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PERFORMANCE ANALYSIS OF HEAT-EXCHANGE TYPE THERMOELECTRIC GENERATOR

Performance analysis of a thermoelectric generator integrated into a compact plate heat exchanger is considered. The dependences of the generator technical and economic characteristics on the regime and geometrical parameters are determined. Design recommendations for such devices are given.
Key words: thermoelectric generator, low-grade heat source.

Introduction

One of the promising applications of thermoelectric generators (TEG) is their use for low-grade thermal into electric energy conversion. In the majority of cases heat transfer from low-grade sources takes place by means of liquid heat carriers, which predetermines possible TEG design. The most common for such TEG is a scheme where thermopiles are equipped with heat exchangers with direct current or counter current flow of heat carriers realizing supply and removal of heat. The main requirement to TEG of this type is to provide minimum mass-dimensional characteristics of a device with maximum possible efficiency. A scheme of TEG where thermopiles are integrated into a compact plate heat exchanger [1] seems to be rather promising for solving these problems. In this design the function of heat exchanger plates is performed by thermopiles with heat carrier flow channels arranged between them by means of gaskets. Due to high intensity of heat exchange in the slot channels between the thermopiles and doing away with the bulky and metal-consuming heat exchangers, such a design allows reducing the mass and dimensions of TEG practically by an order as compared to conventional devices.

In this work, the specific features of the design under study are analyzed and possible technical and economic characteristics of such thermoelectric generators are estimated.

Problem formulation

The problem consists in creation of a mathematical model describing correctly the relation between the regime and geometrical parameters of TEG, and in using it for performance analysis of system under consideration. A design scheme of the problem is represented in Fig. 1.

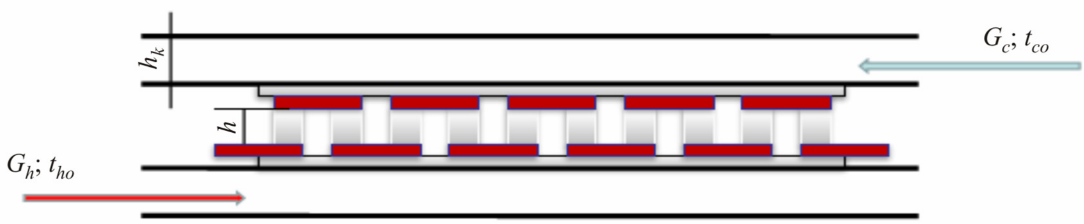


Fig. 1. Design scheme of TEG.

Heating and cooling heat carriers passing through the slot channels between thermopiles flow around the surface of the latter, keeping temperature difference ΔT on the thermoelements. It is obvious that due to irreversible heat exchange losses, as well as due to change in heat carrier temperature along the thermopile, the operating temperature difference on thermoelements will be always less than the available difference:

$$\Delta T < dt_o = t_{ho} - t_{co}; \tag{1}$$

here t_h and t_c are the initial temperatures of heat carriers; indices h и c refer to heating and cooling heat carriers, respectively.

Moreover, part of the energy generated by TEG is spent on circulating pump drive for pumping of heat carriers. It is necessary to minimize these losses and determine the conditions whereby the net power of TEG reaches maximum values under the existing restrictions.

As is known from heat exchange theory, with a counter current flow of heat carriers with the same mass specific heat, the difference in temperature between heat carriers is kept constant along the heat exchange surface

$$dt = t_h - t_c = const \tag{2}$$

As long as for TEG mode the influence of the Peltier heat on temperature distribution in heat carriers can be ignored, in the first approximation the temperature difference between heat carriers can be also considered to be constant and determined as [2]:

$$dt = \frac{dt_o}{1 + \frac{KF}{W}} \tag{3}$$

where $W = Gc_p$ is specific heat of heat carrier mass flow rate (water equivalent), W/K; F is heat exchange surface area, cm^2;

