

Research Article

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Experimental performance evaluation of phase change material integrated thermoelectric generator

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Highlights

- Integration of Phase Change Materials (PCMs) with Thermoelectric Generators (TEGs) was experimentally investigated.
- Two PCMs with distinct thermophysical properties were tested to evaluate their impact on TEG performance.
- The energy generated by PCM-1 and PCM-2 during charging was 6910.12 J and 7157.75 J, respectively.
- Results contribute to advancements in waste heat recovery and sustainable energy solutions.

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ABSTRACT

Increasing energy demands have created an urgent need to explore alternative energy solutions. Waste heat, commonly lost in energy production, can be effectively utilised through thermoelectric generators (TEGs). These devices generate electricity when a temperature difference is employed across a thermoelectric material. The efficiency of TEGs can be significantly improved by combining them with Phase Change Materials (PCMs). PCMs help maintain a steady temperature gradient over a longer period, leading to better system efficiency and power output. The goal of this study is to experimentally evaluate the thermal and electrical performance of TEGs integrated with PCMs for efficient waste heat recovery at low temperatures. Two paraffin-based PCMs with distinct thermophysical properties were used to assess their performance during charging and discharging cycles. The results showed that the PCM-1-TEG system achieved an average power output of 0.27 W and an efficiency of 1.11 % during charging, while the PCM-2-TEG system produced 0.28 W and an efficiency of 0.8 %. However, both systems experienced a sharp drop in power and efficiency as the stored energy diminished. During the discharge phase, PCM-1 delivered an average power output and efficiency of 0.03 W and 0.3 %, while PCM-2 achieved 0.029 W and 0.31 %. The selected PCMs enabled continued electricity generation for up to 180 minutes after external heat was removed, highlighting their role in stabilizing the thermal gradient and sustaining power output during discharge. Based on the comparative performance of two PCMs, the results suggest that phase change temperature range and latent heat capacity significantly influence thermal buffering and electrical output behavior. Therefore, these properties should be considered when selecting PCMs for real-world waste heat applications.

Keywords: Waste heat, Thermoelectric generator (TEG), Phase change material (PCM), Energy harvesting

1. INTRODUCTION

The world is facing an expanding demand for energy due to the global population growth. In response to this, there has been a rise in the utilization of fossil fuels. Unfortunately, this has also caused an increase in environmental damage, including air pollution, acid rain, and water contamination, which can be diminished by utilizing alternative energy sources. [1,2]. Conversely, although the utilization of renewable energy sources is expanding, the energy generated by fossil fuels represents more than 80 % of global energy production today [3]. However, in the process of energy conversion, 66 % of the main energy source is lost as waste heat, leaving just 34 % for effective usage. Therefore, it has been of interest to several researchers to recover a part of the lost energy [4].

Thermoelectric generators (TEGs) can be used to harness waste heat by converting it directly into electricity (this process is known as the Seebeck effect). TEGs are composed of several thermoelectric (TE) materials and have the advantage of silent operation and require no maintenance as there are no moving parts within the system [5].

TEG performance depends on thermoelectric materials, system geometry, and operating conditions. The following dimensionless figure of merit (ZT) is used to characterize the performance of a thermoelectric material as:

$$ZT = \frac{S^2 \sigma}{k} T_m \quad (1)$$

where S , σ and k represent the Seebeck coefficient, electrical resistivity, and the thermal conductivity, respectively. T_m is the thermodynamic temperature (the average of the hot and cold side). As seen from the equation, materials with high Seebeck coefficient and electrical resistivity and low thermal conductivity will have a higher ZT value, which enhances the efficiency of heat-to-electricity conversion. However, due to the low ZT value ($ZT \leq 1$), the efficiency of TEGs is limited and is restricted by the development of such thermoelectric materials. In addition to this, altering the geometry and structure of the TEG, such as the semiconductor leg length or shape, could enhance efficiency. However, these parameters differ depending on the working environment and should be optimized according to the operating conditions. Alternatively, altering the external working conditions and improving the thermal management of TEGs could improve system efficiency [6].

