**DOI**: 10.63527/1607-8829-2024-4-61-68

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# THERMOELECTRIC POWER SOURCES USING LOW-GRADE HEAT (PART 3)

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

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

## Introduction

*General characterization of the problem.* Further improvement of the efficiency of thermoelectric generators using low-grade heat is largely related to the optimization of their heat exchange system [1 – 5]. The most promising in this context is a combination of a combined liquid and air heat exchange system using heat pipes and thermosyphons [6 – 9], which ensure the transfer of a large amount of thermal energy with minimal losses. Their use also simplifies the integration of a thermoelectric generator with industrial installations that emit a large amount of waste thermal energy.

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 an air-liquid heat exchange system and heat pipes for supplying thermal energy to it, as well as their comparison with previous design options described in [1 – 2], are presented.

## Physical and mathematical models of a thermoelectric generator

The physical model of a thermoelectric heat recuperator with heat removal by a liquid-air heat exchanger is presented in Fig. 1. This model is the most general and takes into account all the possibilities of heat exchange systems in combination with thermoelectric energy conversion. Therefore, the direct conversion of thermal energy of the waste heat source into electrical energy of electric power W is carried out using thermoelectric generator modules 4. The heat flux $Q_h$ from the hot coolant 1 with temperature $T_{gas\ c}$ and flow rate $G$ is transferred to the fins 2 of the heat pipe 3, which transfers heat $Q_h$ to the thermoelectric module 4. Heat removal from the cold side of the thermoelectric module is carried out by a cold heat exchange circuit containing a liquid heat exchanger 5 and a liquid-air heat exchanger 7. The movement of the liquid is provided by a liquid pump 6, which consumes electrical power $W_1$, and the movement of the air is intensified by a fan 8, which consumes electrical power $W_2$. In this model, heat losses occur on the elements of the heat exchange system and due to the presence of contact thermal resistances.

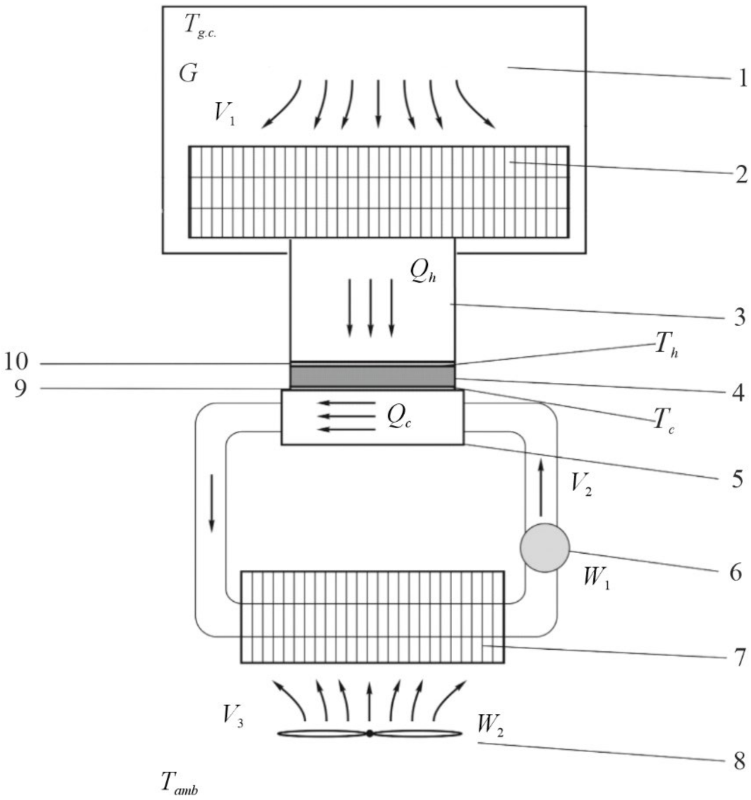


*Fig. 1. Physical model of a thermoelectric heat recuperator: 1 – volume filled with hot coolant, 2 – heat pipe fins 3, 4 – thermoelectric modules, 5 – liquid heat exchangers, 6 – liquid pump, 7 – liquid-air heat exchangers, 8 – air fan, 9, 10 – thermal contact area between the elements of the recuperator structure*

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.), moreover, there are always heat losses in its structural elements $Q_{loss}$, 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 $W_p = W - W_1 - W_2$, accordingly, the real efficiency will be determined by the value of $W_p$ and the real heat flux $Q_p$, which will take into account all losses in the TEG structural elements $\eta_{TEG} = W_p / Q_p$.

