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Increase in the efficiency of electricity production with a thermoelectric generator (TEG)

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Abstract
Currently used TEG modules have low efficiency of about 5%. The energy generated by the TEG module depends on the temperature difference between the module surfaces. Heat exchange between the heat source and the module surface takes place through the contact between two rough solid surfaces. This creates contact resistance. It can be reduced by using a substance filling the empty spaces between the contact surfaces and applying pressure. During the tests, the efficiency of electricity generation with a thermoelectric generator was measured (TEG) at various pressure forces. The tests were carried out at a pressure force of 250 N, 500 N, 750 N and 1000 N. The selected values of pressure do not exceed the limit value arising from the thermoelectric generator (TEG) design. A copper element constituting the heat source was heated in a furnace. Next, it was pressed at an adequate force to the generator, which was placed on a water cooler. The impact of conductive materials placed between the faces of the heat source and the TEG on the generation of electricity was examined. At low forces, the use of a thermal pad as an intermediary substance does not result in improved heat transfer in the heat source—TEG generator system. Better filling of voids is provided by thermally conductive paste due to its properties.

Keywords Thermoelectric generator · Surface roughness · Waste heat · Heat recovery · TEG effectiveness · Heat exchange at a contact

List of symbols

α	Seebeck coefficient/V K^{-1}
σ	Electric conductivity coefficient/S m
λ	Thermal conductivity coefficient/W m^{-1} K^{-1}
T	Temperature/K
Rc	Thermal contact resistance/m^2K W^{-1}
T_{HOT}	Temperature of heat source/K
T_{COLD}	Temperature of the cooler/K
ΔT	Temperature difference/K

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Introduction

Everyday life is dependent on electricity, which is also the basis for other applications. Nowadays, the best-known challenges faced by humankind include the depletion of fossil resources, continuously growing electricity consumption, global warming, and environmental problems [1, 2]. In recent decades, the development and improvement of industry, transport systems and people's lifestyle in general are based primarily on transforming the chemical energy of fossil fuels into thermal, mechanical, and electrical forms [3]. The thermal energy is a waste product of every generation of energy and every production process. Recovery of waste heat is one of the most promising methods of improving the energy efficiency of many production processes and power equipment [4]. Thanks to the implementation of waste heat recovery systems, it will be possible to limit the emissions of CO_2 and to reduce the consumption of fossil fuels [3]. The high temperature of steelmaking processes forces steel companies to use large amounts of energy. This brings about high costs as well as a large amount of waste heat of various temperatures. The recovery of high-temperature waste heat is relatively easy, and this process can be conducted with good efficiency. For a lower temperature or for dispersed heat sources, the heat recovery process is difficult [5].

Forecasts concerning waste energy expect a further growth of the waste heat share from industrial processes at various stages of production (Fig. 1). There is a large share of waste heat with a temperature below 300 °C. The utilisation of this heat source in the existing processes is very difficult due to low exergy [6].

Data concerning the future utilisation of energy from waste heat generated in various sub-sectors in 2030 is taken from the World Energy Outlook 2016 [7]. It forecasts the estimated future energy consumption according to a few scenarios.

The first one, which is called the Current Policies (CP), assumes that no new regulations will be implemented after the first half of 2016, ignoring those that have already been planned but not implemented yet. The least ambitious goal is selected from a series of them. The next scenario is called the New Policies (NP). It includes the regulations that are already in force as well as the regulations and objectives that have been undertaken to be accomplished but were not implemented by the first half of 2016. The next scenario is the 450 Scenario, which is based on limiting the increase in the average global temperature increase to 2 °C of the industrial level by 2100 by restricting the atmospheric concentration of CO_2 to 450 ppm. These concepts originate from the projection of current policies and global trends. They do not include the risk of a breakthrough change in the technology or policy and are considered the "primary" scenarios of energy consumption.

In addition, the fourth scenario with an increase in the share of renewable energy sources (called the aggressive scenario) was derived from studies by Jacobson and Delucchi [8, 9]. In this case, the entire electric power is generated from water, wind, and sun, which leads to the electrification of most end use processes while ensuring the same total number of power services in each sub-sector as in the CP scenario. However, whereas the paper [8] assumes that hydrogen obtained by electrolysis is used to replace fossil fuels where electrification is not possible, this scenario assumes the continuation of the utilisation of fossil fuels. The graph in Fig. 1 visualises the distribution of waste heat in various sectors of the economy. The graph in Fig. 2 shows the distribution of waste heat temperature.

