Research Square

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Monitoring of electricity generation from exhaust waste heat and wireless data recording from a mobile phone in real driving conditions of a vehicle

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Research Article

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Abstract

This study is aimed to design electrical energy production and wireless data monitoring system by utilizing the working principles of thermoelectric generators from the exhaust waste heat of vehicles in traffic. In order to transmit the heat transfer in the exhaust pipe to the thermoelectric generators, a modular system has been developed in a hexagonal form that can be dismounted and mounted from aluminum material. Six thermoelectric generators (TEG-SP1848) are used on the aluminum module, and a heat sink is used to cool each thermoelectric generator. The voltage and current values of the electrical energy produced from the exhaust waste heat of the vehicle in real driving conditions are recorded with a special program written on the card on the system. Depending on the results obtained from the test drives, electrical energy was obtained at a maximum voltage of 9.8 V and a current of 0.32 A. This electrical energy obtained from the exhaust waste heat can be stored in the vehicle's existing battery if desired. In this way, since the alternator used for the electricity generation of the vehicle will be activated less, some fuel savings will be achieved in the engine, and harmful exhaust emissions will be reduced. In addition, the electrical energy obtained by this method can be stored in an external battery independent of the vehicle battery and used for various purposes when the vehicle is at a standstill or with a portable battery.

Introduction

Recently, different searches have emerged in energy production due to reasons such as excessive energy expenditures, global warming, economic problems, and the decrease in fossil fuel reserves with the increase in the world population. In addition to meeting the energy needs of many countries, it is also important to ensure environmental awareness, efficiency, resource diversity, and continuity. With the increase in energy demand in the future, it is thought that costs and environmental problems will increase even more. Many countries, aware of this situation, evaluate various alternative energy sources according to their own climatic and economic conditions to meet the increasing energy demand. In this sense, electric, hybrid, and fuel-cell engines have been developed. However, the fact that most vehicles in use are still petroleum-derived, depending on the world population, poses a serious problem. In recent years, manufacturers have continued to work to reduce the volume, efficiency, and harmful exhaust emissions of internal combustion engines. In addition, if systems that will benefit from the waste heat of motor vehicles are developed, the electrical energy obtained will also reduce the alternator load, fuel consumption, and harmful exhaust emissions. In today's vehicles, larger alternators are needed as electricity consumption increases depending on the comfort level (Mazlan et al., 2017). It is a known fact that this situation reduces the output power of the engine and causes an increase in fuel consumption as the alternator is activated more. It is thought that by designing various heat recovery systems in motor vehicles in the future, the alternator's load will be alleviated, and some more fuel savings will be achieved. The interest in energy recovery units will increase. Thus, using the exhaust waste heat of internal combustion engines provides additional electrical energy and fuel economy and reduces harmful exhaust emissions (Deng et al., 2017). Apart from the automotive sector, Industrialists in the production sector are

also continuing research on the recovery of waste heat energy and energy efficiency (Champier, 2017). Reducing harmful exhaust emissions from heavy-duty vehicles, used extensively in the transportation sector, gains importance with each passing day. In order to reduce both electrical energy and emissions from waste heat, heat exchangers and thermoelectric generator designs with different structures are applied to the exhaust systems of heavy-duty vehicles (Heber et al., 2022). The low conversion efficiency of thermoelectric generators used to obtain electrical energy from waste heat in today's conditions prevents the increase in application areas (Tohidi et al., 2022). However, since there are no moving parts in the structures of thermoelectric generators, they are silent and economical, so researchers continue to increase efficiency (Mamur et al., 2021). Also, one of the important features of these materials is that they have the ability to convert thermal energy into electrical energy in a very short time. With this aspect, the future of thermoelectric generators looks bright (Wu et al., 2022). In addition to all these, very different exhaust temperatures are obtained due to the structural features of motor vehicles and the variability in working conditions. For this reason, some difficulties are encountered in designing and optimizing thermoelectric generators on the exhaust systems of motor vehicles (Zhu et al., 2022). The location and design of thermoelectric generators on the hot side of thermoelectric generators are very important to obtain high electrical energy from waste heat (Luo et al., 2022). Electricity generation by utilizing thermoelectric generators is limited to internal combustion engines and can also be used in electric, hybrid, and fuel-cell vehicles. Recently, there has been an increasing interest in research on this type of vehicle (Olabi et al., 2022). It is seen as a promising solution for the industry in producing electrical energy from waste heat by increasing the efficiency of thermoelectric generators, which have many positive structural features (Zoui et al., 2022). The fact that researchers have recently turned to issues such as air pollution, global warming, climate change, and energy recovery will also increase the interest in future clean energy use and energy efficiency (Kuah et al., 2022).

When the current studies on the production of electrical energy by using thermoelectric generators from the exhaust waste heat of motor vehicles in the literature are examined.

A thermoelectric generator (TEG-12715) was applied to the exhaust system of the single-cylinder Honda brand GX-120 model engine to obtain electrical energy from waste heat. A maximum voltage of 1.4V and a current of 0.98A was obtained at 3000 rpm (Raut & Vohra, 2022). Thermoelectric generators' power output is closely related to the number of modules. A study obtained a maximum power of 25.16 W with 40 modules (Ge et al., 2022). In internal combustion engines, approximately 65–70% of the energy input is lost as waste heat. This heat source is the exhaust gas system (~ 35–40%) and the radiator in the cooling system (~ 30%). If some of the wasted heat is recovered, the thermal efficiency will be increased. For this reason, by positioning thermoelectric generators in the exhaust and cooling system, both better power outputs and a reduction in harmful emissions will be achieved (Burnete et al., 2022). According to the theoretical analysis results, 1.1% more net output power was obtained from the circular section thermoelectric generator (Huang & Shen, 2022). The electrical energy produced by a single thermoelectric module (SP1848-27145) was investigated using a simple heat source experiment set. When the temperature difference between the hot and cold sides of the thermoelectric generator is 60°C, a voltage of 1.6 V and a current of 100 mA are obtained (Collins, 2022). The test setup and numerical simulation

results were compared to evaluate the performance of a thermoelectric generator. Depending on the data obtained, the numerical simulations showed that the test results were consistent with the test results. With the thermal temperature of 623 K, an output power of 29.15 W was obtained (Wang et al., 2022). Thermal and economic analyzes were made in a study where the exhaust gas temperature from the truck engine as a heat source was 708 K. Optimization was achieved with the boundary condition that the thermoelectric generators were 1.5 mm high and 144 units (Cai et al., 2023).

