Yu. M. Lobunets

Yu. M. Lobunets

Institute of Thermoelectricity NAS and MES of Ukraine
1, Nauky Str., Chernivtsi, 58029, Ukraine

HEAT EXCHANGE-TYPE TEG FOR MARINE PROPULSION PLANTS. Part II.

The characteristics of heat exchange-type thermoelectric generators using the heat of marine engine cooling system are analyzed. The prospects of using such TEG are outlined.
Key words*:* thermoelectric generator, low-grade heat source, marine propulsion plants

Introduction

In [1], the scheme of heat exchange-type thermoelectric generator (TEG) utilizing the exhaust gas heat of marine diesel engines was analyzed. It was shown that technical and economic features of the above scheme permit to expect wide application of similar TEG on water transport. At the same time, in this scheme there is another source of secondary energy, namely the heat of engine cooling system which accounts for 10 to 15% of fuel consumption. Despite the relatively low temperature potential, the use of this source can be no less attractive due to the simplicity of application scheme – actually it requires only substitution of standard heat exchanger by thermoelectric generator which performs the functions of heat exchanger and simultaneously generates additional electric power. Below are discussed the peculiarities of such TEG, and the estimates of its technical and economic features are given.

Scheme of heat exchange-type TEG for diesel propulsion plant cooling system

In the general case, marine diesel plant cooling system (Fig.1) comprises two heat carrier circuits with cooling liquid circulating in one of them (fresh water or antifreeze) and sea water circulating in the other. Optimal temperature of cooling liquid is 90...100°C; the temperature of sea water varies within 5 to 30°C. The difference in heat carrier temperature at the inlet and outlet

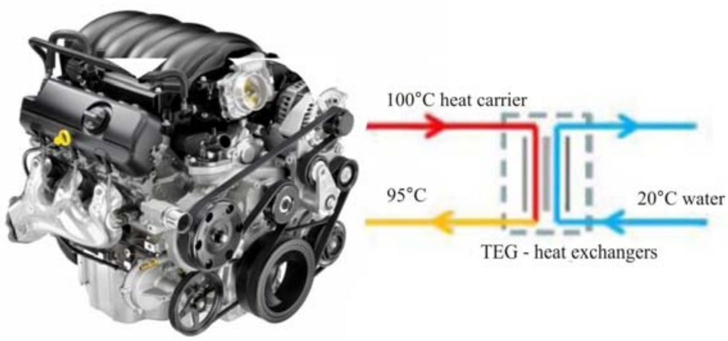

Fig. 1. Schematic of TEG for a marine plant.

of cooling system must not exceed 5 to 10°C. Heat carrier consumption in the circuits is determined by propulsion plant power and heat exchanger efficiency. The most efficient cooling systems employ plate heat exchangers [2].

The scheme of heat exchange-type TEG is similar to that of a plate heat exchanger where thermopiles are installed instead of plates [3]. The thermopiles are comprised of thermoelectric modules arranged between two metal plates with four openings that form collectors for heat carriers. The thermopiles are divided by elastic spacers forming channels for passage of heat carriers and tightening the entire structure which is clamped between two end plates, *Fig.2*.

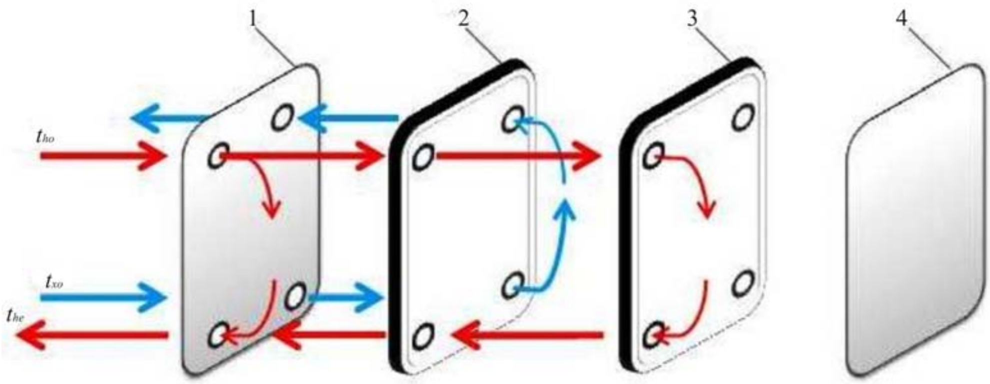

Fig. 2. Schematic of heat-exchange type TEG 1, 4 – end plates (TEG housing), 2, 3 – thermopiles.

The main function of heat exchange-type TEG in the scheme under study is to provide heat carrier cooling to given temperature. At the same time, it is necessary to optimize TEG parameters with a view to obtain maximum electric power.

