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Experimental Performance Evaluation and Feasibility Assessment of Thermoelectric Water Heating Systems for Low-Voltage DC Applications

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ABSTRACT

Water heating is among the most energy-consuming operations in residential and industrial setups, prompting the development of alternative, sustainable, and efficient methods of heating. This paper experimentally evaluates the operational performance of a low-voltage DC-powered thermoelectric water heating unit utilizing Peltier modules through key parameters such as heating time, energy utilization, heating rate, and coefficient of performance (COP).The results revealed that the thermoelectric water-heating unit took about 60 minutes to heat 1 liter of water from 25°C to 60°C, whereas the resistance water-heating unit completed the same task in only 15 minutes. Energy utilization by the thermoelectric unit was higher at 0.835 kWh than that of the resistance unit at 0.500 kWh. In addition, the COP analysis indicated lower energy efficiency for the thermoelectric heating system. Nonetheless, the thermoelectric water heating unit had the capability of controlling water heating in low-voltage DC electrical operation. It can be seen that a thermoelectric water heating system is possible for use in portable, non-conventional, and grid-free heating applications, prioritizing safety and compactness over heating rate and energy efficiency.

1. INTRODUCTION

Energy for water heating forms an appreciable percentage of the overall consumption in residential and industrial buildings throughout the world. The International Energy Agency (IEA) notes that water heating is a big source of end-use energy demand in buildings, forming a significant share of global electricity consumption and carbon emissions. In view of the rising prices of energy and increasing environmental consciousness, it is becoming more imperative to explore efficient water-heating systems [1, 2].

Traditional electric resistance heating elements remain among the most commonly used techniques for heating water because of their ease of use, effectiveness, low setup cost, and efficiency in converting electrical energy into heat. Resistance heating elements operate on the principle of Joule heating, in which electrical energy is converted directly into heat. If there is perfect efficiency, then practically all electrical energy input will be converted into heat energy [3].

However, there has been substantial interest in exploring thermoelectric technologies that employ the Peltier effect since they offer small physical dimensions, solid-state technology, no moving parts, and accurate temperature regulation capabilities. The Peltier element works on the principle of the thermoelectric effect, wherein electrical energy is applied to transfer heat from one surface to another surface. Although there has been much interest generated by these thermoelectric elements in applications like cooling, heat management, energy recovery, and generation, the use of thermoelectric systems for water heating purposes has not yet become common because of poor heat transfer efficiency, limitations in terms of heat generation, and heat transfer issues at high temperatures [4].

Several studies have been carried out on the performance characteristics of thermoelectric modules at various operating conditions. According to Riffat & Ma [5], one of the strengths of thermoelectric technology is the reliability of the system and its environmental compatibility, although it typically has lower efficiencies compared to conventional systems of heating and cooling. On the other hand, according to Rowe, one of the limitations of applying thermoelectric technology is due to energy conversion problems as well as material performance limitations [6].

Even though there are a number of scientific works on thermoelectric technology, there has not been much research conducted on the performance characteristics of thermoelectric systems and the comparison of Peltier modules and resistance heaters for use in DC water-heating systems.

Despite the growing body of research on thermoelectric technology, limited studies have focused on evaluating the heating performance of thermoelectric Peltier modules and comparing them directly with conventional resistance heaters for DC water-heating applications.

Therefore, there is a need for an experimental investigation to assess the feasibility and effectiveness of thermoelectric heating systems under practical operating conditions. This study aims to test a low-voltage DC thermoelectric water-heating system that uses Peltier modules. We'll be comparing it to a standard 220 V electric resistance water heater. The focus is on heating time, energy use, heating rates, and the coefficient of performance. This research will give us an idea of how well thermoelectric heating can work for portable and off-grid situations that run on low-voltage DC power.

2. LITERATURE REVIEW

2.1 Overview of Water Heating Technologies

There have been several advancements made in water heating techniques due to growing energy demands and environmental problems in recent decades. The available techniques of water heating include electric resistive heater, gas-based heater, solar water heating system, heat pump water heating system, and thermoelectric water heater system. As stated by Goldsmid [7], the choice of an appropriate water heating technique is influenced by criteria like thermal efficiency, initial cost of installing the system, cost of maintenance, and scale of applications.

