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HEAT EXCHANGE-TYPE TEG FOR MICRO-CHP

The application potential of heat exchange-type TEG in micro-CHP (combined heat and power) schemes is discussed. The outlook for using such TEG is outlined.

Key words: thermoelectric generator, micro-CHP, cogeneration

Introduction

Combined heat and power production (cogeneration) is one of the most efficient trends in energy saving that has an exceptionally wide application field. This trend is based on the fact that all thermal energy consumers use low-grade heat carriers (hot water, saturated steam), while production of such heat carriers is based on high-grade sources of energy (organic fuel combustion products). Fraction of thermal energy used in the high-temperature range for electric energy generation permits to increase considerably the efficiency of fuel utilization and reduce the working cost of thermal and electric energy. First and foremost, cogeneration schemes found application in industry where all prerequisites existed to this end, and then started to extend to municipal engineering, one of the largest consumers of organic fuel. Primarily it is related to district heating systems where it is possible to complete water heaters with gas steam or gas reciprocating units. At the same time, methods for economic encouragement of resource-saving technologies are improved. Scientific and technical progress in the field of using renewable energy sources (wind, solar, geothermal, biomass energy) inevitably results in the expansion and practical implementation of the concept of decentralized power supply, where on an equal basis with heavy power plants, of considerable importance are low-power distributed sources of electric energy working for a unified power grid. In the most developed countries this process is encouraged by special legislative acts and pricing system that assure the cost effectiveness of such sources of energy and the respective inflow of investments to this field, which also stimulates development of new technologies and equipment for cogeneration microsystems (according to the rules adopted in the EU, micro-CHP include systems of less than 50 kW power output). As an example, we refer to micro-CHP systems based on domestic gas boilers using for their operation the Diesel [1], Stirling [2] and Rankine [3] cycles. An exceptionally wide market for such systems in the European Union countries, USA and Japan is supported by legislative acts that permit to supply generated power to electric grid according to tariffs assuring equipment payback. Preliminary analysis of technical and economic features of such systems provides an opportunity to predict that thermoelectric generators also can find their niche in this market.

Fig.1 shows a cogeneration scheme of a gas boiler operated with the use of organic Rankine cycle (ORC) [3]. High-temperature combustion products of gas fuel 1 come to steam generator 2, where overheated steam of organic heat carrier 3 is generated, which actuates turbo-generator with the rotor wheel of spiral type 4. Then the steam comes to a condenser 5 where it gives heat to heat carrier of heating system and is condensed. Condensate comes back to steam generator and the cycle is closed. A mandatory requirement for this scheme is the availability of storage tank in heating system, assuring a more uniform generator operating mode.

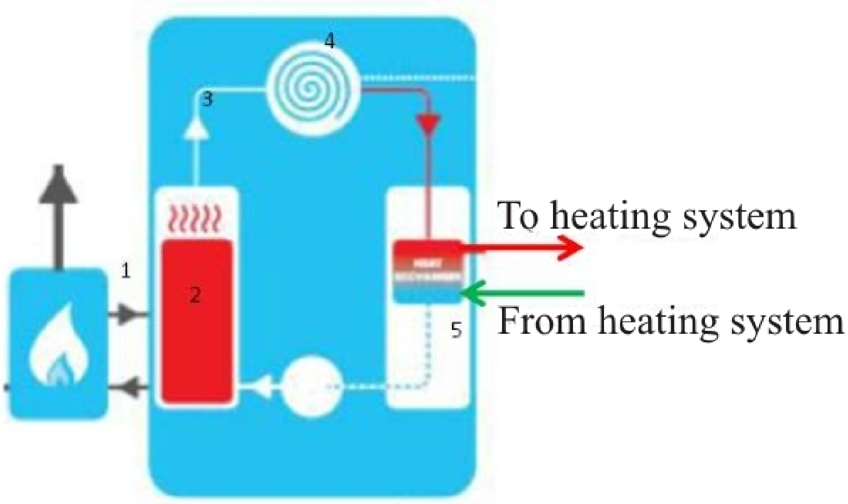


Fig.1. Schematic of micro-CHP with ORC [3]

Such Flow Energy –manufactured micro-CHP [3] has the following characteristics:

- thermal power – 16.9 kW;
- electric power - 1000 W;
- average productivity – 2000 kW-h/year;
- hot water delivery to heating system – 0.217 kg/s;
- maximum water temperature - 82°C;
- gas flow rate – 1.8 m^3/h;
- thermal efficiency – 92%;
- retail cost - 3675£ (5700$US);
- electricity tariff 0.1345 £/kW-h (0.2$US/kW-h) [4];

The above data imply that coefficient of thermal into electric energy conversion for this micro-CHP is about 6%, that is, parameters of the generating part correlate completely with the level of modern TEG parameters. Below we consider one of possible schemes of TEG for micro-CHP and give the results of analysis of its technical and economic characteristics.

