Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 51, Issue 1 (2018) 19-30

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Thermoelectric Combined Heat and Power Generation System Integrated with Liquid-Fuel Stove

Open Access

Mustafa Sabah Mahdi[1,*], Jasim Abdulateef[1,2], Ammar Mohammed Abdulateef[1,2]

[1] Mechanical Engineering Department, University of Diyala, 32001 Diyala, Iraq
[2] Solar Energy Research Institute, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 23 August 2018
Received in revised form 19 October 2018
Accepted 4 November 2018
Available online 6 November 2018

Keywords:
Thermoelectric, TEG CHP, heat transfer, Kerosene stove

ABSTRACT

Liquid-fuel stoves (kerosene heaters) are extensively used in developed and non-developed countries and rural communities. In addition, these stoves are generally common due to their convenient fuel cost for space heating. Moreover, the possibility of using these stoves for water heating and generating electricity represents an extra benefit. This study presents an application of thermoelectric devices to a liquid-fuel stove to concurrently charge a 12-V lead-acid battery and transfer heat to circulating water for heating or normal household purposes. The feasibility of the proposed thermoelectric generator (TEG) for combined heat and power system is demonstrated for a common kerosene indoor stove. This system generates an average of 235Wth and 12.2Wele (19Wel peak) during a three-hour-long burning experiment. The proposed system produced 0.25 Wel/cm2 on average on the TEG area in which the obtained TEG efficiency is around 5%.

1. Introduction

Approximately 2.5 billion people around the world are still highly dependent on traditional domestic stoves [1]. In cold climates, kerosene stoves are widely used for space heating and cooking. One interesting option to obtain electricity when the electric power lines are not existent is to retrofit these stoves with simple low cost thermoelectric generators (TEGs).

Thermoelectric power generators are reliable solid-state energy devices that directly convert heat into electric power through the thermoelectric effect. The applications of TEGs to recover waste heat energy have rapidly increased in recent years in fields, such as automotive [2-5], remote sensing [6-8], geothermal [9], space systems [10], cooling [11-13], industrial power plants [14-16], and stove [17-34]. Moreover, thermoelectric is recently combined to photovoltaic, solar thermal or thermos-photovoltaic systems [35-39]. The requirements of electric power strongly depend on the application, spanning the range from microwatts to kilowatts [34].

* *Corresponding author.*
E-mail address: mustafasmahdi@gmail.com (Mustafa Sabah Mahdi)

Several TEG modules can be deployed in arrays with series and/or parallel interconnections to generate the required power level.

In the case of TEG integrated with stoves, the application of TEG to a wood stove was first investigated by Bass and Killander [17] in a study for off-grid areas in extreme North Sweden. This stove produced maximum power of 10 W from a 75 × 75 mm^2 TEG with force convection cooling by a 2 W fan. Nuwayhid *et al.*, [18] presented a similar system, producing maximum power of 4.2 W from a 56 × 56 mm^2 TEG. Lertsatitthanakorn [19] investigated the feasibility of adding a commercial TEG to the side-wall of a biomass cooking stove; the results showed that the system produces output power up to 2.4 W from a temperature gradient of 150 ^oC. Champier *et al.,* [20] proposed a TEG system to an improved biomass-fired stove and obtained a useful power of approximately 6 W from 56 × 56 mm^2 TEG modules. Rinalde *et al.*, [21] developed a prototype TEG system that was tested with a wood-burning stove and produced 12.3 W when the ΔT is 200 ^oC. Champier *et al.*, [22] modify a gas heater stove with a TEG system that produced a maximum of 9.5 W from a 56 ×56 mm^2 device; they mentioned the influence of the gas heater stove on heat transfer by thermal contact resistance and mechanical pressure. Codecasa *et al.*, [23] added two TEGs (with finned heat sink) to a gas stove and produced an electric power of 2.75 W with 2.1% efficiency. O'Shaughnessy [24,25] and Kinsella *et al.*, [26] proposed a TEG system integrated with a portable biomass cooking stove, producing maximum power of 5.9 W. They run a field trial test in rural Malawi [27] to analyze the performance of the stoves.

