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THERMOELECTRIC HEAT EXCHANGER

Key words: waste heat, renewable energy, thermoelectric generator, heat exchanger, TEG thermoelectric modules, thermocouples.

Abstract: The article presents a heat exchanger with thermoelectric generators, which consists of two single sheet heat exchangers, between which thermoelectric generators are placed. The heat exchanger in question is used to convert waste heat energy into DC electricity. The construction of the heat exchanger is described in detail in the article, and the study of temperature distribution of both the high and the low temperature side is presented. The basic parameters of the heat exchanger are also given. They were determined with the current-voltage characteristics method, and then they were compared with the values established in the conventional way.

Termoelektryczny wymiennik ciepła

Słowa kluczowe: ciepło odpadowe, energia odnawialna, termogenerator, wymiennik ciepła, moduły termoelektryczne TEG.

Streszczenie: W artykule przedstawiono wymiennik ciepła z termogeneratorami, który składa się z dwóch pojedynczych płytowych wymienników wymiennika ciepła, pomiędzy którymi umieszczone są termogeneratory. Wymiennik służy do przetwarzania energii cieplnej w energię elektryczną prądu stałego. Przedstawiono konstrukcję wymiennika oraz badania rozkładu temperatury stron o wysokiej i niskiej temperaturze. Opisano podstawowe parametry wymiennika, wyznaczone metodą charakterystyki prądowo-napięciowej. Porównano je z wartościami wyznaczonymi w klasyczny sposób.

Introduction

Waste heat is currently processed to a minimal extent. In the most cases, it returns to the environment thus worsening the environmental conditions and energy balance of manufacturing processes. Thermoelectric generators can answer the problem, and they can be used to properly manage waste heat energy. TEG thermoelectric modules [1–3] are used to directly convert thermal energy into electricity. Their construction does not require any moving parts or working fluids, they start up immediately, they can work in any position, they do not need any spare parts and maintenance, they have a long service life (20–30 years), and they work in a wide temperature range. It has been proved that the supply of higher thermal energy to the thermocouple results in higher conversion efficiency and the amount of recovered electricity. The technological progress and lowering prices mean that it is economically and technically justified to use thermocouples for generating electricity even from low-temperature heat [8].

The efficiency of thermoelectric modules is the ratio of the electrical power released in the external circuit to the amount of heat supplied to the QH module. Presently, the efficiency of thermocouples is 5-8%. Improvements of those modules result in achieving better thermoelectric properties that allow efficiency above 10% [10–12]. One thermoelectric module can generate up to 20 W of electrical power. Such values are achieved by modules in which the temperature difference between the sides exceeds 300°C [13]. For $\Delta T<100^{\circ}C$ values, the achieved powers are usually not more than 5W and the generated voltages do not exceed 5V [8]. When a thermocouple is used to power, e.g., a measuring system, these values are sufficient. The use of thermocouples for the production of electricity with higher values reaching many kilowatt hours requires the use of several interconnected modules. TEG modules are placed in a heat exchanger. The parameters of a single thermoelectric generator depend on the type of thermoelectric material used. These are primarily efficiency and maximum power for a given temperature difference.

The article presents the design of a thermoelectric heat exchanger and the results of measuring the temperature distribution of both the high and the low temperature side worked out in the task realised in the frame of the EU project "Establishment of the Intelligent Specialization Centre in the field of Innovative Industrial Technologies and Technical and Environmental Safety." The basic parameters of the exchanger were determined with the current-voltage characteristics method [14] and compared with the parameters obtained in the conventional way. The conditions necessary to increase the efficiency of obtaining electricity are also given.

1. Heat exchanger design

The heat exchanger consists of four aluminium sheets (Figs. 1, 2). There are 20 thermoelectric modules (type TEC1-12730) between the top two and bottom two sheets. The dimensions of a single sheet are a length of 680 mm, a width of 200 mm, and a thickness of 34 mm.