Scheme of TEG for micro-CHP

Schematic of micro-CHP/TEG under study is given in Fig.2. Unlike that considered above, it requires minimal modification of the boiler and can be adapted to any gas boiler through change of its temperature conditions. Gas boiler 1 heats intermediate heat carrier to temperature t_{ho}, following which the latter comes to the hot channels of heat exchange-type TEG 2 [5]. Heat carrier from the storage tank of heating system 3 with temperature t_{xo} comes to the cold channels of TEG, where it is further heated to the necessary temperature t_{xe}, following which it returns to heating system. Part of heat flux flowing between heat carriers is converted into electric energy. Inverter 4 must be also used in the scheme to convert direct current of TEG to alternating current of required parameters.

Fig. 2. Schematic of micro-CHP/TEG

Let us consider conditions whereby such micro-CHP/TEG can compete with the scheme based on the use of ORC. It is evident that the main requirement for this is to assure technical and economic features that correspond to the above and guarantee acceptable equipment repayment periods. The basic data for the analysis of micro-CHP/TEG can be defined as follows:

- electric power	N_o = 1000 W;
- thermal power	Q_o =16,9 kW;
- hot heat carrier temperature	t_{ho} = 250°C;
- TEG input water temperature	t_{xo} = 65°C;
- maximum TEG unit cost	$Price_{max}$ = 1200 $US/kW.

Hot heat carrier temperature was selected on the basis of using low-temperature thermoelectric material (Bi_2Te_3) in the TEG. Maximum unit cost of the TEG was determined on the basis of 3-year repayment period with regard to tariff for electric energy 0.2$US/kW-h.

Micro-CHP/TEG performance analysis

The task of the analysis is to define in the space of the basic technical and economic parameters of TEG such ratios thereof which assure the solution of the problem. For this purpose, we shall use a mathematical model given in [6]. Under conditions in hand, the decisive influence on the technical and economic features of TEG is exerted by thermal resistance ratios characterizing the process of heat transfer in the heating heat carrier – thermoelement – cooling heat carrier system. In the generalized form they are defined by the Biot criteria values on the cold (Bi_x) and hot (Bi_h) thermopile side

$$Bi = \frac{\alpha h}{\lambda}, \tag{1}$$

where $\alpha = \frac{1}{R_t}$ is the effective coefficient of heat exchange between the surface of junctions and heat carrier that takes into account all thermal resistances on the way of heat flux the sum of which comes to $R_t = \frac{1}{\alpha_0}$. Here, α_o is coefficient of heat exchange; h_i and λ_i is the thickness and thermal conductivity of each layer on the way of heat flux (connecting elements, heat spreader, thermopile package, solder layers, etc).

As long as $\sum_{i} = \frac{h_i}{\lambda_i}$ component is primarily defined by thermopile fabrication method, to independent parameters one should refer only thermoelement height h and coefficients of heat exchange on the cold α_x and hot side α_h. Let us consider in more detail the effect of these parameters and their related restrictions.

In [7], it was shown that for fixed heat exchange conditions (α_x=const; α_h=const) maximum power is realized under $Bi = 1$, that is, there is a completely defined optimal thermoelement height h that assures maximum power. In this case, the available temperature difference $dt_o=[t_{ho} - t_{xo}]$ is equally divided between the useful drop ($dT=T_h - T_x$) and the loss in the drop ($dt=[(t_{ho} - T_h) + (T_x - t_{xo})]$) on thermal resistances R_t. The influence of thermoelement height on these parameters in dimensionless form is illustrated in Fig.3.

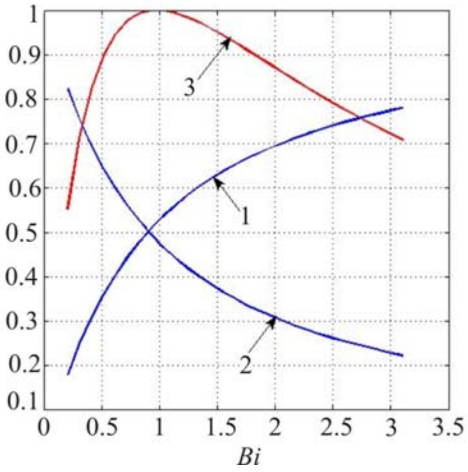


Fig.3. Dependences of the useful temperature drop (1), the loss in temperature drop (2) and thermoelement power (3) on the Biot criterion.

