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APPLICATION OF THERMOELECTRIC GENERATORS FOR ELECTRICAL ENERGY PRODUCTION WITH A LOW-TEMPERATURE HEATING SOURCE

Key words: thermoelectric generator TEG, thermoelectric cells, thermogenerator, electrical energy production, renewable energy, DC/AC converter.

Abstract: The article presents a model system for the production of AC electrical energy from a low temperature heat using thermoelectric generators TEGs. Combinations of many TEGs in various configurations have been described. The results of the mutual influence of thermoelectric generators on the ability to generate resultant electrical energy depending on the temperature distribution and the heat supplied are presented. The conditions necessary to increase the efficiency of electrical energy yield have been given.

Zastosowanie ogniw termoelektrycznych do wytwarzania energii elektrycznej ze źródeł ciepła niskotemperaturowego

Słowa kluczowe: generator termoelektryczny TEG, ogniwa termoelektryczne, termogenerator, produkcja energii elektrycznej, energia odnawialna, przetwornica DC/AC.

Streszczenie: W artykule przedstawiono modelowy układ do wytwarzania energii elektrycznej prądu przemiennego z ciepła niskotemperaturowego z zastosowaniem ogniw termoelektrycznych. Opisano badania połączeń wielu termoogniw w różnych konfiguracjach. Przedstawiono wyniki wzajemnego wpływu ogniw termoelektrycznych na zdolność generowania wypadkowej energii elektrycznej w zależności od rozkładu temperatury i dostarczanego ciepła. Podano warunki konieczne do zwiększenia efektywności uzysku energii elektrycznej.

Introduction

Energy management begins to include low-temperature sources, i.e. those whose temperature does not exceed 150°C. Examples of such sources are geothermal water, operating fluids from machine cooling, combustion gases from combustion processes in which the temperature has been lowered in the exhaust-air heat exchangers, water from heat releases in summer, when there is no demand for it, or waste heat from industrial processes. Heat from these sources is currently used to a minimal extent. In most cases, it is distributed to the environment, thus worsening the environmental conditions and energy balance of manufacturing processes.

For the direct conversion of thermal energy into electrical energy, thermoelectric generators TEGs [1, 2, 3] can be used. They do not have moving parts and operating fluids, they start immediately, can work in any position, do not require spare parts and maintenance, have a long service life (20–30 years), and they can also work in a wide temperature range. The higher thermal energy supplied to the TEGs, the greater the conversion efficiency and the amount of electrical energy recovered. Technological progress and a drop in prices mean that it is economically and technically justified to use the thermoelectric generators to generate electrical energy also from low temperature heat [4].

Thermoelectric phenomena, such as the Peltier effect, the Thomson effect, and the Seebeck effect occur in thermoelectric generators. In general, they relate to a circuit consisting of two conductive elements, on whose joints, due to the temperature difference, an electromotive force is generated [5–7]. Circuits connected in groups and bounded with ceramic plates form the thermoelectric generator – TEG (Fig. 1).

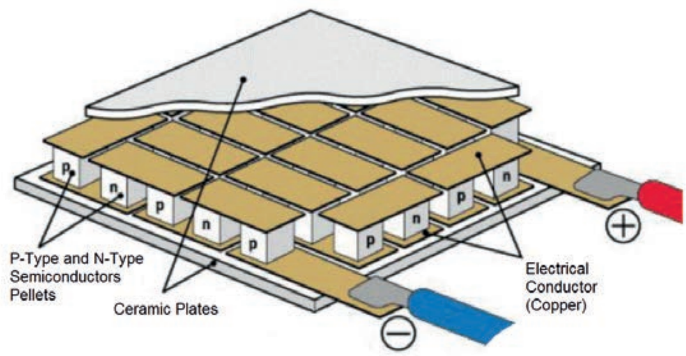

Fig. 1. The cross-section of a thermoelectric generator TEG
Source: Authors, based on [8].