Although an increase in the energy demand is expected, a huge part of it can be reduced by improving the energy efficiency of power systems [10]. One of methods for utilising waste heat is the use of thermoelectric generators (TEG). Thermoelectric generator (TEG)—it is a kind of a heat engine using the Seebeck effect to generate electrical power because of a temperature difference. The generator (Fig. 3) consists of alternately arranged materials of *p*-type (dark grey) and n-type (bright grey) connected electrically in series (connections marked with yellow) and thermally in parallel.

The advantages of these technologically advanced devices include environmental friendliness because during operation they neither generate nor release any contaminants. As they do not have any moving parts, their reliability and life increases. Thanks to the conversion of waste heat to electrical power, such thermoelectric generators can be used to improve the efficiency of the devices that generate large amounts of heat as a by-product.

The main disadvantage of thermoelectric generators is their low conversion efficiency, which is an obstacle to their wide application [3]. The efficiency of a TEG depends on the temperature difference and the value of the thermoelectric figure of merit *ZT*. This parameter is described with the formula:

$$ZT = \frac{\alpha^2 \sigma}{\lambda} \cdot T \tag{1.1}$$

To improve the efficiency of this device, it is imperative to improve the heat transfer between the source and the generator face as well as to discharge heat from the other face

Fig. 1 Waste heat sources in various sectors [6]

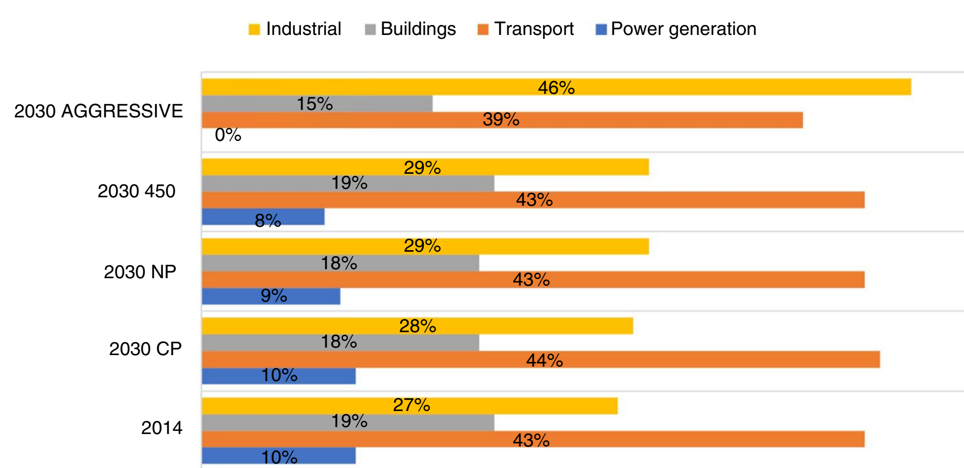
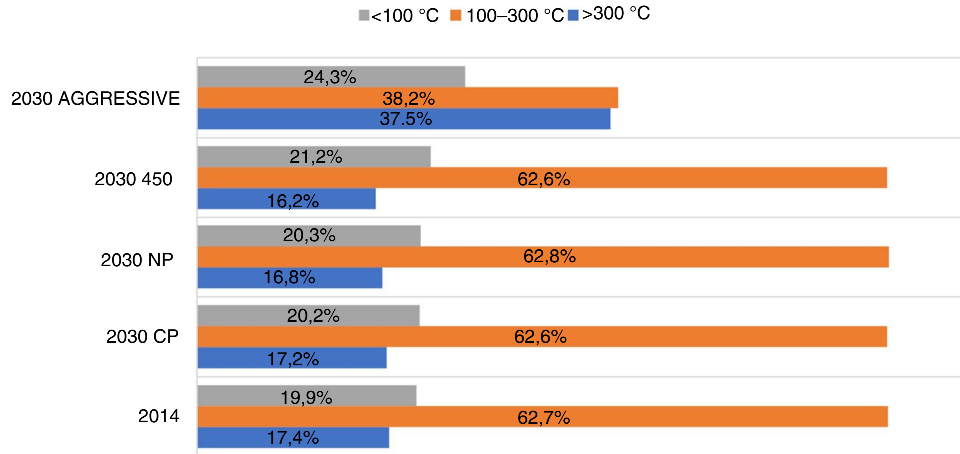


Fig. 2 Waste heat sources at various temperatures [6]