2.2 Performance Characteristics of Electric Resistance Heating

Electric heating resistance has been among the most popular water heating technologies owing to its reliability and high efficiency of energy conversion to heat in situ. Electric resistance heating operates via Joule effect when electric energy is converted directly into heat in resistive material. Research has indicated that electric resistance water heaters could provide fast temperature rising and consistent heating performance, rendering these devices applicable in both domestic and industrial settings [8-10].

Notwithstanding the above benefits of resistance-based water-heating devices, such technologies involve rather high consumption of electricity because of the necessity to supply all energy consumed in the process of water heating from the power grid. In response to increasing energy requirements across the world and the need to develop sustainable solutions, researchers have considered other water heating technologies, such as heat pumps, solar thermal energy-based devices, and thermoelectric devices [11-13]. Thus, conventional electric resistance heating serves as the standard when considering novel water heating techniques.

2.3 Thermoelectric Technology and Heating Applications

In thermoelectric devices, the heat is transferred from one junction to another when an electric current passes through semiconductors by the Peltier effect. As pointed out by Goldsmid [7], thermoelectric devices are excellent solutions for applications in which size, low maintenance, and precise temperature control are important. Development in thermoelectric materials has made them more efficient and extended their application areas.

Some of the recent research works have brought to light the potential of utilizing thermoelectric cooling devices for low-power thermal management purposes due to their compactness, efficiency, and accurate control [13, 14].

Furthermore, the utilization of thermoelectric technology is gaining popularity among researchers nowadays, owing to its sustainability in comparison to traditional thermal techniques, as they do not use any refrigerants, have zero moving components, generate little noise, and require less maintenance.

2.4 Experimental Studies on Thermoelectric Water Heating System

Many researchers have focused on the use of thermoelectric energy technology in heating and cooling systems. Twaha et al. [15] examined thermoelectric energy technology and concluded that system efficiency is heavily reliant on material properties, temperature gradients, and heat transfer mechanisms. Similarly, Reddy et al [16] looked into the uses of thermoelectric energy technology in heating and cooling and discovered that the efficiency of such systems is greatly affected by the arrangement of modules and thermal management techniques. Additionally, Ahiska and Mamur [17] noted the increasing importance of thermoelectric energy technology in sustainable energy because of its small size, reliability, and environmentally friendly operation. Despite all of the benefits offered by these technologies, thermoelectric devices still suffer from inefficiency in converting energy, which is much lower than in the case of regular heating systems [18, 19].

2.5 Research Gaps

While there is an abundance of research that deals with the thermoelectric devices used for cooling and heat recovery purposes, there is little research that compares the real-world heating capability of the thermoelectric Peltier modules to that of electrical resistance heating systems while using the same parameters in water heating operations.

Additionally, very little data is available comparing the performance parameters like energy consumption, heating rate, COP, and practicality between the two devices when used for heating water under a DC power supply at smaller scales. Consequently, the necessity arises for an experiment aimed at providing scientific evidence regarding their comparative performance and the feasibility of use in practice.

This work attempts to fill the void by comparing the thermoelectric Peltier device and 220 V resistance heating device under the same experimental conditions [20, 21].

3. MATERIALS AND METHODS

This research made use of an experimental comparative study methodology to assess the performance and energy efficiency of a thermoelectric Peltier module and a traditional 220 V heating element. An equal volume of water was used in both cases during experimentation, carried out under identical environmental conditions within the laboratory setting [22-24]. This was done in order to measure certain parameters like time taken to heat up, energy efficiency, rise in temperature, and coefficient of performance (COP).

3.1 Experimental Setup

Two different heating systems were made and tested. These were as follows:

- A thermoelectric heating system using a Peltier device.
- A normal electric heating system operating with a 220 V heater.

These systems were connected to an insulated tank of water of known volume, and the changes in temperature were observed at different times until the required temperature was reached [25].

The experimental setup consisted of:

- Thermoelectric Peltier module,
- Heat sink and cooling fan assembly,
- 220 V electric heating element,
- Water container,
- Digital thermometer/temperature sensor,
- DC power supply,
- Energy meter/power measurement device,
- Digital mustimeter.