The major objective of the above-mentioned TEGs systems that applied to stoves is to generate electricity. Moreover, these systems depend on inefficient air cooling for the cold side of TEGs. Min and Rowe [28] developed a combined heat and power (CHP) system that the heat rejected by the TEG cold side was used for water heating. Another combined system was created by Vieira and Mota [29]. Chen *et al.*, [30] investigated the development of TEGs in different system, analyzing efficiency enhancements, and economic benefits. Alanne *et al.*, [31] analyzed the benefit of installing TEG to boiler (wooden-pellet fueled). Goudarzi *et al.*, [32] presented a prototype of 56 × 56 mm^2 TEGs with firewood stove, which was estimated and produced a maximum power of 351 W at 1% TEG efficiency. Favarel *et al.*, [33] developed a similar system and obtained 28 W electrical power. Montecucco *et al.*, [34] presented a CHP system in which the TEG power production is maximized using maximum power point tracking (MPPT) converters. They integrated four 40 × 40 mm^2 TEGs to a solid-fuel stove; this system generates an average of 600 W_{th} and 27 W_{el} with 5% efficiency.

The current study presents a TEG system that includes fins (heat absorber) that sits on the top surface of a kerosene heater, three 40 × 40 mm^2 TEGs with universal water-cooling block, and a water piping system and a 30-L water storage tank. This system absorb part of the waste heat obtained by kerosene stove and directing it through the TEGs to water for pre-heating while the TEGs generate electric power. The basic diagram of the built TEG system is shown in Figure 1. Although a similar symbiotic system has already been proposed in the literature, the authors believe that the experimental results presented in this paper are the first to investigate the application of the TEG CHP system to kerosene heaters as common liquid-fuel stoves. The principle behind TEG is to convert the waste heat of the kerosene stove into electricity, which is regarded as a completely green technology because the input energy is free of cost. In addition, the output of the TEG device is highly significant because of its power-producing feature and leads to economically viable kerosene stoves. Regardless of the low efficiency of TEGs, all the heat transferred through them is notably used for normal household activities such as heating and showering.

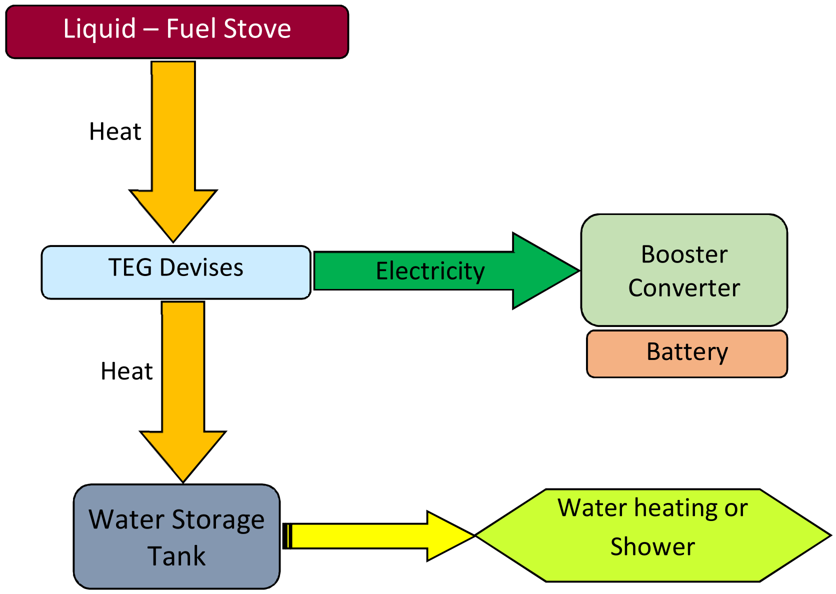

Fig. 1. Energy diagram of the built TEG system

2. Advantages of TEG Incorporated with Kerosene Stoves

The use of liquid-fuel stoves is still widespread in the domestic sector of most countries. The study investigate the feasibility of adding a commercially available TEG to the top surface of the stove, thereby creating a TEG system that utilizes a part of the flame heat of the stove and advancing the versatility of the liquid-fuel stove. The benefits of TEG incorporated with kerosene stoves are listed as follows:

- The flame heat from the kerosene stove serves as input to the TEG and no additional energy is required.
- The TEG module is integrated in the top of the kerosene stoves. Unlike solar panels, the TEG module does not require an external electric link.
- TEG is very rugged and almost maintenance free. Also, TEG has no moving parts; thus, its operation is silent.
- Unlike solar panels, TEG starts working as the kerosene stove is set on fire regardless of the time of day or the weather.
- The entire module is placed indoor and is used to run equipment or continuously recharge the batteries. Only the batteries need replacement when exhausted.