A good thermoelectric material should be characterized by the following:

- High electrical conductivity (low electrical resistivity) to minimize Joule's heat; and,
- High Seebeck coefficient, so that a small temperature difference generates high voltage and low thermal conductivity.

Semiconductor components made of bismuth telluride (Bi2Te3) or lead telluride (PbTe) are used in the mass-produced of TEGs [9]. The combined semiconductor device assemblies are limited by alumina ceramic plates (aluminium oxide Al_2O_3) enabling the supply of heat on one side of the generator and picking up on the other. Electrical wires are led out from between the generator plates. The dimensions of typical TEGs are: 30 × 30 mm, 40 × 40 mm, 50 × 50 mm, 56 × 56 mm and 62 × 62 mm.

The efficiency of thermoelectric generators is the ratio of the electrical power output in the external circuit, i.e. $P = R*I^2_{TEG}$, to the amount of Q_{IN} heat supplied to the TEG. Currently, the TEG's efficiency is about 5–8%. Development works on materials with better thermoelectric properties allow achieving efficiency above 10% [10–12]. One thermoelectric generator can produce up to 20W of electrical power. Such values are achieved by TEGs in which the temperature difference between the parties exceeds 300°C [13].

For values ΔT <100°C, the power achieved is usually not higher than 5W and the generated voltages do not exceed 5V [4]. If a TEG is used to supply, for example, a measuring system, such values are sufficient. The use of thermoelectric generators for the production of electrical energy delivered to the public power grid requires the use of many connected TEGs. The following section presents the possibility of using thermoelectric generators for generating AC electrical energy and the conditions necessary to increase the efficiency of energy yield.

1. Connecting thermoelectric generators into groups

To generate electrical energy in the order of kilowatt-hours (kWh), a large number of TEGs connected to each other should be used. Q_{IN} heat is supplied to the hot poles of the thermoelectric generators group, while the cold poles give the unused part of the Q_{OUT} heat to the environment (Fig. 2). As a result of the temperature difference ΔT, the resultant U_{TEG} voltage is created. The generated DC electrical energy is converted into AC electrical energy in the DC/AC converter. At the output of this inverter, one should maintain alternating voltage at 50 Hz and a constant RMS value of 230 V. Permissible deviations amount to +/- 10%, i.e. from 207 V to 253 V. The structure and operation principle of the DC/AC converter shows that the higher the voltage at the input, the higher the ability to maintain a given voltage at the output regardless of the power changes of the energy supply source [14–18].

Figure 3a shows the dependence of the voltage U on the flowing current I for one thermoelectric generator. With the increase of the current I, the voltage U decreases. It is a linear relationship and results from the internal resistance of the TEG. The series connection of TEGs increases the resultant internal resistance and the parallel decreases it. The lower the internal resistance, the lower the slope $U = f(I)$ and the more flat characteristic $P = f(I)$. Figure 3b shows that there is maximum power for a certain current value. For efficient energy production, the DC/AC converter system must be able to determine the maximum power point.

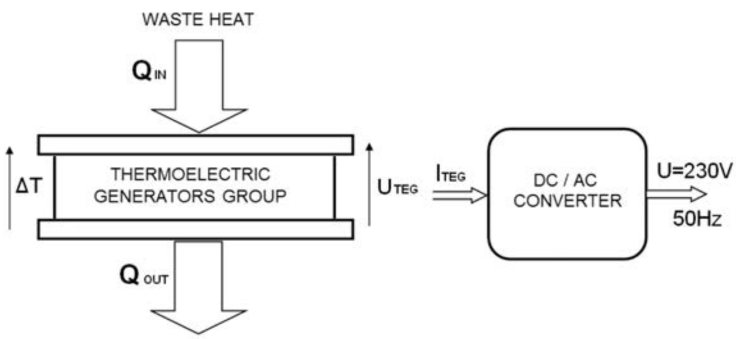

Fig. 2. Diagram of AC electric energy generation from thermal energy by TEGs
Source: Authors.