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

where $\eta_{TEG}$ is TEG efficiency, $W_u$ is useful electric power, $Q_{cons}$ is consumed thermal power.

$$W_u = W_{thermopile} - W_{loss}, \tag{2}$$

where $W_{thermopile}$ is the electric power of the thermopile, $W_{loss}$ is the electric power used for additional power supply to the TEG (power supply to electric fans and electric liquid pumps).

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

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

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

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

where $C$ is coolant heat capacity, $m$ is coolant mass, $G$ is coolant flow rate, $\rho$ is coolant density, $T_{g.c.}$ is gas coolant temperature, $T_{amb}$ is ambient temperature, .

The heat flux and the temperatures of the hot and cold sides 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 liquid-air heat exchanger, which is a function of the hot coolant velocity, $S_1$ is the area of the outer surface of the liquid-air heat exchanger in contact with the hot coolant, $T_1$ is the temperature of the surface of the heat pipe in contact with the hot coolant;

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

where $\chi_1$ is the thermal resistance of the heat pipe, $T_2$ is the c old side temperature of the heat pipe;

$$Q_h = \chi_2 \cdot (T_3 - T_h), \tag{8}$$

where $\chi_2$ is the thermal contact resistance between the heat pipe and thermoelectric modules;

$$Q_h = \chi_3 \cdot (T_h - T_c) + W_{ТЕБ}(T_h, T_c), \tag{9}$$

where $\chi_3$ is the thermal resistance of thermoelectric modules;

$$Q_c = \chi_4 \cdot (T_c - T_4), \tag{10}$$

where $\chi_4$ is the thermal contact resistance between the thermoelectric modules and the liquid heat exchanger, $T_4$ is the temperature of the liquid heat exchanger surface in contact with the thermoelectric modules;

$$Q_c = \chi_5 \cdot (T_4 - T_5), \tag{11}$$

where $\chi_5$ is the thermal resistance of the water heat exchanger, $T_5$ is the temperature of the cold liquid heat exchanger surface in contact with the liquid;

$$Q_c = \alpha_2(v_2) \cdot S_2 \cdot (T_5 - T_6), \tag{12}$$

where $\alpha_2(v_2)$ is heat transfer coefficient of the liquid heat exchanger, which is a function of the liquid velocity $v_2$, $S_2$ is surface area of the liquid heat exchanger, $T_6$ is average fluid temperature between the inlet and outlet of the cold liquid heat exchanger;

$$Q_c = \alpha_3(v_2) \cdot S_3 \cdot (T_6 - T_7), \tag{13}$$

where $\alpha_3(v_2)$ is the heat transfer coefficient of the inner surface of the liquid-air heat exchanger, which is a function of the liquid velocity $v_2$, $S_3$ is the internal surface area of the liquid-to-air heat exchanger, $T_7$ is the average temperature of the liquid between the inlet and outlet of the cold liquid-to-air heat exchanger;

$$Q_c = \chi_6 \cdot (T_7 - T_8), \tag{14}$$

where $\chi_6$ is the thermal resistance of the liquid-air heat exchanger, $T_8$ is the temperature of the liquid-air heat exchanger surface in contact with the environment;

$$Q_c = \alpha_4(v_3) \cdot S_4 \cdot (T_9 - T_{amb}), \tag{15}$$

where $\alpha_4(v_3)$ is the heat transfer coefficient of the outer surface of the liquid-air heat exchanger, which is a function of the air velocity $v_3$, $S_4$ is the surface area of the liquid-air heat exchanger in contact with the environment.