3. Experimental Set-up and Calculations

3.1 Liquid-Fuel Stoves

Most liquid-fuel stoves used in urban and rural areas of Iraq are imported from Japan and Korea and are typically of the portable kerosene-heating type. The kerosene heaters have a heating compartment around the firebox (fire ball), as well as a sufficient top surface area, which can be used for water boiling or pan cooking. These stoves typically have two variants: convection kerosene stove and radiant kerosene stove. Local market prices are approximately $50 and $120 for the two types. For our study, the *Alpaca TS*-77 convection kerosene heater was used as a liquid-fuel stove. Only kerosene from dealers who offer state certified 1-K grade kerosene (burning with 99% efficiency) was purchased to ensure safe use. The price of 1 gallon of 1-K kerosene in the local market as of January 2017 was approximately $1.25.

For each experiment, the stove was filled with 1-K grade kerosene in the time of lighting and then lighted to achieve normal operating temperatures. A steady state condition was achieved when the measured temperatures at two locations no longer changed. These locations were selected above the fire ball of the kerosene stove where no direct contact occurred with the flame. Furthermore, the fire ball of the kerosene heater can provide nearly continuous and steady burning, in which the temperature difference does not significantly vary during the experiment compared with the results reported by Montecucco *et al.*, [34].

3.2 Description of TEG-CHP system

An experimental rig was designed and built to study in detail the behavior of the TEG devices under steady-state thermal conditions. The block diagram of the complete liquid-fuel stove CHP system is shown in Figure 2. This rig was based on the design reported by Montecucco *et al.*, [34] and comprised a TEG hot side was added to the stovetop opening where the flame (heat) was available.

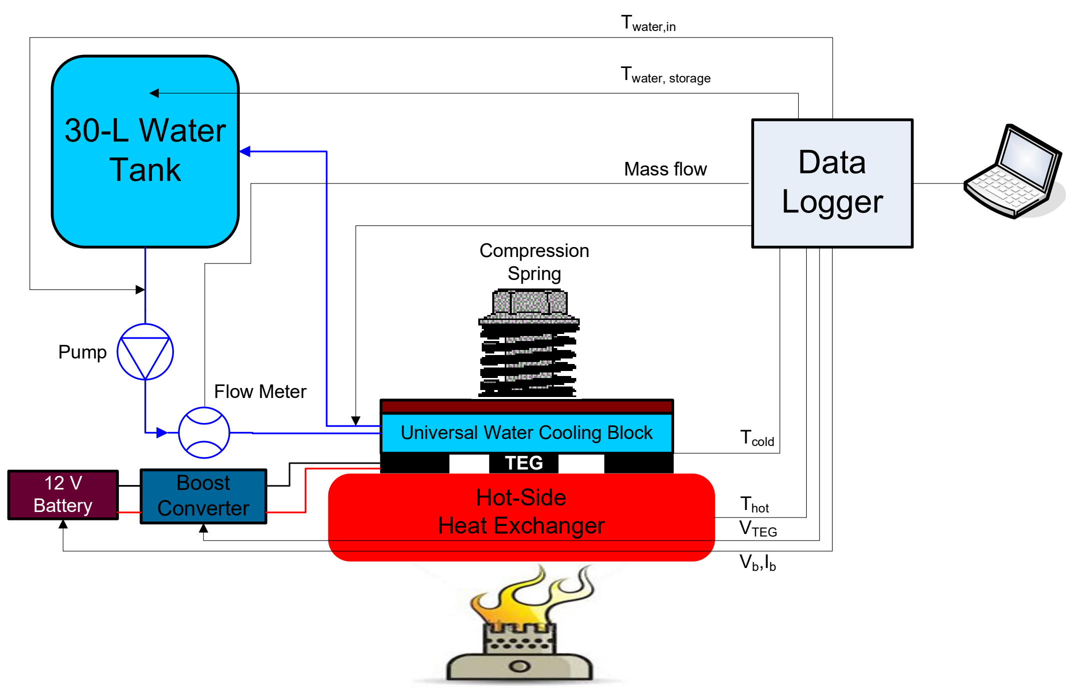

Fig. 2. Schematic of the detailing of TEG system.