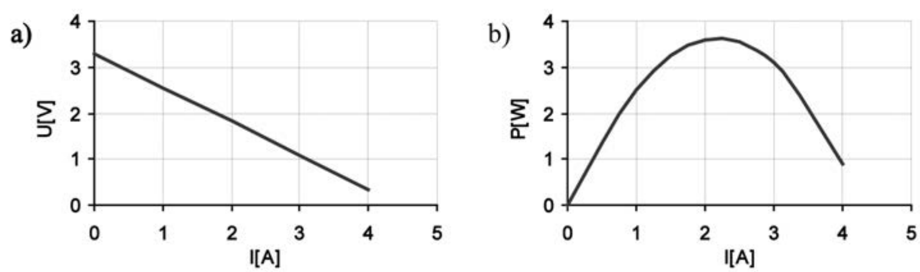

Fig. 3. Thermoelectric characteristics U = f (I) and P = f (U) of the TEC1-12730 module for ΔT = 70°C
Source: Authors.

The above requirements and properties cause that the TEGs should be combined with each other in a mixed way, i.e. in series and in parallel.

2. Methodology for testing connections of thermoelectric generators

The thermoelectric generator is a semiconductor element that can operate in two ways: convert thermal energy into electrical energy (the Seebeck effect) or vice versa, or convert electrical energy into thermal energy (the Peltier effect). The transition from one state to another and vice versa takes place smoothly (when the thermoelectric generator is in certain conditions). Therefore, it is necessary to analyse the mutual influence of TEGs on the ability to generate resultant power energy with serial and parallel connection depending on the temperature distribution and the heat supplied. For this purpose, two groups of thermoelectric generators connected in series were created (Fig. 4).

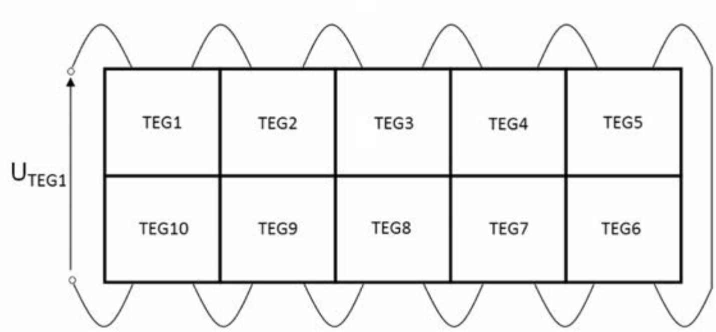

Fig. 4. Diagram of connections and positions of 10 TEGs that form one group
Source: Authors.

The TEC1-12730 module was used, which has a better efficiency for low-temperature heat than the TEGs intended for the production of power energy from high-temperature thermal energy (Table 1).

Table 1. Parameters of electric current generated by various types of thermocouples [4]

TEG type	Maximum electric power for ΔT=80°C	Current and voltage of the generated power	
	P[W]	I[A]	U[V]
TEC1-12730	4.63	2.52	1.84
TEG1-12611-6.0	3.38	1.93	1.75
G2-56-0352	2.97	1.70	1.75
G2-56-0375	2.78	1.75	1.59
G2-56-0570	2.52	0.89	2.83

Groups of 10 TEGs were placed between aluminium plates. On the upper plate with a thickness of 5 mm, electric heaters with continuously adjustable power were placed, and in the bottom plate with a thickness of 40 mm, holes for water flow were made (Fig. 5). The water flow is also regulated smoothly. A thermal paste with a coefficient of 2.8 W/(m·K) was used to mount the TEGs on the aluminium plates to reduce the thermal resistance.