The original parameters of the problem are:

Q_o – heat exchanger thermal power (in the calculations below it is assumed that Q_o = 10 kW);

t_{ho} = 100°C – TEG inlet heat carrier temperature;

t_{he} = 95°C – TEG outlet heat carrier temperature;

t_{xo} = 30°C - sea water temperature.

Mathematical model of TEG

Design model of TEG is represented in Fig.3.

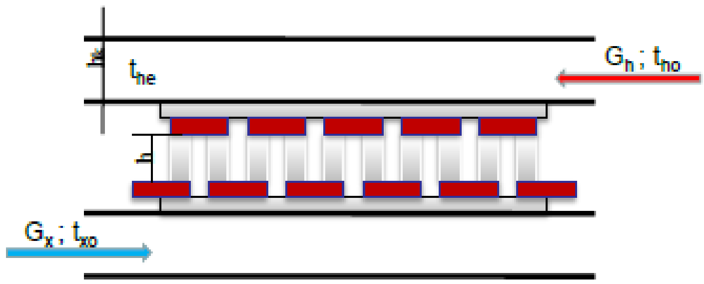

Fig.3. Design model of TEG.

In the general case, the mathematical model of TEG is composed of a system of equations that permit to determine temperature distribution in heat carriers and thermoelements [4]:

- equation for temperature distribution in thermoelements for boundary conditions of the third kind:

$$\Theta(Y) = C_1 + C_2 Y - \frac{J^2}{2I_0} Y^2, \tag{1}$$

where integration constants C_1, C_2 are determined as:

$$C_1(J + Bi_x) - C_2 = Bi_x \vartheta_x, \tag{2}$$

$$C_1(Bi_h - J) + C_2(Bi_h - J + 1) = Bi_h \vartheta_h + \frac{J^2}{I_0}(1 + 0.5Bi_h - J), \tag{3}$$

- equation for determination of heat exchange coefficients:

$$Nu = 0.022 Re^{0.8} Pr^{0.43} \tag{4}$$

- equation for determination of temperature distribution of heat carriers along the channel:

$$\frac{d\nu h}{dX} = \frac{dKih}{Wh}; \tag{5}$$

$$\frac{d\nu h}{dX} = \frac{dKix}{Wx};$$

$$Ki_h = Bi_h(\vartheta_h - \Theta_h); \tag{6}$$

$$Ki_X = Bi_X(\Theta_X - \vartheta_X).$$

In the above equations, criterion *Bi* is the ratio of thermoelectric material thermal resistance to the sum of thermal resistances on the way of heat flux from thermoelement surface to heat carrier, i.e.

$$Bi = R_O / R_t, \tag{7}$$

Where $R_t = \frac{1}{\alpha} + \sum_i \frac{hi}{\lambda i}$, *hi* and λi is the thickness and thermal conductivity coefficient of each layer on the way of heat flux (connecting elements, heat spreader, thermopile housing, solder interlayers, etc).

As long as the system of equations (1– 7) is nonlinear, it will be solved by numerical methods.

Analysis results

Formulation of the problem in hand stringently specifies heat carrier parameters in the first circuit and, accordingly, determines its overall consumption:

$$G_o = Q_o / \left[Cp \left(t_{ho} - t_{he} \right) \right]. \tag{8}$$

The purpose of calculations is to determine the total area of TEG that meets the reference conditions of the problem. As long as TEG is composed of identical thermopiles, at the first stage it is necessary to determine conditions, whereby given temperature condition of heat carrier in cooling system is assured within one thermopile. That is, for given thermopile structure it is necessary to determine the required consumption of heat carrier G_i through one TEG channel whereby hot heat carrier is cooled to given temperature. This allows defining the required number of thermopiles n_b, as well as the temperature condition of each module in thermopiles, its power N_m, as well as the power of thermopile NS and of generator on the whole N_T:

$$N_m = \frac{E^2}{4R}; \; NS = \Sigma N_m; \; N_T = n_b NS, \tag{9}$$

where $E = n_v e(T_h - T_x)$ is module electromotive force; $R = n_V \frac{\rho h}{s}$ is its electric resistance.

Temperature distribution of heat carriers and thermoelement junctions along the thermopile composed of 10 modules is illustrated in Fig.4.

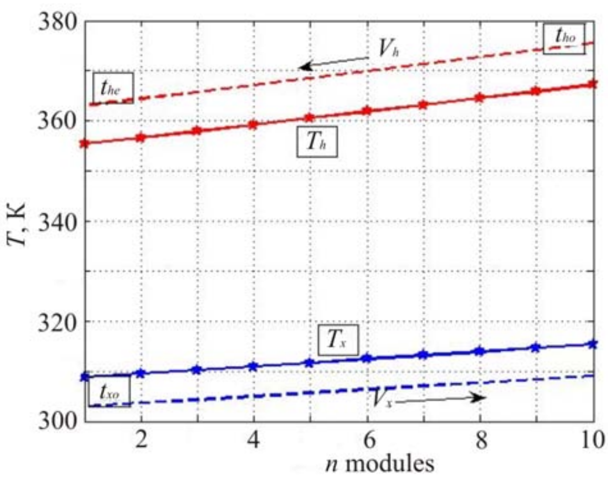

Fig. 4. Temperature distribution along the thermopile.

