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HEAT EXCHANGE-TYPE TEG FOR MARINE PROPULSION PLANTS

The characteristics of heat exchange-type thermoelectric generators using the exhaust gas heat of marine engines are analyzed. The prospects of using such TEG are outlined.

Key words: thermoelectric generator, low-grade heat source, marine propulsion plants

Introduction

There is a wealth of papers on the subject of using thermoelectric generators (TEG) for the recovery of exhaust gas energy of automobile internal combustion engines. This line is considered to be one of promising spheres of TEG application [1-8]. However, the use of TEG in similar schemes on water transport is more attractive due to the absence of essential restrictions typical of automobile transport. The advantages of such use are listed in [7]:

- much higher powers of propulsion plants;
- much greater scope of saving energy resources;
- much better cooling conditions (outside water);
- absence of weight and size limitations;
- numerous options of recovery schemes;
- TEG unification capability allowing their use for any type of ship.

Conditions of using TEG on ships are essentially different from those on automobile transport, so these applications require special developments. With regard to high power of propulsion plants, conventional schemes of automobile TEG with arrangement on the exhaust pipe are unsuitable for marine propulsion plants. Schemes with the use of cassette-type thermopiles that are arranged in exhaust gas flow [8] or schemes with intermediate heat carrier [4] are discussed. Schemes using phase transitions for thermal energy transportation, i.e. heat pipes [5] or two-phase thermosiphons [3], where thermopiles are heated by heat carrier steam condensed on their surface (Fig.1) also seem to be rather efficient.

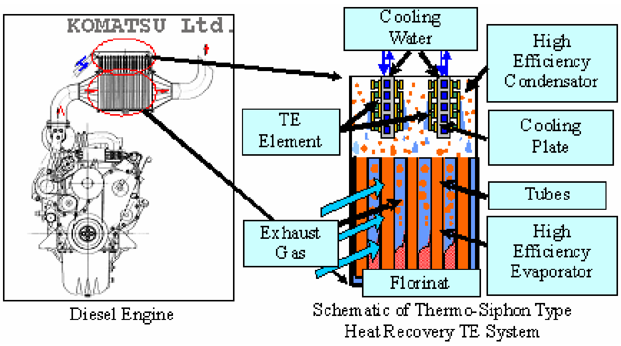


Fig.1. Schematic of TEG with a two-phase thermosiphon [3]

In my opinion, the scheme of heat exchange-type TEG proposed in [9] is most efficient for the application under study. It permits the use of both liquid and steam-like heat carriers, provides for the highest specific power and is well adapted into the flowchart of propulsion plant. The basic peculiarities of such TEG combined with a marine propulsion plant are considered and the technical and economic features of this scheme are analyzed.

Scheme of heat exchange-type TEG for diesel propulsion plant

Distribution of energy fluxes in a marine diesel engine is illustrated in Fig.2 from which it follows that about 25% of primary energy is lost with exhaust gases. Normally, gas temperature is approximately 500°C.

TEG under study is schematically represented in Fig.3.

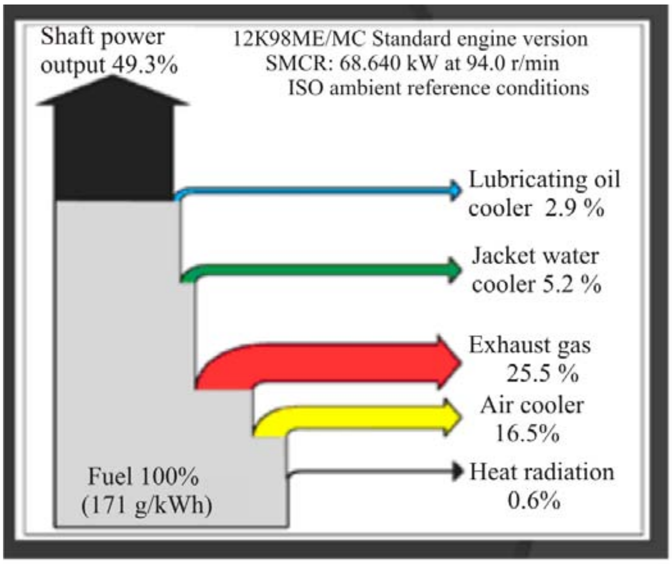


Fig.2. Distribution of energy fluxes in a marine diesel engine [7]

