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PERFORMANCE EVALUATION OF THERMOELECTRIC GENERATOR IN THERMAL ELECTRICITY GENERATION CELLS

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Abstract

It is commonly known that most of the research deals with evaluating and analysing the performance of thermoelectric cells based on the first law of thermodynamics. They are focusing on energy conservation and thermal efficiency only. The objective of the current research is to experimentally evaluate the performance of the thermoelectric cell using the first and second laws of thermodynamics as a methodology analysis and the calculation of exergy efficiency or maximum work available. Hence, the research parameters measured in the experiments are the temperature difference, the liquid flow rate, and the rate of thermal energy. The results reveal that increasing the temperature difference between the hot and cold sides of the thermoelectric by 25 - 40 °C leads to an increase in thermal efficiency and Exergy efficiency by 0.4% - 1% and 4% - 6%, respectively. When thermal energy supplied to the cell increases by 15 - 35 W, it results in a decrease in the amount of thermal efficiency by 0.65% - 0.6% and exergy efficiency by 6% - 2%, respectively.

Keywords: Exergy efficiency, Thermal electricity generation, Thermoelectric cells.

1. Introduction

In the current era, the acceleration in the depletion of traditional energy sources has led to an increase in fuel prices, as well as an increase in environmental pollution due to the waste and products of the combustion of fossil fuels. Among the alternative solutions for conventional fossil fuels are renewable energies, as well as the recovery of waste energy because of industrial and human activities, such as waste thermal energy Tian et al. [1]. In a widely mentioned industry of energy transmissions, it had been conducted that almost 50% of the total input of the energy vanished and was lost in the form of wasted heat from variant applicable sources like cooling equipment, convection from hot surfaces, and exhaust gases [2-4]. It is vital to compensate for this wasted energy heat to acquire a fully positive output [5, 6]. Therefore, numerous studies were involved in a recovery form to compensate for this wastage, such as the use of technology in thermoelectric generators (TEGs), where harnessing the new technology is due [7]. These thermoelectric generators that produce power are emerging to be an extremely useful alternative green technology because of huge advantages and neglected negatives [8, 9].

Converting the thermal energy into electrical energy by means of the Seebeck effect is demonstrated to be applicable only to the usage of TEGs [10]. Moreover, these TEGs are all considered to be environmentally friendly, because they contain no chemical wastage or products for fuelling them. In addition to that, they do not possess mechanical structures or movable parts that produce heat or frictional effects in their operating structures. Herewith, these TEGs are fabricated and designed by other materials like silicon, polymeric materials, or ceramics which are all eco-friendly [11]. These TEGs are also time efficient as their lifetime is extremely suitable for integration into bulk or flexible operational devices [12]. For better elaboration, Fig. 1 depicts the Seebeck effect that was previously mentioned in this paragraph.

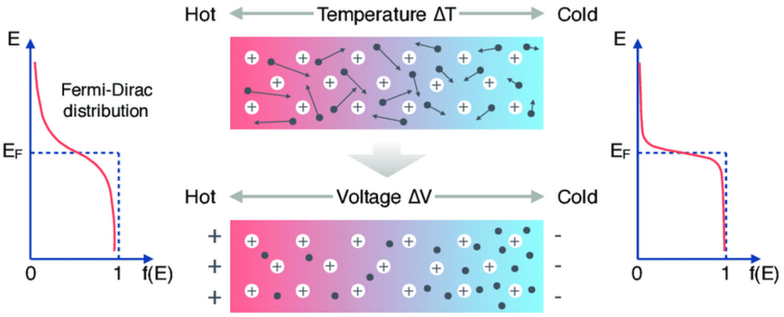


Fig. 1. Seebeck effect [13].

It has been established that looking for alternative sources of renewable energy is vital. Therefore, the thermoelectric developer is said to be one of those major alternatives because they utilize decay warmth, which is present in huge masses in the surrounding boundary conditions. These thermoelectric developers usually consist of many thermoelectric contents, which are known to be called Bismuth Telluride (Bi2Te3). These bismuth tellurides use the Seebeck impact and effect to change the decay warmth into means of electrical current and useful power. Consequently, the TEGs are collectively used to harness electrical output from the heat or produce energy. As a major drawback, the energy conversion rate of the mentioned techniques and devises is low and undependable, which is barely reaching a percentage of 15%. In practice, the efficiency and accuracy of the overall harvested thermal energy is even at lower maximum values, which is said to reach a percentage of around 5 to 6% [4].