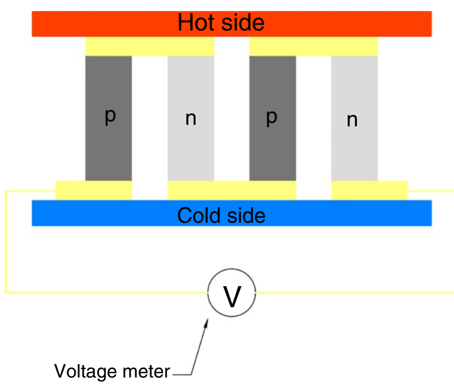


Fig. 3 Design of the thermoelectric generator [1]

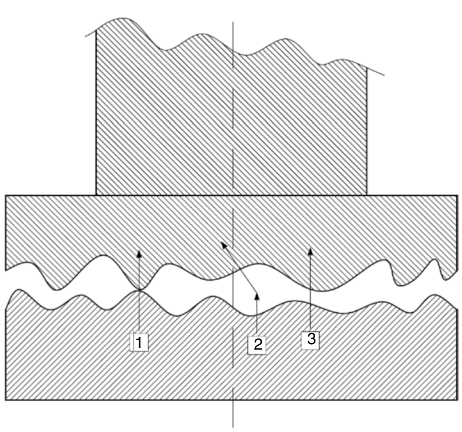


Fig. 4 Mechanisms of heat transfer at a contact of two faces

of the TEG with an adequate intensity. In both cases, heat transfer at the contact appears. A few mechanisms take part in the heat transfer at the contact of two solids (Fig. 4) [11]:

1. Heat conduction at points of contact of surface irregularities.
2. Heat conduction in a medium present in gaps between the faces.
3. Radiation between the walls limiting the spaces formed between the points of contact (if the medium has appropriate properties).

For the mechanism of the actual contact of two faces, the thermal contact resistance *Rc* is observed. The reason for its existence is the lack of an ideal contact of surfaces of two bodies. The contact takes place only at the contact of the tops of irregularities present at the surfaces of the bodies. A temperature difference appears at the contact face, which is called the temperature gap. The heat flux transferred between the faces depends on the temperature, pressure force, surface roughness and the presence of an intermediate substance.

Impact of heat transfer on the electric voltage generation

The actual faces of the TEG and the heat source and the cooler have some roughness resulting from the manufacturing process. They feature the lack of an ideal contact, which weakens the heat transfer. To intensify the heat transfer, intermediate substances with a higher value of heat conductivity are applied. Thanks to their properties, they should fill the empty spaces between surface irregularities. An increase in the pressure force causes local deformations of irregularities, thus increasing the contact area. In effect, the heat transfer improves.

An increase in the temperature difference between the faces of the thermoelectric generator results in an increase in the generated electric voltage.

In the research conducted, the impact of pressure force and the presence of an intermediate substance on the electric voltage generated by the TEG was analysed. Two materials applied in solid-state devices were used for testing. The first one was a silicone thermal paste with a semi-fluid consistence [12]. The second material was a thermal pad made of a carbon-based polymer with nanoparticles in the form of a non-adhesive pad [13]. The heat source and the cooler were made of copper, which ensures a high value of thermal conductivity. The values of thermophysical parameters for the materials applied in the tests are shown in Table 1.

The maximum value of the copper application temperature was selected based on its yield strength. Above the temperature of 400℃, the yield point rapidly declines, which can lead to a deformation of the element being in contact with the TEG. The values of thermal conductivity for the materials used as the substance filling empty spaces are substantially different. The conductivity of the thermal paste is only 1.5 W m^{-1} K^{-1} compared to 62.5 W m^{-1} K^{-1} of the thermal pad.

The surface morphology was examined with an electron microscope. The fibre morphology was examined with a scanning electron microscope (SEM) (Hitachi 3500N). To examine the morphology of sample surfaces, their faces were covered with a thin layer of gold with a thickness of approx. 7 nm to improve the electrical conductivity during tests. To ensure the uniformity of the samples tested, the microscopic observations were carried out in three various and distant areas. The test results showed that the samples tested were uniform in terms of morphology.

The TEG surface was analysed: clean, coated with the thermal paste and covered with the thermal pad after deformation. In addition, the thermal pad surface was analysed in the initial state before deformation. The structure of the generator surface and of the thermal pad before deformation under small magnification is shown in Fig. 5. Details of the surface morphology for the selected fragments under larger magnification (500x) are shown in Fig. 6.

