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OPTIMIZATION OF THERMAL SCHEMES OF THERMOELECTRIC GENERATOR WITH CONSTANT-POWER HEAT SOURCE

A scheme of thermoelectric generator (TEG) with constant-power heat source (radiating surface with fixed temperature) is considered. With specific reference, the peculiarities of scheme presented here caused by strict restrictions on device thermal conditions are analyzed. A solution is proposed assuring the possibility of drastic improvement of techno-economic and mass-dimensional characteristics of TEG due to transformation of heat fluxes at heat supply and removal.
Key words: thermoelectric generator, heat scheme of TEG, TEG efficiency.

Introduction

The specific features of heat source employed have a considerable impact on the performance of thermoelectric generators (TEG) and largely determine the choice of device thermal scheme and its techno-economic figures. In the classification of TEG by the heat source type, a method of heat supply to thermopiles, namely due to convection, radiation or thermal conductivity, is commonly used as a governing criterion [1, 2]. One of particular cases of this problem is the use of heat sources with given power of heat release, such as radioisotope sources of thermal energy [3] or radiation sources [4]. In some cases the problem is complicated by introducing additional restrictions, such as restrictions on the temperature of radiating surface [5], narrowing problem definition domain. This creates additional rigid relations in the heat source-TEG-heat sink system determining the peculiarities of solving the optimization problems of TEG parameters. The purpose of this paper is to analyze the characteristics of TEG with constant-power heat source under additional restrictions on the temperature conditions.

Problem formulation

Let us consider the problem of calculation and optimization of TEG with constant-power heat source under given restrictions on the temperature of radiating surface and the temperature of heat-absorbing junctions. Conditions for the uniqueness of the problem: T_o = const is radiator temperature; q = const is heat flux on heat absorber surface; T_h = const is heat absorber temperature; t_x = const is heat sink temperature.

Such problem formulation severely restricts heat transfer conditions in the heat source-TEG-heat sink system. In [5], a problem in similar formulation is considered in detail and the conditions of equilibrium in the heat source (cement kiln surface) – heat absorber system are determined. As the initial data, we will use the values and results given in this paper:

$$\begin{aligned} q &= 4.5\ \text{kW/m}^2; \\ T_o &= 300\ °\text{C}; \\ T_h &= 80\ ...170\ °\text{C}; \\ t_x &= 30\ °\text{C}; \end{aligned} \qquad (1)$$

The specific feature of scheme under consideration is that to maintain given boundary conditions it is also necessary to assure strictly defined value of thermal resistance on the heat absorbing surface-heat sink area, otherwise it would be impossible to fulfill the condition of constant radiator temperature (T_o = const) and heat flux

$$q = K\left(T_h - t_x\right) = \text{const}, \qquad (2)$$

where $K = \dfrac{1}{\dfrac{1}{\alpha_x} + \dfrac{h}{\lambda} + \dfrac{2\delta}{\lambda k}}$ is heat transfer coefficient; α_x is coefficient of heat exchange at heat removal; h is thermoelement height; λ is thermal conductivity coefficient of thermoelectric material; δ is heat spreader thickness; λ_k is heat spreader thermal conductivity.

The values of heat transfer coefficient K satisfying conditions (1, 2) are shown in Fig. 1.

As is seen from (2), the ratio between the net temperature difference on thermoelements, $\Delta T = (T_h - T_x)$, and the available difference $(T_o - t_x)$ is proportional to the ratio between thermal resistance of thermoelement legs (h/λ) and thermal resistances.

The thermoelement height satisfying conditions (2) is:

$$h_{opt} = \lambda / q[(T_h - t_x) - 1/\alpha_x - 2\delta/\lambda k] \qquad (3)$$

That is, under known cooling conditions (α_x) there is always only one value of thermoelement height satisfying the conditions of the problem. The permissible values of h_{opt} versus α_x for the initial data (1) are illustrated in Fig. 2.

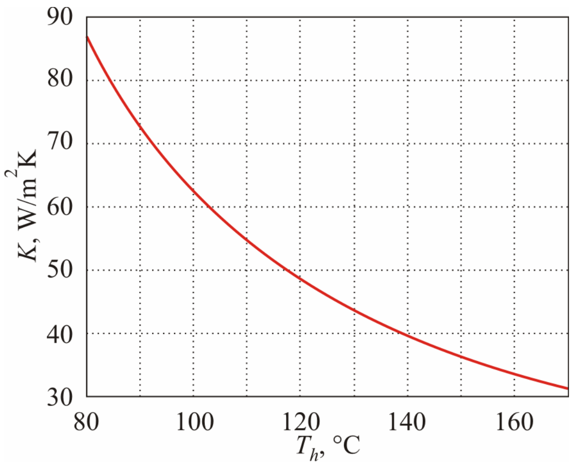

Fig. 1. Dependence of heat transfer coefficient K on temperature T_h.