Jaziri et al. [12] presented a review of a deep analysis of TEGs, stating an extensive description of the adopted methodology. The authors described the used materials, different types of experimental data, and the figures of merit to collectively help in improving the adopted techniques. Different thermoelectric material arrangements were properly used, such as conventional arrangements, segmentation-based, and cascaded types. Following up, Cekdin et al. [14] had their specific measurements that showed that more temperature difference induced, higher electrical induced energy can be produced. Nevertheless, this temperature difference has limits. When exceeding a specific value, it will harm the semiconductor material that is set to be used in the experimental study. Consequently, after the TEG starts to work, it will produce high voltages and electrical wanted current. Moreover, Khan et al. [15] discussed the same topic. The number of thermopiles that were used in this suggested program was 3, which are thermally in a parallel arrangement and electrically in a series arrangement. Therefore, the total generated on two junctions is 8.46V and 7.2 mA at 79 °C. The maximum output and calculated efficiency at 79 °C are 5%.

Rohit et al. [7] dealt with the study of the performance of a TEG module for different hot surface temperatures. Performance characteristics used here are voltage, current, and power developed by the TEG. One side of the TEG was kept on a hot plate where uniform heat flux was supplied to that. Furthermore, the other side was cooled by supplying cold water. The results show that the output power increases significantly with an increase in the temperature of the hot surface. Ji et al. [16] presented a 1-D model developed in MATLAB, taking into consideration the multi-physics phenomena within TEG. To compensate for this and to develop and fabricate a useful TEG heat exchanger that recovers the waste heat, a dependable model is desired for a system overall design that predicts the performance accurately. They found that the heat exchanger and module design have an impact on the total TEG output power in waste heat recovery systems, and a systematic design approach is needed.

Another work by Xiao et al. [17] has provided reliable experimental data and an efficient design for the application of TEGs in industrial pipes. The effects of some key factors, such as topology of TEMs, heat source temperature, cooling water temperature, and velocity, on the generating performance are studied. Adding up, Qasim et al. [18] experimentally investigated a combination of many TEG modules connected in series and parallel. The panel of the TEGs was exposed to high heat due to solar radiation during summer, either directly or through a Fresnel lens. It was found that the maximum open-circuit voltage was 9.35 V with a Fresnel lens, without a lens, 11.75 V at 14:00 h local time. To extend the usage of TEG, Lim et al. [19] proposed the utilization of solar radiation as the heat source and integrated the TEG module with phase change material TES. They proposed two different designs of portable solar TEG and compared their functionality.

Most of the researchers focused on the principle of energy conservation in calculating the efficiency of the thermoelectric cell (the first law of thermodynamics). Therefore, the objective of this research is to study the efficiency of the thermoelectric cell type TEG SP 1848-27 145 SA as an example of this application and the effect of the important factors in its operation, which are the temperature difference and the rate of thermal energy supplied to it, and the effect of this on the efficiency of the cell (calculated according to the first and second laws of thermodynamics) and evaluate its performance. The novelties of the present work might be summarized by Utilizing both the first and second laws of thermodynamics to assess the efficiency of TEGs and introduce performance analysis, including exergy efficiency. In addition, new findings have been added to the field by an experimentally demonstrated impact of temperature differences of 25 - 40 °C on thermal and Exergy efficiency of TEG cells, and also, adding new data on the inverse relationship between increasing thermal energy input of 15 - 35 W and efficiency to optimize the TEG performance.