Phase change materials (PCMs), which absorb heat during their phase change and release stored energy when the process is reversed are used as energy storage materials. PCMs have been utilized for the thermal management of TEGs as they offer several advantages [7]. For instance, as PCMs

can store and release significant amounts of thermal energy, they maintain a consistent heat supply to the TEG, extending the operational time as well as power generation. PCMs can regulate temperature fluctuations by absorbing excess heat and releasing it when required, reducing the risk of overheating and potential damage to the TEG. Furthermore, PCMs maintain a stable temperature gradient across the TEG (between the hot and cold ends), which enhances overall efficiency [8,9]. Therefore, the integration of PCM with TEGs has been of interest to several researchers. For instance, Jaworski et al. [10] designed a TEG module using solar energy as the heat source. PCM was used as the cooling method, which helped to keep the temperature low by removing heat in both sensible and latent form from the cold side. From the experimental results obtained, it was concluded that PCMs are suitable for use with TEGs. In another study, Tuoi et al. [11] conducted an experimental investigation of a TEG using ambient temperature variation as a heat source integrated with PCM. The system achieved a maximum power generation of 0.6 mW under conditions where the ambient temperature varied from 5 °C to 35 °C. To examine the effects of various heat source powers, heat sink thermal resistances, and PCM types on system performance, Sui et al. [12] experimentally examined the thermoelectric performance of a two-stage TEG-PCM system. They concluded that the heat source significantly influenced the system's performance more than the thermal resistance of the heat sink and the type of PCM.

Furthermore, integrating PCM and TEG in building envelopes can generate power day and night [13]. For instance, Byon and Jeong [14] designed and fabricated a system that integrates a TEG and a phase-change material, which they referred to as an energy harvesting block. The fabricated system collects waste heat from the exterior walls of buildings and generates electricity. The existing system converts heat into electricity by means of the Seebeck effect, which varies depending on the temperature difference between the two surfaces of the TEG. This is achieved by using a phase-change material that acts as a heat sink on the cold surface of the TEG. The experimental tests of the fabricated system utilized the calculated representative wall temperatures as the heat source. The results showed that the existing system produced 2.1 kWh/m² of electricity in one year with an average power and voltage of 0.03 W and 0.3 V. In another study, a three-dimensional model of a solar TEG block using PCMs on both sides was built to determine its energy conservation potential by [15]. The power generation of the solar TEG brick with and without PCM was compared. It was concluded that the system with PCM integrated on both sides could increase the outpower by 138.5 % for solar radiation of 600-1000 W/m².

Also, the utilization of TEGs with PCM in waste heat recovery systems for vehicles and industrial applications can lead to significant improvements in energy efficiency [16,17]. For instance, Wang