Fig. 1 shows the thermoelectric Peltier module assembly used in the experimental setup. The module was mounted between heat transfer plates and connected to a DC power source. Flexible water tubing was integrated into the system to facilitate heat transfer to the water reservoir.

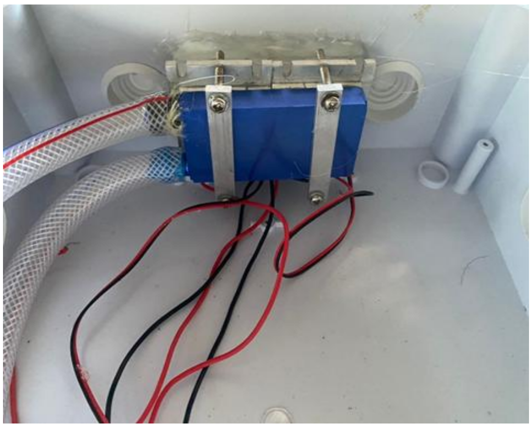

Fig. 1. Thermoelectric Peltier heating unit integrated into the water-heating test rig.

3.2 Materials and Equipment

Table 1 presents the primary equipment used during the experiment.

Table 1. Experimental Equipment.

Equipment	Specification	Purpose
Peltier Module	TEC1-12706 (or actual model used)	Thermoelectric heating
Heating Element	220 V AC (actual rating)	Resistance heating
Thermometer	Digital temperature sensor	Water temperature measurement
Power Supply	DC regulated supply	Peltier power source
Mustimeter	Digital	Voltage and current measurement
Energy Meter	Digital wattmeter	Energy consumption measurement

3.3 Experimental Procedure

The experimental procedure took place in the following manner:

- A predetermined volume of water was measured and placed in the test container.
- The initial water temperature was recorded.
- The heating system under investigation was activated.
- Water temperature readings were recorded at fixed time intervals.
- Voltage, current, and power consumption data were measured throughout the experiment.
- The experiment continued until the target water temperature was achieved.
- Total heating time and energy consumption were recorded.
- The procedure was repeated for both heating systems under identical conditions.

To improve reliability, each experiment was repeated multiple times, and average values were used for analysis.

3.4 Performance Evaluation Parameters

The performance of both heating systems was evaluated using the following parameters.

The thermal energy gained by the water was calculated using

$$Q = mc\Delta T \tag{1}$$

where: Q - heat energy transferred (J), m - mass of water (kg), c - specific heat capacity of water (4186 J/kg°C) and ΔT - temperature rise (°C).

Electrical energy consumption was determined from:

$$E = Pt \tag{2}$$

where: E - electrical energy consumed (Wh), P - electrical power input (W) and t - heating duration (h).

The coefficient of performance was calculated as follows:

$$COP = \frac{Useful\ Thermal\ Energy\ Output}{Electrical\ Energy\ Input} \tag{3}$$

The COP acts as an indicator of the efficiency of each heating system in converting the electrical energy into thermal energy output [22, 25].

The heating rate was calculated as follows:

$$Heating\ Rate = \frac{\Delta T}{\Delta t} \tag{4}$$

where: ΔT is temperature increase (in °C) and Δt is heating time (in min).

This factor served as a criterion for evaluating the speed of heating by each heating system.

3.5 Data Collection and Analyses

Data for each heating system were collected and analysed based on:

- Heating time.
- Temperature increase.
- Electrical energy consumed.
- Heating rate.
- Coefficient of performance.

3.6 Limitations of the Experiment

The experiment was carried out in laboratory conditions with a constant amount of water and constant environmental conditions. Changes in environmental conditions, water volume, insulation, and voltage input could affect the performance of heating systems in real-life application scenarios.

4. RESULTS

4.1 Heating Time and Energy Consumption Analysis

In this experiment, the efficiency of the thermoelectric Peltier module system was tested by comparing it against the efficiency of a normal 220 V electric resistance heating system. The aspects under consideration include the heating time, energy consumption, and the total heating efficiency.

Table 2. Heating Time and Energy Consumption Comparison.