2. Methodology

2.1. Exergy analysis

Exergy analysis can be beneficial in creating new process designs by means of avoiding the same inefficiencies for greater performance. Simulating thermodynamic analysis of power systems needs powerful and great tools. The Exergy analysis, which follows the second law analysis, is said to be a great simulator when needed. In other meaning, design, simulations, and performance evaluation of power systems have always been conducted by means of this exergy analysis. This methodology can be utilized to diagnose and assess the quantitative numbers and causes of any thermodynamic imperfections in a specified process of choice. To predict the performance parameters, the following expressions recommended by Zhao et al. [8] have been used as the total energy input equals the total energy output.

$$\sum \dot{E}_{input} = \sum \dot{E}_{output} \tag{1}$$

The exergy balancing would be written as follows:

$$\sum \dot{E}x_{input} - \sum \dot{E}x_{output} = \sum \dot{E}x_{destroyed} \tag{2}$$

The Ex_{input} is the exergy potential in heat energy input($\dot{E}_{input}$) can be evaluated according to equation (3)

$$\dot{E}x_{input} = \dot{E}_{input}(1 - \frac{T_o}{T_k}) \tag{3}$$

where T_k is the temperature as heat energy input, and T_o is the ambient temperature in K.

The exergy output ($\dot{E}x_{output}$) is equal to the electrical power production ($P_{elec.}$)and equal $\dot{E}_{output}$

$$\dot{E}x_{output} = \dot{E}_{output} = P_{elec.} \tag{4}$$

Efficiency, according to the first law of thermodynamics, is a related

$$Efficiency = \frac{\dot{E}_{output}}{\dot{E}_{input}}\% \tag{5}$$

Efficiency, according to the second law of thermodynamics, is a related

$$Exergy\ of \text{Efficiency} = \frac{\dot{E}x_{output}}{\dot{E}x_{input}}\% \tag{6}$$

The reference conditions are at temperature, T_o = 298 K, and atmospheric pressure, P_o = 1.01325 bar.

2.2. Experimental scheme

The experimental setup is designed to evaluate the thermoelectric cell's performance by monitoring its electrical output and thermal behaviour under varying conditions. Figure 2 illustrates the closed electrical circuit utilized in the experiment, which forms a key part of the system. The circuit integrates the thermoelectric module (TEG1-27145 SP1848) as the central component, which generates electricity by exploiting the temperature gradient between its hot and cold sides [20, 21]. A 6 Ω resistive load is connected to simulate an electrical load, dissipating the generated power. A voltmeter is positioned across the load to measure the output voltage, while an ammeter in series monitors the current flow through the circuit. The components are interconnected with conductive wiring, forming a closed loop essential for precise measurement of electrical parameters. This configuration enables the quantification of power generation, which is further analysed to assess the thermoelectric cell's thermal efficiency and exergy efficiency.

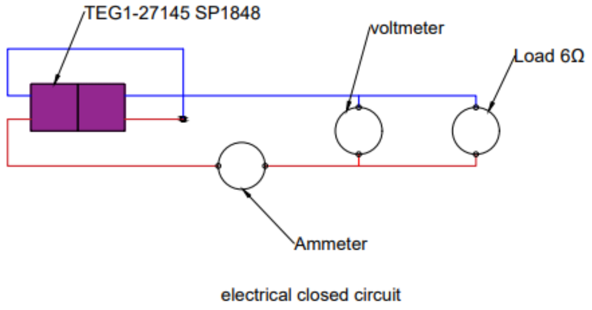


Fig. 2. Closed electrical circuit.

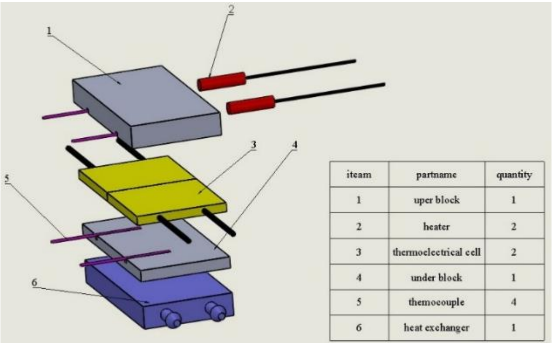
The test setup was designed and fabricated to determine the performance of thermoelectric cells when subjected to inputs at different temperature levels and thermal energy. Table 1 describes details of the TEG SP1848-27145 thermoelectric power generator used in this study. Its dimensions are 40 × 40 × 4 mm, and its mass is 30 g, with a length of wire of 350 mm, able to provide up to 4.8 V for an open circuit voltage. It has an operating temperature maximum of 150 °C and, therefore, is suitable for thermal energy harvesting.