$K = \frac{1}{\frac{1}{\alpha_c} + \frac{1}{\alpha_h} + \frac{h}{\lambda}}$ is heat transfer coefficient, W/cm^{2}K; α_c and α_h are the effective coefficients of heat transfer from the cold and hot sides taking into account the packing density of thermoelements in the module and the presence of ceramic heat spreaders:

$$\alpha_c = \frac{S_m}{S_t} \frac{1}{\frac{1}{\alpha_{co}} + \frac{\delta}{\lambda_k}}; \; \alpha_h = \frac{S_m}{S_t} \frac{1}{\frac{1}{\alpha_{ho}} + \frac{\delta}{\lambda_k}};$$

α_c and α_h are the heat exchange coefficients on the cold and hot thermopile surface; S_m is the module area; S_t is the cross-sectional area of thermoelements in the module; h is the height of thermoelements, cm; λ is the thermal conductivity of thermoelectric material, W/cmK; δ is the thickness of ceramic heat spreader, cm; λ_k is the thermal conductivity of ceramics, W/cmK.

Expression (3) can be used to determine the temperature conditions for the assignment of the boundary conditions in the calculation of TEG. The dependence of temperature difference dt on heat carrier flow rate (W) and heat exchange conditions (KF) is illustrated in Fig. 2. As it follows from the figure, the temperature difference tends to its limiting value $dt \rightarrow dt_o$ with increase in heat carrier flow rate; it is due to a decrease in heat carrier temperature change along the channel. Heat exchange intensification (KF growth), on the one hand, leads to a reduction in temperature difference losses at heat exchange, and on the other hand – to an increase in heat flows and, respectively, to a change in heat carrier temperatures along the thermopile. The latter factor has a great impact on the reduction of temperature difference.

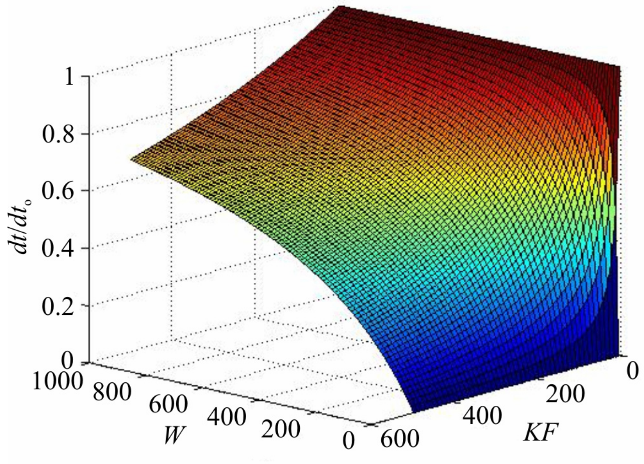


Fig. 2. Effect of heat transfer conditions on the temperature difference dt.

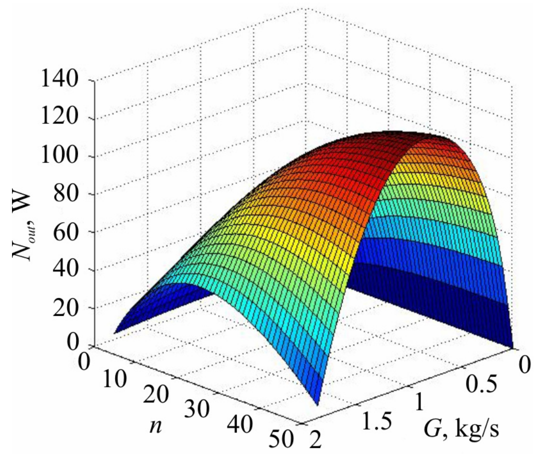


Fig. 3. Dependence of TEG net power on heat carrier flow rate (G) and thermopile area (n).

