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THERMOELECTRIC POWER SOURCES USING LOW-GRADE HEAT (PART 1)

This work is the first part of a series of studies on thermoelectric power sources using low-grade heat. The results of computer design of a thermoelectric generator with heat exchange by natural convection using waste heat from industrial installations are presented. The generator design was developed and a series of its experimental studies were carried out on a test bench.
Key words: thermoelectric generator, computer design, heat recovery, heat exchange.

Introduction

General characterization of the problem. Modern industry widely uses technological equipment and heat engines, such as turbines and internal combustion engines, which generate a significant amount of waste heat during their operation [1, 2]. This heat is usually not reused, but is dissipated into the environment, causing its "thermal pollution". Such a process negatively affects the environment, contributing to global warming and climate change.

Recovery and efficient use of waste heat energy, the capacity of which is estimated at 101 W, makes it possible to significantly reduce the heat load on the environment, increase the energy efficiency of industrial processes and increase the reliability of equipment. One of the common approaches to heat recovery is the use of a steam cycle, which is effective at high exhaust gas temperatures (about 500 ºC and above). However, in many cases, heat losses are low-grade, i.e. have a temperature range of 50 – 500 ºC, which makes the steam cycle ineffective [3].

In such conditions, a promising solution is the use of thermoelectric energy converters, which provide direct thermal into electrical energy conversion. According to preliminary estimates, the use of thermoelectric generators in industry can provide up to 10 % savings in fuel resources [3 – 9].

This paper presents the results of design and experimental studies of thermoelectric energy sources with various types of heat exchange systems for the use of low-grade thermal energy of industrial installations. Examples of the use of thermoelectric generators with free and forced convection, as well as with heat pipes, are given. Each of the above designs has certain advantages and disadvantages, which will be discussed further.

Physical model of a thermoelectric generator with free convection

The most structurally simple is a thermoelectric generator with free convection heat exchange.

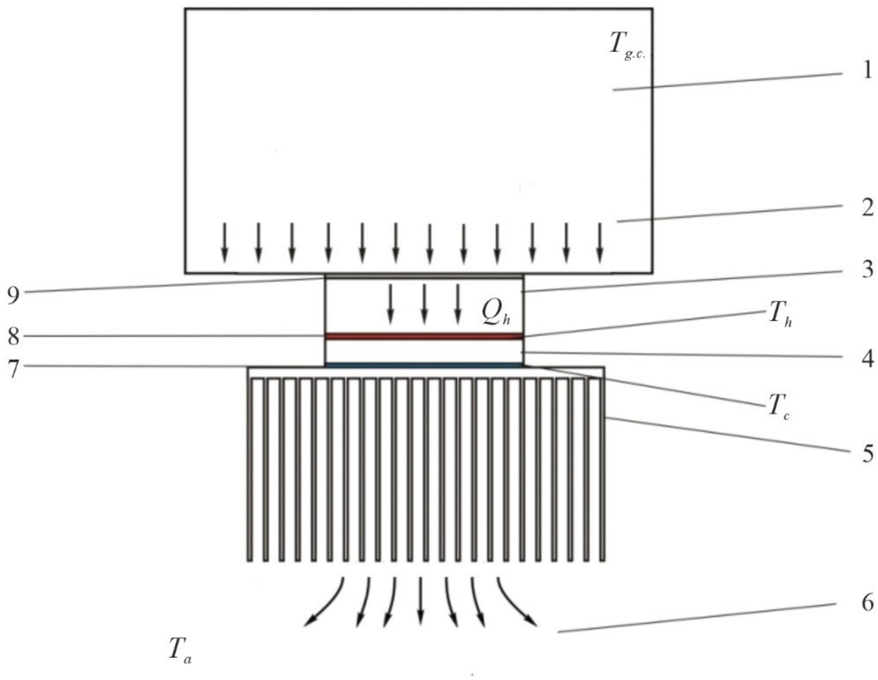

Fig. 1. Physical model of a thermoelectric generator with heat removal by an air heat exchanger: 1 – a source of thermal energy (industrial installation), releasing heat onto its surface with heated gases, 2, 3 – heat spreader between the surface of the heat source and thermoelectric modules, 4 – thermoelectric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

In this case, the recuperator does not require any additional power sources for the functioning of the heat exchange system.