Three TEG modules are set on top of heat exchanger made of aluminum and has fins toward the flame to maximize the absorbed heat. The TEGs are placed in three slots (1 mm milled) on the plane surface of the heat exchanger, as shown in the Figure 3 (left side). The TEG heat exchanger system was mounted at the top opening of the kerosene stove at a specified height to ensure that the hot-side temperature does not exceed 250 °C, which is the maximum temperature working limit of Bismuth Telluride modules. The TEGs code is TEG1-12706, which is supplied by Rongkehui Electronics

Ltd. To minimize thermal contact resistance, graphite-based thermal grease is used on both surfaces of the TEGs. A universal water-cooled aluminum block is used and positioned on top of the TEGs, as shown in Figure 3 (right side). Holes of 1 mm diameter were drilled into the aluminum plates, and calibrated K-type thermocouples with an accuracy of ±1 °C were inserted to measure the temperature of the hot and cold sides of the TEG. The entire system was mechanically screwed by an adjustable clamping pressure acting through a compression spring to ensure an even distribution of the force on all parts of the system.

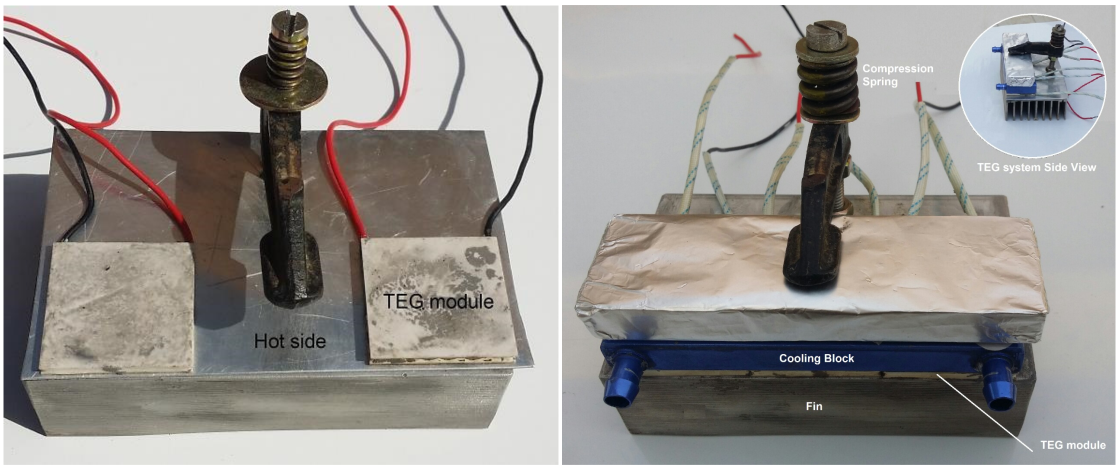

Fig. 3. Mechanical clamping of the TEG modules.