In this study, unlike the studies in the literature, a unique energy conversion unit was designed by utilizing the vehicle exhaust waste heat. Special hardware, firmware, and mobile software have been developed for the system, which can be monitored on a mobile phone and records the electrical current and voltage values produced in thermoelectric generators from the heat released from the exhaust in actual driving conditions of automobiles by wireless data transfer. In addition, the fact that the thermoelectric module unit can be removed and installed in the vehicle's exhaust pipe quickly provides the advantage of use in different cars.

Material and Method

Tools and Hardware

In this study, a modular (removable) system has been developed for converting electrical energy with thermoelectric generators by using the waste heat in the Volkswagen brand 1600 cc 120 Hp engine power Common rail diesel vehicle and the exhaust system under real driving conditions. The technical data of the vehicle are shown in Table 1. In order to transfer the waste heat in the exhaust pipe to thermoelectric generators, a special module in hexagonal geometry is designed from aluminum material. This module is produced in accordance with the pipe diameter and thermoelectric generator dimensions after the exhaust manifold outlet. This system, which provides electrical energy conversion by utilizing the exhaust waste heat, 2-part removable and pluggable aluminum carrier module, 6 thermoelectric generators (TEG-SP1848), 6 heatsinks, 5 temperature sensors, 1 Arduino mega card, voltage / current sensor, DC / DC converter,1 bluetooth module, 1 memory card, cables, consists of sockets and junction box. Thermal paste has been applied to both surfaces of the thermoelectric generators, which enables the conversion of exhaust waste heat into electrical energy to increase heat conduction. High temperature-resistant silicon is used to assemble thermoelectric generators, and heat sinks on the aluminum carrier body.

Experiments were carried out in real driving conditions using the Edirne-Istanbul highway. During the test drives, the outside temperature was measured at 30°C. The total test drive lasted 40 minutes, and a maximum temperature difference of 40°C was achieved in the thermoelectric generators in the first 15 minutes. The temperature difference decreased in all subsequent time periods. The voltage and current values of the electrical energy obtained by thermoelectric generators from the exhaust waste heat in real driving conditions are given in the graphics.

Table 1

Engine specifications

Feature	Value
Engines	Diesel engine
Displacement	1.6
No of cylinders/valves per cylinder	4/4
Power (kW at rpm)	81/3000–4000
Torque (Nm at rpm)	250/1500–3000
Bore (Ø mm)	79.5
Stroke (mm)	80.5
Compression ratio	16.2
Injection/ignition	TDI common rail
Camshaft drive	Toothed belt

The modules and thermoelectric generators designed for the engine's exhaust pipe are shown in Fig. 1.

As a result of connecting two N and P-type semiconductors to each other with a conductive material, a single-cell structure is formed (Fig. 2). Thermoelectric structures (modules) are formed by bringing each cell together. Although thermoelectric generators work with low efficiency, they have become preferable, especially regarding waste heat evaluation.

Depending on the Seebeck coefficient and the temperature difference, the thermoelectric effect is given in equations 1 and 2. WiedemannFranz rule of isotropic metal, semiconductors are widely used in thermoelectric materials. (Uchida et al., 2016; Wang et al., 2021).

V=$\alpha(T_{sh} - T_{sc})$ (1)

$$P = Q_H - Q_C = I^2 R \Delta (T_{sh} - T_{sc}) \quad (2)$$

where; V is the voltage ; α is Seebeck coefficient; Q_C is the heat rate that enters the thermoelectric module of each stage from the cold side and Q_H the heat rate that goes out at the hot side, $T_{sh} - T_{sc}$ is temperature difference ; R is resistance; P is power; I is current. The technical specifications of the thermoelectric generators used in the system are given in Table 2.

Table 2
TEG-SP1848 specifications

Feature	Value
Material	Ceramic/Bismuth Telluride
Color	White
Parametric model	SP1848-27145
Temperature (C)	150 Degree
Open-circuit voltage (V)	4.8V
Current (mA)	20/0.97/225;40/1.8/368;60/2.4/469;80/3.6/559;100/4.8/669
Module weight	25g/0.89oz
Module size	4*4*0.4cm/1.6*1.6*0.2inch (L*W*H)

Error rates of electronic circuit elements are shown in Table 3. The uncertainty analysis of the system is calculated according to these values.

Table 3
Features of devices used in the data system.

Feature	Error rate
DS18 B20 Temperature sensor	±% 0.5
Voltage sensor	±% 1.5
Current sensor	±% 1.5
Load resistance	±% 0.5
Atmega 328P Software card	± 2 LSB (Least Significant Bit)

The power generation of the thermoelectric generator is taken into account. Eq. (3) can be used for this calculation:

$$U = \pm\sqrt{\left(\frac{\Delta V_{TEG}}{V_{TEG}}\right)^2 + \left(\frac{\Delta I_{TEG}}{I_{TEG}}\right)^2}.100$$

3

Total uncertainty for thermoelectric generated generators are calculated as 3.8%.

After the thermoelectric generators, electronic hardware, and software unit were completed, the vehicle was taken to the lift, and the module designed for energy conversion was mounted on the exhaust outlet pipe, as shown in Fig. 3.

The view of all hardware of the system is displayed in Fig. 4.