Mathematical and computer descriptions of the model

Thus, the heat balance equation was used to calculate the thermoelectric generator according to the physical model (Fig. 1).

The hot side contains a heat source with a power of Q_1.

The supply of heat from the heated surface to the hot side of the thermoelectric module and the removal of heat to the cold heat exchanger are described by the equations:

$$Q_1 = \chi_1[T_1 - T_h], \tag{1}$$

$$Q_2 = \chi_2[\mathrm{T}_c - T_2], \tag{2}$$

where χ_1, χ_2 are the thermal resistances of the hot and cold heat exchangers; T_h, T_c are the temperatures of the hot and cold sides of the thermoelectric module, respectively; T_2 is the temperature of the outer surface of the cold heat exchanger.

Thermal power Q_2 is removed from the cold heat exchanger by free convection of air into the environment:

$$Q_2 = \alpha(T_2 - T_0)S_m, \tag{3}$$

where α is the coefficient of convective heat transfer between the heat exchanger surface and the environment; S_m is the area of the heat exchange surface; T_0 is the ambient temperature.

The electrical power generated by a thermoelectric module is proportional to Q_1 and its efficiency η:

$$W = Q_1[T_1)] \cdot \eta, \tag{4}$$

The main heat losses Q_3 occur through thermal insulation:

$$Q_3 = \chi_4(T_M - T_0), \tag{5}$$

where χ_4 is the thermal resistance of the insulation, T_M is the temperature of the inner surface of the thermal insulation.

Thus, the heat balance equation for the selected model of thermoelectric generator can be written as:

$$Q_1 = W + Q_2 + Q_3. \tag{6}$$

For computer representation of the mathematical model of the TEG, the Comsol Multiphysics application package was used. For this, it is necessary to represent our equations in the following form.

To describe the flows of heat and electricity, we will use the laws of conservation of energy

$$div\vec{E} = 0 \tag{7}$$

and electrical charge

$$div\vec{j} = 0, \tag{8}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{9}$$

$$\vec{q} = \kappa\nabla T + \alpha T\vec{j}, \tag{10}$$

$$\vec{j} = -\sigma\nabla U - \sigma\alpha\nabla T. \tag{11}$$

Here $\vec{E}$ is the energy flux density, $\vec{q}$ is the heat flux density, $\vec{j}$ is the electric current density, U is the electric potential, T is the temperature, α, σ, κ are the Seebeck coefficient, electrical conductivity and thermal conductivity.

With regard to (10) – (12), one can obtain

$$\vec{E} = -(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T - (\alpha\sigma T + U\sigma)\nabla U. \tag{12}$$

Then the laws of conservation (7), (8) acquire the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \tag{13}$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma\nabla U) = 0. \tag{14}$$

From the solution of equations (13) – (14) we obtain the distributions of physical fields, as well as the integral values of the efficiency and power of the TEG.

Design results

An analysis of the design results allows us to note that the thermal power for the operation of the specified design option of the thermoelectric generator can only be removed from the surface layers of gas in contact with the internal side walls of the industrial installation unit (1 in Fig. 2). The calculation showed that the heat flux value that can be obtained on the basic module at a hot operating temperature of 300 °C is 0.85 W/cm^2, and at 250 °C – 1.18 W/cm^2. Thus, the total heat power that can be removed from such a unit containing 4 walls measuring, for example, 2000 x 2000 mm^2, will be equal to 136 kW at a temperature of 300 °C and 189 kW at a temperature of 250 °C. With a TEG efficiency of 5 %, this gives a maximum TEG power of 6.8 kW at 300 °C and 7.5 kW at 250 °C.