System	Heating Time (minutes)	Energy Consumed (kWh)	Power Input (W)
Peltier-Module System	60	0.835	835.2
Traditional Resistance Heater	15	0.500	2000

A distinct disparity in the efficiency of both devices was observed from the experimental results. The resistance heater took only 15 minutes to raise the water temperature from 25°C to 60°C while the Peltier device system needed about 60 minutes to attain this result. Despite having a larger wattage output of 2000W compared to the Peltier system, the shorter heating time of the resistance heater made it more energy efficient, with 0.500 kWh consumed. On the other hand, the latter consumed 0.835 kWh (Table 2).

These findings indicate that the resistance heating element provided faster heating and better overall energy utilization than the thermoelectric system under the experimental conditions.

4.2 Coefficient of Performance (COP) Analysis

To further evaluate energy efficiency, the coefficient of performance (COP) was calculated for both heating systems using the measured heating times and energy inputs (Table 3).

From the computations of the COPs, it emerged that the ordinary resistance heater had a better energy conversion efficiency compared to the Peltier system. The ordinary resistance heater attained COP 0.0813, while the Peltier system recorded COP 0.0486.

Table 3. Coefficient of Performance Comparison.

System	Energy Transferred (J)	Energy Input (J)	COP
Peltier Module System	146,300	3,006,720	0.0486
Traditional Resistance Heater	146,300	1,800,000	0.0813

The relatively low COP of the Peltier system means that more electrical energy was consumed to give the same thermal energy in the water. This finding is expected because of the poor heating efficiencies of thermoelectric devices when applied to water heating

4.3 Temperature–Time Characteristics

The temperature profiles of both systems were analysed to evaluate their heating behaviours over time. Fig. 2 illustrates the relationship between water temperature and heating duration for the two heating technologies.

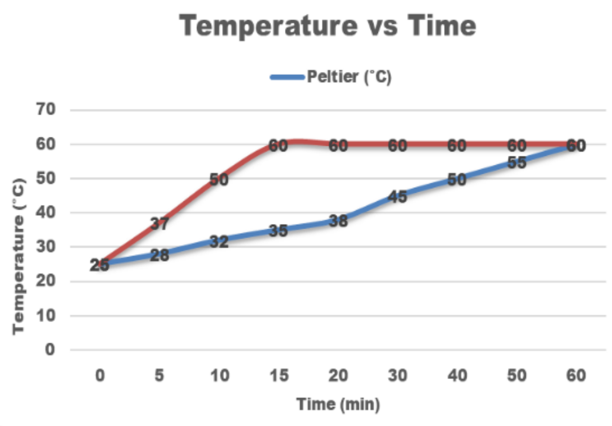

Fig. 2. The temperature-time behaviour of the two heating methods.

The traditional resistance heater at 220 V had a much faster heating rate as seen by the rapid increase in temperature from 25°C to 60°C in less than 15 minutes. However, the Peltier module method needed about 60 minutes to have the same temperature rise.

The faster temperature rise on the resistance heater implies a faster heat transfer process. It is caused by the ability of resistors to directly convert electrical energy into thermal energy. On the other hand, the slow heating time of the Peltier modules is due to heat transfer inefficiencies. It shows that the Peltier modules do not effectively pump heat from one side to another.

4.4 Heating Time Analysis

Fig. 3 compares the time required by both heating systems to raise the temperature of 1L of water from 25°C to 60°C

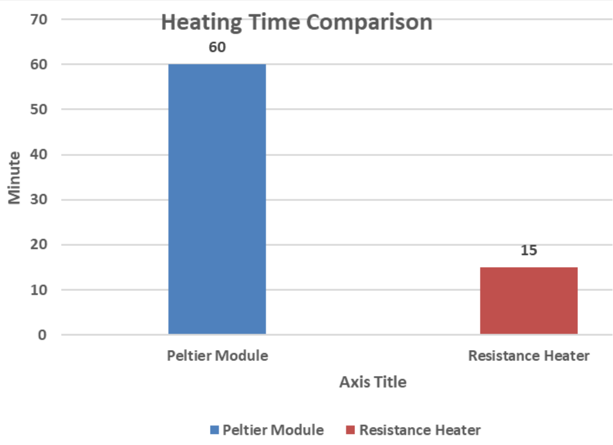

Fig. 3. Comparison of heating time between the Peltier module system and conventional resistance heater.