At the same time, as heat carrier flow rate increases, the hydraulic losses in channels increase, as a result of which the generator net power is reduced. That is, it can be supposed that there are optimal ratios of regime (heat carrier flow rate, TEG load conditions) and geometrical parameters (channel dimensions, the number and dimensions of modules in thermopiles) that assure the best technical and economical figures of TEG. This assumption is well illustrated in Fig. 3 which represents the dependence of net power of TEG thermopile as a function of heat carrier flow rate and thermopile area (the thermopile area is expressed through the number of modules n arranged along the heat carrier flow).

Mathematical model of TEG

The calculation data were obtained with the use of a mathematical model of TEG including:

– solving the equation of heat and electricity transfer in thermoelements with the boundary conditions of III kind in the form [3-5]:

$$\Theta(J,Y) = C_1 + C_2 Y - \frac{J^2}{2I_o} Y^2, \quad (4)$$

where

$$C_1 = \frac{(b_2 Bi_c \theta_c - b_1))}{(J - Bi_h + b_2(J + Bi_c))};$$

$$C_2 = C_1 \frac{(J + Bi_c) - Bi_c \theta_c}{J^2 (J - Bi_h)};$$

$$b_1 = \frac{J^2}{I_o} - 2I_o + Bi_h \theta_h;$$

$$b_2 = J - Bi_h - 1;$$

Here $\Theta = T/t_o$ is the dimensionless temperature of thermoelement; $\theta_{c,h} = t/t_o$ is the dimensionless temperature of heat carrier; $Y = y/h$ is the dimensionless coordinate; $J = jeh/\lambda$ is the dimensionless current density; $Bi = \alpha h/\lambda$ is the Biot criterion; $I_o = zt_o$ is the Ioffe criterion; $z = (e^2\cdot\sigma)/\lambda$ is the thermoelectric figure of merit of material; h is the thermoelement height; t_o = 300 K is the governing temperature.

Criterion equations for the determination of heat transfer coefficients [2]

$$Nu = 0.022Re^{0.8}Pr^{0.43} \tag{5}$$

and coefficients of friction with liquid flow in a plane channel:
for a laminar flow ($Re < 2300$)

$$\xi = \frac{96}{Re}; \tag{6}$$

for a turbulent flow ($Re > 2300$)

$$\xi = \frac{\left(\frac{Pr_f}{Pr_w}\right)0.333}{1.82\log(Re-1.64)}; \tag{7}$$

Here $Nu = \alpha d/\lambda$ is the Nusselt criterion; $Re = Vd/v$ is the Reynolds criterion; Pr is the Prandtl criterion; d is the equivalent diameter of the channel.

As long as the properties of heat carriers are essentially dependent on temperature, the calculation of transfer coefficients was done with the interpolation of tabulated data through use of cubic splines.

The system of equations (2 – 7) allows us to calculate temperature distributions in thermoelements and heat carriers and, accordingly, to determine the characteristics of TEG as a function of the basic regime and geometrical parameters with the assigned properties of thermoelectric material and heat carriers. In the general form the TEG power is:

$$N = \frac{E^2}{R}\frac{m}{(m+1)^2}; \tag{8}$$

Here $E = ne\Delta T$ is the TEG EMF; n is the number of couples connected in series; R is the TEG internal resistance; m is the load factor.

The TEG net power is:

$$N_{out} = N - N_{pump}, \tag{9}$$

where $N_{pump} = \frac{G_c dP_c}{0.9\rho_c} + \frac{G_h dP_h}{0.9\rho_h}$ is energy consumption for pumping; $dP = \xi\frac{L\rho}{d}\frac{V^2}{2}$ is pressure loss in channels; L is channel length; $\rho_{c,\,h}$ is heat carrier density; $V = G/f$ is heat carrier velocity; f is cross-sectional area of channels.

The conversion efficiency of TEG and the total generator efficiency are, respectively

$$\eta = \frac{N}{Q} \tag{10}$$

$$\eta_{out} = \frac{N_{out}}{Q} \tag{11}$$

where $Q = KSdt$ is heat flow through generator thermopiles; S is the effective area of TEG thermopiles.