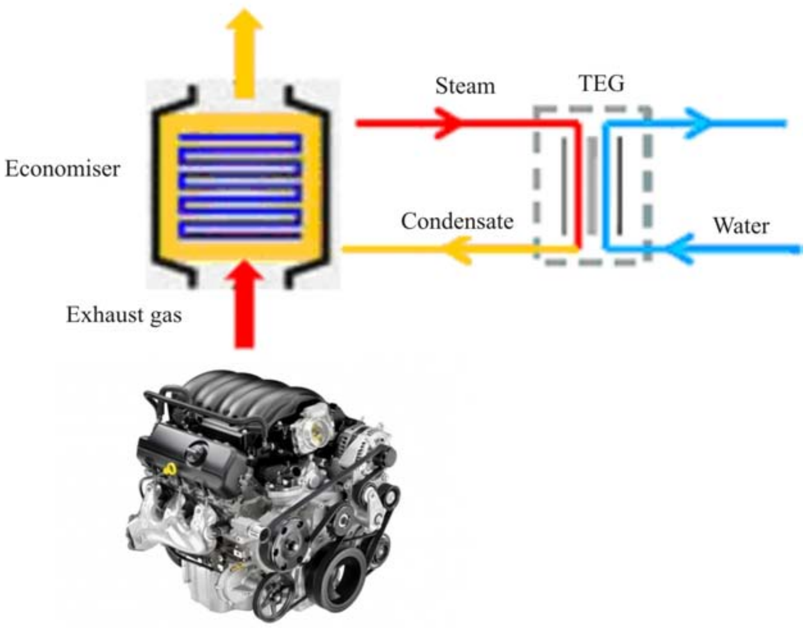


Fig.3. Schematic of TEG for a marine propulsion plant

Exhaust gases with temperature t_{hg}=500°C from the engine come to heat exchanger-economizer where heat carrier coming from TEG is heated to boiling point. Steam with temperature t_{ho} comes to channels formed by thermopiles where it is condensed and returns to economizer. Cooling of thermopiles is done by outside water with temperature t_{xo} that circulates through TEG channels. Packing of thermopiles to prevent leakage of heat carriers is done by gaskets of special shape that form channels and collectors for passage of heat carriers.

The operating temperature of heat carrier at inlet to TEG t_{ho} is easily controlled by maintaining the necessary pressure in the system. The choice of this parameter in the available temperature range $t_{xo}<t_{ho}<t_{hg}$ strongly affects system efficiency and TEG power. It is clear that with a rise in t_{ho}, the amount of heat taken from exhaust gas (Q_h) is reduced, just as the efficiency of heat exchanger K_{heat} and the amount of heat carrier generated by economizer (G_h). At $t_{ho} \rightarrow t_{hg}$; $Q_h \rightarrow 0$; $K_{heat} \rightarrow 0$. Alongside with that, the operating temperature difference on thermoelements and, accordingly, TEG efficiency is increased. When affected by these factors, TEG power reaches a maximum within the available temperature range (Fig.4). As is seen from the presented data, in the first approximation the operating temperature $t_{ho}=(t_{hg}-t_{xo})/2$ is optimal. In our case this corresponds to approximately t_{ho}= 250°C.

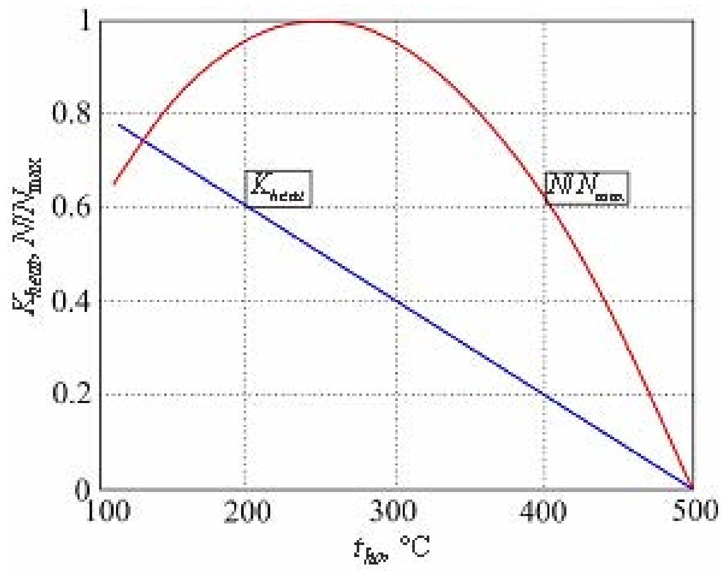


Fig.4. Heat exchanger efficiency K_{heat}
and TEG power N versus heat carrier input temperature t_{ho}

Another restriction imposed on heat carrier temperature is permissible operating temperatures of thermoelectric material and structural components. For the scheme under consideration, critical at the moment is maximum permissible operating temperature of sealing gaskets which for stock-produced items is 180°C.

