencies of the refrigeration coefficient on the current strength at different values of the temperature difference $\Delta T_0$, indicated on the corresponding curves in degrees.

The maximum values of the functions $Q(I)$ and $\varepsilon(I)$ characterize the potential of the applied TEM at the given $R_T$ and $R_S$, since they allow us to determine the achievable limit of the energy efficiency of the TECTC. Dependencies of maximum cooling capacity values $Q(R_S)$ TEM „S–199–14–11" (thin lines) and „D–200–14–06" (thick lines) for $R_T = 0.1$ K/W are shown in Fig. 4, curves *1–3* correspond to the values of $\Delta T_0 = -10, -20$ and $-30^\circ$C. For each value $\Delta T_0$, the graphs $Q(R_S)$ have an intersection point (marked with a circle) at a certain

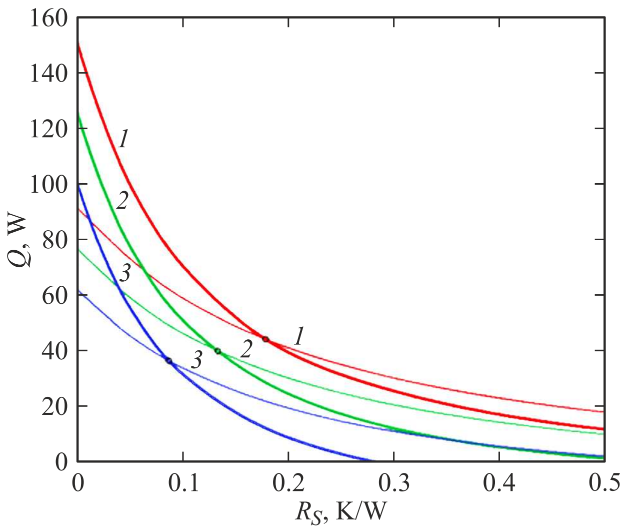


**Figure 4.** The dependencies of maximum cooling capacity on thermal resistance $R_S$ at $R_T = 0.1$ K/W: *1* —$\Delta T_0 = -10$, *2* —$-20$, *3* —$-30$°C.

value $R_{S^*}$, at which the cooling capacity of two TEMs has an equal value $Q^*$. Thus, the high-power TEM „D−200−14−06" provides a higher cooling capacity compared to the standard TEM „S−199−14−11" for $R_S < R_{S^*} = 0.18$ K/W for $\Delta T_0 = -10$°C, for $R_S < R_{S^*} = 0.13$ K/W for $\Delta T_0 = -20$°C, for $R_S < R_{S^*} = 0.09$ K/W for $\Delta T_0 = -30$°C. The lower cooling capacity of the TECTC with a more powerful TEM at $R_S > R_{S^*}$ is due to the fact that such a TEM provides the necessary temperature drop $\Delta T_{\mathrm{TEM}}$ with higher energy consumption, therefore, from a certain value $R_S$, increased heat losses in the HRD neutralize its advantage in cooling capacity.

Dependencies of the maximum values of the refrigeration coefficient $\varepsilon(R_S)$ for TEM „S−199−14−11" (thin lines) and „D−200−14−06" (thick lines) were obtained at thermal resistance $R_T = 0.1$ K/W and values $\Delta T_0 = -10, -20$ and $-30$°C (Fig. 5). It can be seen from the graphs that the standard TEM „S−199−14−11" has higher values of the refrigeration coefficient in the entire range of thermal resistance $R_S$. This is due to its lower energy consumption, which is necessary to ensure a given temperature drop.

To determine the effect of the value of the thermal resistance of the HSD on the energy characteristics of the TECTC, similar calculations were performed for $R_T = 0.3$ K/W and $\Delta T_0 = -10, -20, -30$°C (curves *1*–*3*). The calculation results are shown in Figs. 6 and 7, thin and thick lines show the dependencies for TEM „S−199−14−11" and „D−200−14−06" respectively. The comparison of Figs. 4 and 6 shows that an increase in the value of $R_T$ from 0.1 to 0.3 K/W leads to a noticeable decrease in cooling capacity. At the same time, a decrease of values $R_{S^*}$ is observed at which the TEM „D−200−14−06" ensures higher cooling capacity: $R_{S^*} = 0.14$, 0.1 and 0.068 K/W for $\Delta T_0 = -10, -20$ and $-30$°C respectively. Thus, the high-power TEM „D−200−14−06" has a noticeable advantage in maximum cooling capacity compared to the standard TEM only with relatively small values of thermal resistance of the HSD.

Dependencies $\varepsilon(R_S)$ for TEM „S−199−14−11" (thin lines) and „D−200−14−06" (thick lines) of values $R_T = 0.3$ K/W, $\Delta T_0 = -10, -20$ and $-30$°C (curves *1*–*3*) are shown in Fig. 7. An increase in the value of $R_T$ from 0.1 to 0.3 K/W led to a noticeable decrease in the refrigeration coefficient for both TEMs.