In Fig. 4, the circuit elements that make up the system are given respectively.1-Thermoelectric generator, 2-Aluminum body, 3-Heat sink, 4- Temperature sensors, 5- Arduino mega card, 6-Bluetooth module, 7-Battery, 8-On/off switch.

Software

Two different software were developed using two different IDEs (Integrated development environments) in the system. The first is the firmware of the hardware designed with the Arduino IDE. In the firmware software, the values from the sensors are read and sent via Bluetooth once a second.

The Delphi IDE of Embarcadero was used for the application developed for the mobile phone. The most important advantage of this IDE is that it can be written for Windows, Android, iOS, macOS, and Linux using the same code. For this reason, the written program can work on Android mobile phones and Cross-Platform. Programs written using the Delphi software language are translated by the IDE to the native language of the operating system and compiled, so they work very quickly and without any problems with low resource consumption. For these reasons, this IDE is preferred.

The mobile application parses the data from the hardware via Bluetooth, storing it in a file and showing it instantly graphically. The general flow diagram of the mobile software is shown in Fig. 5.

The mobile application is designed with a user-friendly, easy-to-understand interface. Values from temperature sensors are shown graphically, and recording time, Voltage, and current values are shown as text. When the connect button is clicked, it is opened if Bluetooth is turned off, permission is not granted, and a permission query is made. Then it starts to read the values by connecting directly to the Bluetooth module of the hardware since it is specific to the operation. A screenshot of the program while it is running, is seen in Fig. 6.

The voltage values obtained from the thermoelectric generators depending on the temperature difference, are shown in Fig. 6.

Conclusion and Discussion

In Fig. 7, the voltage values obtained from the thermoelectric generators depending on the temperature difference are seen.

With this system we designed on the exhaust pipe of the vehicle, a voltage of 9.8V was obtained when the temperature difference in the thermoelectric generators reached a maximum of 40°C.

As seen in Fig. 7, as the temperature difference between the hot and cold surfaces in thermoelectric generators increases, the voltage value of the electrical energy obtained increases. However, since aluminum heat sink fins are used for cooling the thermoelectric generators, more temperature difference cannot be obtained because the exhaust temperature depends on the vehicle's driving speed in real driving conditions—the temperature difference between the surfaces of the thermoelectric generators changes. When the vehicle's driving speed decreases, the airflow on the aluminum fins (heatsink) that we use for cooling the thermoelectric generators decreases, decreasing the temperature difference. This situation also reduces the voltage values in the energy obtained from the thermoelectric generators. In order to obtain high voltage values, the temperature difference between the thermoelectric generator surfaces should not be below 40°C. This was impossible with aluminum fins (heatsink) for cooling on the surface.

As can be seen in Fig. 8, the current values of the electrical energy obtained depending on the temperature difference also increases. In this system, which we designed on the vehicle's exhaust pipe, a maximum current value of 0.32 A was obtained when the temperature difference in the thermoelectric generators reached 40°C. Similar to the voltage values, the current values increase as the temperature difference between the surfaces of the thermoelectric generators increases. However, since aluminum fins (heatsink) were used to cool the thermoelectric generators in our designed system, more temperature difference could not be obtained.

If the temperature difference between the thermoelectric generator surfaces reaches higher values with different cooling designs and methods, the electric current obtained will also increase.

Figure 9 shows the power values obtained from the thermoelectric generator depending on the temperature difference. With the system we designed, a maximum power output of 3.13W was obtained when the temperature difference in the thermoelectric generators reached 40°C.

Similarly, the temperature difference must be increased to obtain more power from thermoelectric generators. For this to happen, thermoelectric generators need to be cooled more effectively since the exhaust pipe temperature of the vehicle is constant. Ensuring stable conditions in energy production varies depending on the time taken for the temperature difference between the hot surface and cold surfaces of thermoelectric generators (Atmoko et al., 2022; Thanthong, 2022). Similarly, the heat transfer rate on the hot surface side of thermoelectric generators gains importance. For this reason, it would be beneficial to try the water-cooled method to increase the difference between the surface temperatures of the thermoelectric generators on the module in a shorter time. It is consistent with the statement of S. Wiriyasart in his research, stating that the temperature difference on the surface of the module has a vital role in the electrical power output produced by thermoelectric generators (Wiriyasart & Naphon, 2021).

Conclusion

In this study, a thermoelectric generator module design, which can be dismounted and mounted on the exhaust pipe, has been made for electricity generation by utilizing the exhaust waste heat in the actual

driving conditions of an automobile. In addition, special software has been developed for the system that allows the amount of electrical energy obtained from the thermoelectric generators on this module to be monitored instantly via the mobile phone. The system we designed obtained electrical energy with a maximum voltage of 9.8 V and a current of 0.32 A, depending on the test results. Higher voltage and current values can be obtained by increasing the number of thermoelectric generators. A heatsink with air fins made of aluminum material was used in the system we designed to cool the thermoelectric generators. With this cooling method, a maximum temperature difference of 40˚C was obtained between the cold and hot surfaces of the thermoelectric generators. If higher temperature differences could be obtained, the voltage and current values of the electrical energy produced in the system would also increase. However, this was not possible with the heatsinks we used for cooling. Because the vehicle's speed and exhaust temperature depend on the air-cooling system, the air cooling system is insufficient. It is understood that in future experimental studies, developing different cooling methods and comparing them with the system we have designed to obtain more electrical energy will be useful.

Declarations

Competing interests

The authors have no financial or proprietary interests in any material discussed in this article.

Authors’ Contributions

İlhan UMUT

Implementation of hardware and software

Writing the article

Dincer AKAL

Design, installation and testing of the thermoelectric system

Writing the article

Availability of data and material

The datasets generated during the current study are available from the corresponding author on reasonable request.

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Ethical approval, consent to participate, consent to publish

The research is not applicable because it does not have human participants, human material, or animal subjects.