et al. [18] created a mathematical model to estimate energy harvesting from vehicle exhaust gases. They analysed the impact of various parameters on the performance of the TEG and investigated the potential of using PCM as a heat sink. Their findings showed that using PCM with a suitable phase change temperature could enhance output power and efficiency. They also proposed that combining two different PCMs could yield improved results thanks to high-temperature exhaust gases. In another study, Huang et al. [19] examined the performance of an automotive (TEG) for harnessing energy from exhaust gases under varying input conditions. They chose pentaerythritol as the PCM due to its suitable melting temperature range and minimal volume change during phase transition. However, the PCM's low thermal conductivity resulted in slower heat transfer to the TEG. Despite protecting the TEG from thermal fluctuations, the use of PCM led to only a 1% increase in output power compared to a conventional TEG without PCM. A hybrid thermoelectric generating system that recovers waste heat from an industrial chimney by using phase change materials (PCM) and porous copper foam was experimentally studied by Asadi et al.[20] Ten TEG modules were used in the study, with a heat sink on the cold side and the PCM-copper foam mixture on the hot side. Because the PCM kept the system from overheating, it was able to produce electricity for longer periods of time. The TEGs produced output voltages of 3900 mV and 6100 mV, respectively, when subjected to steady loads of 75 W and 125 W. The voltage increased to 5300 mV when tested with 150 W and 200 W fluctuating loads. The outcomes demonstrate the system's capacity to sustain consistent operation and enhance energy recovery under actual industrial waste heat conditions. Demir and Erden [21] suggested a thermoelectric power generation system for data centers that uses phase change materials (PCMs) and TEGs combined with heat pipes to manage waste heat and increase energy efficiency. Energy, exergy, and exergoeconomic metrics were used to analyze the system after it was modeled using the Engineering Equation Solver (EES). The system produced 125 W of thermoelectric power in a simulated 42U data center rack running at 25 kW CPU power, providing hot water at 68°C with a heating output of 20.1 kW per rack. The TEG output was raised to 219 W by a dual-stage TEG-PCM system, and the energy and exergy efficiencies were 80% and 33%, respectively. In high-density server environments, the study demonstrated the potential of combining PCMs and TEGs for waste heat reuse and passive cooling. In order to track performance throughout the year, Kang et al. [22] examined a hybrid energy harvester (HEH) system that included microencapsulated phase change materials (mPCMs) and thermoelectric generators (TEGs) in building-integrated photovoltaics (BIPVs). According to experimental results, the HEH system produced more electricity than traditional BIPVs, increasing electricity generation by 4.38% to reach 133.4

kWh/m² annually, as opposed to 127.3 kWh/m². In terms of increased energy, the TEGs produced 2.26 kWh/m², a 1.7% increase. Because PCM inclusion helped the surface temperature drop by up to 10 °C, seasonal efficiencies also increased by up to 14.3% in the summer, maintaining steady thermal gradients for dependable TEG performance. In addition, a two-stage TEG system combined with various phase change materials (PCMs) was proposed by Yang et al. [23] to increase thermoelectric conversion efficiency in waste heat recovery scenarios. The effects of different PCM embedding configurations at the heat source, between TEGs, and at the heat sink on electrical energy generation and power output were assessed. According to the study, employing high-temperature PCM on the heat source side improved output stability but reduced the two-stage setup's overall electrical energy. With a conversion efficiency of 6.9%, the optimised two-stage TEG system harvested 44.8% more electrical energy than a single-stage system. These results highlight how crucial PCM arrangement and selection are to optimising energy recovery. Although several studies have shown that PCMs can stabilize the thermal environment of thermoelectric generators (TEGs), most of them concentrate on either a single PCM material or numerical simulations. Furthermore, most experimental research focuses on performance during the heating (charging) cycle, with little attention paid to the cooling (discharging) phase following the removal of the heat source. Because of this, there is not enough experimental data to fully capture the thermal-electrical behaviour of PCM-TEG systems under the same conditions in both cycles. This study aims to address this gap.

The objective of this study is to compare and experimentally assess the thermal and electrical performance of two paraffin-based PCMs integrated with TEGs under a low-grade heat source during the charging and discharging phases.

In this study, a TEG module integrated with PCM for waste heat recovery was designed, fabricated, and experimentally tested. Two PCMs with distinct thermophysical properties were evaluated to determine their applicability to the TEG module and their impact on system performance. The study involved comprehensive thermal and electrical analyses, including measurements of open-circuit voltage, theoretical maximum power output, conversion efficiency, and total energy generation during both charging and discharging cycles. These analyses provide insights into the dynamic behaviour and potential of TEG-PCM systems for continuous and reliable energy generation.

2. MATERIALS AND METHODS

The experimental investigation was carried out in successive stages of material choice, setup construction, test of charging and discharging, and interpretation of data. To give a more explicit account of the procedure, a flow diagram of the process is given in Figure 1.