At the same time, the absolute power value is essentially dependent on heat exchange coefficient and monotonically increases with the latter (Fig.4).

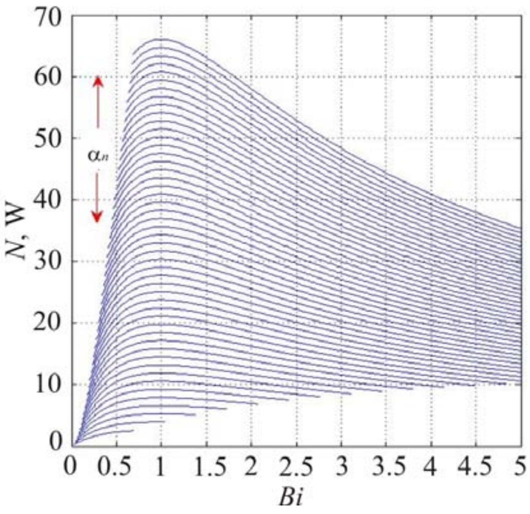


Fig.4. Dependence of thermoelectric module power on Bi for different combinations of thermoelement height h and heat exchange intensity α (arrows are used to denote the direction of parameter growth)

Thus, the optimal value of thermoelement height for known intensity of heat exchange is readily found from condition of Bi =1, Fig.5.

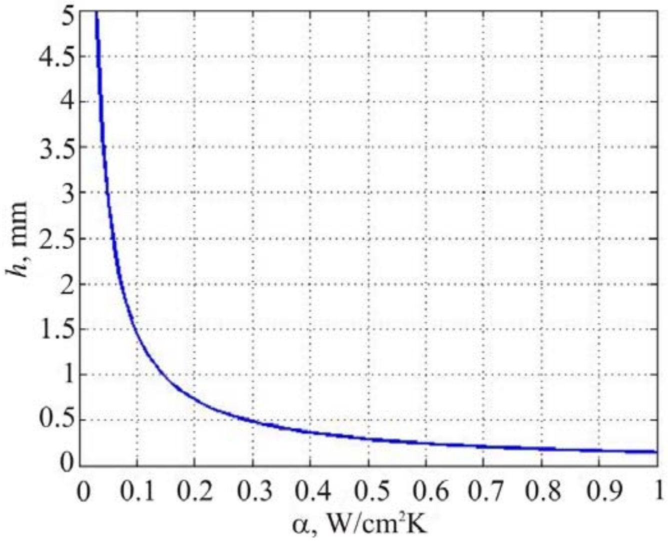


Fig. 5. Dependence of thermoelement optimal height h on the intensity of heat exchange α.

Dependences of power and efficiency of standard module 50×50 mm on the parameters under consideration are given in Fig.6 and Fig.7. Fig. 8 shows a counter plot visualizing the ratios between module power and efficiency that meet one of the main requirements of the problem – the efficiency > 6% (the respective ratio of h to α is marked by arrows).

For the most widespread technologies of thermoelectric module manufacturing the lower limit of thermoelement height can be assumed as h=0.5 mm. As it follows from Fig.8, for the effective use of thermoelements of such height it is necessary to assure condition $\alpha > 0.25$ ($R_t = 1/\alpha < 4$). Taking into account that a typical value of heat exchange coefficient for conditions under consideration is $\alpha_o \approx 1$ W/cm^{2}K (that is, $R_{t\alpha} \approx 1$), one can formulate concrete requirements to quality of thermopile heat spreaders, namely their total thermal resistance must fit in the value of $\sum_i = \frac{h_i}{\lambda_i} < 3$.