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Figures

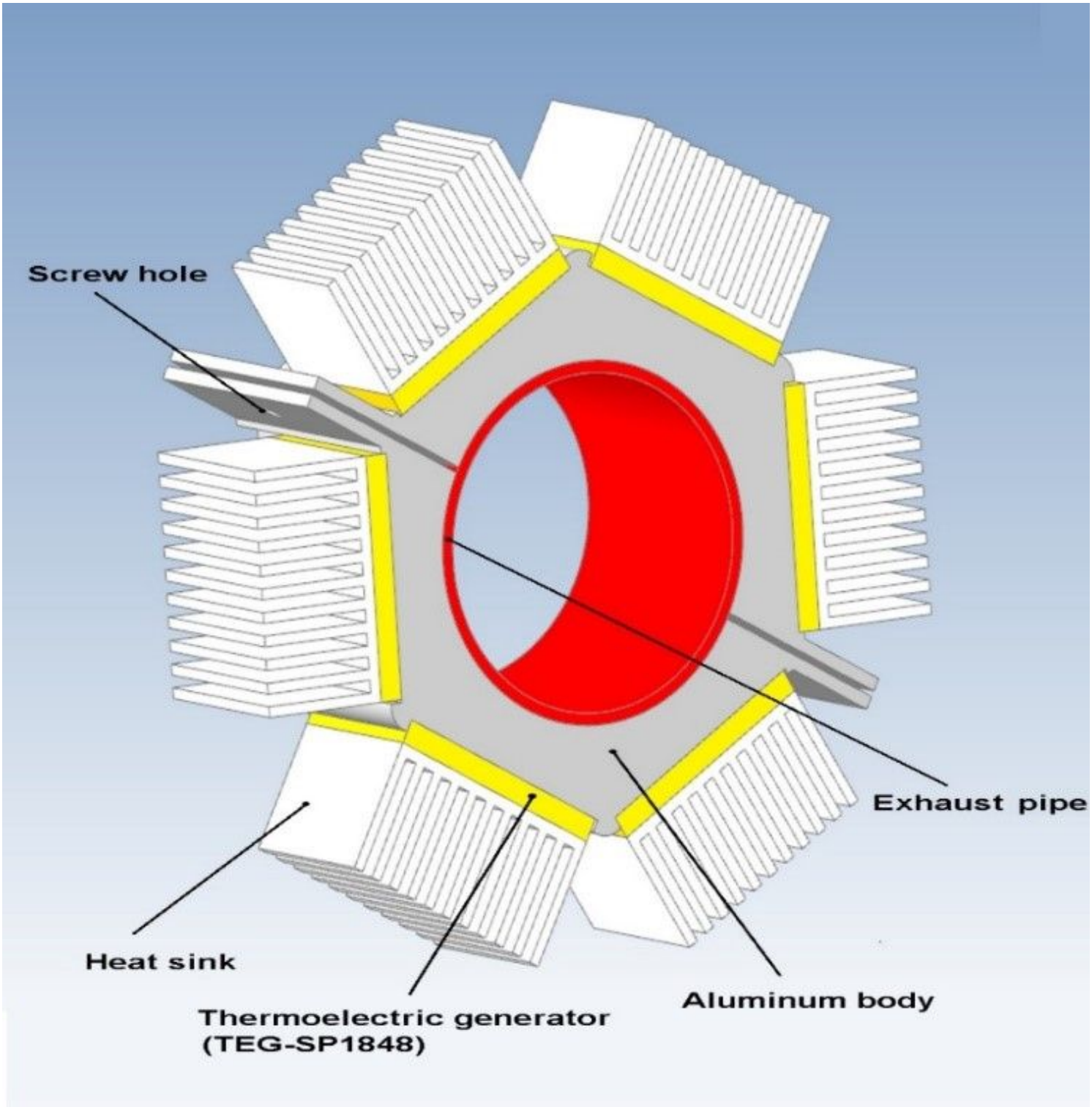

Figure 1

Designed module and thermoelectric generators

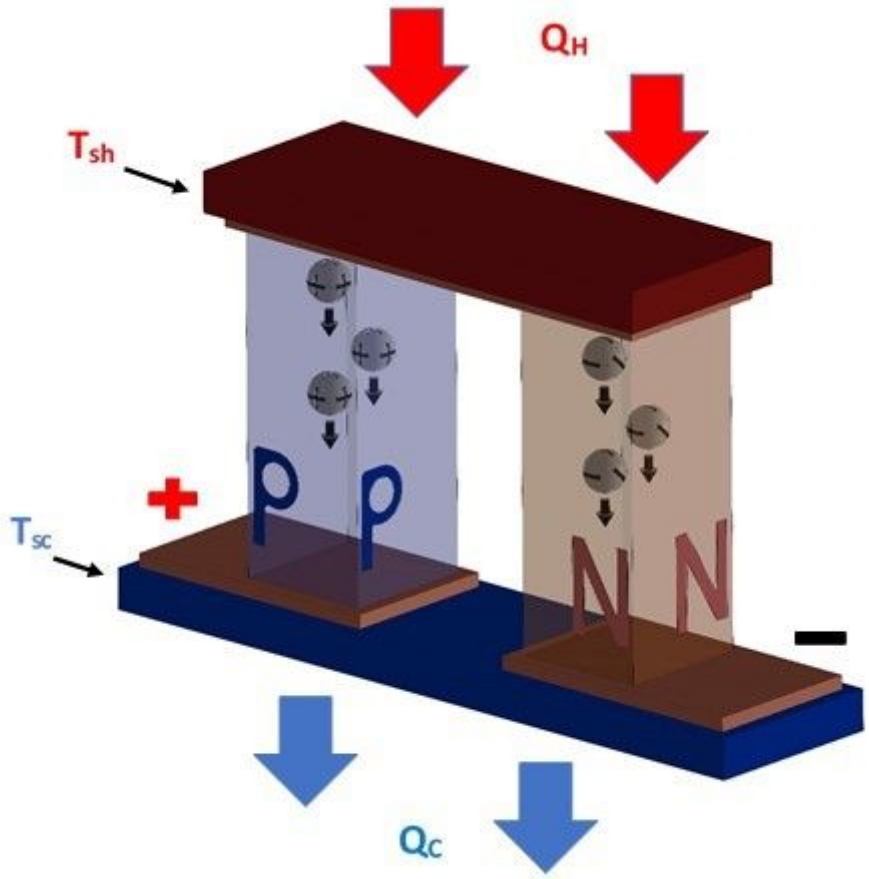

Figure 2

Energy conversion principle with temperature difference in thermoelectric element