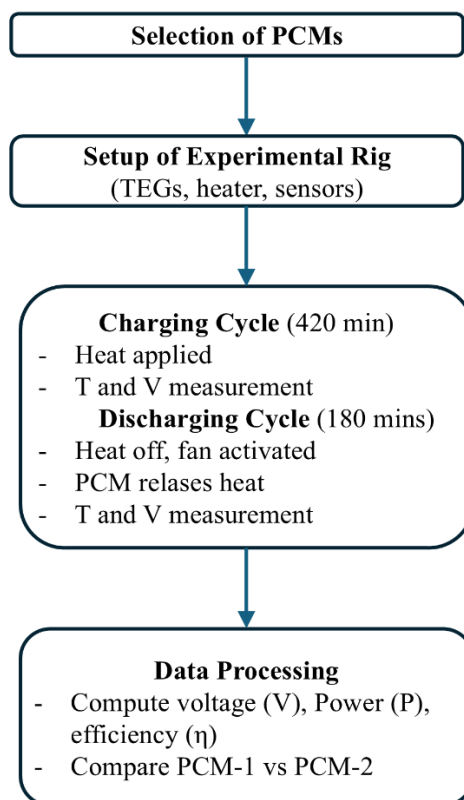


Figure 1. Flowchart summarising the experimental procedure.

2.1. Description of the system

The experimental setup consisted of a heating element, a dimmer, Styrofoam housing, aluminium plates, a fan, four TEG modules, and two PCMs. The setup, as shown in Figure 2, was designed to simulate a waste heat recovery environment. A Styrofoam box with dimensions of $250 \times 300 \times 500$ mm served as the primary housing, with all internal and external surfaces reinforced using adhesive aluminium tape to enhance structural rigidity and thermal insulation. The Styrofoam box was divided into two compartments: an upper compartment housing the TEG modules and PCMs, and a lower compartment containing the heating element. The TEGs were mounted between two aluminium plates (170×250 mm on the upper side and 160×140 mm on the lower side) using thermal adhesive to ensure optimal thermal contact. Electrical connections between the TEGs were established in series using terminal blocks, which were connected to a data logger via external

cables for monitoring voltage and temperature. To replicate a waste heat source, a Resistohm 135 wire (725 mm in length, 0.8 mm in diameter) was coiled and placed on the floor of the lower compartment, maintaining a fixed 300 mm distance from the TEGs. The heat source had a maximum power capacity of 2000 W, with its output regulated using a 220 V AC dimmer. The fan, positioned in the lower compartment, enhanced heat dissipation during the cooling phase.