In the conventional resistance heater, it took around 15 minutes for the water to reach the desired temperature, while in case of the Peltier module system, it took 60 minutes. Thus, in the thermoelectric system, it took four times as much time as compared to the former system to heat up the water. This high performance by the resistance heater could be due to the more efficient heat energy production in this system. On the contrary, the Peltier modules had low thermal efficiency. It can be concluded that thermoelectric heating is not very efficient for rapid water heating applications

4.5 Energy Consumption Characteristics

Fig. 4 presents the total electrical energy consumed by both heating systems during the heating process

Even at a relatively low power value, the Peltier module-based heating system has used about 0.835 kWh to achieve the desired temperature, while the traditional heater needed only 0.500 kWh. The higher energy consumption by the Peltier system can be explained by its longer heating period.

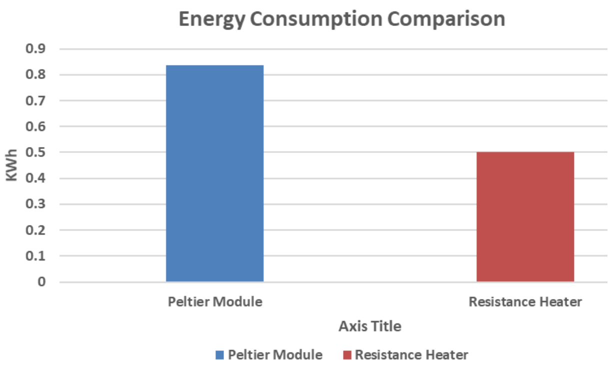

Fig. 4. Energy consumption comparison between the Peltier module system and the conventional resistance heater.

It follows from the findings above that energy efficiency should not be determined by energy consumption alone; the key performance measure is the overall amount of energy needed to heat up to a desired temperature. Therefore, the resistance heater performed better in terms of energy use.

4.6 Coefficient of Performance (COP) Analysis

Fig. 5 compares the coefficient of performance (COP) values obtained for both heating systems.

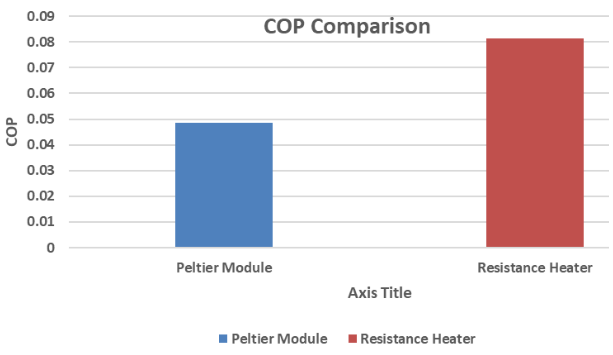

Fig. 5. Coefficient of performance comparison between the Peltier module system and the conventional resistance heater.

A COP of 0.0813 was realized by the resistance heater whereas the COP realized by the Peltier module system was found to be 0.0486. The higher COP exhibited by the resistance heater shows better effectiveness in converting electric energy to heat energy.

The low COP of the Peltier module system is attributed to the fundamental disadvantages of thermoelectric devices when subjected to large thermal stresses. There were losses in terms of heat generation and heat losses besides lower efficiency in thermoelectric conversion.

4.7 Power Input Characteristics

Fig. 6 illustrates the rated electrical power supplied to both heating systems

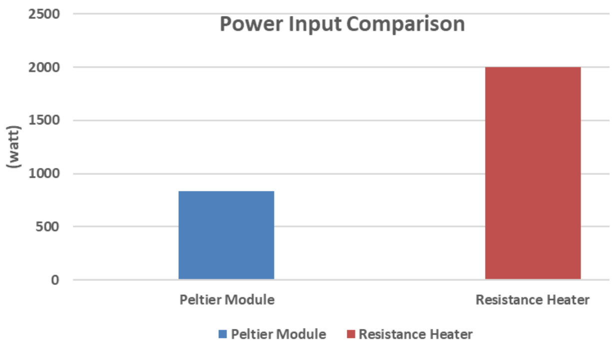

Fig 6. Electrical power input comparison between the Peltier module system and the conventional resistance heater.