Figure 3

Installation of thermoelectric generators and energy conversion syst

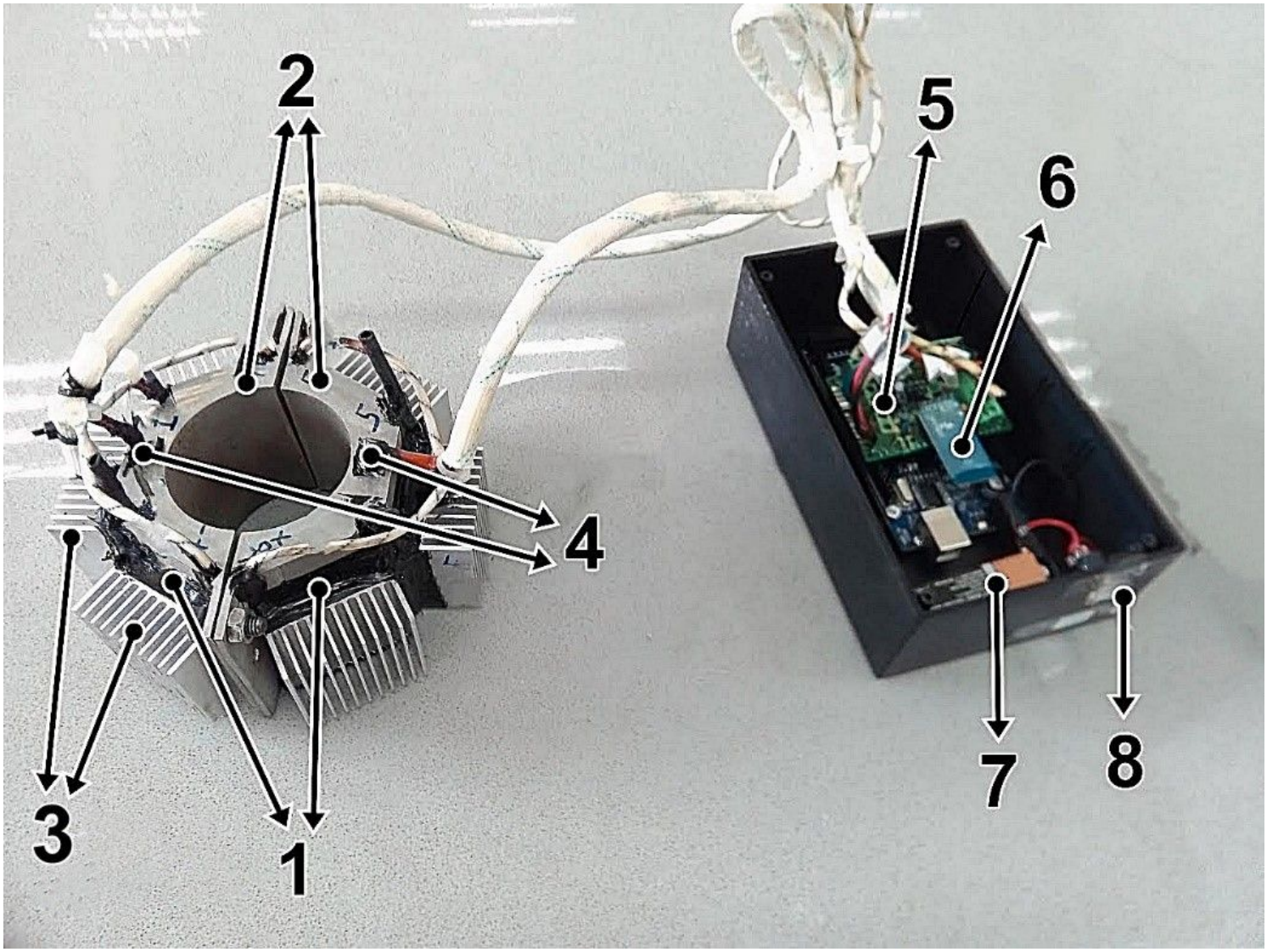

Figure 4

An example view of the system hardware

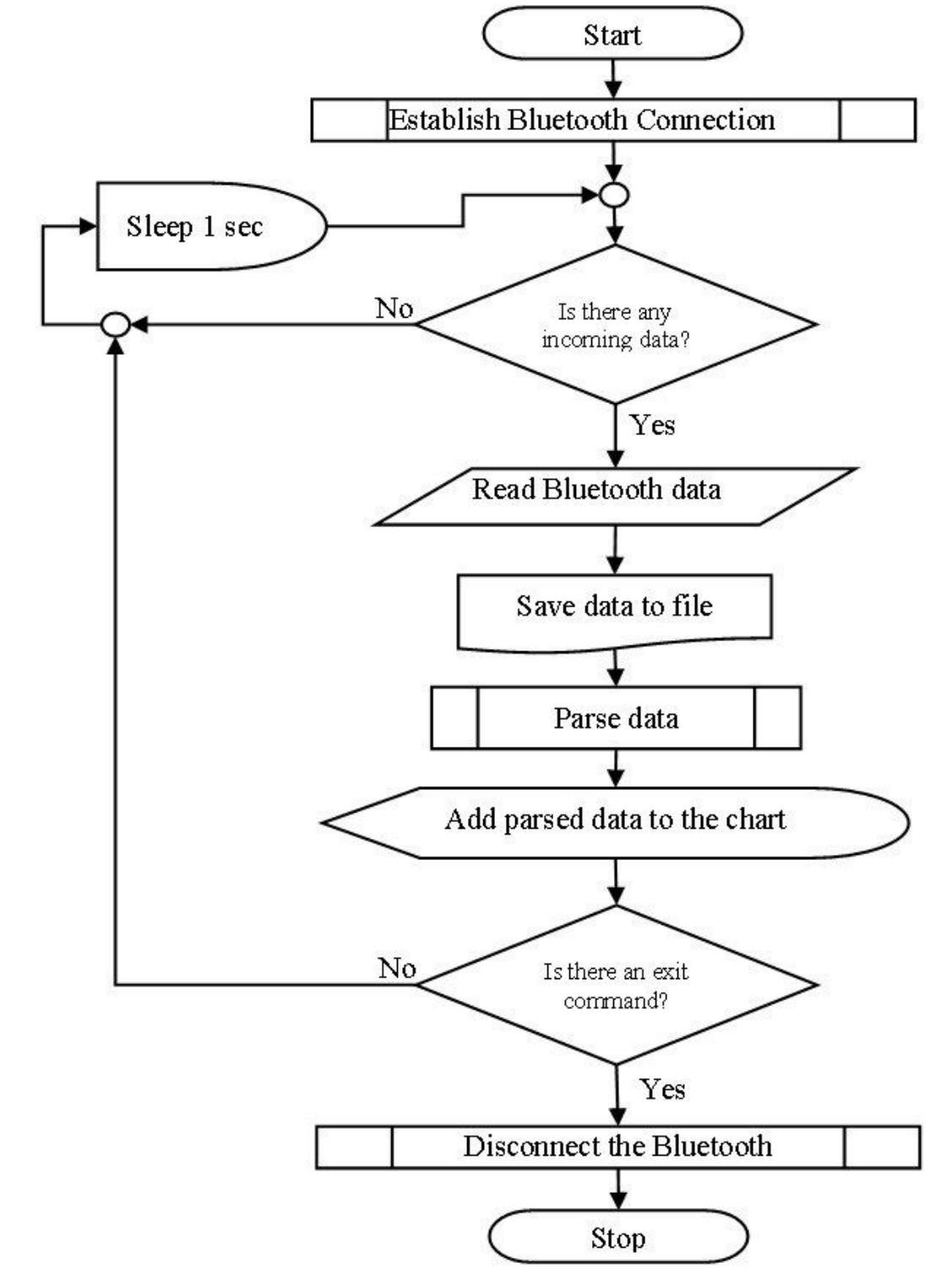

Figure 5

General flow diagram of mobile software.

