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THERMOELECTRIC POWER SOURCES USING LOW-GRADE HEAT (PART 2)

This work is the second part of a series of studies on thermoelectric power sources using low-grade heat. The results of computer-aided design of a thermoelectric generator with forced convection heat exchange that uses thermal waste from industrial installations are presented. The generator design has been developed and a series of experimental studies have been conducted on a test bench. Bibl. 9, Figs. 5.

Key words: thermoelectric generator, computer-aided design, heat recovery, heat exchange.

Introduction

General characterization of the problem. The wide application of thermoelectric equipment, particularly in heat recuperators, is largely determined by the efficiency of thermoelectric energy converters. Traditionally, their productivity has been increased through the study and improvement of thermoelectric materials [1, 2]. However, in recent decades, progress in this area has remained insignificant.

In so doing, the efficiency of thermoelectric devices depends not only on the properties of the materials, but also on their optimal use in the design of the devices. Analysis of scientific sources shows [3–8] that the actual indicators of the efficiency, as well as the coefficient of performance and heating coefficient, are significantly lower than predicted, even with high figure of merit of materials. The main reason for this is the significant energy losses caused by the imperfection of heat exchange systems that provide heat removal and supply to thermoelectric converters. Losses can reach 20–50%, and their compensation would require a significant improvement in the characteristics of thermoelectric materials, which is currently unrealistic.

This paper presents the results of research aimed at improving the design of thermoelectric power sources for the use of low-grade thermal energy of industrial installations. The results of theoretical and experimental studies of a thermoelectric recuperator with forced convection heat exchange are presented, as well as their comparison with the design option described in [9].

Physical model of a thermoelectric generator with a forced convection

A feature of this design option is the presence of fans that force air through the heat sinks to ensure the highest efficiency of heat exchange, while consuming electrical energy.

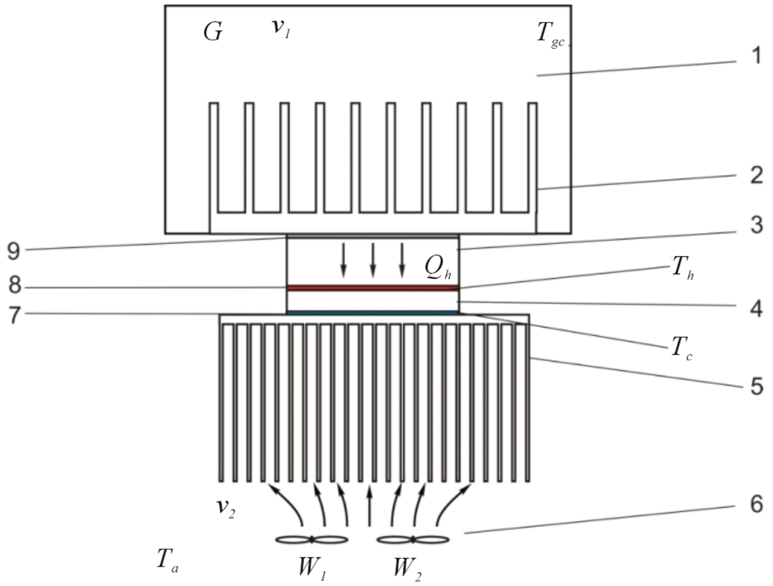

Fig. 1. Physical model of a thermoelectric generator with heat removal by an air heat exchanger: 1– a source of thermal energy (industrial installation) releasing heat onto its surface with heated gases, 2 – air heat exchanger, 3 – heat spreader between the air heat exchanger and thermoelectric modules, 4 – thermoelectric generator modules, 5 – cold air heat exchanger, 6 – electric fans, 7–9 – thermal contact between the structural elements of the thermoelectric generator