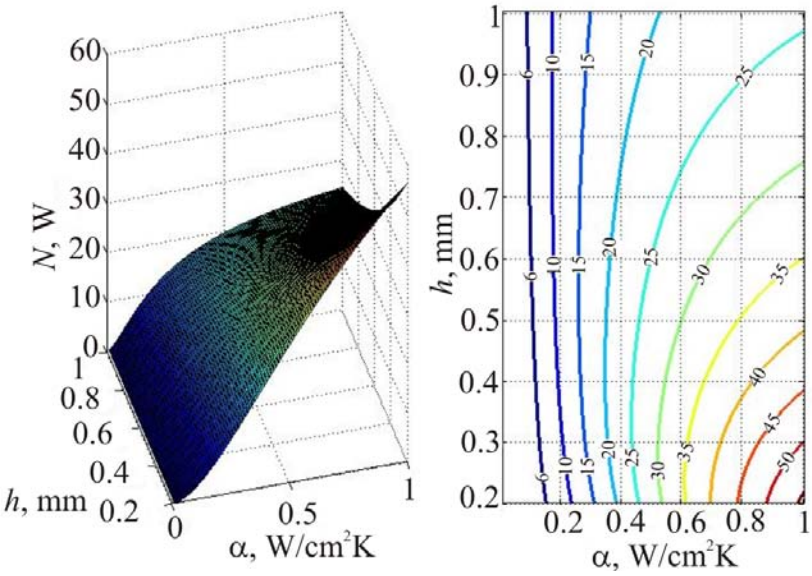


Fig.6. Dependence of TEG module power N on h and α.

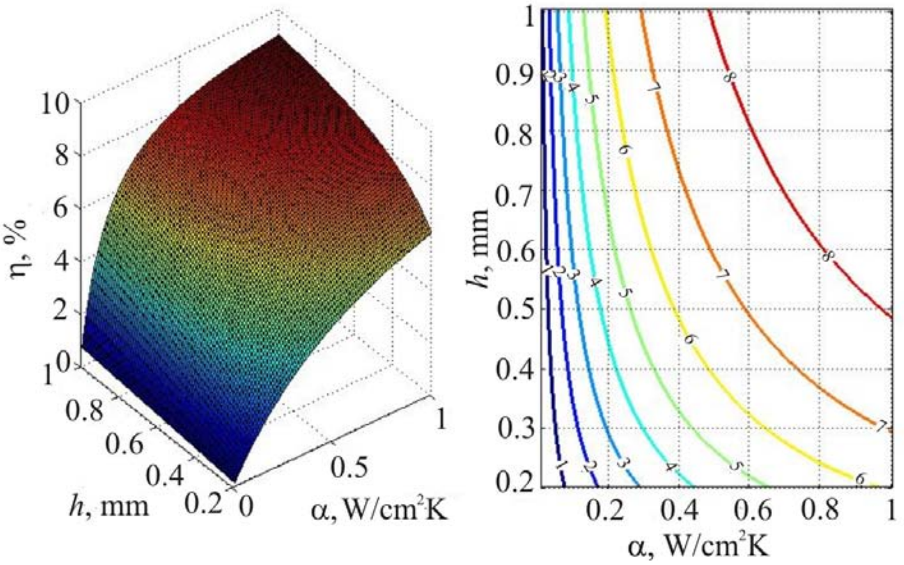


Fig.7. Dependence of TEG module efficiency on h and α.

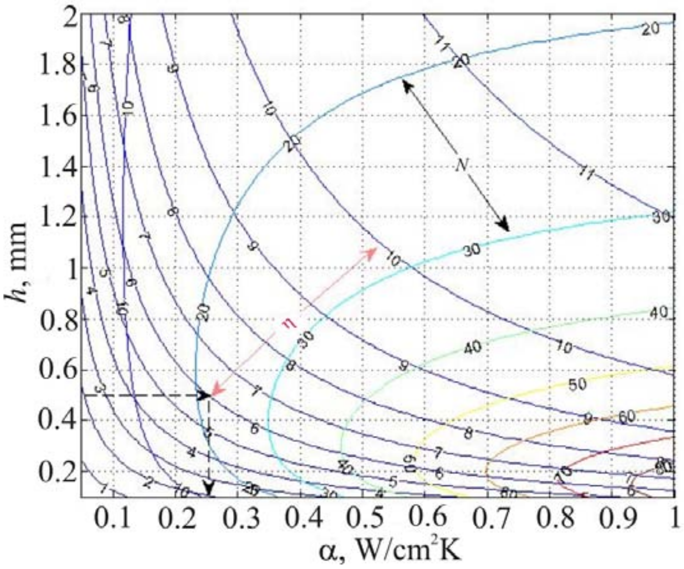


Fig. 8. An area of feasible solutions for TEG module in h, α space.