Table 1. Specifications of TEG SP 1848-27 145 SA thermoelectrical power generator [22].

Specification	Description
Module	Sp1848-27145
Open circuit voltage	4.8 V
Operating temperature	150 °C
Length	40 mm
Width	40 mm
Height	4 mm
Weight	30 g
Wire length	350 mm

Figure 3 presents the test section, showing the components and their respective quantities used in the experiment. It consists of one upper block, two heaters, two thermoelectric cells, one under block, four thermocouples for accurate temperature measurement, and a heat exchanger meant for thermal management. This would enable the provision for realizing a controlled thermal gradient across the thermoelectric cells.

Figure 4 gives a detailed diagram of the experimental apparatus; it shows all the integrations. It essentially consists of an electric heater with a heater controller for supplying heat to thermoelectric cells, a heat exchanger with a water pump for maintaining the cold-side temperature, and an ice water pool for cooling. The electrical performance of the thermoelectric cells is monitored by using an ammeter, voltmeter, and electric load, while the thermal data is recorded with a thermometer reader. The setup is designed with great care to measure the thermal and electrical efficiency of thermoelectric cells under conditions that may be controlled.



iteam	partname	quantity
1	uper block	1
2	heater	2
3	thermoelectrical cell	2
4	under block	1
5	themocouple	4
6	heat exchanger	1

Fig. 3. The test section components and quantity.

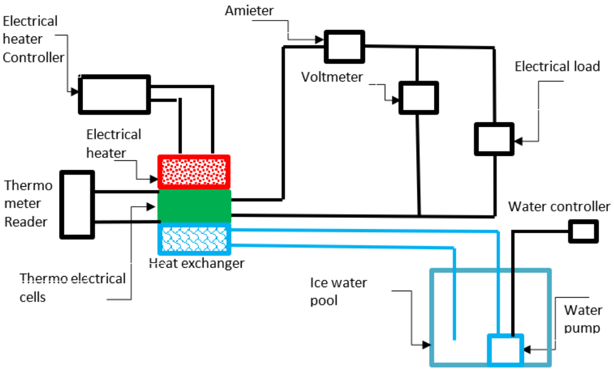
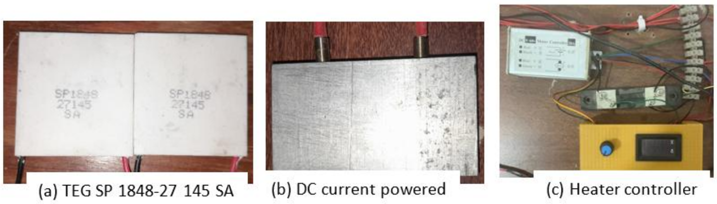


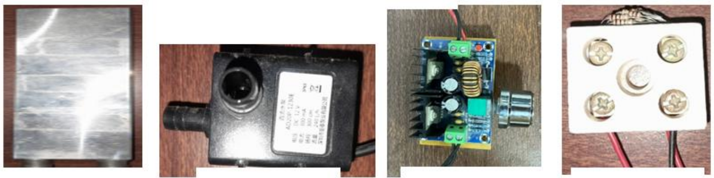
Fig. 4. A diagram of the setup components.

2.3. The experimental test rig

The experimental test rig, as illustrated in Fig. 5, comprises several key components to evaluate the performance of the thermoelectric generator (TEG) SP1848-27145 SA under controlled thermal and electrical conditions. The heating source is a DC-powered heater with a maximum power of 32 watts, consisting of two coil pieces, and its operation is regulated using a heater controller for precise adjustment of voltage and current (components b and c).