Calculation of thermoelectric generator efficiency

Let us consider the main parameters of a thermoelectric generator, the physical model of which is shown in Fig. 1. These include the electric power W generated by thermoelectric modules, as well as their efficiency η, which is determined by the ratio of the obtained electric power W to the thermal power Q consumed by the heat sources. However, during operation, the thermoelectric generator (TEG) additionally consumes electrical energy (powering air fans, electric pumps, etc.) In addition, there are always heat losses in its structural elements Q_l, which are mainly associated with the imperfection of the heat supply and removal systems. Therefore, the real useful electrical power of the TEG will be less than $W_r = W - W_1 - W_2$, accordingly, the real efficiency will be determined by the value of W_r and the real heat flux Q_r, that will take into account all losses in the TEG structural elements $\eta_{TEG} = W_r / Q_r$.

$$\eta_{TEG} = \frac{W_u}{Q_f}, \tag{1}$$

where η_{TEG} is TEG efficiency, W_u .is useful electrical power, Q_f is consumed thermal power.

$$W_f = W_{TEP} - W_{e.p.}, \tag{2}$$

where W_{TEP} is the electric power of the thermopile, $W_{e.p.}$ is the electric power used for additional power supply of the TEG (power supply of electric fans).

$$W_{TEP}(T_h, T_c) = Q_h \cdot \eta_{TEP}(T_h, T_c), \tag{3}$$

$$Q_h = Q_c + W_{TEP}(T_h, T_c). \tag{4}$$

In the formulae, Q_h is heat flux to the thermoelectric module, Q_c is heat flux after the thermoelectric module, T_h is the hot side temperature of the thermoelectric module, T_c is the cold side temperature of the thermoelectric module, $\eta_{TEP}(T_h, T_c)$ is the efficiency of the thermopile.

$$Q_f = C \cdot m \cdot (T_{g.c.} - T_a) = C \cdot G \cdot \rho \cdot (T_{g.c.} - T_a), \tag{5}$$

where C is heat capacity of the coolant, m is mass of the coolant, G is coolant flow rate, ρ coolant density, $T_{g.c.}$ is temperature of the gas coolant, T_a is ambient temperature.

The heat flux and the hot and cold temperatures of the thermoelectric module are determined from the heat balance equations:

$$Q_h = \alpha_1(v_1) \cdot S_1 \cdot (T_{g.c.} - T_1), \tag{6}$$

where $\alpha_1(v_1)$ is the heat transfer coefficient of the outer surface of the air heat exchanger, which is a function of the velocity of the hot coolant v_1, S_1 is the area of the outer surface of the air heat exchanger in contact with the hot coolant, T_1 is the temperature of the surface of the air heat exchanger in contact with the hot coolant;

$$Q_h = \chi_1 \cdot (T_1 - T_2), \tag{7}$$

where χ_1 is thermal resistance of the hot air heat exchanger, T_2 is temperature of the inner surface of the air heat exchanger;

$$Q_h = \chi_{c.r.} \cdot (T_2 - T_3), \tag{8}$$

where $\chi_{c.r.}$ is thermal contact resistance between the hot heat exchanger and the metal heat-conducting element, T_3 is the surface temperature of the metal heat-conducting element in contact with the hot heat exchanger;

$$Q_h = \chi_2 \cdot (T_3 - T_4), \tag{9}$$

where χ_2 is thermal resistance of the metal heat-conducting element, T_4 is the surface temperature of the metal heat-conducting element in contact with thermoelectric modules;

$$Q_h = \chi_{c.r.} \cdot (T_4 - T_h), \tag{10}$$

where $\chi_{c.r.}$ is thermal contact resistance between the metal heat-conducting element and thermoelectric modules;

$$Q_h = \chi_m \cdot (T_h - T_c) + W_{TEP}(T_h, T_c), \tag{11}$$

where χ_m is thermal resistance of thermoelectric modules;

$$Q_c = \chi_{c.r.} \cdot (T_c - T_5), \tag{12}$$

where $\chi_{c.r.}$ is thermal contact resistance between thermoelectric modules and air heat exchanger, T_5 is surface temperature of air heat exchanger in contact with thermoelectric modules;

$$Q_c = \chi_3 \cdot (T_5 - T_6), \tag{13}$$

where χ_3 is thermal resistance of air heat exchanger, T_6 is surface temperature of liquid-air heat exchanger in contact with the environment;

$$Q_c = \alpha_2(v_2)\cdot S_2 \cdot (T_5 - T_a)\,, \tag{14}$$

where $\alpha_2(v_2)$ is the heat transfer coefficient of the outer surface of air heat exchanger, which is a function of air velocity v_2, S_2 is the surface area of air heat exchanger in contact with the environment;