Based on these calculations, one can estimate the unit cost of CHP/TEG. For this purpose, the ratio for estimation of thermoelectric module unit cost has been used in the form:

$$\text{Price } = (k_1 g_m / k_2) / N_m, \text{\$US} / \text{W} \tag{2}$$

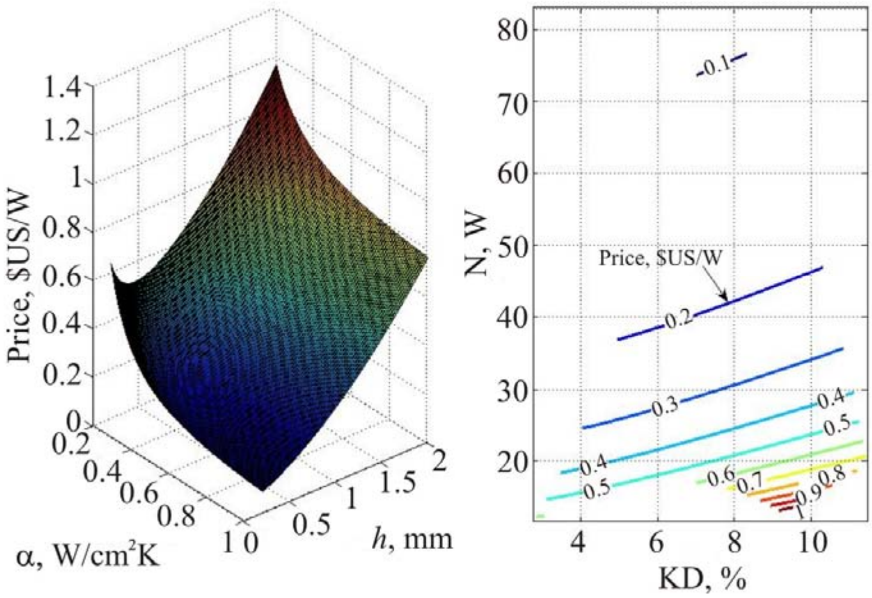
where N_m – is module power, *W*;

g_m is mass of thermoelectric material in the module, *g*;

k_1= 0.4 is thermoelectric material cost, *\$US/g;*

k_2=0.35 is the share of material cost in total module cost.

Coefficients k_1, k_2 have been found from the analysis of market value of thermoelectric modules. The results obtained are given in Fig. 9.



a) *b)*

Fig. 9. Unit cost of TEG module ($US/W) in the area of feasible solutions.

From Fig.6*b* it follows that the real cost of TEG (0.3$US/W) corresponds to power range of standard module 50×50×0.5 mm N_m =25...30 W and efficiency 6...8%. That is, the electric power of micro-CHP/TEG of given thermal power Q_o =16.9 kW can reach 1.3 kW with the total amount of thermoelectric modules about 50 pcs and their total cost about 400 $US which meets completely the requirements of problem set (with account of additional expenses, as well as the cost of inverter and TEG design on the whole, the price of generating part of micro-CHP/TEG fits reliably in the sum of 1200$US).

Conclusions

1. A scheme of micro-CHP/TEG based on gas boiler and heat exchange-type TEG has been considered.
2. It has been shown that the above scheme has quite acceptable technical and economic features that can assure its competitive ability in the market for micro-CHP.
3. The main requirements to TEG parameters assuring optimal technical and economic features of micro-CHP have been formulated.

Designations: h – thermoelement height, mm; T – thermoelement temperature; t – heat carrier temperature; T_p – characteristic temperature; λ – thermal conductivity coefficient, W/cm K; R_t – thermal resistance, cm^{2}K/W; α – heat exchange coefficient, W/cm^{2}K; $Bi = \frac{\alpha h}{\lambda}$ – Biot criterion.

Indices: h – hot; x – cold

References

1. http://world.honda.com/power/cogenerator/
2. http://viessmann.com.ua/sistemy-otoplenia-463/Kogeneracionnaia ustanovka VITOTWIN 300-W Mikro-KWK s dvigatelem Stirlinga.html

3. http://www.flowenergy.uk.com/meet-flow/
4. https://www.ofgem.gov.uk/environmental-programmes/feed-tariff-fit-scheme/tariff-tables
5. Yu.M.Lobunets, Thermoelectric Generator, Patent of Ukraine №8357 of 27.08.2013.
6. Yu.M.Lobunets, Performance Analysis of Heat-Exchange Type Thermoelectric Generator, J.Thermoelectricity 1. – P. 54 – 61 (2014).
7. Yu.M.Lobunets, Heat-Exchange Type TEG for Marine Propulsion Plants, J.Thermoelectricity **5**, 2014. – P. 29-36.

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