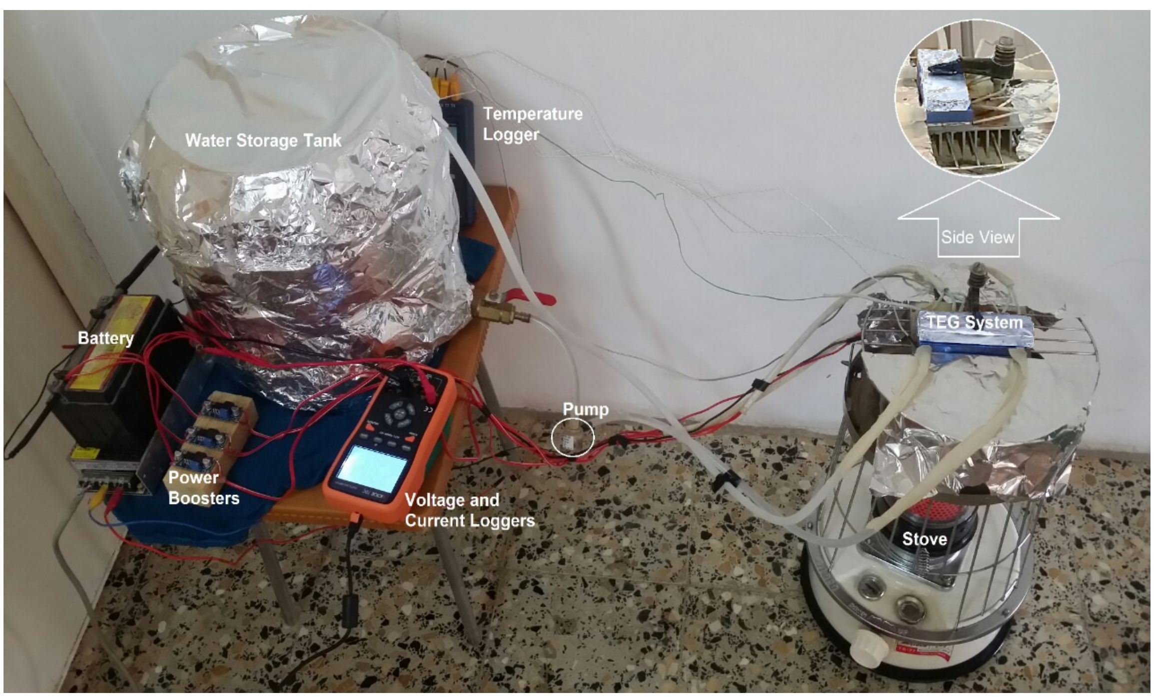

Fig. 4. Picture for the built TEG- stove system

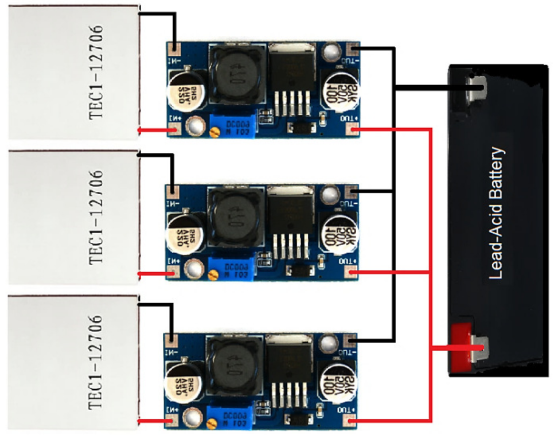

Fig. 5. Diagram shows the electrical connections of the TEG system

A 12-V dc pump circulates water in the flow loop between the 20-L water tank and the universal cooling block. The water pump consumes 2.4 W_{el} at a flow rate of 1.2 L/min (measured by a ZJ-LCD-M LCD water flow sensor). The water tank and piping connections are insulated. Figure 4 shows the complete TEG system and the TEG rig positioned on the stovetop is shown on the right.
Three XL6009 DC-DC boost converters supplied by Vococal *ltd* used to boost the voltage generated by the TEGs and interface them to a 12-V lead-acid battery. These bossters are necessary to ensure that the power output of TEG is improved regardless of temperature variations. Each converter is connected to one TEG, and the outputs of the converters are connected in parallel to the battery, as shown in the diagram on Figure 5. The TEG voltage output, voltage, and current of the battery are directly measured using a digital logger type (two Pro'skit MT-1820 and one Victor 70C voltage and current logger). All thermocouple sensors are connected to a data logger type (HUATO S220-T8) with eight channels to record the temperature data.

4. Efficiency Calculation of TEG

The heat flow, which is partly converted into electric power, is induced by heating one side of the TEG while the opposite side is cooled. The heat power moved to the water, P_h, easly can be determined from the temperature difference between the outlet and inlet of water in the cooling block, as expressed in Equation (1).

$$P_h = \dot{m}C_p(T_{w,o} - T_{w,in}), \quad (1)$$

where $\dot{m}$ is the flow rate in [kg/s], C_p is the specific heat in [J/kg. °C], and $T_{w,o}$ and $T_{w,in}$ are the water temperatures at the outlet and inlet cooling block, respectively.