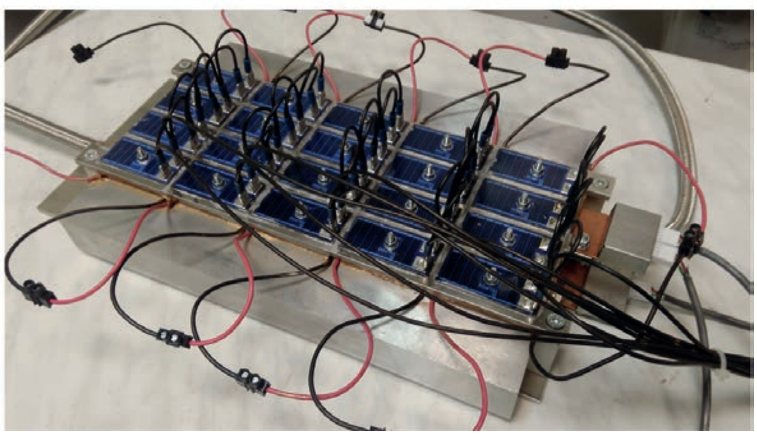

Fig. 5. View of a heat exchanger with the thermoelectric generators
Source: Authors.

The experimental research was carried out under controlled temperature and electrical conditions. Between the plates of TEGs, certain temperatures were maintained for hot and cold sides to maintain a constant temperature difference ΔT. Figure 6 shows the model of the heat exchanger.

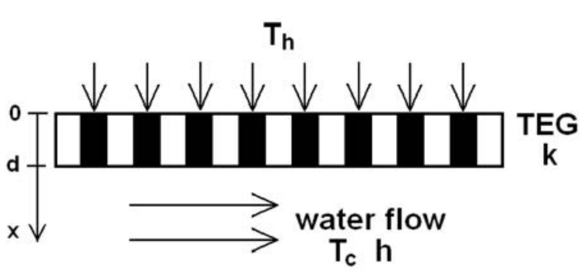

Fig. 6. Model of the heat exchanger
Source: Authors, based on [19].

Assuming that the heat transfer through the TEGs is one-dimensional and fixed, the heat diffusion equation is reduced to the following:

$$\frac{d^2T}{dx^2} = 0 \tag{1}$$

where T – temperature, x – distance. Temperature distribution and temperature gradient can be obtained by solving the above differential heat diffusion equation depending on the boundary conditions. Then the temperature distribution can be described by the following formula:

$$T(x) = \frac{h(T_c - T_h)}{k + ht} x + T_h \tag{2}$$

and the temperature difference describes the dependence:

$$\Delta T = \frac{hd(T_h - T_c)}{k + hd} \tag{3}$$

where, T_h – hot side temperature, T_c – cold side temperature, k – thermal conductivity of TEG, h – convection coefficient, d – thickness of TEG.

From Equation (3), it follows that the temperature difference ΔT at the ceramic plates of the TEGs will be lower than the temperature difference between the temperature of the heat supplied and the temperature of the coolant.

The measurements were carried out with series and parallel connections of two groups of TEGs (G1 and G2) for the idle state and the load state, as well as for supplying thermal energy to only one group (G2). The generated power energy was transferred to a DC/AC converter designed and made in ITeE – PIB with a nominal power of 10 kW (Fig.7).

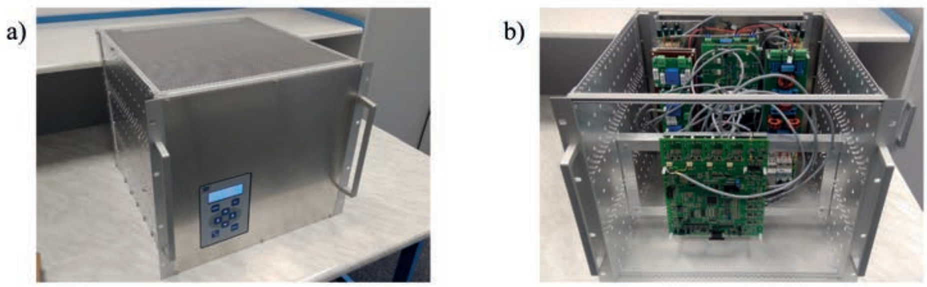

Fig. 7. DC/AC converter: a) general view, b) view of the control and power system
Source: Authors.