Analysis results

The basic problem parameters affecting the characteristics of TEG are the dimensions and number of thermoelectric modules, their properties, the flow rate and temperatures of heat carriers, the size of channels between thermopiles. The possibilities of variation of the majority of these parameters are limited. To the independent variables of the problem in hand that permit variation over sufficiently wide range one can refer heat carrier flow rate G, channel size h_k and, to a lesser extent, thermoelement height h.

From the standpoint of TEG efficiency of primary interest is the effect of these variables on temperature distribution in the system. It is obvious that the purpose of optimization of TEG parameters in the first approximation is to assure maximum possible operating temperature range on thermoelements. Maximum change of temperatures in the system is restricted by the available difference $dt_o = t_h - t_c$. Therefore, for generality of the results, we estimate the changes in governing temperatures with respect to maximum possible temperature difference dt_o. The effect of regime parameters on the temperature mode of TEG is illustrated in Fig. 4. The ranges of change in regime parameters correspond to the domain of definition of the problem under consideration. In this particular case we considered a TEG comprising thermopiles of size 150 × 800 mm. The thermopiles consist of three longitudinal rows 16 modules each, altogether 48 standard modules of size 40 × 40 mm.

For given temperature range of heat carriers (water) which is $t_c = 5$ °C; $t_h = 95$ °C, the permissible flow rate range is $G = 0\ldots1$ kg/s. The channel height varies within $h_k = 1...20$ mm. Under given conditions the relative temperature difference between heat carriers varies within

$$dt = (0.22\ ...\ 0.97)\,dt_o;$$

the losses in temperature difference along the channel are

$$t_{in} - t_{out} = (0.03\ ...\ 0.78)\,dt_o;$$

the temperature difference on thermoelements varies within

$$\Delta T = (0.002\ ...\ 0.79)\,dt_o.$$

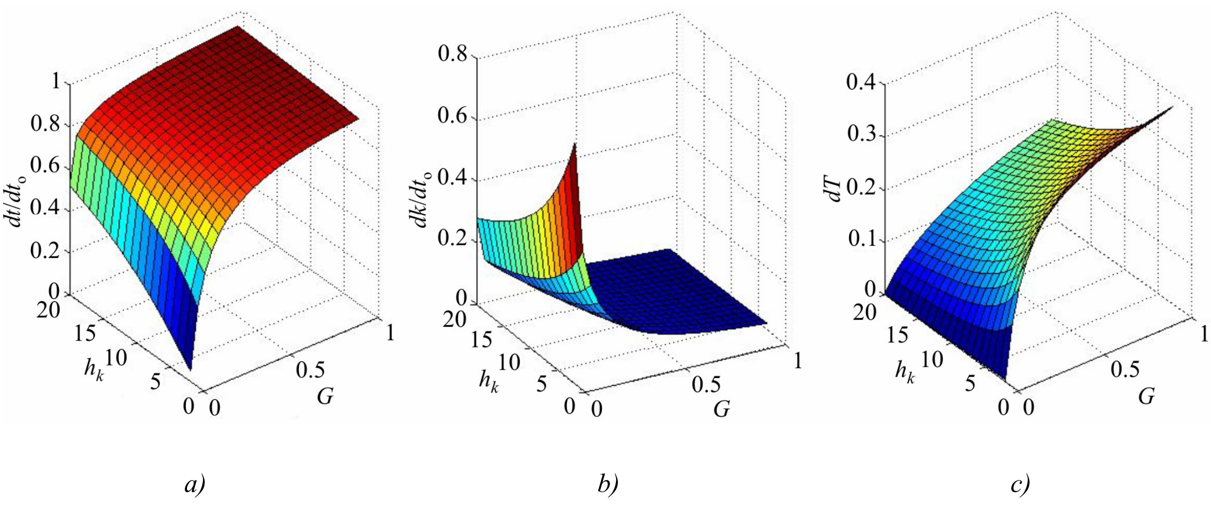
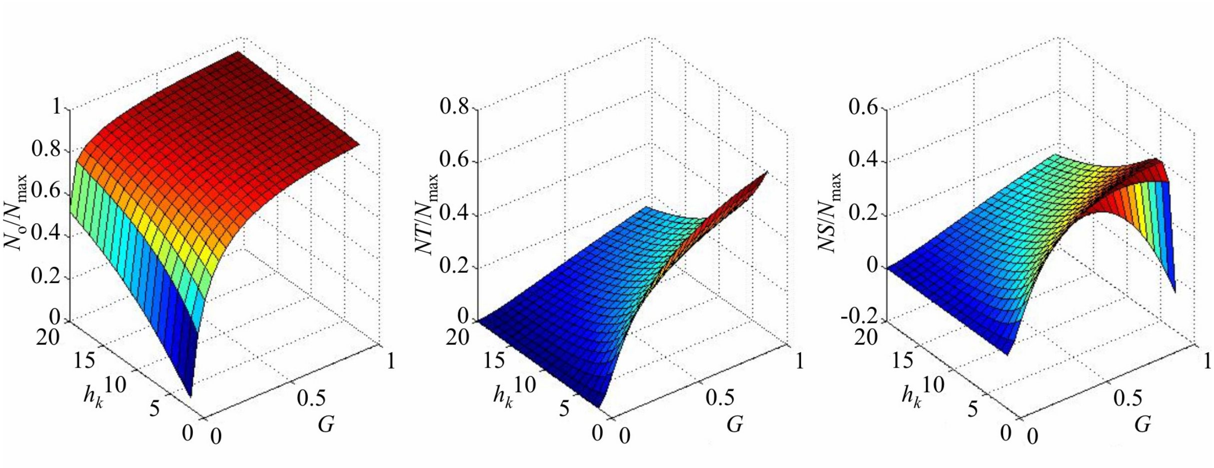