The resistance heater had a power rating of 2000 W, whereas the Peltier-based heating device had an input power of around 835.2 W. Although the resistance heater consumed more input power than the Peltier heater, the shorter operating period of the former made it consume less energy overall.

This example emphasizes the significance of taking into account the operating period alongside the amount of power consumed.

4.8 Heating Rate Performance

Fig. 7 presents the average heating rates achieved by both systems.

While the conventional resistance heater had an average heating rate of about 2.33 °C/min, the Peltier module had a heating rate of about 0.58 °C/min. Hence, the conventional device heats up water nearly four times faster than the Peltier device. Due to the high heating rate, the conventional resistance heater has better performance when used for applications that require a fast heating rate. However, the lower heating rate of the Peltier device makes it unsuitable for other purposes.

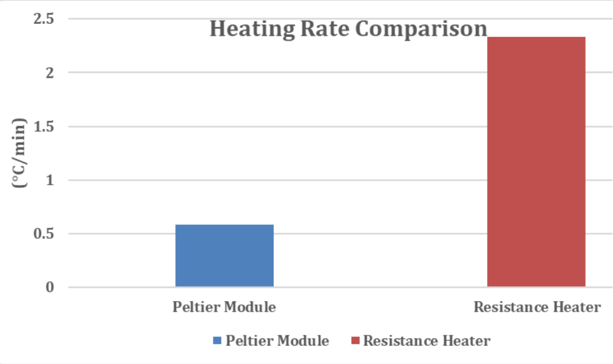

Fig. 7. Average heating rate comparison between the Peltier module system and the conventional resistance heater.

4.9 Relative Efficiency Assessment

Fig. 8 provides a comparative assessment of the relative efficiency of the two heating systems.

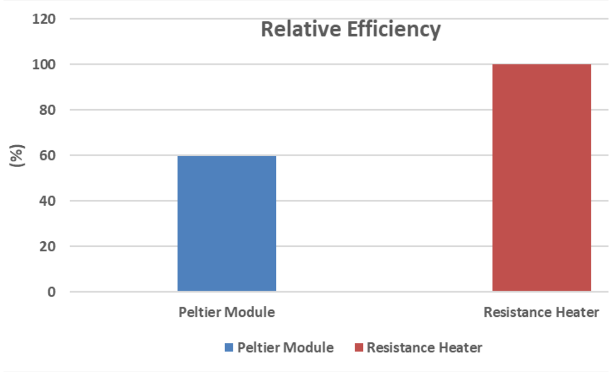

Fig. 8. Relative efficiency comparison between the Peltier module system and the conventional resistance heater.

In the case of a conventional resistance heater, whose relative efficiency is set at 100%, the relative efficiency of the Peltier module system has been obtained to be around 59.8%. The considerable difference arises due to the added energy losses associated with the heating process using Peltier modules.

Despite having the strengths of compactness, noiselessness, and accurate temperature control, the reduced efficiency associated with Peltier modules makes them unfeasible for heating on a wider scale.

5. DISCUSSION

5.1 Comparative Performance Analysis

From the experimental analysis conducted, the conventional 220 V resistance heater was found to have superior performance compared to the heating method that uses the Peltier module system. The resistance heater reached the target temperature in 15 minutes compared to 60 minutes for the Peltier modules.

The superior performance of the resistance heater in this experiment can be associated with the fact that it transforms electrical energy directly into heat energy via Joule effect. The Peltier modules use thermoelectric energy transfer mechanisms which lead to more thermal losses, and require cooling in order to perform well. Therefore, a large part of the input electrical energy was not utilized in producing heat energy [26, 27].

It is worth noting from the comparative analysis of energy consumption that the Peltier module used 0.835 kWh, while the resistance heater only used 0.500 kWh. Even though the Peltier modules were operating at a relatively low power level, the prolonged operation time made the energy consumption higher [28].

5.2 Efficiency of Thermoelectric Heating

In terms of COP, the performance can be evaluated further. The COP value of the conventional resistance heater was 0.0813, while that of the Peltier module system was 0.0486.