(a) TEG SP 1848-27 145 SA (b) DC current powered heater (c) Heater controller

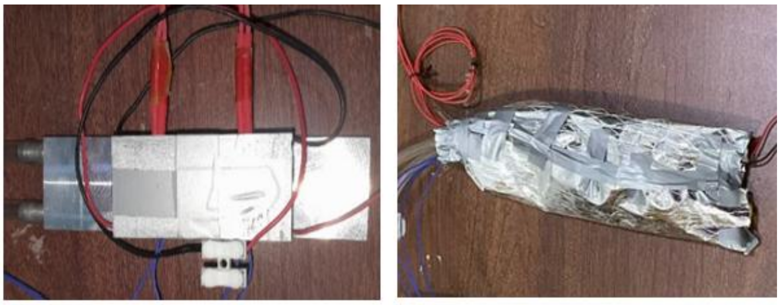


(d) Water heater exchenger (e) Water pump (f) Water pump control unit (g) 6 Ω electric resistance

Fig. 5. Explosive presentation of the Experimental setup (a) TEG SP 1848-27 145 SA, (b) powered heater DC-current, (c) Heater controller, (d) Water heat exchanger, (e) Water pump, (f) Water pump controller, (g) electrical resistance.

The cooling system includes a water heat exchanger (150 × 40 × 10 mm) (d), a water pump with a maximum capacity of 240 L/hr (e), and an ice pool with a 4-litre capacity to provide a stable cold-side temperature. The water pump controller (f) is used to manage the flow rate effectively.

The test section of the TEG arrangement, shown in Fig. 6, was evaluated in two configurations. First is without insulation, as shown in Fig. 6(a), and second, with insulation using glass wool, as shown in Fig. 6(b), to minimize heat losses and improve the thermal gradient. The complete experimental setup, depicted in Fig. 7, integrates all these components, including the icy pool, testing section, and control systems. This design ensures precise monitoring of input and output parameters, enabling a detailed analysis of the TEG's thermal efficiency and exergy performance under varying conditions.



(a) Without glass wool insulation (b) Without glass wool insulation

Fig. 6. The test section: (a) without insulation by glass wool; (b) with insulation.

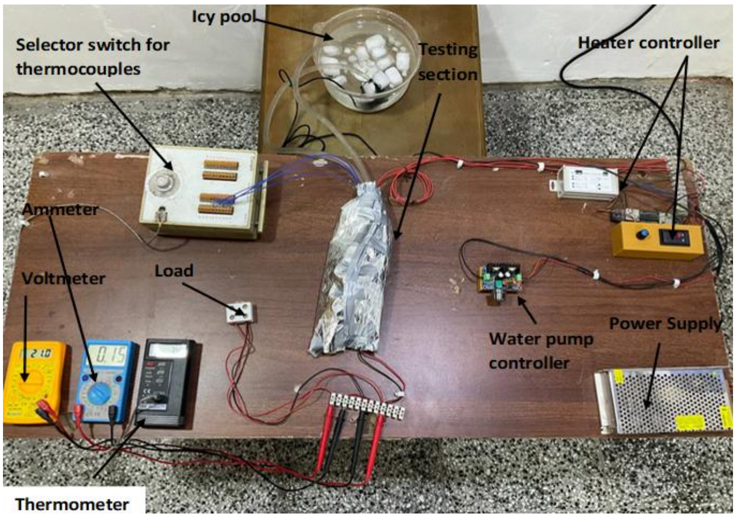


Fig. 7. The experimental setup.

2.4. Measuring instruments and uncertainties

A voltmeter, Ammeter, and thermometer, shown in Fig. 8, were used to monitor and record the electrical and thermal parameters. A 6 Ω electrical resistance, shown in Fig. 5(g), was connected as a load to simulate power dissipation and measure the TEG's electrical performance.

Fig. 8. Measurement instruments include of voltmeter, Ammeter, and thermometer reader.

The accuracy and reliability of the experimental measurements are critical for assessing the performance of the thermoelectric generator (TEG) SP1848-27145 SA. The measuring instruments used in this study, illustrated in Fig. 8, include a thermometer, a voltmeter, and an ammeter, which were selected for their precision and suitability for the experimental conditions. The thermometer, a K-type model (TSE-1310), is capable of measuring temperatures in the range of 50 to 199.9 °C with an uncertainty of ±0.2% of the reading plus 1 °C. This precision ensures accurate monitoring of the temperature gradient across the TEG, which is crucial for evaluating thermal and Exergy efficiency. Two digital multimeters (Aswar AS-M830D and AS-M630D) were utilized for electrical measurements, including voltage and current, with an uncertainty of ±0.003V and ±0.02 mA annually. These devices enabled precise tracking of the electrical output of the TEG under different thermal conditions. The combination of these instruments allows for accurate and reliable data collection, ensuring that the experimental results are robust and reproducible.