Substituting (2–5) into (1), we obtain:

$$\eta_{TEG} = \frac{W_u}{Q_f} = \frac{W_{TEP} - W_{e.p.}}{G\cdot\lambda} = \frac{Q_h \cdot \eta_{TEP}\left(T_h, T_c\right) - W_{e.p.}}{G\cdot\lambda} \tag{15}$$

$$\eta_{TEG} = \frac{\dfrac{\alpha_1 \cdot S_1 \cdot \left(T_{g.c.} - T_a\right)\cdot \eta_{TEP}\left(T_h, T_c\right)}{1 + \alpha_1 \cdot S_1 \cdot \left[N_1 + N_2 \cdot \left(1 - \eta_{TEP}\left(T_h, T_c\right)\right)\right]} - W_{e.p.}}{G\cdot\lambda} \tag{16}$$

where

$$N_1 = \frac{1}{\chi_1} + \frac{1}{\chi_2} + \frac{1}{\chi_3} + \frac{1}{\chi_{c.r.}} + \frac{1}{\chi_m}\,, \tag{17}$$

$$N_2 = \frac{1}{\chi_4} + \frac{1}{\chi_{c.r.}} + \frac{1}{\alpha_2 \cdot S_2} + \frac{1}{\alpha_3 \cdot S_3} + \frac{1}{\chi_5} + \frac{1}{\alpha_4 \cdot S_4}\,. \tag{18}$$

Choosing the optimal heat exchange system

The output electric power of the TEG and its efficiency depend on the temperature and thermal conditions on the thermoelectric modules, provided by the heat supply and removal system. In turn, forced air flow by electric fans is used to increase the efficiency of the heat exchange system.

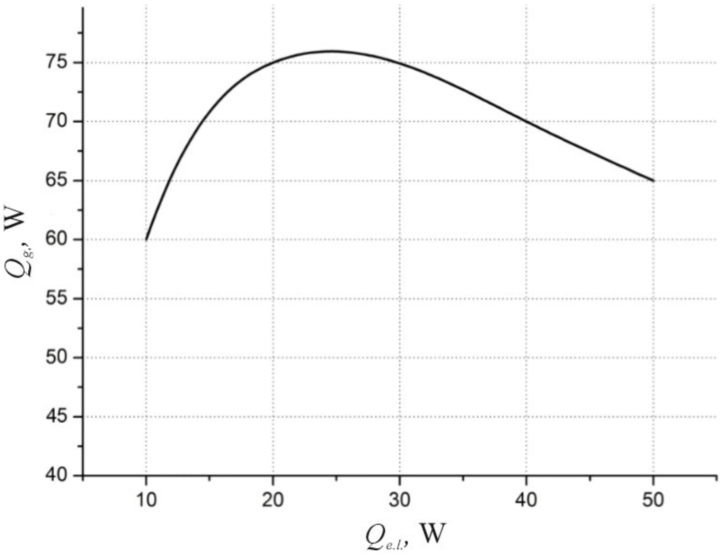

Fig.2. Dependence of the output electrical power of the TEG on the power consumed by the heat exchange system

Fig. 2 shows the dependence of the output electric power of the TEG on the power consumed by the heat exchange system (based on 8 standard thermoelectric modules). As can be seen from the figure, the optimal electric power of the heat exchange system $Q_{e.l.}$ = 25 W was found, which provides the highest efficiency of the TEG.

Development of a thermoelectric generator design with forced air circulation

Figs. 3, 4 show the design results in the form of two options of TEG with forced convection with a design power of 80 and 40 W, respectively.

The TEG unit shown in Fig. 3 contains one hot heat exchanger located on the hot side and an individual cold air heat exchanger. Air blowing is carried out by electric fans through a specially created air collector on the outer cover of the TEG. The air heat sinks are powered by electrical power generated by thermoelectric modules.