Mathematical model of TEG

In view of the fact that heating of TEG is due to phase transitions (condensation), the temperature of hot thermoelement junctions along the channels can be considered constant. The availability of unrestricted source of cooling water allows making an assumption as to slight temperature changes along the cold channels of TEG. In this case it will be correct to use a mathematical model of thermoelement under third-order boundary conditions, taking no account of temperature changes along the thermopiles. According to [10], the equation for temperature distribution in TEG will be written as below:

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

Constants C_1, C_1 are determined as:

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

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

Where:

$\Theta = \frac{T}{T_p}$ is dimensionless thermoelement temperature;

$\vartheta = \frac{t}{T_p}$ is dimensionless heat carrier temperature;

$I_0 = zT_p$ is the Ioffe criterion;

$Bi = \frac{h}{\lambda R_t}$ is the Biot criterion;

$J = \frac{jeh}{\lambda}$ is dimensionless current density.

Indexes *h* and *x* refer to the hot and cold TEG sides, respectively.

In the above expression for the Biot criterion, coefficient R_t characterizes a sum of thermal resistances on the way of heat flux from thermoelement surface to heat carrier, that is

$$Rt = \frac{1}{\alpha} + \sum_i \frac{h_i}{\lambda_i}, \tag{3}$$

where α is heat exchange coefficient between heat carrier and thermopile; h_i and λ_i is the thickness and thermal conductivity of each layer on the way of heat flux (connecting elements, heat spreaders, thermopile package, solder layers, etc).

As long as a system of equations (1– 3) is nonlinear, we shall solve it by numerical methods.

Owing to the fact that in this schematic the isothermal conditions are assured on thermopile surfaces, for its calculation and analysis it is sufficient to consider the characteristics of one module with defined properties under the above conditions. Maximum power of such module in the general case is:

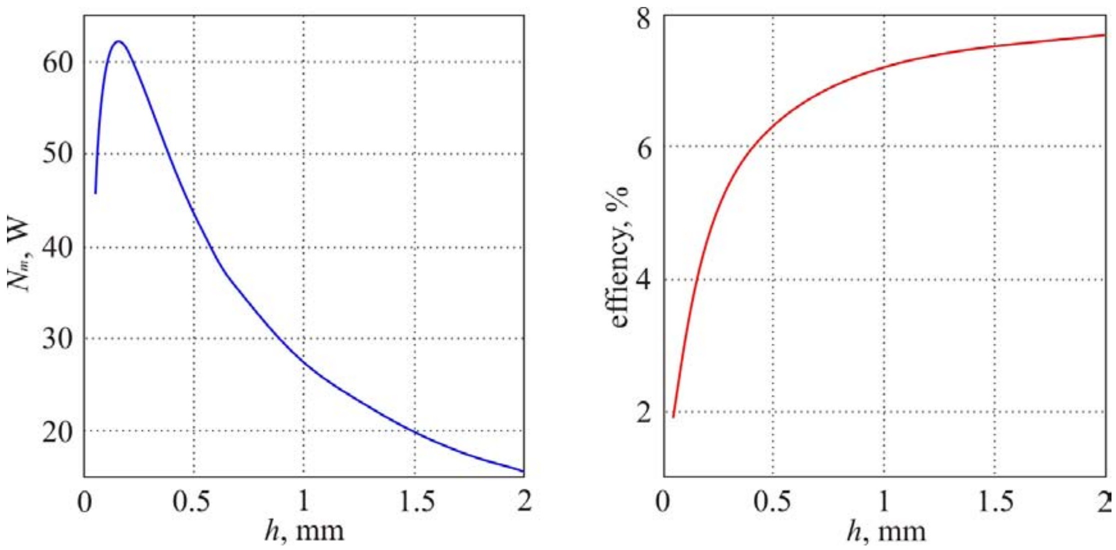
$$N_m = \frac{E^2}{4R}, \tag{4}$$

Where $E = n_v e(T_h - T_c)$ is module EMF; $R = n_v \frac{\rho h}{s}$ is its electrical resistance.