This is the maximum theoretical limit for the case when heat is removed only from the side surfaces of the box. This is natural, since when using such a scheme, only a part of the thermal energy of the gas from the surface layers is carried away from the side walls. The internal layers of the gas under such conditions give off their thermal energy insignificantly.

A standard module with a hot contact area of 40 x 40 mm^2 consumes about 120 – 150 W of heat flux. In reality, when the module is in contact with the hot wall of an industrial unit, the heat flux will be about 13 – 15 W for a temperature of 300 °C and 8 – 20 W for a temperature of 250 °C, which is approximately almost 10 times less than the required heat flux values of 120 – 150 W. Thus, the idea of hot connection by pressing the module to the hot wall cannot be realized. The required heat flux value can be achieved by using heat concentrators, for example in the form of thickened internal walls. Fig. 2 shows the movement of heat flux to the module through such walls. The wall thickness of 1 mm, corresponding to the unit design, is insufficient. Special calculations have established that for steel sheets and effective heat transfer to the module, the wall thickness should be at least 3 – 4 mm.

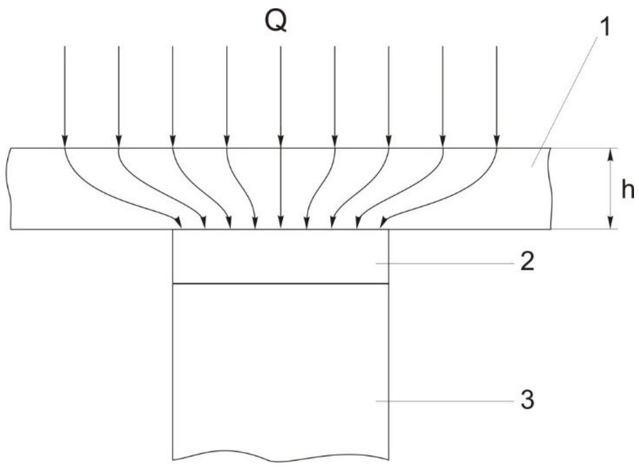

Fig. 2. 1 – inner wall of industrial installation unit; 2 – thermoelectric module;
3 – heat removal to air heat sink.

It is simpler at first glance to use small heat sinks for each module to remove heat from the hot gas. To determine the configuration of such a heat sink, a simulation was conducted and it was determined that its design should have the form shown in Fig. 3 (1 in Fig.3). The design of a cold heat sink with natural heat removal (3 in Fig.3) was calculated in a similar way. It consists of 15 plates 200 x 200 x 1 mm3, which provide the necessary heat removal without using additional energy for blowing. The design efficiency of such a generator is 1.9 %, which ensures the generation of electrical energy at the level of 5 W from one thermoelectric module.