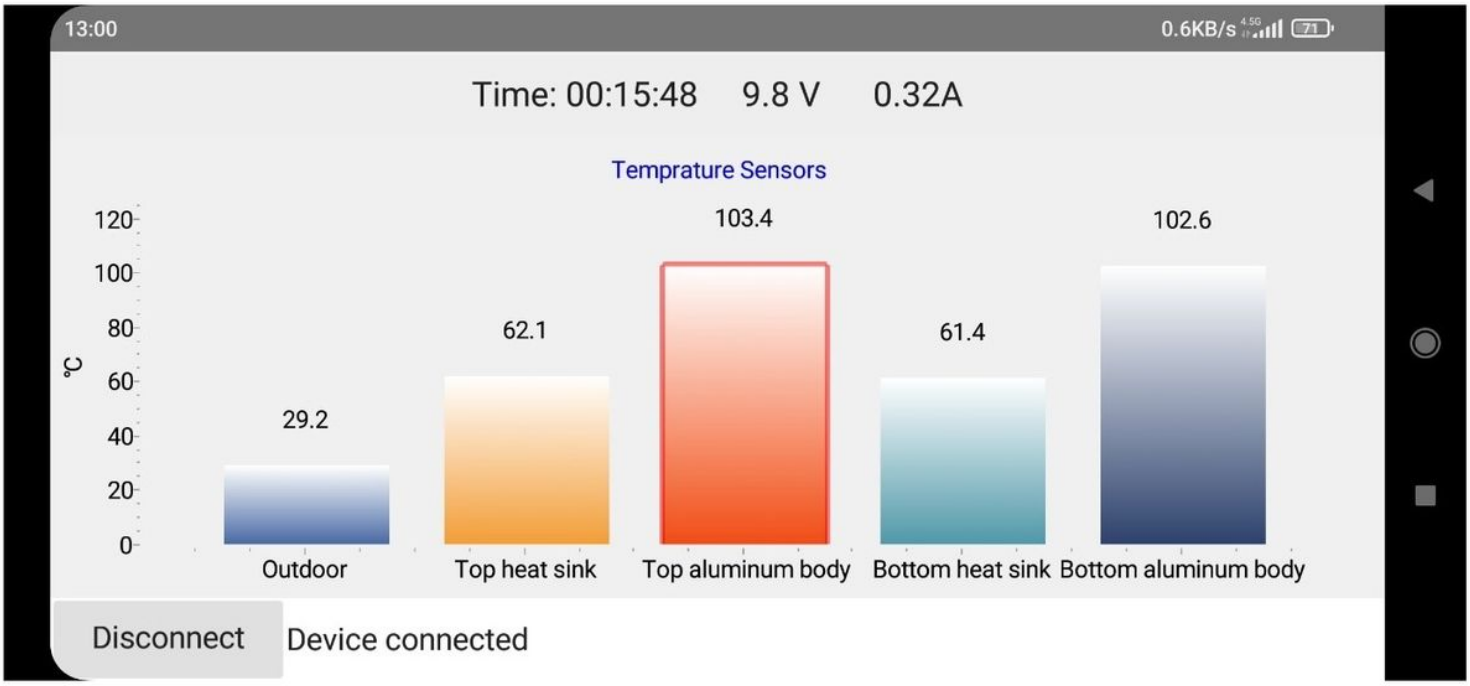

Figure 6

The user interface of the mobile program

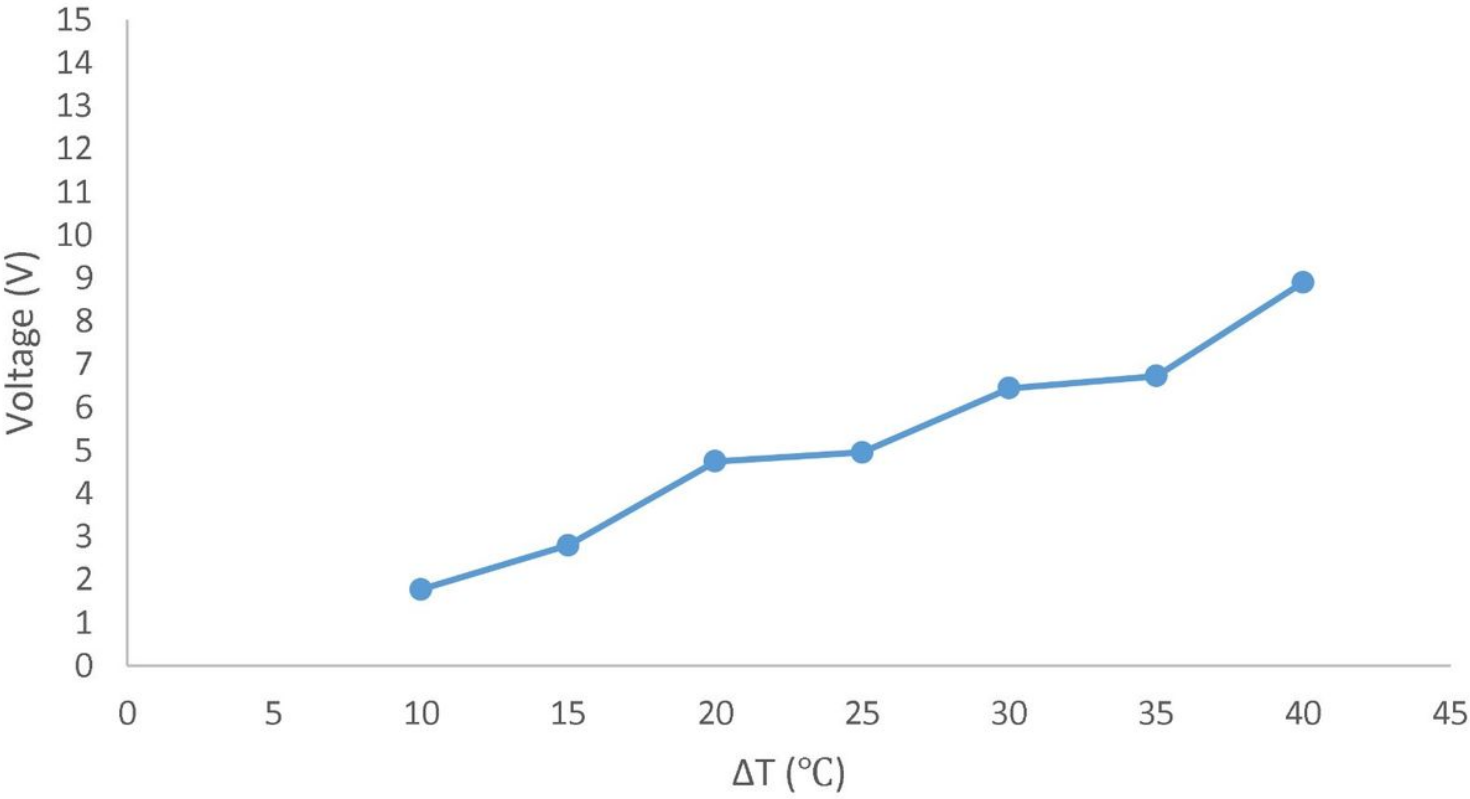

Figure 7