The next task is optimization of thermoelectric module parameters with a view to assure the best economic efficiency of TEG. Taking into account that thermopile dimensions are limited by housing dimensions of standard heat exchanger of internal combustion engine, thermoelement height h remains practically the only independent parameter which determines thermal resistance of thermopiles and, accordingly, all technical parameters of TEG, i.e. the necessary number of thermopiles and modules, heat exchange conditions in the channels, temperature difference on thermoelements, generator power and its cost.

Dependence of TEG power and efficiency is given in Fig. 5.

It is evident that increase in thermoelement height provides the opportunity of a more complete use of available temperature difference and the respective increase in thermoelement

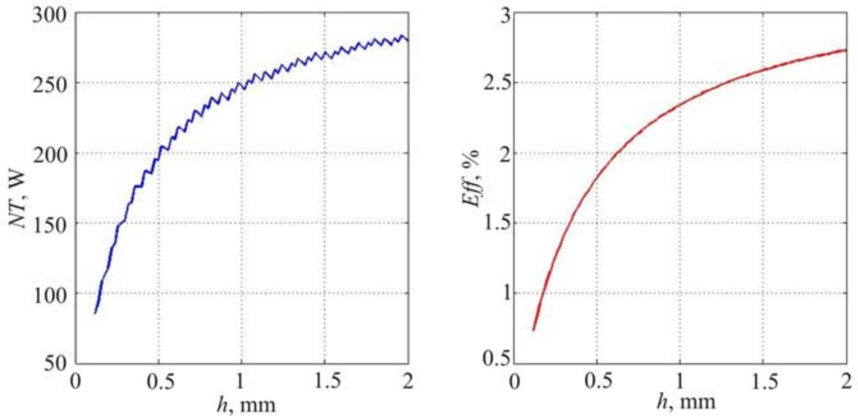

Fig. 5. Dependences of TEG power (NT) and efficiency (Eff) on thermoelement height h.

efficiency and total TEG power. However, increase in thermal resistance of thermoelements results in the reduction of heat transfer coefficient, which necessitates increase in heat exchange surface, i.e. increase in the number of thermopiles and TEG cost growth. Dependence of the necessary number of modules on thermoelement height is shown in Fig. 6 (fluctuations of curves are due to a discrete character of mathematical model – TEG dimensions can change only to integer values of the number of modules).

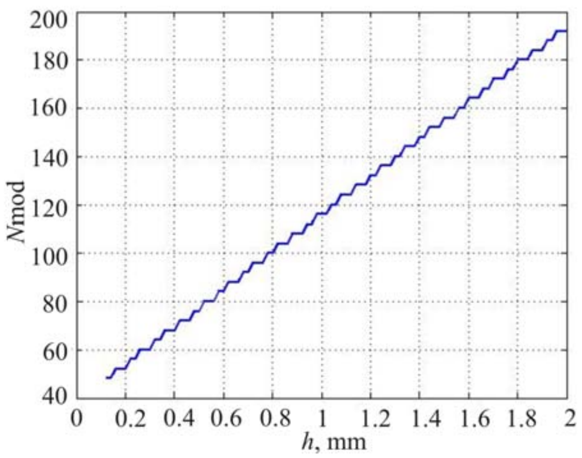

Fig. 6. Dependence of the necessary number of modules N_{mod} on thermoelement height h.

It should be noted that the cost of individual module is also a function of thermoelement height, as long as the necessary amount of thermoelectric material is changed. Dependence of specific cost of TEG power on thermoelement height with and without regard to this factor is given in Fig. 7 (as the base price, the retail cost of module 40x40 mm with thermoelement height 2 mm is taken, namely $P_\$ = 5$ \$ US; the cost of thermoelectric material in module price is 20%).