In the figures shown above, you can observe that the thermoelectric generator surface is very rough. The thermal pad surface (Fig. 6b) features a very developed surface quality with perpendicularly arranged elements of the structure. The roughness was measured with an optical profile measurement gauge. For the TEG surface, it was 2.0 µm. The thermal pad surface roughness in the initial condition was 5.0 µm. In addition, the surface roughness of the copper face constituting the heat source was measured with a mechanical profile measurement gauge, and it was 1.2 µm. Such a high

Table 1 Properties of the substances used in the tests [12–14]

	Thermal paste	Thermal pad	Copper
Heat conductivity/W m^{-1} K^{-1}	1.5	62.5	370
Temperature range/°C	−50 for + 250	−250 for + 150	for 400

roughness of the generator and the copper plate faces results in a low actual contact area. The contact between the faces is not uniform at the surface of the generator, and therefore, the heat transfer is hindered.

Due to the developed structure of the faces of the TEG and the heat source, it is necessary to use an intermediate substance to fill the voids formed at the contact of two rough surfaces in as much as possible. The selected substances have different forms, which results in a different degree of filling the irregularities of the contacting faces (Fig. 7).

The intermediate substance should be characterised by as high heat conductivity as possible and the ease to fill the voids caused by the roughness of contacting faces.

Test stand

Figure 8 shows a diagram of the test stand. A copper bar is heated in an electric furnace to a constant temperature. At the top, the bar is secured with a water-cooled grip to a hydraulic cylinder. Subsequently, the heated bar, because of the imposed force, contacts the thermoelectric generator (Fig. 9a). The cell is placed on a water cooler, which keeps the constant temperature of the other side of the thermoelectric generator. As a result of the temperature difference, the thermoelectric generator produces electricity, which is measured with a digital voltmeter (Fig. 9b).

During the experiment conducted, the temperature measurements as well as all other measurements of physical properties such as voltage or pressure force were burdened with measurement uncertainties. Many factors influence the measurement accuracy. They depend, for instance, on the applied measurement systems or the measurement methodology.

The extensometer sensor used in the measurement system, which is designed to measure compressive forces, was connected in a bridge system. The measurement range and accuracy of the instruments used for the tests are shown in Table 2.

The copper bar was pressed to the thermoelectric generator with a force of 250 N, 500 N, 750 N and 1000 N. The pressure values were selected on the basis of the thermoelectric generator catalogue sheet, and they did not exceed the limit value resulting from its design. The limit value of the thrust force on the thermoelectric generator was 1360 N. The TEG system without any intermediate substance was tested as the reference point. The subsequent test variants involved the thermal paste and the thermal pad as intermediate substances. The measurements were performed after stabilising the temperatures of the heat source and the cooler. The heat source temperature was $T_{HOT} = 100$ °C, the temperature of the cooler was $T_{COLD} = 18$ °C, which generated the temperature difference of $\Delta T = 82$℃. The thermal paste was applied

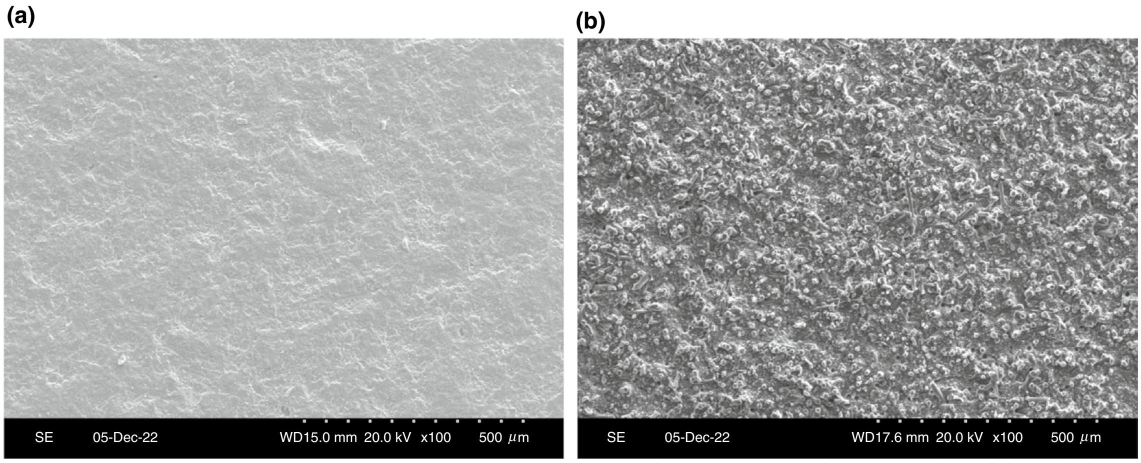


Fig. 5 Structure of the surface under magnification of 100× for: (**a**) TEG, (**b**) thermal pad before deformation