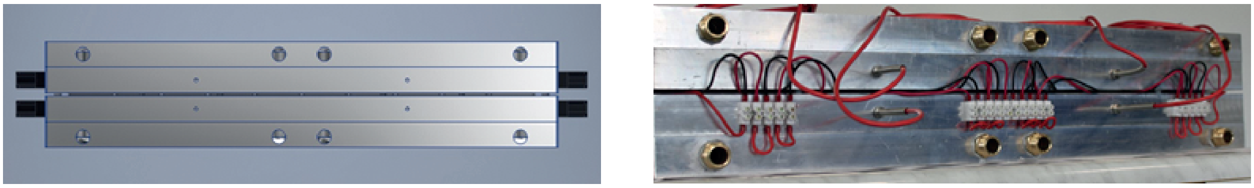

Fig. 1. Heat exchanger for liquid-liquid thermoelectric modules: a) 3D model of thermoelectric heat exchanger and its implementation (b)

In each outer aluminium sheet, two coil-shaped ducts were milled to supply heat (top sheet) and to dissipate heat (bottom sheet) (Fig. 2). Inlet and outlet openings were drilled on the side of each sheet. The heat transmission medium is water. It was assumed that the exchanger will be used for low temperature heat management at a temperature of about 90°C, i.e. just below the boiling point of water. The design allows for even temperature distribution in planes parallel to the planes of thermoelectric modules.

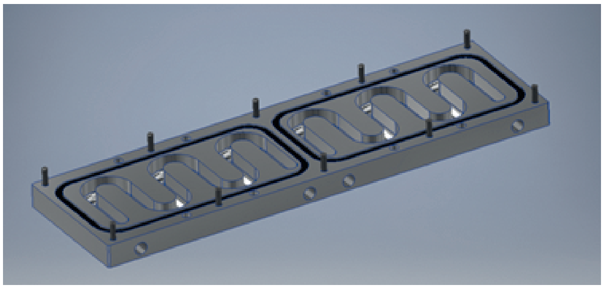

Fig. 2. The heat exchanger for thermoelectric modules. View from the inside

2. Temperature distribution in the heat exchanger

The temperature distribution in the heat exchanger was measured for water at a temperature of 59°C supplied to the hot side of the exchanger (upper sheet) and for water at a temperature of about 25°C supplied to the cold side (lower sheet). The results are shown in Fig. 3 and Fig. 4.

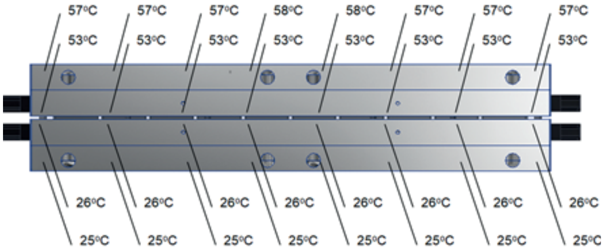

Fig. 3. Temperature values at individual points of the heat exchanger side part

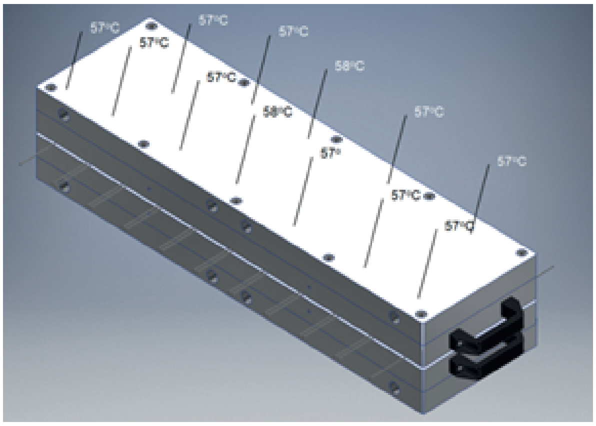

Fig. 4. Temperature values at individual points of the upper part (hot side) of the heat exchanger

The values of voltages generated by individual thermocouples without load and with load were also measured. The results are shown in Fig. 5 and Fig. 6.