As summarized in Table 2, the error margins of these devices were considered in the analysis to account for uncertainties in the measurements. By quantifying the uncertainties, the study ensures the validity of the experimental data and the derived conclusions. The use of high-precision instruments minimizes potential errors and enhances the reliability of the performance evaluation, allowing for a comprehensive assessment of the TEG's capabilities under various operating conditions.

Table 2. Error margins of the used devices.

Instrument	Model	Uncertainty
Thermometer K type	TSE – 1310	50°C to 199.9°C...0.2% RDG + 1°C
Digital Multimeter	Aswar AS-M830D	0.003V & 0.02 mA annual
Digital Multimeter	Aswar AS-M630D	0.003V & 0.02 mA annual

3. Results and Discussion

The investigations were performed at various conditions to explore the proposed device performance and enable comparison between the various operational and design conditions, in terms of the temperature difference between the two sides of the thermoelectric cell with the generated open voltages. The results of the measured open circuit are shown in Fig. 9. Much of the published research that dealt with the subject of thermoelectric cells focused on the amount of thermal energy supplied to the cell, the electrical current generated, the voltage, and the temperature difference between the two sides of the cell as important factors by applying the concept of energy conservation (the first law of thermodynamics) [7, 16, 20]. The novelty of this research is to study the efficiency of the electrical cell and the effect of key factors in its work according to the first and second laws of thermodynamics. These factors are the temperature difference, and the rate of thermal energy supplied to the cell. The interaction of these factors, according to exergy analysis, shows the thermal efficiency of the equipment by converting thermal energy into electrical energy (useful work) [23]. This is done by controlling the voltage and current of the heater, As well as the flow rate of cold water for the heat exchanger inside the test section, which is sometimes ice water, for the purpose of obtaining the required temperature difference.

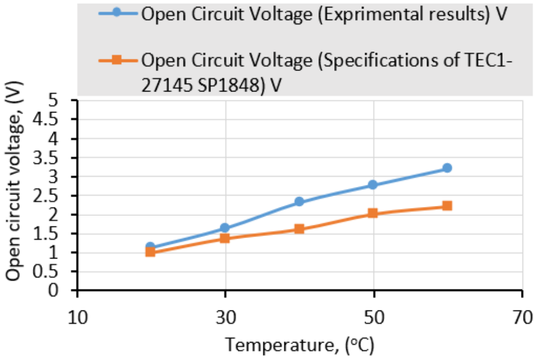


Fig. 9. Temperature difference between the two sides of the thermoelectric cell with the generated open circuit voltages.

When the thermal energy supplied to the cells is constant, the following results can be conducted. These data were obtained by setting the thermal power supplied at a value of 20 watts and changing the temperature difference between the two sides of the thermoelectric cell by controlling the amount of iced water supplied to the heat exchanger by increasing and decreasing the speed of the pump to obtain the required temperature difference. Results in terms of the effect of the temperature difference across the hot and cold sides of the thermal cell in a range of 25 to 40 °C, effect on efficiency according to the first law of thermodynamics 0.4% - 1%, as shown in Fig. 10, The observed low efficiency of the thermoelectric cells, reaching maximum of only 1% at a temperature difference of 40 °C, could be attributed to the inherently low efficiency of thermoelectric materials used in the experiment. Therefore, for effective thermoelectric generation, a high-temperature difference is required to enhance the voltage generation output and maximize the power conversion efficiency.

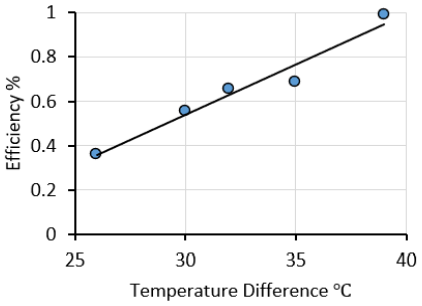


Fig. 10. Variation of the tested TEG efficiency with temperature difference.