The inverter has implemented the MPPT (Maximum Power Point Tracking) maximum power tracking algorithm. The P&O method (Perturbation and Observe method) [20, 21] was applied. It consists in forced changes in the operating current of thermoelectric generators and the observation of power changes in accordance with Figure 3. The current changes should be continued in the same direction (increase or decrease) if this change increases the power. However, if the power decreases, the direction of changes in the work current should be changed. If the current was increased, start reducing it, and when it was reduced, start to increase it, until the maximum power is reached.

3. The research results of the experiment

The obtained values of thermoelectric parameters of the analysed groups of TEGs connections are presented in Table 2. The measurements were made for the same temperature difference ΔT = 60°C, when thermal energy was supplied to a given group of the TEGs.

Table 2. The values of thermoelectric parameters of the analysed groups of TEGs connections

Working conditions	Type of connection G1 and G2	U_{TEG} [V]	I_{TEG} [A]	P_{TEG} [W]	U_{TEG1} [V]	ΔT_1 [°C]	U_{TEG2} [V]	ΔT_2 [°C]
idle condition group G1 – hot group G2 – hot	serial	58.3	0	0	29.5	60.0	28.8	60.0
	parallel	28.0	0	0	28.0	60.0	28.0	60.0
load condition group G1 – hot group G2 – hot	serial	24.4	2.1	51.2	12.3	60.0	12.1	60.0
	parallel	12.9	4.0	51.6	12.9	60.0	12.9	60.0
idle condition group G1 – cold group G2 – hot	serial	28.2	0	0	0	0	28.2	60.0
	parallel	27.2	0	0	0	0	27.2	60.0
load condition group G1 – cold group G2 – hot	serial	1.0	2.1	2.1	-12.0	-5.0	13.0	60.0
	parallel	6.7	2.1	14.1	6.7	0.0	6.7	60.0
load condition group G1 – cold group G2 – hot	serial with separating diodes	0.3	2.1	0.63	-12.1	-5.0	12.9	60.0
	parallel with separating diodes	12.1	2.1	25.4	0	0.0	12.1	60.0

where U_{TEG} – resultant voltage of the connected groups, I_{TEG} – resultant current of the connected groups, P_{TEG} – resultant power of the connected groups, U_{TEG1} – voltage of the group G1, ΔT_1 – temperature difference of the group G1, U_{TEG2} – voltage group G2, ΔT_2 – temperature difference of the group G2.

In the idle state and thermal energy supply to both groups, the voltage U = 58.3 V was obtained with the series connection of groups G1 and G2 and the voltage U = 28.0 V with the parallel connection. In the load condition for different connection configurations, nearly the same power was obtained at around P = 51.4 W. The voltage reached for the serial connection was higher than for the parallel connection, but the current was lower.

When one group of the TEGs (G1) was cold and the second one (G2) supplied thermal energy, in the idle state, the combination of groups did not matter. A voltage of approximately 28 V was reached, being the sum of the voltages of the individual hot TEGs. The cold TEGs had no effect, as if they were not included in the system.

In the load condition, it was observed that cold TEGs have a negative impact on the operation of the entire system. With serial connection, the power energy generated by the hot TEGs is used by the cold TEGs to the Peltier effect. The temperature of the hot side becomes lower than the cold side. Despite the flowing current I = 2.1 A, a small resultant useful power was obtained. With the same operating conditions and parallel connection, there is no Peltier effect, however the cold group is charged with the warm group.

In order to eliminate the negative impact of a non-working group on the efficiency of the entire system, we used separation diodes. For a parallel connection, it has a positive effect, and maximum power is achieved. For serial connection, the diodes are not able to block the unfavourable current flow. Additional voltage drops on the diodes cause the resulting power output to be even smaller.

During the tests, it was found that the even temperature distribution on the ceramic plates of individual TEGs on both the hot and cold side is very important. The use of a thermally conductive paste increases the noticeably achieved power energy of a given TEG. The paste fills the micro-space between the TEG and the heat exchanger. This increases the heat flow through the TEG and thus its electrical efficiency.