The generated electrical power, P_{ele}, by the TEG is calculated from the measured voltage and current of the battery circuit, as shown in Equation (2).

$$P_{ele} = V_b . I_b \quad (2)$$

Calculating the efficiency of the TEG module is complicated because it requires an accurate estimation of the heat absorbed by the module, Q_H. However, the efficiency can be easily calculated using the first law of thermodynamics.

$$Q_H = P_h + P_{ele} \tag{3}$$

Therefore, the conversion efficiency, η, can be easily calculated if the input and output power to the TEG system are known, as shown in Equation (4).

$$\eta = \frac{P_{ele}}{P_h + P_{ele}} \tag{4}$$

5. Experimental Results

The parameters recorded in the experiment include voltage and current of the TEG device, voltage and current of the battery, and temperature of the hot and cold side. The tank water temperature, as well as at the water temperature at the inlet and outlet of the cooling block, are also measured. The kerosene stove used during the experiment has a fuel tank with 1.2 gallon capacity, which can provide continuous and nearly steady burning for 12 hours. The results are obtained during three hours of burning, because of the experimental setup the first the 15 min of testing is omitted.

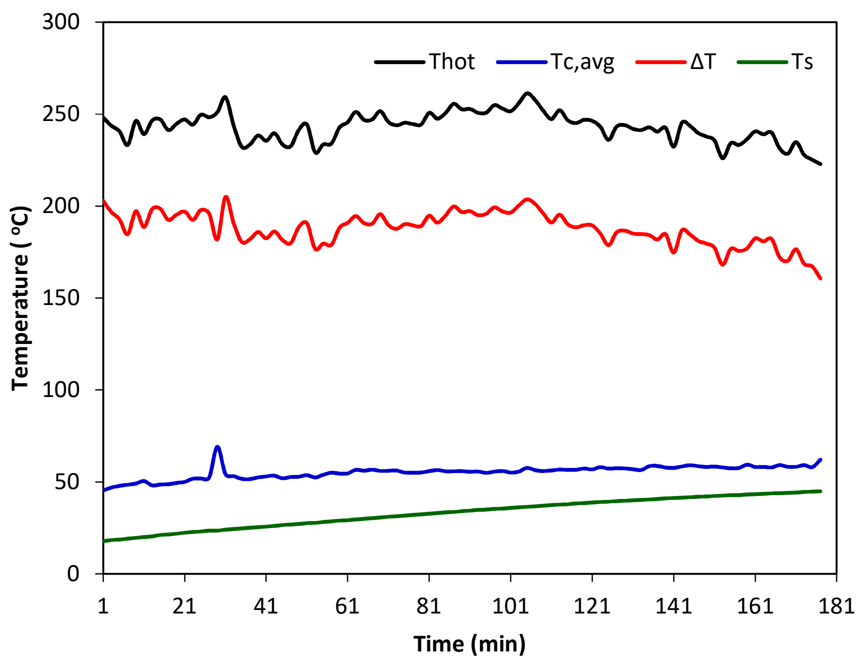

Fig. 6. Measured temperature distribution versus time of the experiment

Figure 6 shows the measured temperatures at the hot (T_{hot}) and cold ($T_{c,avg}$) sides of the TEGs, the temperature difference across the TEGs (ΔT), and the temperature inside the storage tank (T_s). A single thermocouple is used to record T_{hot} and is located in direct contact on top of the hot side of TEG. Three thermocouples in contact directly with the cold sides of the TEGs are used to record $T_{c,avg}$. After approximately 30 min, the kerosene stove operation provided a maximum hot side temperature of 250 ^{o}C, while the cold side temperature was 45 ^{o}C. For this temperature difference of 205 ± 0.5 ^{o}C, the TEG produces a voltage of 6.2 V (Figure 7).

Although the TEG modules used are specified for a maximum continuous operating temperature of 250 ^{o}C, they can function below 300 ^{o}C for short periods. The burning of a kerosene heater can be easily adjusted manually to prevent excessive temperature on the hot side of the TEG.