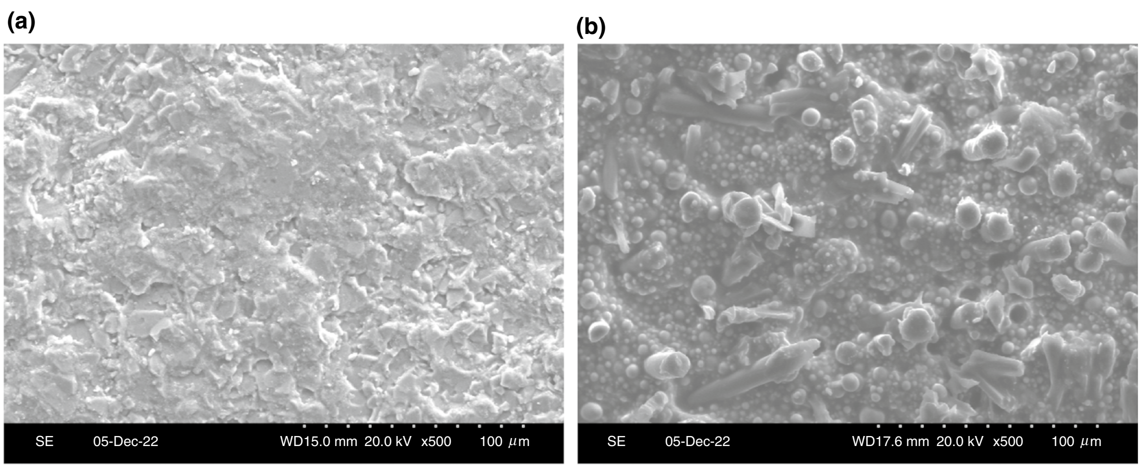
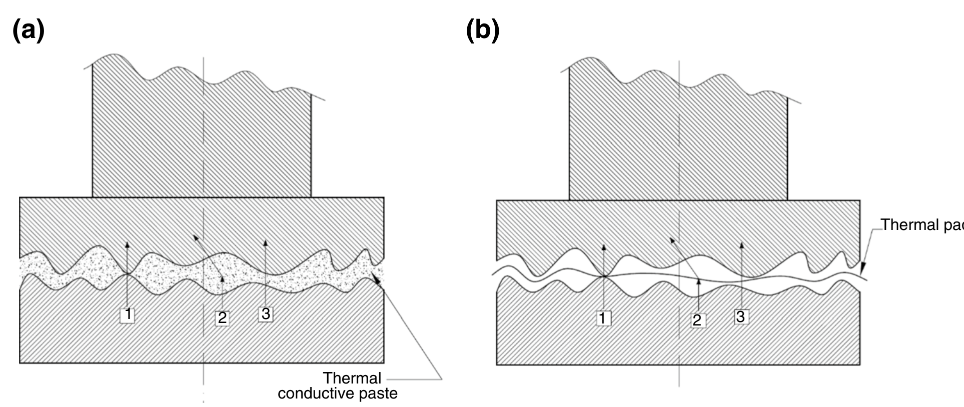