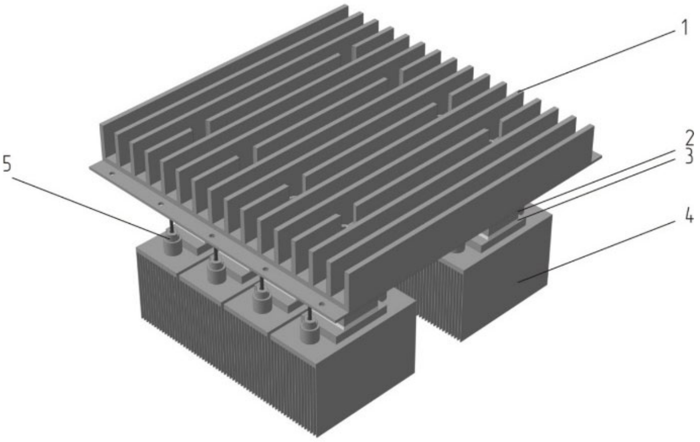

Fig.3. Design of an 80-watt thermoelectric recuperator unit with forced convection:
1 – hot heat exchanger, 2 – heat-conducting metal element, 3 – thermoelectric modules,
4 – cold heat exchanger, 5 – thermoelectric module mounting element

The disadvantage of this design was its bulkiness and difficulty in scaling.

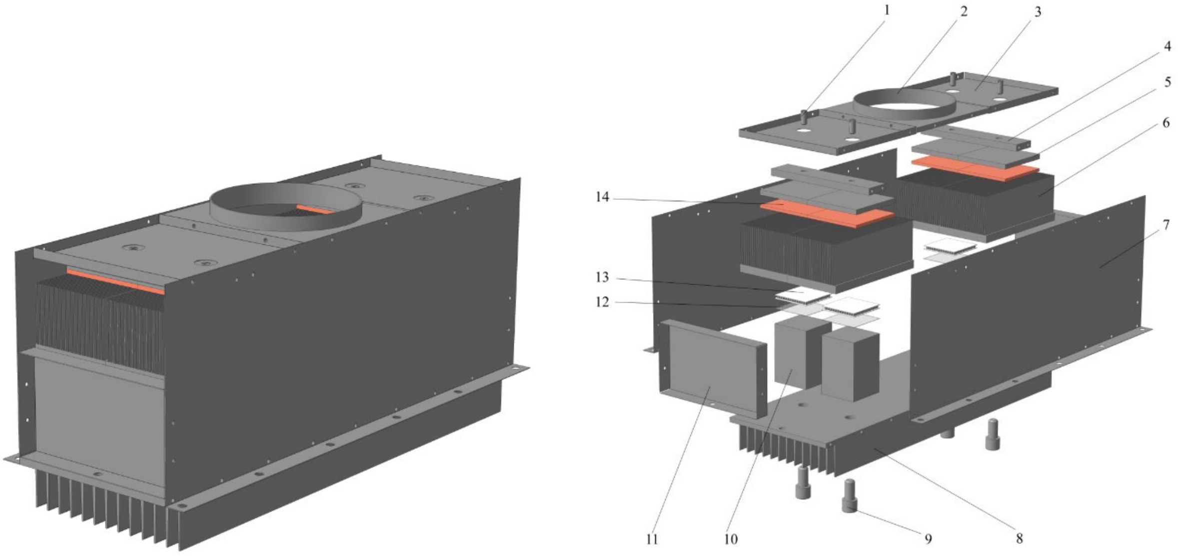

Fig.4. Design of a 40-watt thermoelectric recuperator unit with forced convection:
1 – clamping screw, 2 – fan mount, 3 – top cover, 4, 5, 14 – clamping plates, 6 – cold heat exchanger,
7 – side cover, 8 – hot heat exchanger, 9 – hot heat exchanger mounting screws, 10 – heat spreader,
11 – end cover, 12 – mica plate, 13 – thermoelectric module

Therefore, to eliminate these shortcomings, a block design of a thermoelectric heat recuperator was developed. It consists of 4 Altec-1061 thermoelectric modules with an individual heat removal system.