The battery was discharged before the experiment. During the experiment, two LuLofe white LED lamps were connected in parallel to the battery. Then, the DC-DC converters were connected between the TEG and the lead-acid battery. The output voltage of a single TEG module (V_m) and the power gained (P_{ele}) by the system are presented in Figure 7, together with battery current and voltage (I_b, V_b). Figure 8 plots the P_{ele}, P_h and η versus time of experiment.

6. Results and Discussion

For the maximum temperature difference of 205 ^{o}C, the single TEG produced a voltage of 6.2 V while the battery circuit voltage produced 13.6 V (Figure 7). The water temperature in the storage tank was raised by 28 ^{o}C by an average heat gained, P_h of 235 W. When the cold weather is common all year, this condition is considered a convenient outcome because the heat can be used for water heating or other household activities, thereby reducing the electricity consumption used in electric heaters. Simultaneously, the heat produced by the kerosene heater still transferred by convection to other parts of a house.

In Figure 7, the results established the flat voltage characteristics of lead-acid batteries during charging. The TEG voltage can be seen to closely follow the temperature gradient of TEG, as shown in Figure 6. The total output power, P_{ele} from three 40 × 40 mm^2 TEGs does not exceed 19 W when the maximum temperature difference is 205 ^{o}C. The average electrical power generated by the TEG system during the considered experiment time was 12.2 W, which is sufficient to cover basic needs such as lighting and mobile-device charging. To compare this TEG performance to prior ones, this system generated 0.25 W_{ele}/cm^2 of the TEG area on average, which was less than the 0.42W_{el}/cm^2 reported by Montecucco *et al.*, [34] and outperformed the 0.11W_{el}/cm^2 reported by Favarel *et al.*, [33].

In Figure 8, the TEG conversion efficiency was between 4% and 5%, which was in accordance with the performance of commercial Bi_2Te_3 devices. The efficiency of the system was approximately similar to that obtained by Montecucco *et al.*, [34] and was better than the 1% efficiency obtained by Goudarzi *et al.*, [32]. Evidently, an increase in temperature difference across TEG is desirable and provides a corresponding increase in available heat for conversion.

The experiment was switched off after three hours because the output voltage decreased to approximately 12.1 V during that period (Figure 7), which was a low voltage difference to charge a 12 V battery. The decrease in the output voltage of the TEG system was due to the increased temperature of the cold water tank, which in turn decreased the temperature difference across the TEG sides. A TEG CHP system can guarantee a long operation time (if the input heat is always provided) to generate electrical power (at low efficiency), while the water inside the storage tank is necessary to periodically change and maintain the cold side of the TEG at the main water temperature.