Voltage values obtained from thermoelectric generators depending on temperature

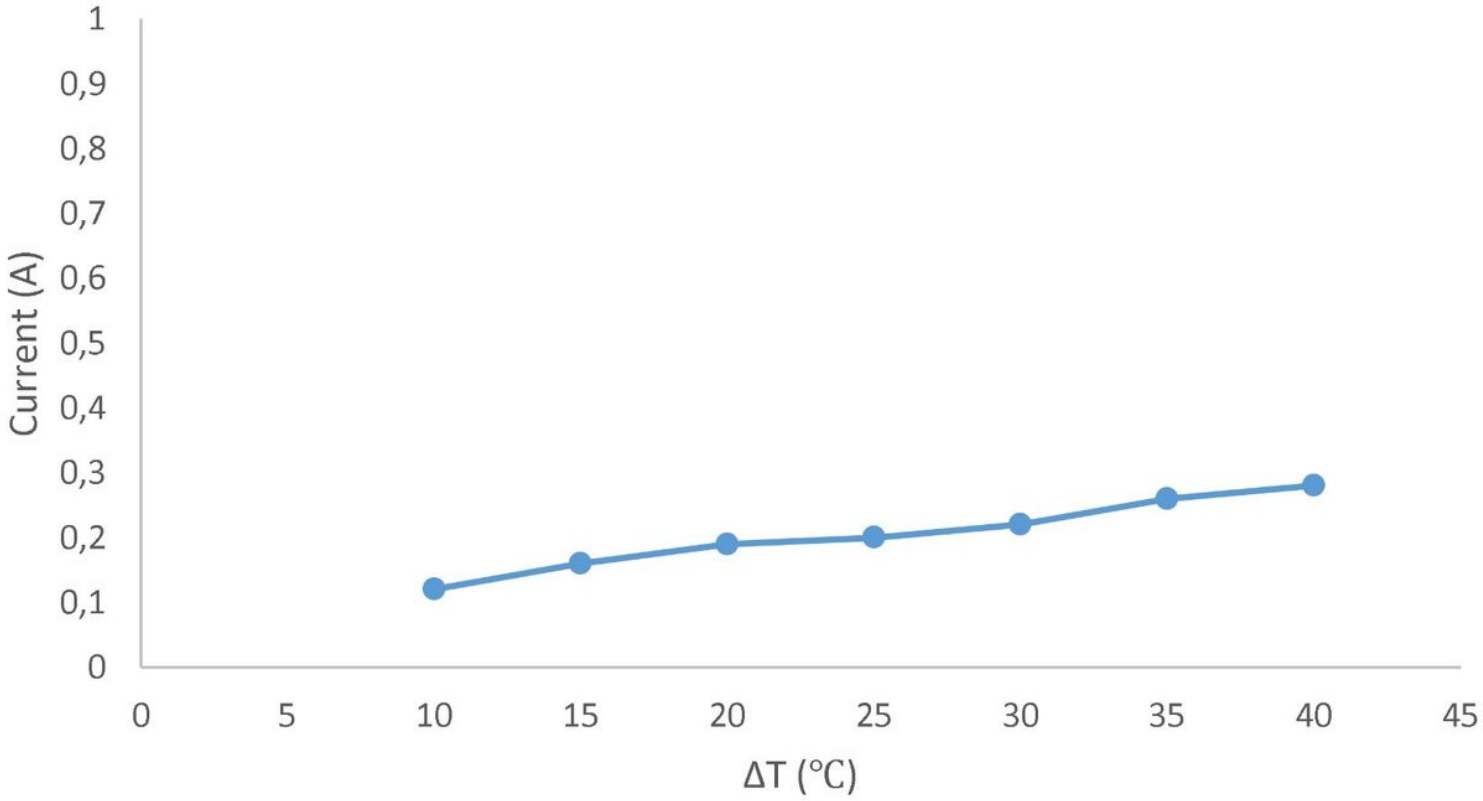

Figure 8

Current values obtained from thermoelectric