In view of the above, let us determine the characteristics of TEG scheme under study with the following input data:

- diesel plant power P = 1 MW (gas enthalpy Q_h =500 kW);
- warming heat carrier temperature at inlet to TEG t_{ho} = 180°C;
- water temperature in cooling system t_{xo}= 15°C;
- water velocity in TEG cooling channels - V_x= 2 m/s;
- heat exchanger efficiency will be determined from known t_{ho} as $K_{heat}= (t_{hg} - t_{ho})/t_{hg}= 0.64$;
- figure of merit of thermoelectric material $z = 0.0026\mathrm{K}^{-1}$;
- number of thermoelements in modules n_v = 526;
- thermoelement cross-section s = 0.026 cm^2;
- thermal resistance Rt_x=1.7 cm^{2}K/W; Rt_h=1.5 cm^{2}K/W.

According to (1-4), characteristics of TEG scheme are determined by the available temperature difference $\Delta t_o=t_{ho}-t_{xo}$, the properties of thermoelectric material *Io*, heat exchange conditions *Rt* and module characteristics -n_v, *h, s*. The majority of said parameters is determined by problem formulation conditions and has fixed values. Only module characteristics can be considered as independent parameters that can be varied over a wide range. With regard to the fact that the impact of n_v and *s* is of extensive nature, only thermoelement height *h* should be referred to independent parameters. The impact of height lies in the fact that it determines thermal ($R_o=h/\lambda$) and electric (*R*) resistance of thermoelements. Increase in *h* leads to increase in thermal resistance and useful temperature difference, at the same time, the electric resistance of module is increased which has a negative impact on its power. As a result, one can always find the optimal value of *h* that assures maximum module power (Fig.5a). The dependence of module efficiency on *h* is monotonic, since increase in thermoelement thermal resistance simultaneously results in temperature difference increase and reduction of heat flux through thermoelements (Fig.5b).



a) *b)*

Fig.5. Power (a) and efficiency (b) of module versus thermoelement height

Analysis of the task shows that the optimal ratio between thermal resistances of thermoelement R_o and heat transfer R_t is constant and always equals to R_o/R_t =2 (Fig.6). As a consequence, maximum power mode is realized at temperature difference which is equal to half of the available (Fig.7). It is clear that R_t increase brings about the respective reduction of maximum power.

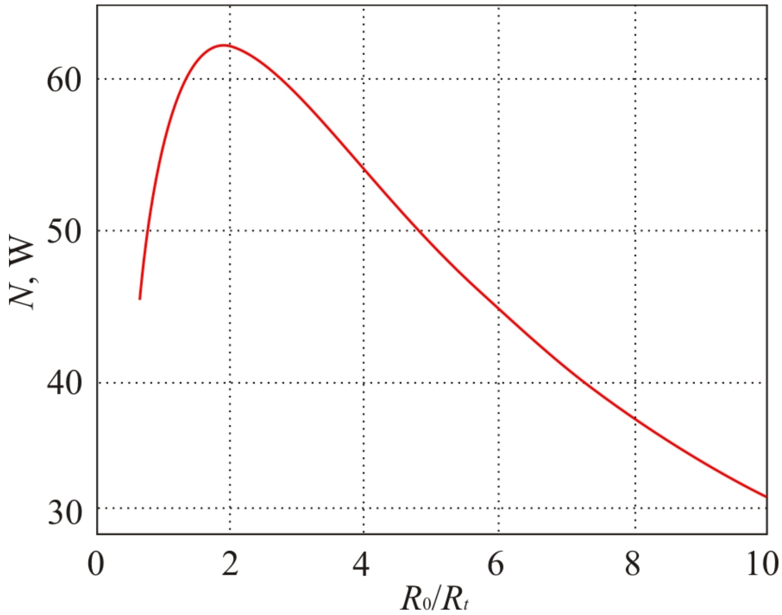


Fig.6. Module power versus the ratio between thermal resistances of thermoelement R_o and heat transfer R_t