Fig. 4. Effect of regime parameters on the temperature mode of TEG.
a) –temperature difference between heat carriers; b) – temperature difference along the channel; c) – temperature difference on thermoelements.

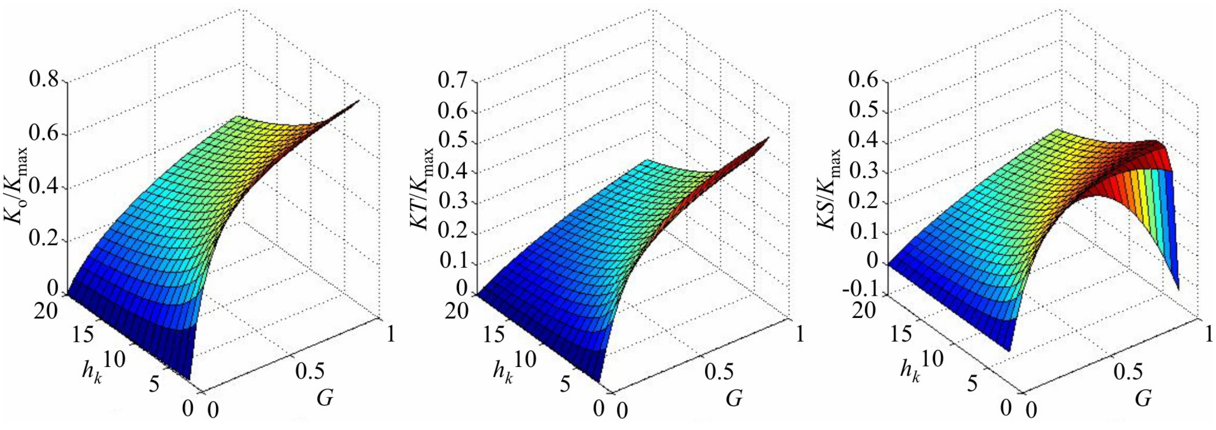
The net temperature difference ΔT monotonously increases with increase in consumption G and reduction of channel height h_k, since in this case the flow rate is increased and temperature difference along the channel is reduced; at the same time, heat exchange is intensified and the losses of temperature difference between heat carriers and thermoelement junctions are reduced. However, with increase in flow rate, the energy consumption on heat carrier pumping increase as well, which predetermines the presence of optimal values of parameters G and h_k, assuring the achievement of maximum TEG power and efficiency. The effect of regime parameters on the TEG power and efficiency is illustrated in Figs. 5 and 6.