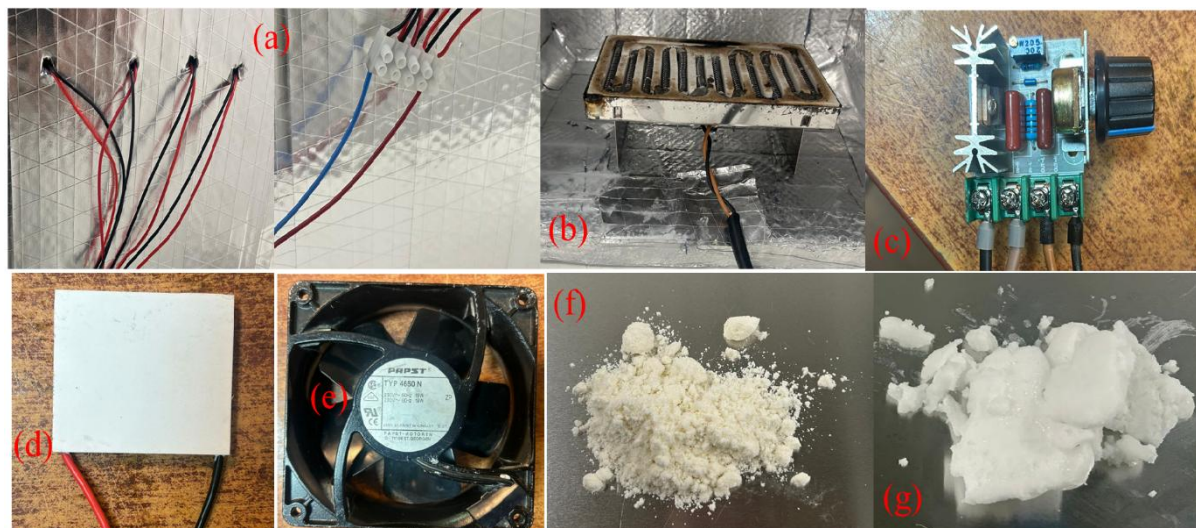


Figure 2. Photo of the experimental facility. a) TEG electrical connections, (b) heating element, (c) dimmer, (d) TEG, (e) fan, (f) PCM-1, (g) PCM-2

The TEG modules (SP 1848 27145 SA), constructed from Bismuth Telluride (Bi_2Te_3), were optimized for low-power applications. Table 1 provides their key specifications, including dimensions, thermal conductance, and electrical output at varying temperature differences. Despite being primarily intended as a thermoelectric cooler (TEC), the SP1848-27145SA module has been also utilized in the literature as an inexpensive TEG substitute for experimental energy harvesting applications. All electrical outputs were experimentally measured while it was in generator mode for this investigation.

Two paraffin-based PCMs with distinct thermophysical properties (PCM-1 and PCM-2) were employed, as summarized in Table 2, to evaluate their effects on system performance.

Table 1. Details of the TEG module [24,25].

Description	Value
Dimensions	40 mm × 40 mm × 4 mm
Material	Ceramic/Bismuth Telluride (Bi ₂ Te ₃)
Temp. difference (°C) /Open-circuit voltage(V)/Current (mA)	20/0.97/225; 40/1.8/368; 60/2.4/469;
Number of semiconductor pairs	127
Thermal conductance	0.85 K/W

Table 2. Thermophysical properties of PCM-1 and PCM-2 [26,27].

Properties	PCM-1	PCM-2
Phase change temperature range (°C)	29-36	19-28
Latent heat capacity (kJ/kg)	160	200-220
Thermal conductivity (W/m.K)	0.2 (solid) 0.2 (liquid)	0.15 (solid) 0.2 (liquid)
Specific heat capacity (kJ/kg.K)	2	1.77-1.86 (solid) 2.24-2.34 (liquid)
Density (kg/m ³)	860 (solid) 770 (liquid)	770

2.2. Experimental methodology

The experimental analysis consisted of two sets of experiments, each incorporating charging and discharging stages. PCM-1 (powder form) was used in the first set, while PCM-2 (wax form) was evaluated in the second set. Each experiment aimed to simulate a waste heat recovery system and assess the performance of the integrated TEG-PCM module under dynamic thermal conditions.

Charging Stage

As illustrated in (Figure3-a), the charging stage involved applying heat to the hot surfaces of the TEG modules using a resistive heating element. The PCMs, positioned on the cold surfaces of the TEG modules, absorbed heat from the system and stored it as latent heat. This process stabilized the temperature gradient across the TEGs, facilitating voltage generation via the Seebeck effect. The heating cycle lasted 420 minutes, during which temperature and voltage data were recorded.

Discharging Stage

The discharging stage, depicted in Figure 3-b, began with the removal of the heat source and its replacement by a fan to enhance heat dissipation. The stored heat in the PCMs was released to the cold surfaces of the TEG modules, reversing the temperature gradient. This allowed the TEGs to continue generating voltage for an additional 180 minutes.