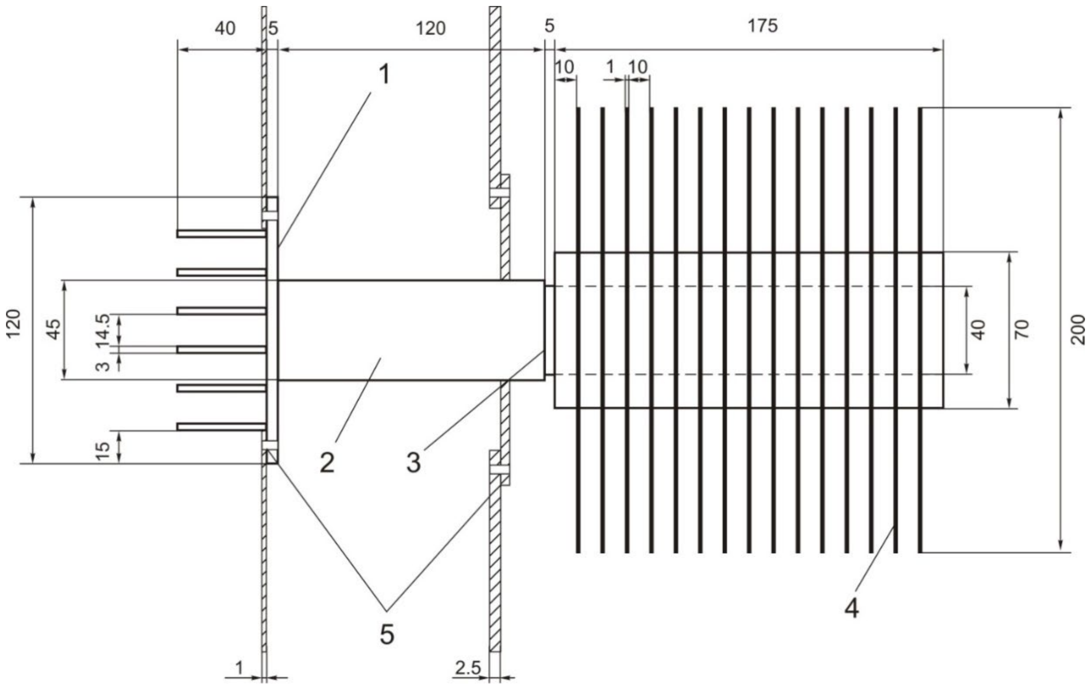

Fig. 3. Diagram of the TEG unit. 1 – hot heat exchanger, 2 – heat spreader, 3 – thermoelectric module, 4 – cold heat exchanger; 5 – generator mount.

Experimental test results

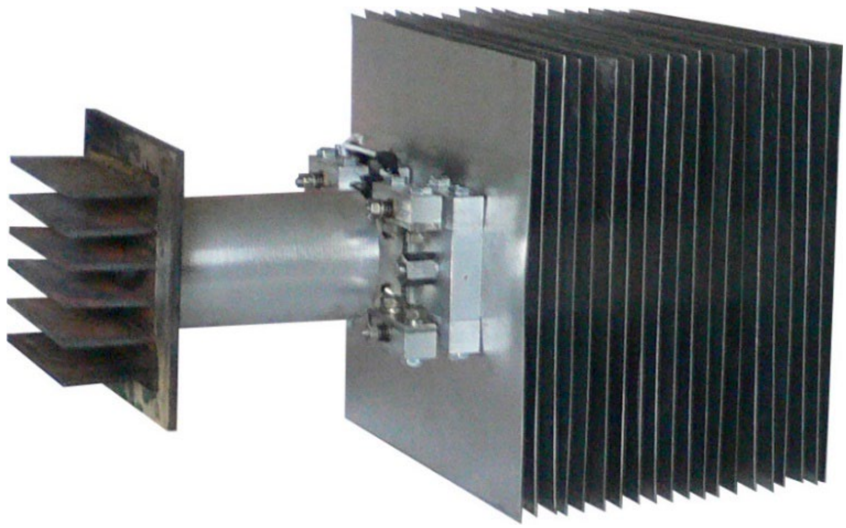

Fig. 4. Appearance of thermoelectric generator unit "Altec-8043".

Based on the theoretically calculated design of the thermoelectric generator, its experimental model was manufactured, shown in Fig. 4. Its testing was performed on a bench that best simulated the thermal operating conditions of the industrial installation, which were laid down during the design.

Therefore, as a result of the measurements, the efficiency and electrical power of the generator were determined, which are – efficiency = 1.5 % and power W = 3.9 W.

It should be noted that the considered design of a thermoelectric generator with heat exchange by natural convection is the least efficient, but the simplest and most reliable in use.

The topic of subsequent research, presented in part 2 of this work, will be the design, experimental studies, and comparative analysis of a modernized design of a thermoelectric generator with forced convection.