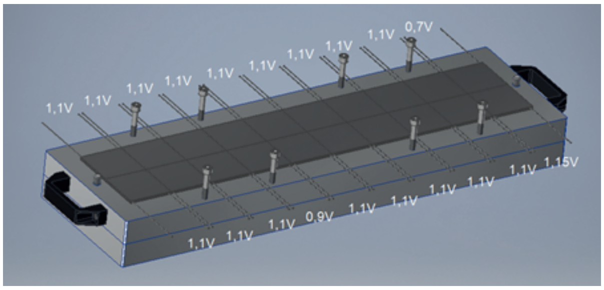

Fig. 5. Voltage values generated in the heat exchanger by individual thermocouples in idle state

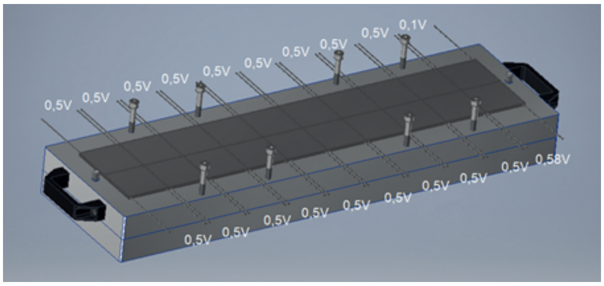

Fig. 6. Voltage values generated in the heat exchanger by individual thermocouples under load

The temperature distribution in the heat exchanger is even, both on the hot and cold side, especially in places where the heat exchanger contacts thermocouples. This is very important for the effective recovery of electricity. In case one thermocouple receives less heat than other modules, it will limit the electricity produced.

Despite the even distribution of temperatures, not all thermocouples generated the same voltage. One thermocouple was clearly less efficient; the voltage on it was U_0=0.7V in idle state and U_L=0.1V under load. It was caused by an assembly error, i.e. an uneven distribution of thermal compound between the thermocouple and the heat exchanger plane. Other thermocouples generated voltages in the same range of values, i.e. U_0=1.1V in idle state and U_L=0.5V under load. The resultant voltage of all thermocouples connected in series was U_0=21.4V in idle state and U_L=10.2V under load at I_L=0.97A. In the case of a disconnection of the least efficient thermocouple, the resultant voltage of the remaining 19 thermocouples was U_0=20.7V in idle state and U_L=10.1V under load at I_L=0.98A. After disconnecting the least efficient module, the current increased slightly, and the total generated power remained at almost the same level (P=9.9W). In conclusion, the larger the heat flux flows through the thermocouples and the greater the differences between the electric energy generated by the individual thermocouples, the greater will be the counteraction of the weakest thermocouple [15].

3. Basic parameters of the exchanger with thermoelectric generators

A single thermoelectric module has specific parameters that result from the thermoelectric material used. Manufacturers provide its parameters and characteristics for a given temperature difference ΔT for a given module. The use of multiple thermoelectric modules connected together and placed in a heat exchanger does not mean that the resulting power will be directly proportional to the number of modules and the efficiency of one module. It depends on the design of the heat exchanger and the resulting thermal resistance between the exchanger and the individual modules. Nevertheless, it is possible to determine the resultant electrical parameters of a heat exchanger built of many individual thermocouples using the current-voltage characteristics method for one thermocouple [14].

The method consists in determining the current-voltage characteristics of the thermoelectric generator on the basis of current and voltage time histories at the transition from short-circuit to open and from open to short-circuit at a given temperature ΔT (Fig. 7).

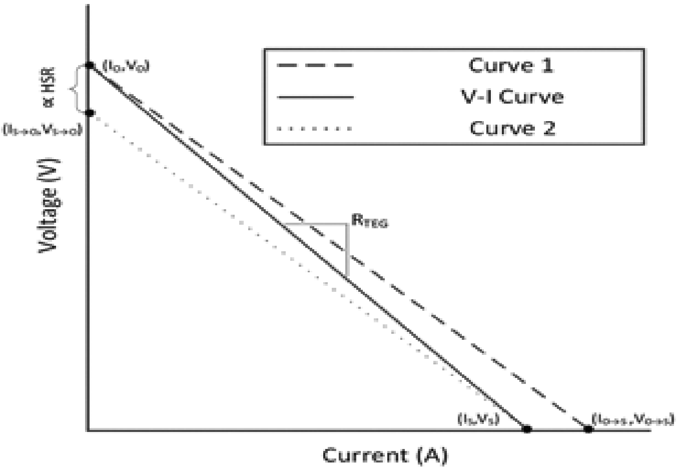

Fig. 7. Method for determining the V-I characteristics on the basis of measured characteristic points [14]