This inefficiency, represented by a relatively low COP value, aligns with the findings of previous researchers, who have indicated that Peltier modules, which are used for heating purposes, are not efficient due to the limited efficiency of commercial Peltier modules. These devices are primarily meant for use in cooling rather than heating and, thus, are less effective in water-heating systems [29, 30].

It can be stated that thermoelectric heating is currently unable to replace conventional heating methods in cases where high thermal output and quick heating are necessary.

5.3 Practical Implications

Even though they lack efficiency, Peltier modules have some properties that can make them appropriate for certain uses. They are small in size, work on low-voltage DC power, have no moving parts, and are able to control temperatures precisely, which may become useful during particular engineering projects.

Possible fields of use are:

- Solar water-heating appliances.
- Devices for laboratory experiments demanding controlled heating.
- Devices used in medicine and bio-medicine that require precise temperature control.
- Thermal management systems in embedded electronics.

In such applications, heating speed may be less critical than safety, portability, or temperature precision.

5.4 Limitations of the study

There are several limitations that should be taken into account while considering the results of this experiment.

First, the experiment was performed in a small amount of water, only 1liter. With larger amounts of water, other thermal features may manifest themselves.

Second, only one configuration of Peltier modules was analysed. Other configurations may work better.

Third, the environmental factors – temperature and air flow – were not controlled during the experiment. Their impact may play an important role.

Lastly, the thermal performance and power consumption were the main concerns of the experiment. An economical estimation of the experiment was out of scope for the research.

5.5 Future Research Directions

Future studies can be directed towards the development of high-performance thermoelectric water heaters using advances in materials and intelligent approaches to thermal management.

Some possible areas of future research include:

- Developing high-performance thermoelectric materials with enhanced values of efficiency figure-of-merit (ZT).
- Improving the heat sink and cooling systems so that higher temperature differences can be sustained across the Peltier modules.
- Creating thermoelectric hybrid heaters by incorporating both Peltier elements and traditional resistive heaters.
- Incorporating renewable energy sources like solar photovoltaic systems.
- Using machine learning approaches for optimizing temperature and energy use.

These approaches could lead to better efficiency and increased applications for thermoelectric heating technology.

6. CONCLUSION

An experimental performance analysis and feasibility study of the thermoelectric water heating system were carried out. The parameters employed in the assessment included the heating period, energy use, heating rate, and coefficient of performance. A normal resistance heater running on 220V electric supply was selected as a reference system in the evaluation.

The experiment findings revealed that the heating period taken by the thermoelectric heating system in raising the temperature of 1liter of water from 25°C to 60°C was 60 minutes while that of the resistance heater took 15 minutes. The amount of energy used by the thermoelectric heater was 0.835 kWh compared to 0.500 kWh used by the resistance heater. The same trend applied to the coefficient of performance of both systems.

In spite of all those disadvantages, this paper has managed to show that the concept of water heating through the use of thermoelectric generators or Peltier modules is technically possible when used at low voltages and within the DC domain. The technology provides a number of important benefits such as compatibility with photovoltaics, power from batteries, miniature dimensions, silent functioning, and precision of temperature regulation. These traits make it especially relevant to portable and remote areas where fast heating is not needed.

All in all, it becomes obvious that, when the rate of heating and efficiency of the process are essential, then a traditional resistance heater cannot be replaced by anything else but itself. Thermoelectric water-heating can become an interesting solution for certain applications; however, there are plenty of areas where it can and should be further developed in the future.

Future research should look at making thermoelectric water-heating systems better by focusing on advanced materials, improved heat sinks, and better ways to manage heat [26, 31, 32]. Also, studying hybrid systems that use both thermoelectric modules and regular resistance heaters or even combining them with solar power could lead to higher performance and efficiency [32, 34]. Moreover, researchers should run more tests with bigger water volumes and various conditions, and do long-term assessments too, to really see how well these thermoelectric systems work in real life [29, 35].

While regular resistance heaters still come out on top for needing quick and highly efficient heating, thermoelectric water-heating is cool because it can be perfect for special low-voltage and off-the-grid uses. But we need those tech upgrades to make it happen.

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