Conclusions

1. A thermoelectric generator with heat exchange by natural convection, which uses low-grade thermal waste from industrial installations, has been designed and developed.
2. It has been established that the design efficiency of such a generator is 1.9 %, which ensures the generation of electrical energy at the level of 5 W from one thermoelectric module.
3. Experimental studies were conducted, confirming the main design results.
4. It was determined that the experimental values of the energy characteristics of the thermoelectric generator are efficiency = 1.5 % and power W = 3.9 W.
5. It was analyzed that the considered design of a thermoelectric generator with heat exchange by natural convection is the least efficient, but the most simple and reliable in use.

References

1. European Commission. Energy 2020: Roadmap 2050. – http://ec.europa.eu/energy/energy2020/roadmap/index_en.html.
2. European Commission. Energy strategies: Roadmap 2050. – http://ec.europa.eu/energy/strategies/2011/roadmap_2050_en.html.
3. Anatychuk L.I., Lysko V.V., Prybyla A.V. (2022). Rational areas of using thermoelectric heat recuperators. *J. Thermoelectricity*, 3-4.
4. Anatychuk L.I. (2001). Rational areas of research and applications of thermoelectricity. *J. Thermoelectricity*, 1, 3 – 14.
5. Anatychuk L.I. (2007). Current status and some prospects of thermoelectricity. *J. Thermoelectricity*, 2, 7 – 20.
6. Anatychuk L.I., Hwang Jenn-Dong, Lysko V.V., and Prybyla A.V. (2013). Thermoelectric heat recuperators for cement kilns. *J. Thermoelectricity,* 5, 36 – 42.
7. Anatychuk L.I., Kuz R.V., Hwang J.D. (2012). The energy and economic parameters of *Bi-Te* based thermoelectric generator modules for waste heat recovery. *J. Thermoelectricity*, 4, 73 – 79.
8. Anatychuk L.I., Kuz R.V., Rozver Y.Y. (2012). Efficiency of thermoelectric recuperators of the exhaust gas energy of internal combustion engines. *AIP Conference Proceedings*, 1449, 516 – 519.
9. Anatychuk L.I., Kuz R.V. (2016). Thermoelectric generator for trucks *Journal of Thermoelectricity*, 3, 40 – 45.

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ТЕРМОЕЛЕКТРИЧНІ ДЖЕРЕЛА ЕЛЕКТРИКИ, ЩО ВИКОРИСТОВУЮТЬ НИЗЬКОПОТЕНЦІЙНЕ ТЕПЛО (ЧАСТИНА 1)

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

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

Література

1. European Commission. Energy 2020: Roadmap 2050. – http://ec.europa.eu/energy/energy2020/roadmap/index_en.html.
2. European Commission. Energy strategies: Roadmap 2050. – http://ec.europa.eu/energy/strategies/2011/roadmap_2050_en.html.
3. Anatychuk L.I., Lysko V.V., Prybyla A.V. (2022). Rational areas of using thermoelectric heat recuperators. *J. Thermoelectricity*, 3-4.
4. Anatychuk L.I. (2001). Rational areas of research and applications of thermoelectricity. *J. Thermoelectricity*, 1, 3 – 14.
5. Anatychuk L.I. (2007). Current status and some prospects of thermoelectricity. *J. Thermoelectricity*, 2, 7 – 20.
6. Anatychuk L.I., Hwang Jenn-Dong, Lysko V.V., and Prybyla A.V. (2013). Thermoelectric heat recuperators for cement kilns. *J. Thermoelectricity,* 5, 36 – 42.
7. Anatychuk L.I., Kuz R.V., Hwang J.D. (2012). The energy and economic parameters of *Bi-Te* based thermoelectric generator modules for waste heat recovery. *J. Thermoelectricity*, 4, 73 – 79.
8. Anatychuk L.I., Kuz R.V., Rozver Y.Y. (2012). Efficiency of thermoelectric recuperators of the exhaust gas energy of internal combustion engines. *AIP Conference Proceedings*, 1449, 516 – 519.
9. Anatychuk L.I., Kuz R.V. Thermoelectric generator for trucks (2016). *Journal of Thermoelectricity*, 3, 40 – 45.

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