Determination of characteristic points on the waveforms (Fig. 8, Fig. 9) allows one to calculate the $I_{MP}=I_S/2$ current and the voltage $U_{MP}=V_S/2$ for the maximum power $P_{MP}=I_{MP}*V_{MP}$ and the internal resistance of $R_{TEG}=V_O/I_S$ of the thermocouples.

When the value of thermal energy QH supplied to the thermocouple is known, the efficiency and thermal resistance of HSR can also be calculated according to the following formula:

$$HSR = \frac{\Delta T(V_{S\to O} - V_O)}{2(Q_{HO}V_{S\to O} - Q_{HS}V_O)} \tag{1}$$

QHO and QHS are the heat supplied to the thermocouple (1) in the open state and short circuit state, respectively.

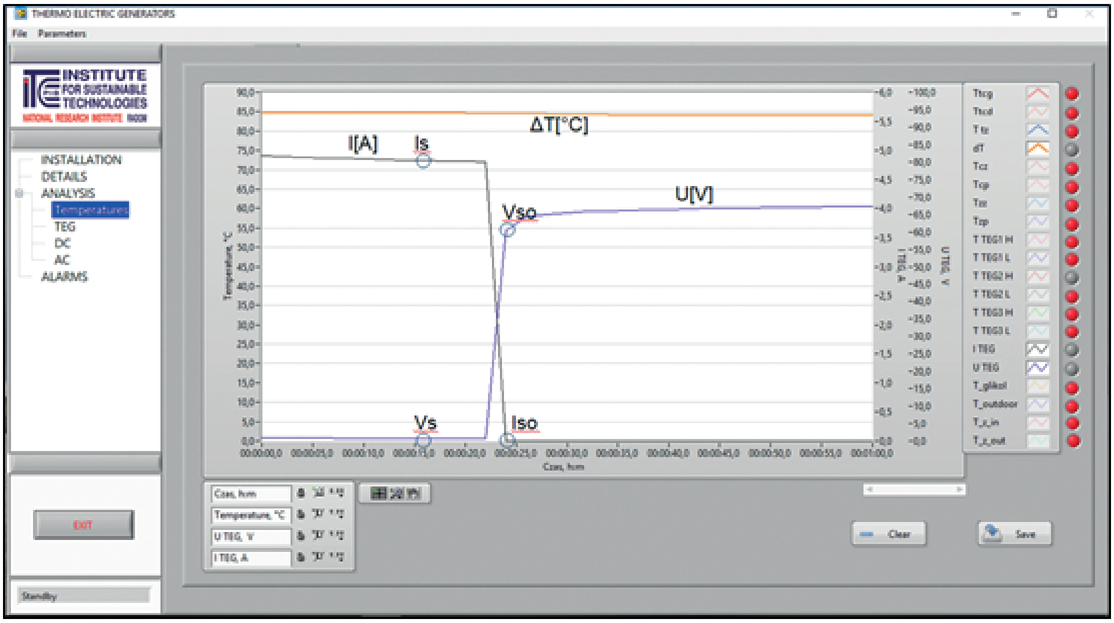

Fig. 8. Transition from short circuit to open state at ΔT = 85 °C

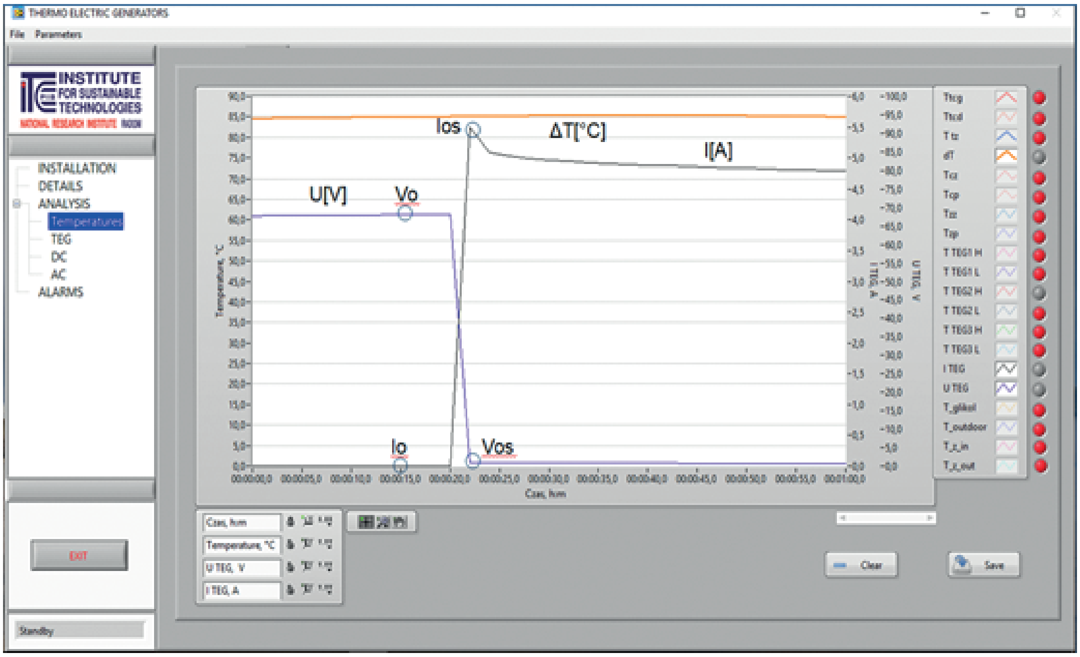

Fig. 9. Transition from open to short-circuit at ΔT = 85 °C.

The recorded time series for ΔT=85°C at the transition from the short to the open state (Fig. 8) allowed determining the characteristic points: Vs = 0V, Is = 4.9A, Vso = 60V, and Iso = 0A. When moving from an open state to a short-circuit state (Fig. 9), the characteristic points are