a) *b)* *c)*

Fig. 5. Effect of regime parameters on the TEG power; a) – effect of heat exchange losses on the junctions; b) – effect of temperature difference along the channel; c) – effect of electricity consumption on heat carrier pumping.

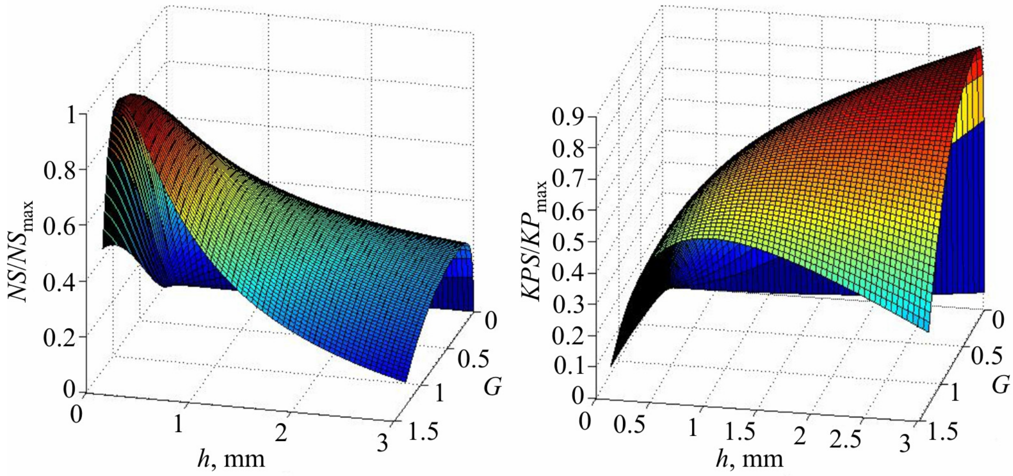
Power losses due to irreversibility of heat exchange between the heat carrier and thermoelement junctions are of the order of 7 %; the losses from the reduction of temperature difference along the channel can reach 30 %; the losses for heat carrier pumping make 15 %...20 % from maximum possible generator power. As a result, maximum net power of TEG is of the order of 40 % of the theoretically possible.



a) *b)* *c)*

Fig. 6. Effect of regime parameters on the TEG efficiency; a) – effect of heat exchange losses on the junctions; b) – effect of temperature difference along the channel; c) – effect of electricity consumption on heat carrier pumping.

Efficiency reduction due to the losses in question amounts to nearly 60 % as compared to theoretical efficiency for the available temperature difference. The optimal channel height for given conditions is $h_k \approx 5$ mm, the optimal heat carrier flow rate is $G = 0.9$ kg/s. The dependences of the TEG power and efficiency on the height of thermoelements at the optimal G and h_k are given in Fig. 7.



a) *b)*

Fig. 7. Effect of thermoelement height on the TEG characteristics.
a) – dimensionless power of TEG; b) – relative efficiency of TEG.

As is evident from the above data, there is an optimal value of h assuring maximum TEG power (in the case under study $h_{opt} \approx 0.3$ mm). However, the generator efficiency with increase in h grows monotonously. Hence it follows that the value of h optimal in terms of maximum economic efficiency of device should be selected with regard to cost characteristics of both generator and heat energy source.

Conclusions

A mathematical model of heat-exchange type thermoelectric generator is represented, assuring the possibility of calculation and optimization of such device parameters.

Performance analysis of a TEG integrated into a plate heat exchanger is made, the domain of problem definition is specified and the estimates of optimal TEG parameters are obtained.

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