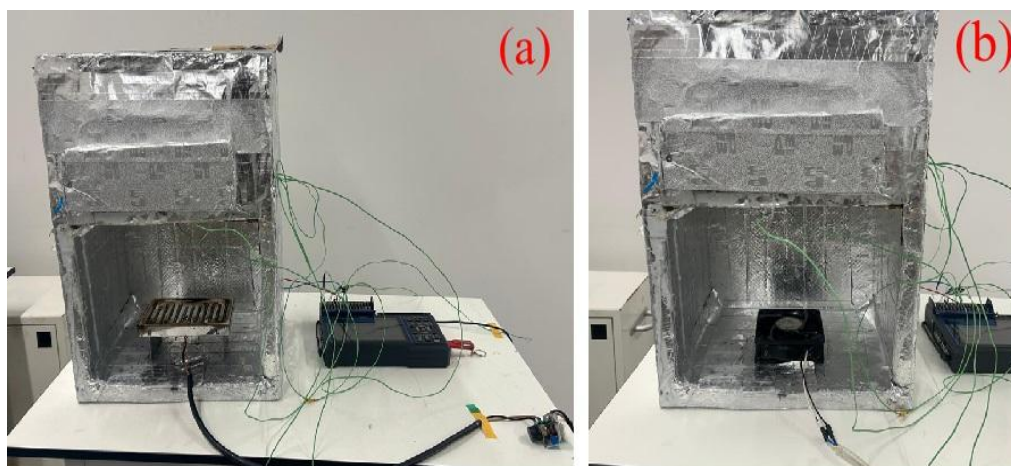


Figure 3. Schematic diagram of the experimental test rig. a) charging stage b) discharging stage.

Figure 4 illustrates the schematic layout of the measurement points within the experimental system. Thermocouples were positioned to monitor:

- The hot surfaces of the TEGs (T_{hot}).
- The cold surfaces of the TEGs (T_{cold}).
- Inside the PCMs (T_{PCM}).
- Ambient air (T_{amb}).

Temperature and voltage readings were recorded every minute using an automatic digital recorder (model: LR-8431-20, HIOKI). To ensure accurate measurements, holes were drilled into the Styrofoam housing to insert thermocouples, and the box was re-insulated after their placement. This setup ensured consistent environmental conditions for all tests, enabling a direct comparison between PCM-1 and PCM-2 performance.

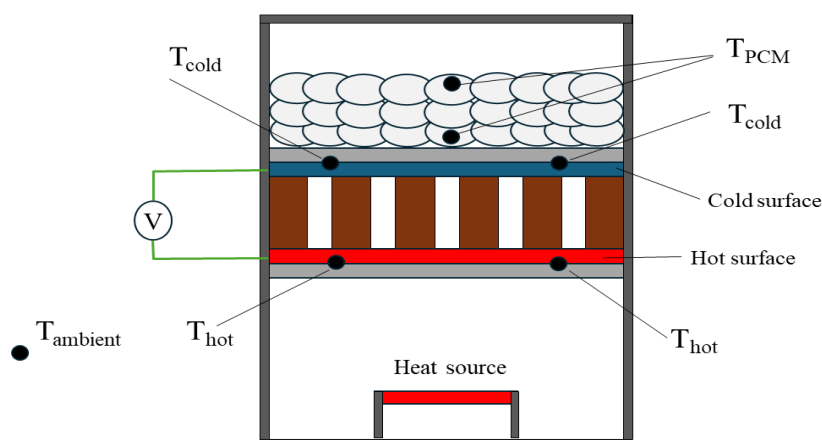


Figure 4. Schematic diagram of the measuring points.