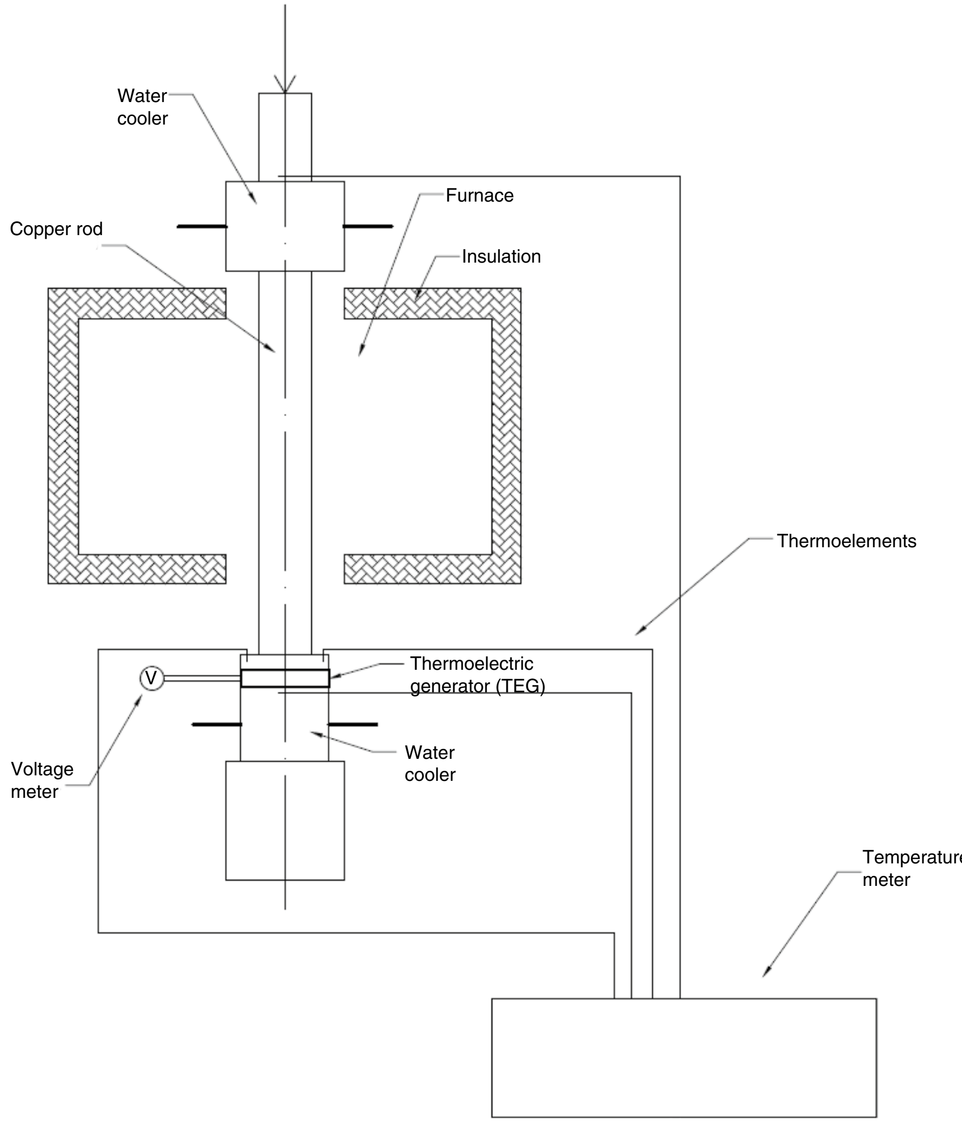
Fig. 6 Structure of the surface under magnification of 500× for (**a**) TEG, (**b**) thermal pad before deformation

Fig. 7 Diagram of the heat flow at the contact of two bodies for (**a**) thermal paste, (**b**) thermal pad



uniformly on the whole face of the TEG, in the amount causing an outflow of the excess paste as a result of the applied force. The thermal pad was cut to size to ensure that the whole face of the thermoelectric generator was covered.

Fig. 8 Test stand diagram



For these parameters and materials, voltage values were generated with the TEG.

A graph of the dependence of the voltage on the pressure force (Fig. 10) was created on the basis of these readings for three variants of the experiment.

On the graph (Fig. 10), you can see an increase in the voltage versus the applied force. The application of a thermal paste or pad results in an increase in the heat takeover by the thermoelectric generator, and consequently an increase in the voltage generated. This increase is at 21% for the thermal pad and 38% for the thermal paste. The higher voltage generated by the thermoelectric generator with the application of the thermal paste can result from the fact that the paste has a different state of aggregation than the thermal pad, and therefore, it better fills the hollows in the thermoelectric generator surface and facilitates heat transfer, despite a lower heat conductivity.