Vs = 0V, Is = 4.9A, Vso = 60V, Iso = 0A. It is possible now to prepare the current-voltage characteristics of the tested exchanger with thermoelectric generators according to the described method (Fig. 10).

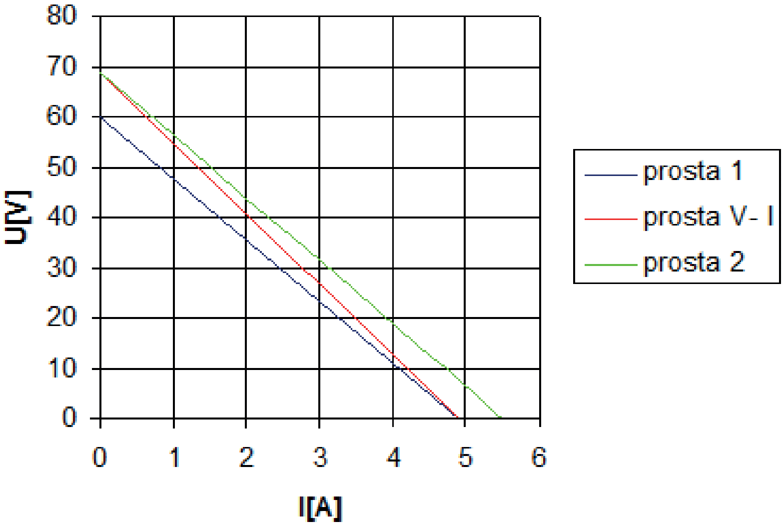

Fig. 10. Current-voltage characteristics of the tested thermoelectric generator for ΔT=85°C

Consequently, the determined parameters have the following values: current I_{MP}=2.45A and voltage U_{MP}=34.5V for maximum power P_{MP}=84.5W and R_{TEG}=14.1Ω. The graph in Fig. 11 shows the relationship between voltage and power as a function of the exchanger current obtained with the conventional method for temperature difference ΔT=85°C. This method consists in collecting measurement data of currents and corresponding voltages for a specific temperature difference. Based on the collected measurements, a graph of U=f(I) and P=f(I) was created, where P=U*I. The P=f(I) graph is an inverted parabola that has its extreme [16]. The extreme of this parabola is the maximum power point of MPP. The maximum power value read is approximately 85W and coincides with the calculated PMP value (P_{MP}=84.5W).