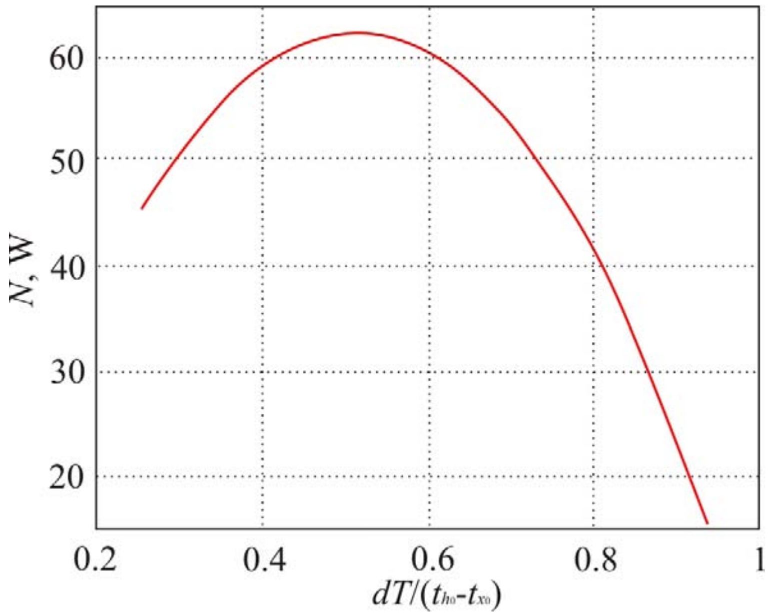


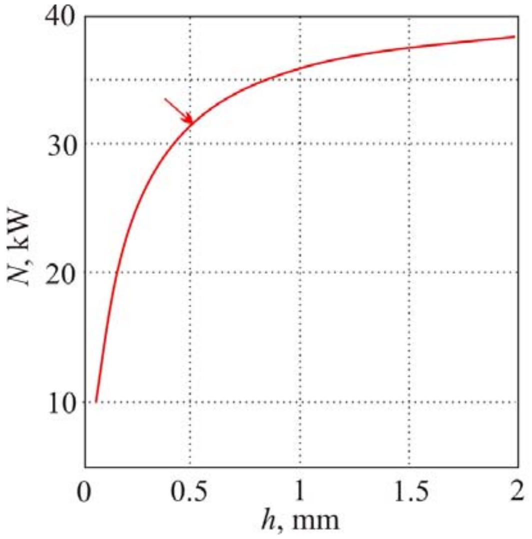
Fig.7. The ratio between module power N and temperature difference which is a function of height ΔT= f(h)

Knowing heat flux through the module Q_m, the total number of modules in TEG can be determined as

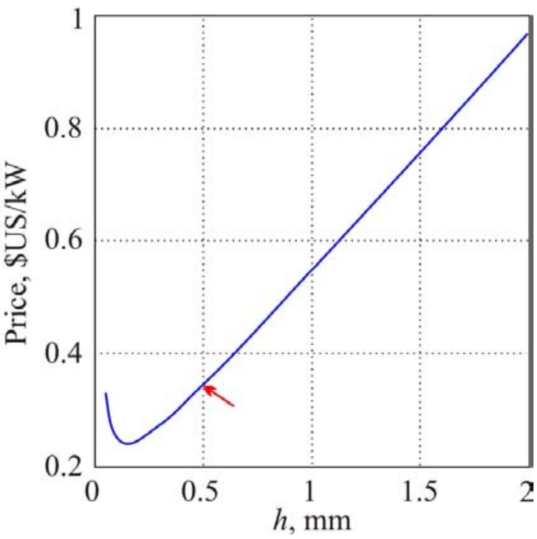
$$n_m = Q_h K_{heat} / Q_m \,. \tag{5}$$

The total power of TEG is, accordingly

$$NS \;=\; n_m N \,. \tag{6}$$



a)



b)

Fig.8. Power (a) and unit cost of TEG (b) versus thermoelement height

As is apparent from the data given in Fig.8a, despite the availability of extreme point on the curve $N=f(h)$, a dependence of total TEG power on thermoelement height is monotonic and similar to efficiency dependence. At the same time, it should be borne in mind that at $h>h_{opt}$ the necessary number of modules, hence, the cost of TEG increases considerably (Fig.8b). It is evident that a compromise solution should be the choice of h in the zone of acceptable TEG cost, close to boundary value line N, as marked by arrows in Fig.8. With this approach, the scheme of TEG under study assures quite acceptable values of unit cost (on the level of 350 $US/kW) and efficiency (close to 5%). One should also note high specific power of such generator – according to our estimates the above TEG will have the dimensions about 250×700×300 mm. These figures do not take into account the cost and dimensions of heat exchanger-economizer. To estimate possible scope of using such TEG, it can be noted that marine vessels of medium class have propulsion plants 10...15 MW. That is, for instance, using the above scheme of TEG on a Mistral class ship would yield additional 400...500 kW of electric power and provide fuel saving nearly 100 liters per hour.

Conclusions

1. The scheme of heat exchange-type TEG utilizing as the source of heat the exhaust gases of marine propulsion plants is discussed.
2. It is shown that maximum power of individual module in the above scheme meets the condition $R_o/R_t = 1$, whereas total power of TEG can monotonically increase to the limit restricted to theoretical efficiency, i.e. defined only by thermoelectric material properties.
3. Technical and economic features of the above scheme permit to expect wide application of similar TEG on water transport.

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