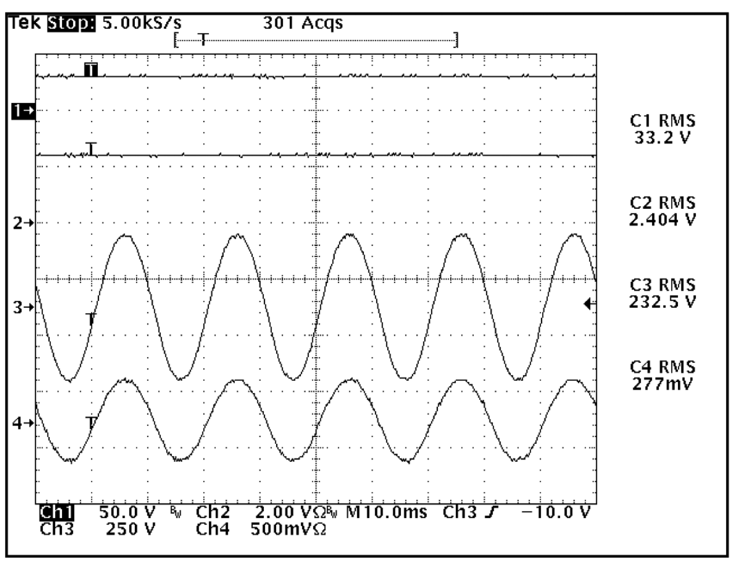

Fig. 8. Oscillograms of U_{TEG} [V] voltage (Ch1), I_{TEG} current [A] (Ch2), U_{AC} voltage [V] (Ch3), I_{AC} current [mA] (Ch4)
Source: Authors.

Figure 8 shows voltage and direct current waveforms generated by TEGs connected in series (G1 and G2) as well as voltage and alternating current waveforms with frequency 50 Hz at the output of the DC/AC converter. The electrical power of 79.8 W is available at the temperature difference ΔT = 75°C. Under these thermal conditions, the maximum power point tracking algorithm set the operating current I = 2.4 A. At the temperature difference ΔT = 60°C, the maximum power point is for I = 2.1 A. At the output, there are 64.4 W of power available. The difference is due to losses in the DC/AC conversion circuit. This system needs minimal energy for correct operation, below which it will not generate AC current while maintaining the voltage value U = 230 V.

Summary

The use of multiple connected the thermoelectric generators allows the generation of AC electrical energy with the parameters of the power grid. At the temperature difference $\Delta T = 60°C$ of the thermoelectric generators, significant useful power values can be obtained. It should be noted that, for the temperature difference $\Delta T = 60°C$, the temperature of heat supplied to the hot side of the TEGs is higher than the temperature of the refrigerant by more than $\Delta T = 60°C$. However, it is located in the low-temperature heat range and includes such heat sources as geothermal water, operating fluids from machine cooling, combustion gases from the combustion process, the temperature of which was lowered in the exhaust-air heat exchangers, water from heat releases, and waste heat from industrial processes.

For efficient energy recovery, it is important to evenly distribute temperatures on the plates of individual TEGs, both hot and cold. The proper connection of TEGs is of great importance. Serial connections are necessary to obtain higher voltages; however, in the case of a loss of heat energy supplies to one of the TEGs in the chain, this TEG will take power energy produced by other TEGs. With parallel connections, the lack of thermal flux in a given TEG does not have as much impact as with a serial connection.

In the construction of heat exchangers, however, it is necessary to strive for the most evenly supply of thermal energy to all TEGs. This will allow optimal use of the surface of thermoelectric generators. On the other hand, the optimization of electrical energy yield depending on changes in the amount of thermal energy is made in a DC/AC converter system.

The described works on the use of thermoelectric generators for the production of electrical energy from low temperature heat confirm the possibility of their practical application.

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