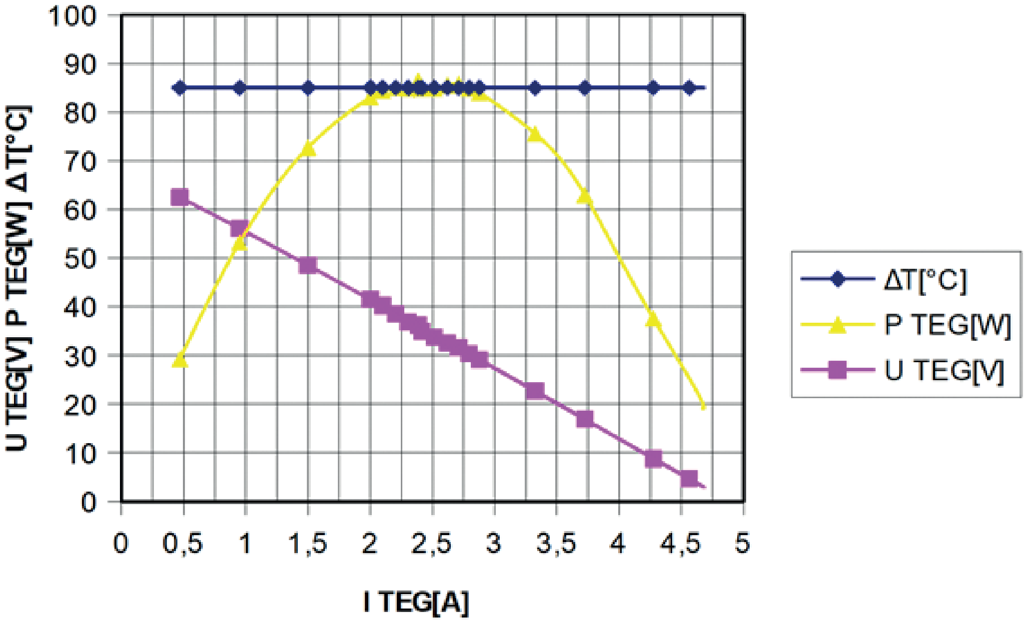

Fig. 11. Graph ΔT [° C], PTEG [W], and UTEG [V] as a function of ITEG current [A] of a thermoelectric generator (20 thermocouples connected in series).

Summary

The thermoelectric heat exchanger is used to properly manage waste heat energy. Its design and the use of water as a refrigerant ensures easy heat transfer to thermoelectric generators. A single thermocouple has specific parameters that result from the thermoelectric material used. In the case of many thermoelectric generators connected in series and placed in a heat exchanger, the resulting power depends on the design of the heat exchanger and the resultant thermal resistance between the heat exchanger and individual thermoelectric generators. Using the method described in the article, one can quickly determine the resultant maximum power of such a heat exchanger for a given temperature difference. In addition, this method allows one to determine the internal resistance and thermal resistance after making measurements at only four characteristic points, provided that thermoelectric generators are under a constant output load. Compared to the conventional method in which several points are determined at different load values, it accelerates the characterization of this type of thermoelectric systems.

The method was used in the test stand, described in a separate article, which was created in the previously mentioned project and is used for testing waste heat recovery systems.

It is important to evenly distribute the temperature on the covers of individual modules, both on the hot and the cold side, in order to efficiently converse the heat energy into electricity in a heat exchanger with many thermoelectric generators. The design of the heat exchangers should strive for the most uniform delivery of heat energy to all thermoelectric modules.

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