The calculated values of efficiency and the electrical power generated by it are: efficiency = 2.9% and power $W = 30$ W.

Experimental test results

To determine the characteristics of the heat recovery unit shown in Fig. 4, bench tests were conducted. Fig. 5 shows the dependence of the electric power of the thermoelectric generator unit containing 4 thermoelectric modules on the hot side temperature of the thermoelectric modules.

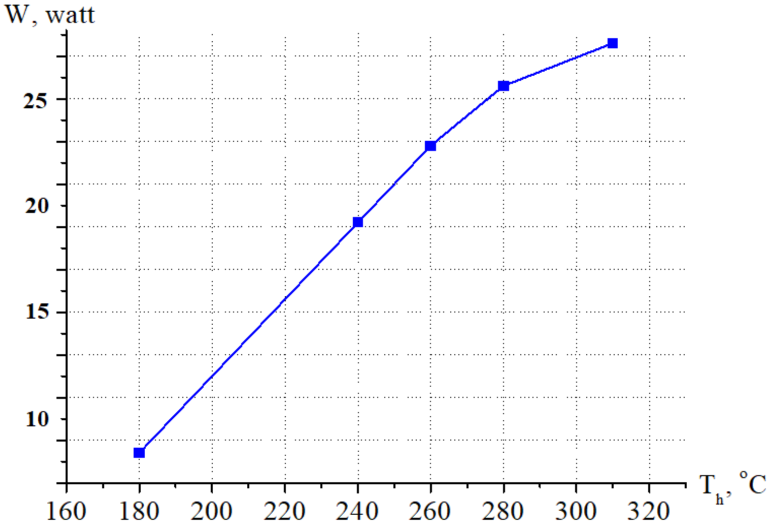

Fig.5. Dependence of the electric power of the thermoelectric generator unit on the hot side temperature of the thermoelectric modules

Thus, the output power of such a thermoelectric generator is $W = 28$ W at an efficiency of = 2.7%. It should be noted that the efficiency of the specified design is 1.8 times higher than for the option without forced air blowing by air fans. In addition, the specific dimensions of such a generator per 1 thermoelectric module are also almost 5 times better.

The topic of further research, presented in part 3 of this work, will be the design, experimental studies, and comparative analysis of a modernized design of a thermoelectric generator with liquid heat exchange and heat pipes.

Conclusions

1. A thermoelectric generator with forced convection heat exchange that uses low-grade thermal waste from industrial installations has been designed and developed.
2. Optimal parameters of the heat exchange system power supply have been established to ensure the highest efficiency, amounting to $Q_{e.l.} = 25$ W, calculated to provide the heat exchange system with 8 thermoelectric modules.
3. It has been established that the design efficiency of such a generator is 2.9%, which ensures the generation of electrical energy at the level of 7.5 W from one thermoelectric module.
4. Experimental studies were conducted that confirmed the main design results.
5. It was determined that the experimental values of the energy characteristics of the thermoelectric generator are: efficiency = 2.7% and power $W = 7$ W.
6. It has been analyzed that the considered design of the thermoelectric generator with heat exchange

by forced convection has the efficiency of the specified design 1.8 times higher than for the option without forced blowing by air fans. In addition, the specific dimensions of such a generator based on 1 thermoelectric module are also better by almost 5 times.

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ТЕРМОЕЛЕКТРИЧНІ ДЖЕРЕЛА ЕЛЕКТРИКИ, ЩО ВИКОРИСТОВУЮТЬ НИЗЬКОПОТЕНЦІЙНЕ ТЕПЛО (ЧАСТИНА 2)

Дана робота є другою частиною із циклу досліджень термоелектричних джерел електрики, що використовують низькопотенційне тепло. Приведені результати комп'ютерного проектування термоелектричного генератора із теплообміном вимушеною конвекцією, що використовує теплові відходи промислових установок. Розроблена конструкція генератора та проведена серія його експериментальних досліджень на випробувальному стенді. Бібл. 9, рис. 5.

Ключові слова: термоелектричний генератор, комп’ютерне проектування, рекуперація тепла, теплообмін.

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