Substituting (2-5) into (1), we get:

$$\eta_{TEG} = \frac{W_u}{Q_{cons}} = \frac{W_{thermopile} - W_{loss}}{C \cdot G \cdot \rho \cdot (T_{g.c.} - T_{amb})} = \frac{Q_h \cdot \eta_{thermopile}(T_h, T_c) - W_{loss}}{C \cdot G \cdot \rho \cdot (T_{g.c.} - T_{amb})}. \tag{16}$$

Using the heat balance equation in (16), we obtain

$$\eta_{TEG} = \frac{\dfrac{\alpha_1 \cdot S_1 \cdot (T_{g.c.} - T_{amb}) \cdot \eta_{thermopile}(T_h, T_c)}{1 + \alpha_1 \cdot S_1 \cdot \left[ N_1 + N_2 \cdot \left(1 - \eta_{thermopile}(T_h, T_c)\right) \right]} - W_{loss}}{C \cdot G \cdot \rho \cdot (T_{g.c.} - T_{amb})}, \tag{17}$$

where

$$N_1 = \frac{1}{\chi_1} + \frac{1}{\chi_2} + \frac{1}{\chi_3},$$

$$N_2 = \frac{1}{\chi_4} + \frac{1}{\chi_4} + \frac{1}{\alpha_4 \cdot S_4} + \frac{1}{\alpha_5 \cdot S_5} + \frac{1}{\chi_6} + \frac{1}{\alpha_3 \cdot S_3} \tag{18}$$

## Development of a thermoelectric generator design

As a result of the design, a thermoelectric recuperator with a heat pipe was proposed (Fig. 2). It consists of a heat pipe with fins on the hot side and a platform for placing 10 thermoelectric modules on the cold side. The movement of the liquid in the cold heat exchange circuit is carried out using liquid pumps powered by the electrical power generated by the thermoelectric modules. Heat removal from the thermoelectric modules is provided by a liquid-air heat exchange system.

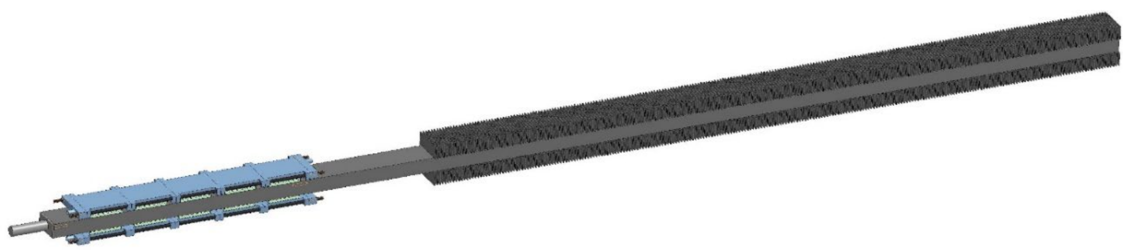

*Fig. 2. Schematic diagram of a thermoelectric recuperator with liquid heat removal*

The finned part of the heat pipe is placed inside the exhaust pipe into which the exhaust gases move. Such use significantly expands the possibilities of its practical use due to the possibility of converting not only the heat of the surface layers of exhaust gases of industrial installations (Fig. 3), but also virtually the entire volume filled with gases. The calculated efficiency of the generator is efficiency

= 3.8 % and the electric power W = 9.8 W per thermoelectric module. Therefore, by placing about 100 units of such a thermoelectric generator in the internal cavity of the exhaust gas pipe, it is possible to obtain an electric power of up to 100 kW (Fig. 3).