The calculated results shown in Fig. 4–7 indicate that in the case of $R_S > R_{S^*}$ the optimal choice is TEM „S−199−14−11", since it has higher indicators both in terms of cooling capacity and refrigeration coefficient. With

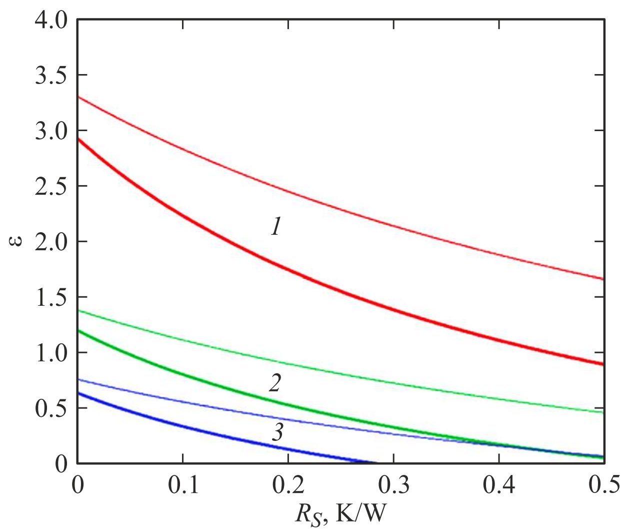


**Figure 5.** The dependencies of the maximum refrigeration coefficient on thermal resistance $R_S$ at $R_T = 0.1$ K/W: *1* —$\Delta T_0 = -10$, *2* —$-20$, *3* —$-30$°C.

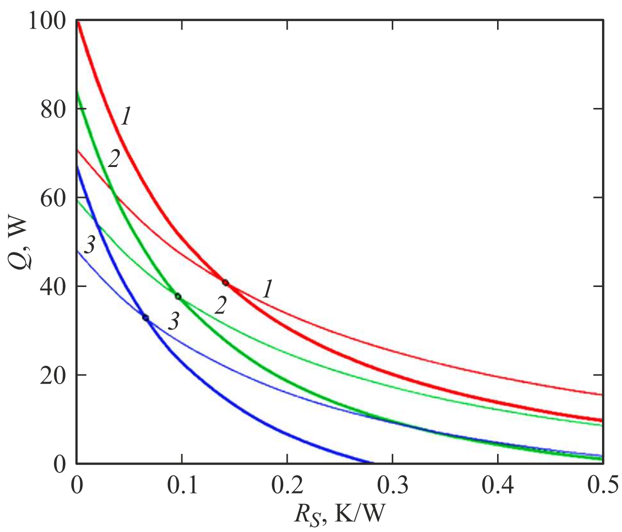


**Figure 6.** The dependencies of maximum cooling capacity on thermal resistance $R_S$ at $R_T = 0.3$ K/W: *1* —$\Delta T_0 = -10$, *2* —$-20$, *3* —$-30$°C.

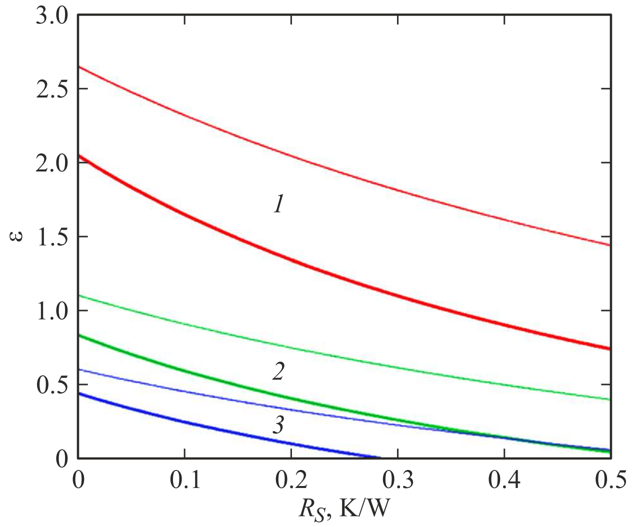


**Figure 7.** The dependencies of maximum refrigeration coefficient on thermal resistance $R_S$ at $R_T = 0.3$ K/W: *1* —$\Delta T_0 = -10$, *2* —$-20$, *3* —$-30°$C.