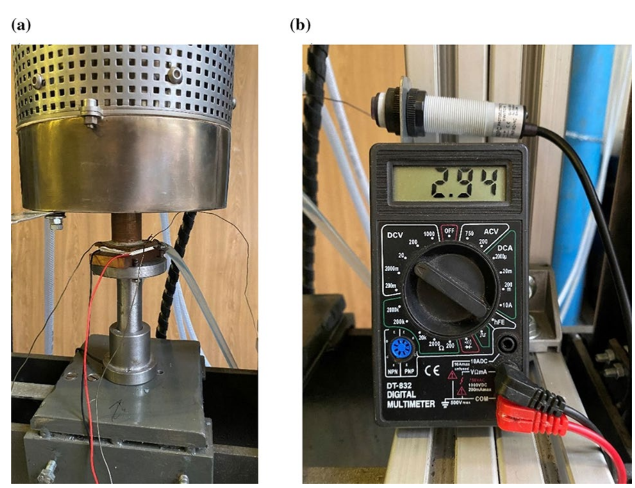


Fig. 9 Diagram of the test stand: (**a**) TEG, (**b**) digital voltmeter

Table 2 Measurement range and accuracy of instruments used

Instrument	Measurement range	Measurement accuracy
K-type thermocouples	−40 °C to + 375 °C	± 1.5 °C
Temperature recorder	− 100 °C to 1370 °C	0.05%
Voltmeter	0–20 V DC	± 0.5% indications for ± 2 digits
Extensometric sensor	for 10 kN	0.5%

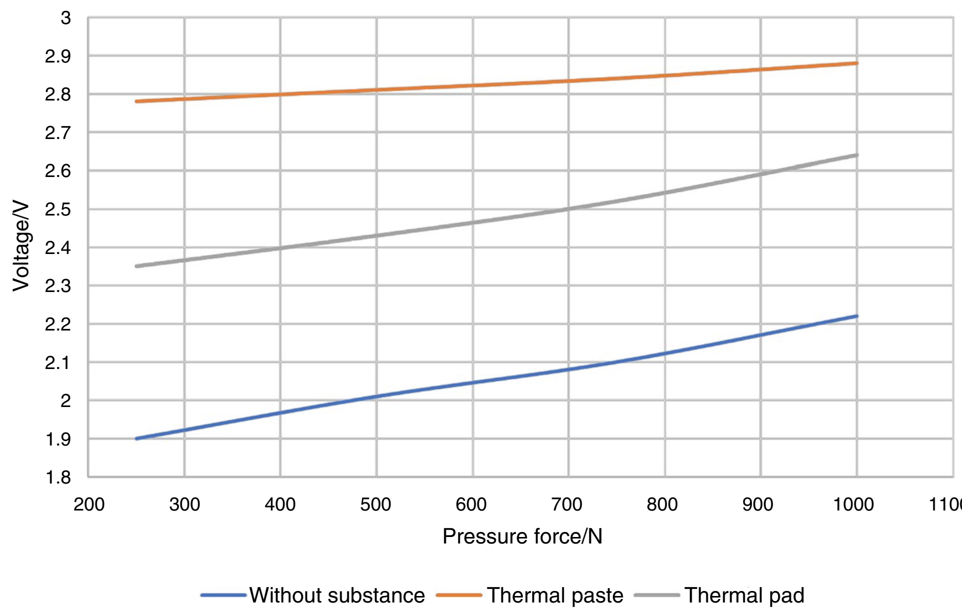


Fig. 10 Graph of the voltage change because of the pressure forces

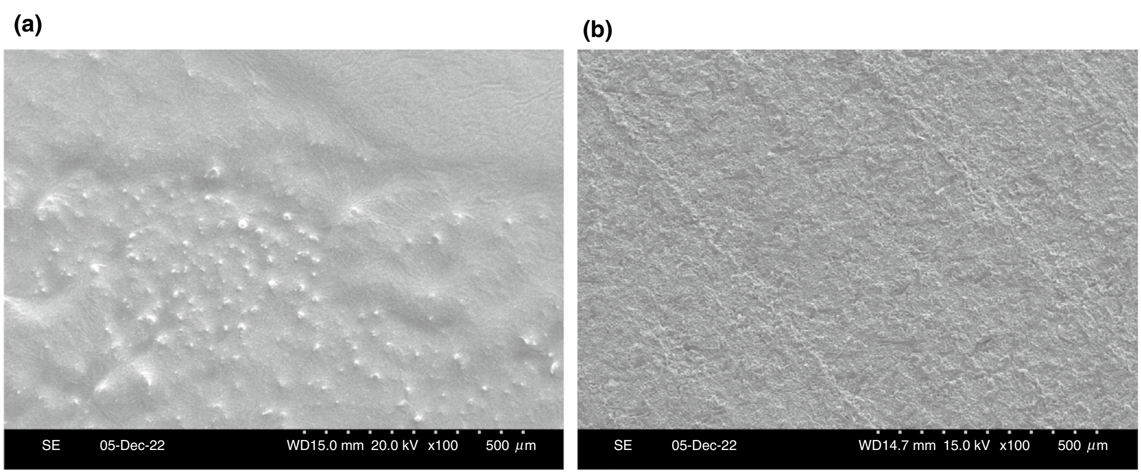


Fig. 11 Structure of the surface under magnification of 100× for: (**a**) thermal paste, (**b**) thermal pad after deformation