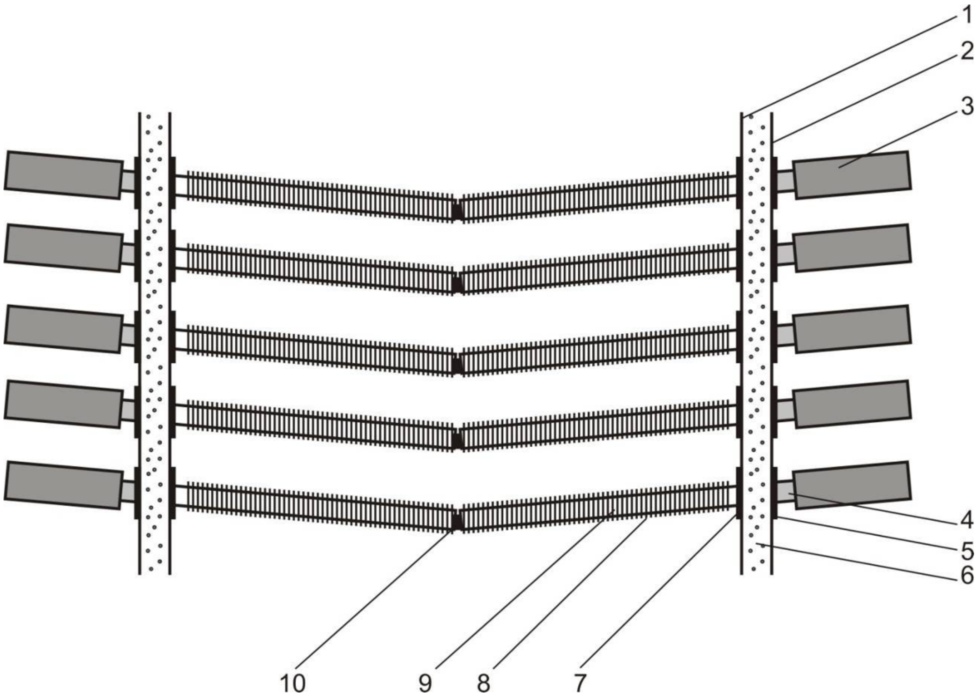


*Fig. 3. Cross-sectional diagram of a possible arrangement of thermoelectric generator units inside the pipe of an industrial installation*

Fig. 3 shows a cross-sectional diagram of the exhaust gas box of an industrial installation with thermoelectric generator units placed in it: 1 – inner wall of the box, 2 – outer wall, 3 – thermoelectric generator unit, 4 – part of the heat pipe placed outside the box (condensation zone) of the generator on the walls of the box, 6 – thermal insulation, 8 – rectangular plates placed on the vertical surfaces of the heat pipe and form a heat-absorbing heat sink, 9 – part of the heat pipe placed in the box with waste gases, 10 – clamps with which two oppositely placed heat pipes are fastened.

## Experimental test results

To verify the design results, an experimental model of a thermoelectric generator with a heat pipe was manufactured and its studies were carried out using a measuring bench that maximally reproduces the thermal conditions of an industrial installation.

Therefore, the measurements gave the following results (Fig. 4): the power generated by one recuperator unit is ~ 90 W.

Additionally, the uniformity of temperature distribution in the heat pipe was investigated (Fig. 5).

Thus, the output power of such a thermoelectric generator is $W = 91$ W (9.1 W per 1 thermoelectric module) at an efficiency of $\eta = 3.5\%$. It should be noted that the efficiency of the specified design is 1.3 times higher than for the recuperator option with forced air and 2.3 times higher than the option with natural convection. In addition, the specific dimensions of such a generator per 1 thermoelectric module significantly exceed those of analogues with air heat exchange, which provides it with wide scalability capabilities to achieve the required values of the output electric power.

It should be noted that, despite the significant advantage in energy and mass-dimensional characteristics of the specified design, other considered options can also find their use due to the simplicity of the design, the absence of liquid coolants and, in general, the need for additional provision of additional power supply to the heat exchange system.