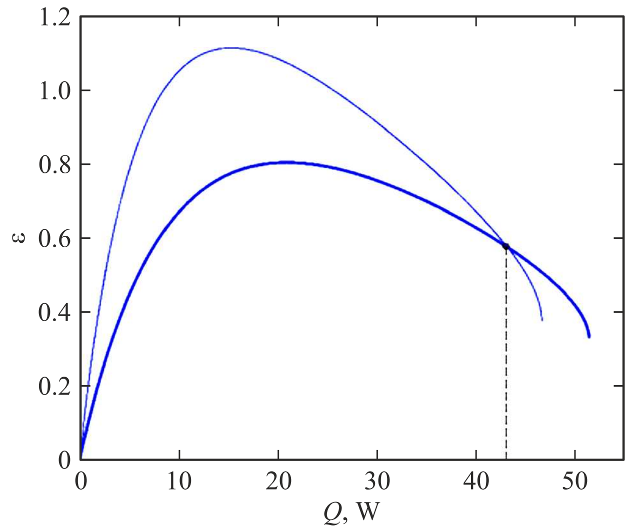


**Figure 8.** The dependencies of the refrigeration coefficient on the cooling capacity.

the inverse inequality $R_S < R_{S^*}$, the high-power TEM „D–200–14–06" allows achieving a higher maximum cooling capacity with a lower refrigeration coefficient. In this case, the choice of TEM requires additional analysis, therefore, we will compare the energy characteristics of TECTC for the following initial parameters to justify the choice: $R_S = R_T = 0.1$ K/W, $\Delta T_0 = -20°$C. The maximum values of $Q = 51.3$ W, $\varepsilon = 0.81$ for TEM „D–200–14–06", $Q = 46.5$ W and $\varepsilon = 1.12$ for TEM „S–199–14–11". The calculation results are also presented in Fig. 8 in the form of dependencies $\varepsilon(Q)$ for TEM „S–199–14–11" (thin line) and „D–200–14–06" (thick line). The criterion for choosing TEM is determined by the coordinate of the intersection of these dependencies, which is marked with a vertical dashed line. The intersection point corresponds to the value $\varepsilon^* = 0.58$ at $Q^* \approx 43$ W for this set of initial parameters. Therefore, for the heat dissipation capacity of the cooled object $Q_0 < 43$ W, the TEM „S–199–14–11" will ensure a more efficient operation of the TECTC TEM „D–200–14–06" has the priority for the CO heat dissipation capacity of more than 43 W. At lower values of thermal resistances, the intersection point of the dependencies $\varepsilon(Q)$ shifts towards a decrease $Q$ and an increase $\varepsilon$. So, for example, with the values $R_S = 0.05$ K/W and $R_T = 0.1$ K/W coordinates of the intersection point $Q^* = 40.4$ W, $\varepsilon^* = 0.91$, and with $R_S = 0.05$ K/W and $R_T = 0.05$ K/W — $Q^* = 38.5$ W, $\varepsilon^* = 1.06$.

Thus, the TEM selection algorithm for the cooling system includes the following steps.

1. The initial parameters of the thermoelectric cooling system are defined: the required temperature difference $\Delta T_0$, the heat dissipation capacity of the cooled object $Q_0$, the thermal resistances of heat exchangers and thermal contacts are also determined, according to which the values $R_S$ and $R_T$ are calculated.

2. From the technical documentation of the manufacturer, the performance characteristics $Q(\Delta T_{\mathrm{TEM}})$ and $U(\Delta T_{\mathrm{TEM}})$ of the thermoelectric modules that are being considered for use in the cooling system are determined.

3. For the given values $R_T$ and $\Delta T_0$ by the formula (1) using interpolation polynomials, the construction of which is described in [17], calculations are performed and graphs of the maximum values of the cooling capacity $Q$ and the refrigeration coefficient$\varepsilon$ are plotted. If the obtained maximum cooling capacity values are less than the set value $Q_0$, then the cooling system needs to be redesigned primarily for reducing the values of $R_S$ and $R_T$.

4. The $Q(R_S)$ curves determine the coordinates of $R_{S^*}$ and $Q^*$ points of their intersection. When the condition $R_S > R_{S^*}$ is met, a less powerful TEM is selected, which in this case has higher values $Q$ and $\varepsilon$.

5. In the case of $R_S < R_{S^*}$, additionally for both TEM dependencies $\varepsilon(Q)$ are calculated and the coordinate $Q^*$ of their intersection is determined. When performing the ratio $Q_0 < Q^*$ , a less powerful TEM has the advantage, with the opposite ratio $Q_0 > Q^*$ , only a more powerful TEM will provide the necessary cooling capacity.

The above algorithm makes it possible to select a TEM for the given $Q$ and $\Delta T_0$ , which provides the maximum cooling coefficient of the TECTC, depending on the thermal resistances of the heat supply and removal devices. In the manufacturer's information about high-power TEMs, only their higher performance is reported, without mentioning any restrictions that may hinder its achievement; the above methodology allows us to quantify these restrictive conditions.

## Conclusion

The presented methodology enables to calculate and analyze the energy characteristics of TECTC and to carry out, taking into account the initial technical conditions, a purposeful choice of the optimal thermoelectric module that ensures maximum efficiency of the cooling process. A comparative analysis of the energy characteristics of TECTC for two serial TEM with different cooling capacities showed that a high-power TEM provides higher cooling efficiency only with relatively small values of thermal resistances of the HSD and HRD. The limited use of high-power TEM is due to its higher own energy consumption, necessary to maintain a given temperature drop, and a proportional increase in heat losses with an increase in thermal resistance.

### Conflict of interest

The author declares that he has no conflict of interest.

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