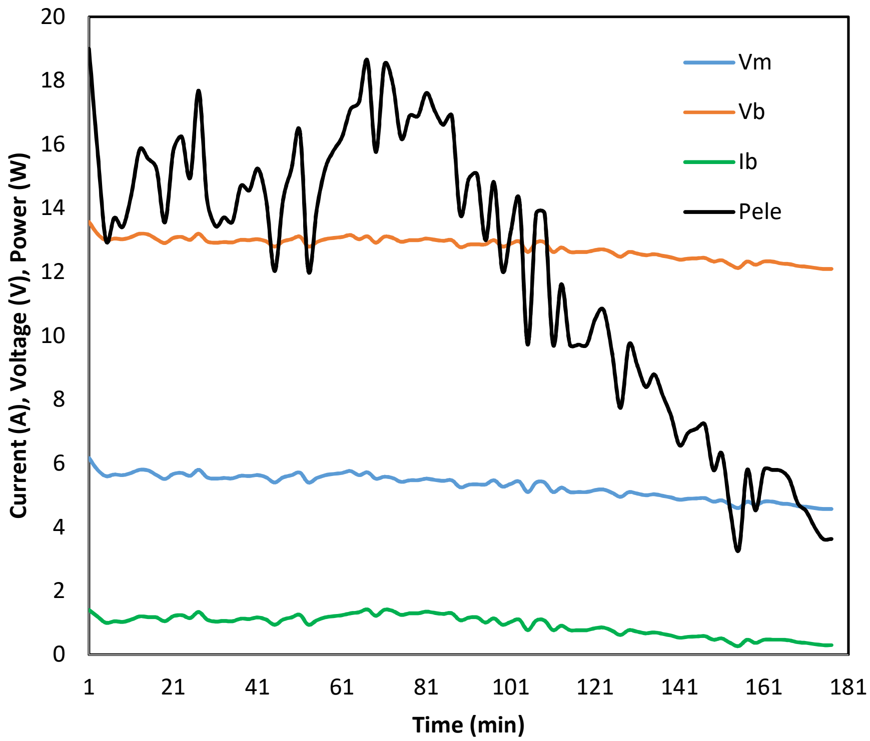

Fig. 7. Measurements of Current, voltage and power during experiment time

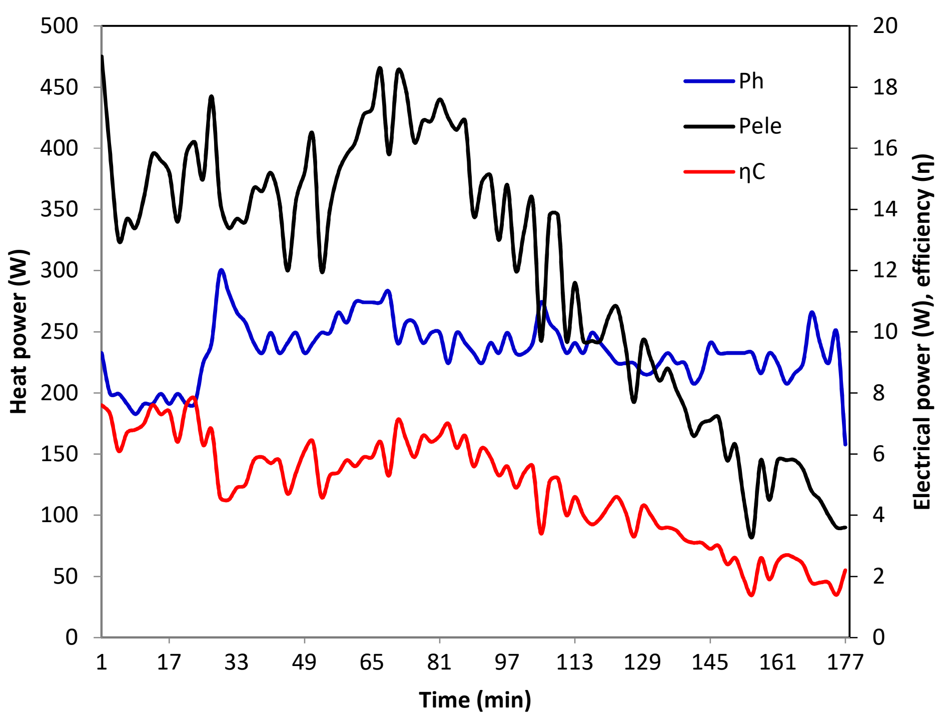

Fig. 8. Variation of thermal power (P_h), output power (P_{ele}) and TEG efficiency (η) versus time of the experiment

7. Conclusion

This study conducts an experimental investigation to demonstrate the technical feasibility of the proposed TEG CHP system for a kerosene-fired domestic stove. This system both transfers heat from the kerosene heater to circulating water for heating or household purposes and generate electricity for low-power electrical devices. Almost $235W_{th}$ and $12.2W_{ele}$ are obtained on average during a three-hour-long experiment. The maximum matched load power (19 W) used three TEG models when the temperature difference was 205 ^{o}C, and the power generated on an average area of TEG was 0.25 W/cm^2. The temperature in the water tank with a volume of 30 L has increased to approximately 28 ^{o}C. Simultaneously, the kerosene heater still works effectively for space heating by convection for the other parts of the house. The efficiency of this system is around 5%. In a practical application, the voltage and power have to be considered, which may require the use of additional TEG modules.

With the use of TEG, the various functions (space and water heating, cooking, and electricity supply) of the liquid-fuel stove can be increased. The input heat of the kerosene stove is continuously provided, and the storage tank water is periodically placed to transfer heat. This technology could be beneficial especially if retrofitted to stoves in rural areas or in houses at low cost with minimal complexity.

Acknowledgement

The ongoing work on TEG CHP system owes much to the assistance of the mechanical engineering workshop of Diyala University for their work in creating the test rig used for the experiments.

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