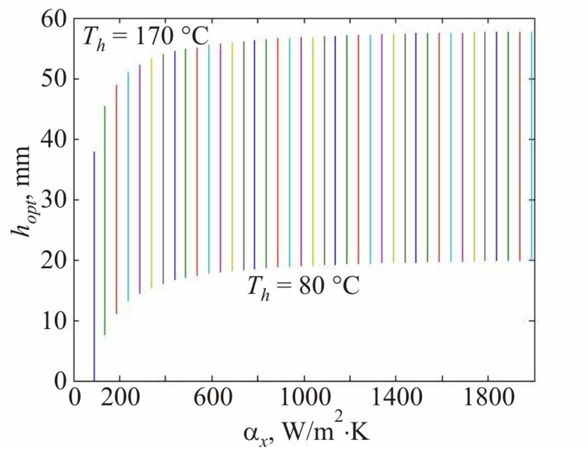

Fig. 2. Dependence of permissible thermoelement height h_{opt}, mm, on heat exchange intensity α_x, W/m^{2}K for T_h = 80...170 °C.

As it follows from the data given in the figure, the problem definition domain lies in the zone of unacceptably high values of h_{opt}. Whereas the use of thermoelements of standard height will reduce considerably the net temperature difference and TEG power, respectively. For instance, for thermoelements 1.5 mm high (typical height for standard thermoelectric modules) the established restrictions are matched by heat exchange coefficient $\alpha_x = 35$ W/m^{2}K. In so doing, the net temperature difference will make of the order of 3.5 K, and the specific power of TEG will not exceed $N = 3$ W/m^2. In the limiting case, at $h \to 0$, the equilibrium in the system is assured at $\alpha_{x\,\min} = q/(T_h - t_x)$; $\Delta T = 0$, $N = 0$. The dependences of TEG specific power on heat exchange intensity and the temperature of heat absorbing surface T_h at the optimal height of thermoelements is illustrated in Fig. 3.

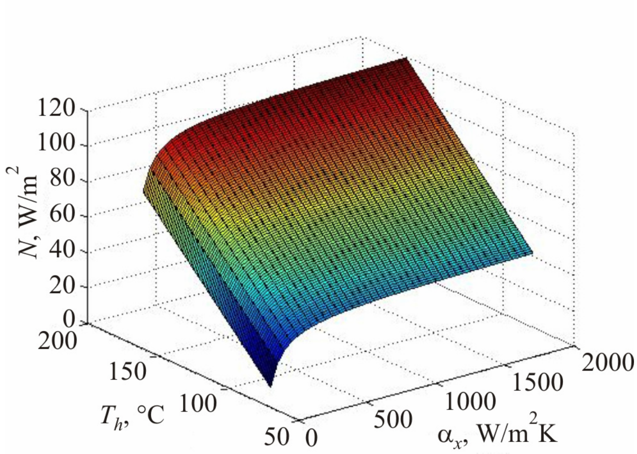

Fig. 3. Dependence of TEG specific power N, W/m^2, on the temperature of heat-absorbing layer T_h and heat exchange coefficient α_x, W/m^{2}K.

An important feature which largely determines the cost of TEG is specific consumption of thermoelectric material per unit power g, kg/W.

In the first approximation, this parameter can be found from the known relations

$$N = \frac{E^2}{4R} = \frac{(e\Delta T)^2}{4\rho h},$$

In the limiting case

$$\Delta T \to (T_h - t_x) \to \frac{qh}{\lambda},$$

whence we get

$$g = \frac{4\lambda\nu}{zq^2} \qquad (4)$$

where λ, ν and z is thermal conductivity, density and figure of merit of thermoelectric material, respectively.

That is, in the problem formulation under study the specific consumption of thermoelectric material g depends only on heat flux q. For the initial data assumed this parameter calculated by (4) is equal to 1.2 kg/W. In fact, Eq.(4) yields maximum possible value of g, since it does not take into account the irreversible losses at heat removal. Actually, this value for given conditions (1) over a wide range of α_x variation is of the order of 4.7 kg/W. It is clear that despite possible achievement of the acceptable values of specific power and efficiency, such a TEG cannot find practical application because of too large consumption of thermoelectric material.

To reduce material consumption of TEG, measures must be taken to increase the density of heat fluxes at heat supply to thermoelements. For this purpose, intermediate coolant circuit can be used, which, on the one hand, will allow heat removal from the source under given restrictions, and, on the other hand, intensification of heat supply to TEG. For instance, for a design described in [5] it is reasonable to use a water jacket, namely vapour generator, the assigned temperature of which is easily stabilized by maintaining the necessary pressure of saturated vapours in the loop. The resultant vapour is directed to heat exchanger-thermoelectric generator [6]. This helps to release rigid relationship between the characteristics of heat source, TEG and heat sink. Due to high intensity of heat exchange at vapour condensation, the density of heat flows at heat supply to TEG increases by several orders, which allows a drastic reduction of mass-dimensional and cost characteristics of TEG. Preliminary evaluation of such device characteristics under the above formulated restrictions shows that at T_h = 170 °C the specific power of TEG will make of the order of 12 kW/m^2, and material consumption – not more than 0.33 g/W. The generating part proper of such 200 kW TEG will represent a compact device of dimensions 500 × 1000 × 500 mm, which is quite acceptable for the application discussed.

Conclusions

A scheme of thermoelectric generator with a constant-power heat source and restrictions on the temperature conditions is considered. Analysis of the scheme is made and it is shown that a decisive influence on techno-economic characteristics of similar TEG is produced by heat flux density restrictions. A decision is proposed assuring the possibility of drastic improvement of techno-economic and mass-dimensional characteristics of TEG due to transformation of heat fluxes at heat supply and removal.

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