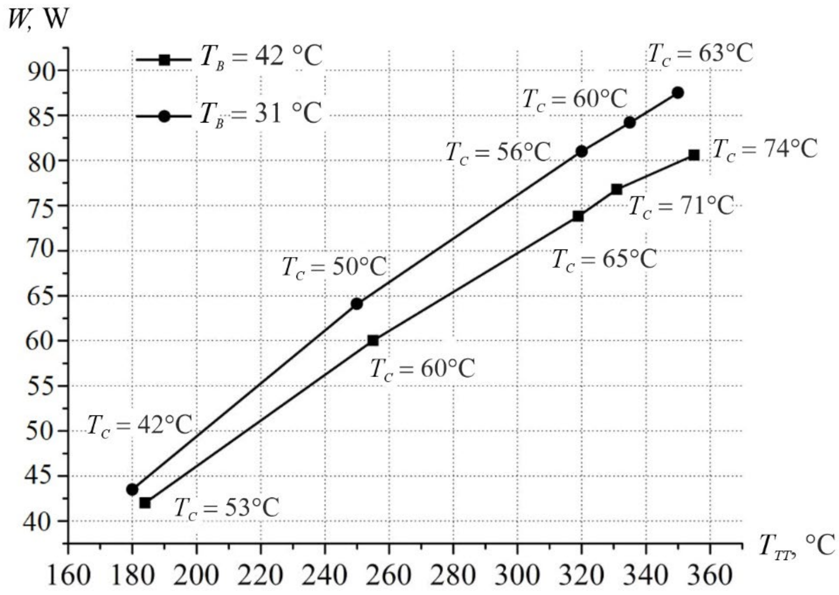


*Fig. 4. Measurement results.*

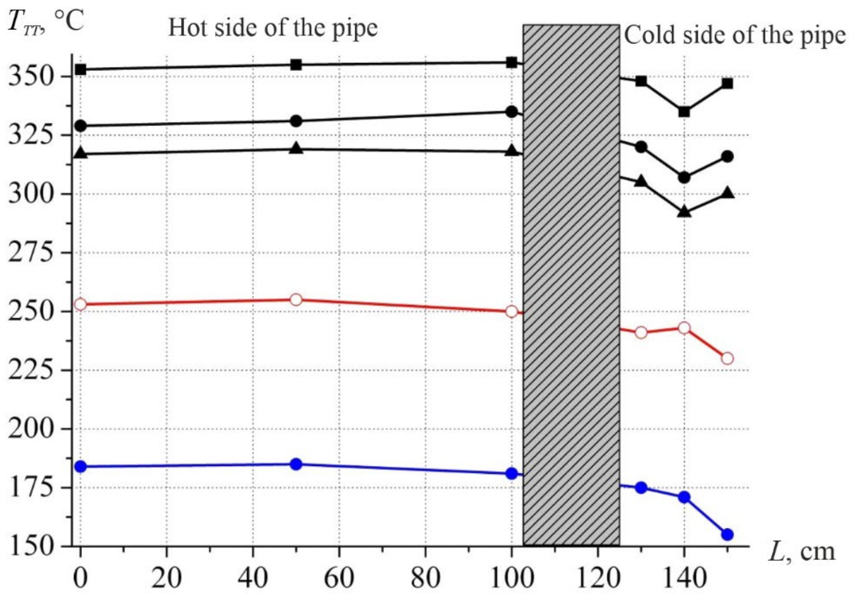


*Fig. 5. Distribution of temperature distribution non-uniformity along the heat pipe.*

### Conclusions

1. A thermoelectric generator with liquid-air heat exchange and a heat pipe that 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 3.8 %, which ensures the generation of electrical energy at the level of 9.8 W from one thermoelectric module.
3. Experimental studies were conducted, confirming the main design results.

4. It was established that the experimental values of the energy characteristics of the thermoelectric generator are: efficiency η = 3.5 % and power $W$ = 9.1 W.
5. It has been analyzed that the efficiency of the specified design is 1.3 times higher than for the recuperator option with forced air flux and 2.3 times higher than for the option with natural convection.

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Submitted: 16.10.2024

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# ТЕРМОЕЛЕКТРИЧНІ ДЖЕРЕЛА ЕЛЕКТРИКИ, ЩО ВИКОРИСТОВУЮТЬ НИЗЬКОПОТЕНЦІЙНЕ ТЕПЛО (ЧАСТИНА 3)

*Дана робота є третьою частиною із циклу досліджень термоелектричних джерел електрики, що використовують низькопотенційне тепло. Приведені результати комп'ютерного проектування термоелектричного генератора із тепловими трубами та рідинним 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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Надійшла до редакції 16.10.2024