After the test, the TEG surface was analysed—coated with the thermal paste and covered with the thermal pad after deformation. The structure of the generator surface with the thermal paste and with the thermal pad after the deformation under small magnification is shown in Fig. 11. Details of the surface morphology for the selected fragments of the surface under larger magnification (500x) are shown in Fig. 12.

In Figs. 11 and 12 shown above, it is observed that, during the deformation, the elements of the structure at the thermal pad surface flattened, but the surface does not remain uniform, which resulted in a smaller area of the actual

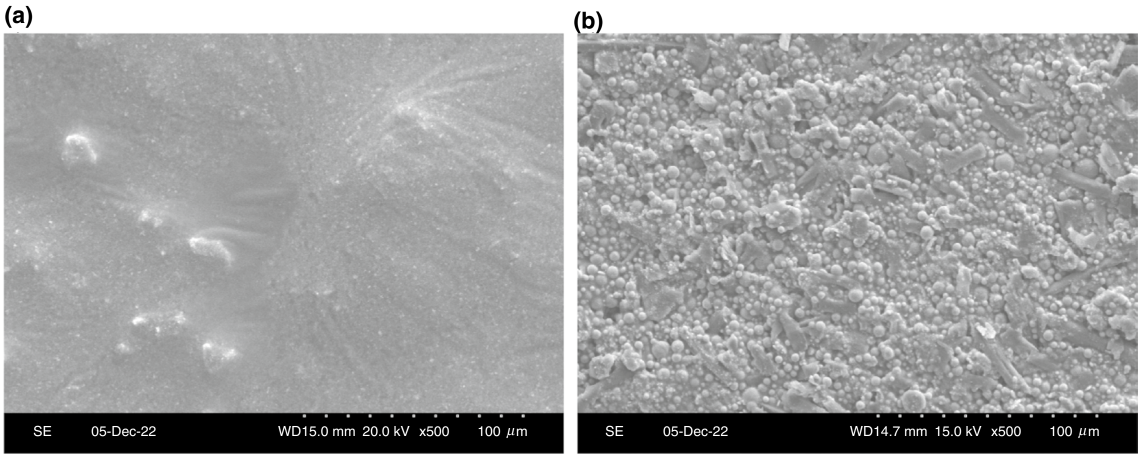


Fig. 12 Structure of the surface under magnification of 500×for: (**a**) thermal paste, (**b**) thermal pad after deformation

contact. The contact between the faces is not uniform at the surface of the generator, and therefore, the heat transfer is hindered. In Fig. 12a, it is visible that the thermal paste filled the irregularities of the thermoelectric generator surface, and therefore, the contact between the surfaces improved. After the completed experiment, the roughness of the thermal paste and thermal pad surface was measured. The values were 1.8 µm for the thermal paste and 1.9 µm for the thermal pad. Within the range of forces applied in the experiment, the thermal pad did not undergo a complete deformation in accordance with its characteristic curve. The thermal paste filled the surface irregularities well and provided a better heat transfer within the system. In both variants of the experiment with the intermediate substance, the heat transfer improved, which resulted in an increase in the voltage generated.

Conclusions

In the conducted experiment, the impact of the pressure force on the electricity generation with the thermoelectric generator was examined. The objective of the research was to increase the heat transfer between the rough surface of the TEG and the rough copper surface serving as the heat source. Two intermediate substances were selected: a thermal paste and a thermal pad, which were to fill the voids related to the surface quality. Therefore, for the tested range of pressure forces, the thermal paste better filled its role. Such low pressure forces were sufficient for the paste to better fill the generator and the heat source surface irregularities, increasing the number of contact points of heat transfer by conduction. Even though, in the experiment carried out, the thermal pad performed worse than the thermal paste, the application of both materials as the intermediate substances improved the heat transfer, which had a direct impact on the generation of voltage. To conclude, the application of a higher pressure force, an intermediate substance, and various technologies of material treatment to reduce the roughness of the contacting faces and increase the number of actual points of contact improves heat transfer and increases the generated voltage.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

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