Likewise, upon application, the data we obtained related to the effect of the temperature difference across the hot and cold sides of the thermoelectric cell on the efficiency of the cell according to the second law of thermodynamics, as in Fig. 11, where it becomes clear that an increase in the temperature difference leads to an increase in the Exergy efficiency. This effect is consistent with the reported findings of [23, 24].

The efficiency values calculated according to the second law of thermodynamics are higher than those based on the first law. This difference is because the first law of efficiency, which is often referred to as energy efficiency, considers only the total energy input and output of the system. However, the second law is efficiency, which relates to the portion of thermal energy that can be converted into useful work [8, 20].

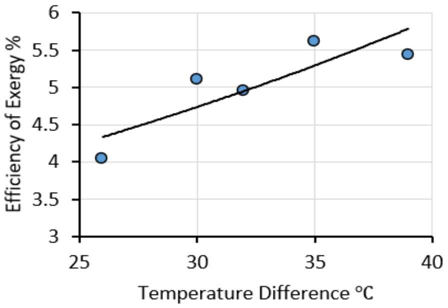


Fig. 11. Variation of exergy efficiency with varying temperature differences.

In this experiment, the temperature difference across both sides of the thermoelectric cell was fixed at a value of 35 °C, and the input thermal energy was changed. The voltage and direct current supplied to the heaters in the test section were controlled according to the desired values. In return, for the purpose of stabilizing the temperature difference at the required value, the amount of water flowing to the heat exchanger is reduced or increased. When the amount of thermal energy in the test section increases from 15 W to 32 W, the efficiency decreases according to the first law of thermodynamics from 0.64% to 0.61%. This suggests that the increase in energy supply does not lead to an improvement in efficiency, as the results shown in Fig. 12.

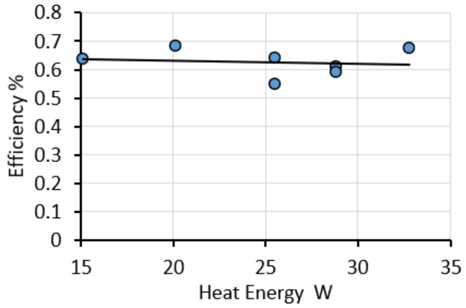


Fig. 12. Efficiency change with varying amounts of heat supplied.

Increasing heat energy from 15 to 32 W leads to reducing the efficiency of Exergy from 6.5% to 3%, as shown in Fig. 13. The reason for this is that when the thermal energy supplied to the cell increases, the random movement of electrons and positive holes increases due to the increase in internal energy, and thus, the polarization of the movement of particles in the correct direction decreases due to the effect of the temperature difference [25].

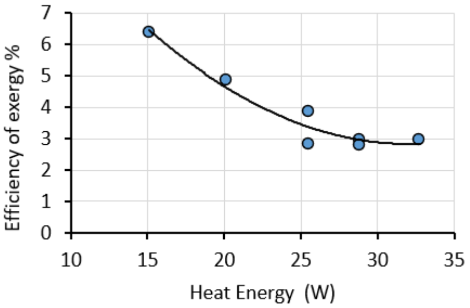


Fig. 13. Exergy efficiency changes with varying amounts of heat supplied.

4. Conclusions

From the above results, it is clear to us that the efficiency of thermoelectric cells increases according to the first and second laws of thermodynamics whenever the temperature difference between the hot and cold sides of the thermoelectric cell increases. by 25 – 40 °C leads to an increase in thermal efficiency and Exergy efficiency by 0.4% -1.0 % and 4.0% - 6.0%, respectively. This is the opposite in the case of increasing the value of the thermal energy supplied to the thermoelectric cell. Results revealed that as the greater the amount of thermal energy supplied from 15 W to 35 W, a decline in the efficiency value of the thermoelectric cell has been realized. This leads to a decrease in the amount of thermal efficiency and Exergy efficiency by 0.65% - 0.6 % and 6% - 2%, respectively.

Nomenclatures

$\dot{E}_{in}$	Energy input, W
$\dot{E}_{out}$	Energy output, W
$\dot{Ex}_{in}$	Exergy input, W
$\dot{Ex}_{out}$	Exergy output, W
T_o	Ambient temperature, °C or K
T_k	Temperature as heat energy input, °C or K

Abbreviations

TEGs	Thermoelectric generators

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