From the above data it is seen that minimum specific cost of TEG is achieved in the range of relatively low powers, i.e. a desire to assure maximum TEG power leads to essential increase of capital outlay. To overcome this contradiction, a compromise solution should be found that will guarantee the best technical and economic parameters of TEG. As the criteria for such solution,

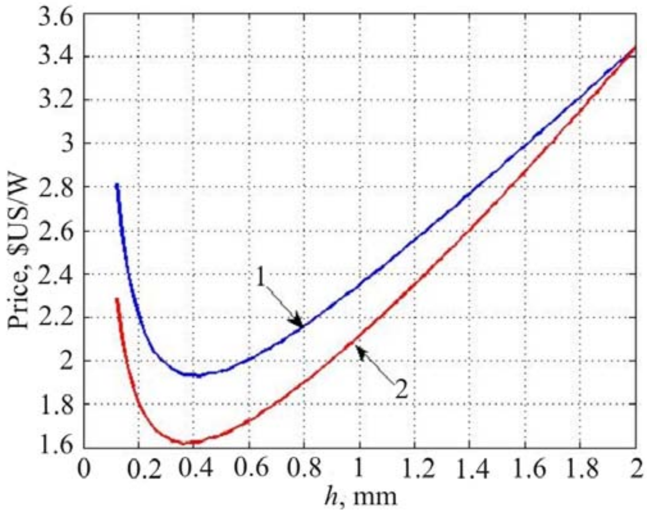

Fig. 7. Dependence of TEG specific cost, $US/W on thermoelement height h.
1 – without regard to h effect on material amount;
2 – with regard to h effect on material amount.

one can use the figures of fuel saving or TEG repayment period that can be calculated as:

$$T_O = \frac{\text{Price}}{\tau g P f}, \text{ years},$$

where Price is specific cost of TEG, $ US/kW; g is specific fuel cost for generation of 1 kW-h electric energy by marine plant (0.2 kg/kW-hour); P_f is fuel cost (approximately 1 $ US/kg); τ = 8640 hours/year.

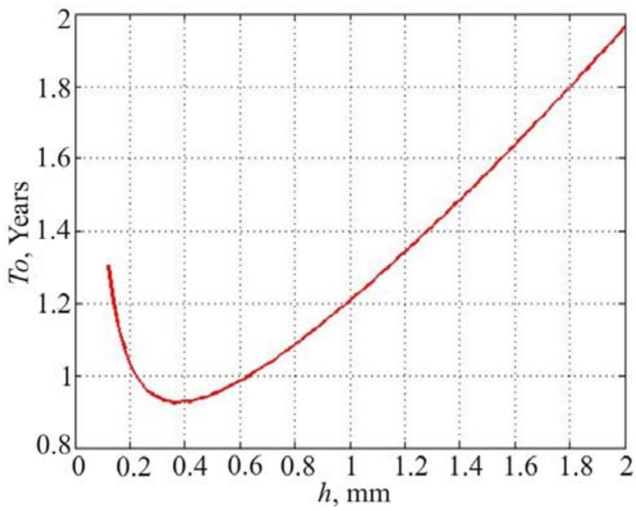

Fig. 8. Dependence of TEG repayment periods on thermoelement height h.

As follows from the foregoing, the scheme of TEG discussed above assures quite acceptable technical and economic features over a wide range of possible design concepts.

Conclusions

1. The scheme of heat exchange-type TEG using as the source of energy the heat of cooling system of marine propulsion plants is considered.
2. It is shown that the above scheme assures quite acceptable repayment periods which allow to expect wide application of similar TEG on water transport

Designations

L – thermopile length, cm;
b – thermopile width, cm;
F – thermopile area, cm^2;
h –thermoelement height, cm;
n_v – number of thermoelements in a module;
n_m – number of modules in a thermopile;
$P_\$$ – module cost, \$ US;
$X = \frac{x}{L}, \; Y = \frac{y}{L},$ – dimensionless coordinates;
G – heat carrier losses, kg/s;
Cp – heat carrier specific heat, J/kgK;
$W = GCp/b\lambda$ – dimensionless water equivalent;
T – thermoelement temperature;
t – heat carrier temperature;
$\Theta = \frac{T}{T_p}$ – dimensionless thermoelement temperature;
$\vartheta = \frac{t}{T_p}$ – dimensionless heat carrier temperature;
T_p – characteristic temperature;
σ – electric conductivity coefficient $(\text{Ohm cm})^{-1}$;
e – the Seebeck coefficient, V/K;
λ – thermal conductivity coefficient, W/cmK;
j – current density, A/cm^2;
$R_o = \frac{h}{\lambda}$ – thermal resistance of thermoelectric material, cm^2K/W;
α – heat-exchange coefficient, W/cm^2K;
K – heat-transfer coefficient, W/cm^2K;
$z = e^2\sigma/\lambda$ – thermoelectric figure of merit, K^{-1};
$Io = zT_p$ – Ioffe criterion;
$Bi = \frac{h}{\lambda Rt}$ – Biot criterion;
Ki – Kirpichev criterion;
Nu – Nusselt criterion;
Re – Reynolds criterion;
Pr – Prandtl criterion;

$J = \dfrac{jeh}{\lambda}$ – dimensionless current density;

Indices: h – hot; x – cold.

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