generators depending on temperature

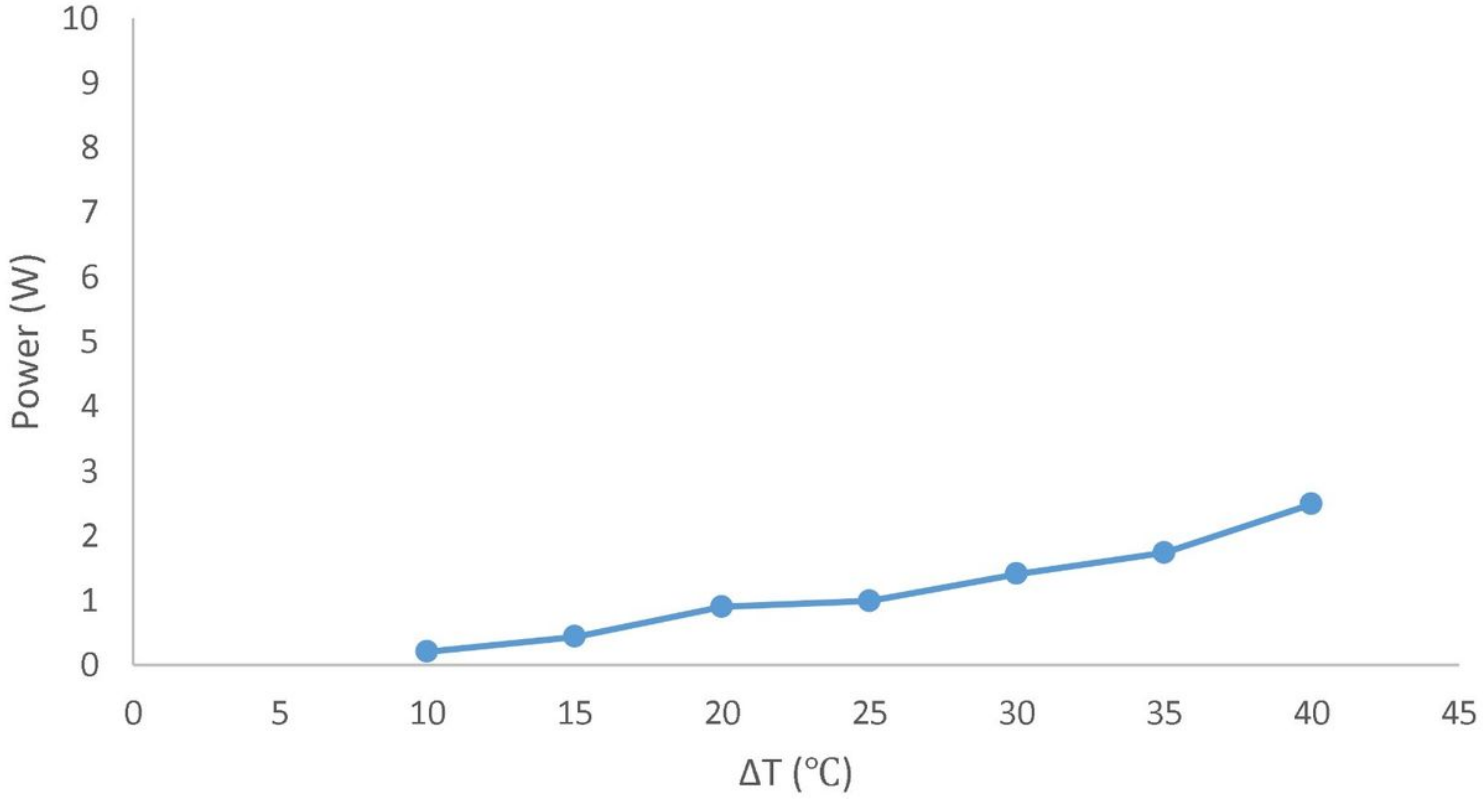

Figure 9

Power values obtained from thermoelectric generators depending on temperature