3. THEORY (DATA REDUCTION)

The Seebeck effect, which produces an electric voltage when two distinct materials have differing temperatures, is the basis for how (TEGs) work. The voltage generated by a TEG is directly proportional to the temperature difference across the thermoelectric material:[28]:

$$V = S \cdot \Delta T \quad (2)$$

Where V is the Seebeck voltage, and ΔT is the temperature difference between the hot and cold sides. The power generated by a TEG can be expressed as:

$$P = \frac{S^2 \Delta T^2}{(R_{int} + R_L)} \quad (3)$$

Where R_L is the load resistance, and R_{int} is the internal resistance of the TEG. When the load resistance equals the TEG's internal resistance, the maximum power output can be calculated [29]:

$$P_{max} = \frac{(S\Delta T)^2}{4R_{int}} = \frac{(V)^2}{4R_{int}} \quad (4)$$

The theoretical maximum efficiency of TEG is expressed as [29]:

$$\eta_{max} = \frac{\Delta T}{T_h} \times \frac{\sqrt{1 + ZT_m} - 1}{\sqrt{1 + ZT_m} + \frac{T_c}{T_h}} \quad (5)$$

where $\eta_{TEG,max}$ is the theoretical maximum efficiency of TEG. ΔT is the temperature difference between the hot side (T_c) and cold side (T_h) and T_m is the average of T_c and T_h .

4. RESULTS AND DISCUSSION

4.1. Thermal results

The TEG, PCM, and ambient surface temperatures for the charging and discharging processes are displayed in Figure 5. In the charging section, an external heat source was applied to the aluminium plate attached to the hot side of the TEG. As a result, the temperatures of both the hot and cold sides of the TEG increased. However, the rate of temperature growth was different for each side. This is due to the PCM attached to the cold side of the TEG, which acted as a heat sink. PCM absorbed heat from the cold side, diminishing its temperature increase. It was also observed that the cold side's temperature closely matched the temperatures of both PCMs throughout the entire experiment. The same trend can be found in Ref. [29]

As shown in Figure 5-a), the charging process of the PCM-1 consisted of three phases: pre-sensible, latent, and post-sensible heating. The initial temperature of PCM-1 was 20°C, and it took almost 60 minutes to reach the starting temperature of the phase transition (around 29 °C). PCM-1 continued to absorb heat from the cold surface, storing it as latent heat as the material experienced a phase change. This phase lasted for about 45 minutes. After the phase change process was

completed, PCM-1 continued to increase its temperature by absorbing heat in the form of sensible heat from the cold side again. The heating cycle was terminated at the end of 420 minutes. After the charging cycle ended, the heat source on the hot surface of the TEG module was removed and replaced by a fan. The hot surface, which was affected by the heat source during the charging cycle, became the cold surface of the TEG module in the discharging cycle, and the fan was used to increase heat transfer between the surrounding environment and the cold surface, thus increasing the amount of heat extracted from the cold surface. During the charging cycle, PCM-1, which released the energy stored in the form of both sensible and latent heat to the environment, enabled the cold surface to function as the hot surface in the discharging cycle, generating voltage. The discharging cycle also consisted of three phases: pre-sensible cooling, phase change, and post-sensible cooling after phase change. In the pre-sensible cooling phase, PCM-1, which had an initial temperature of 74 °C, started to lose heat by transferring the stored heat to the cold surface of the module, and thus its temperature decreased. The temperatures of the cold and hot surfaces of the TEG also decreased along with PCM-1. When the PCM-1 temperature reached 36 °C, the phase change (solidification) began. The phase change continued for approximately 50 minutes, and then sensible cooling started. The cooling cycle was terminated at the end of 600 minutes, which is also the point at which the temperatures of both surfaces of TEG equalized.

Figure 5-b) indicates that the charging process of PCM-2 consisted of only two phases: phase transition and post-sensible heating. No pre-sensible heating phase was observed during the charging process because the initial temperature of PCM-2 (22 °C) fell within the phase transition temperature (19-28 °C). It took around 15 minutes to complete the phase transition, after which the post-sensible heating section began. The temperature increase trend observed in PCM-1 was also observed in PCM-2. The external heat source caused the temperatures of both the hot and cold surfaces to increase, but this increase was lower for the cold surface. This is because PCM-2, in contact with the cold surface, absorbed heat from the surface, delaying the temperature increase of the cold side. PCM-2 continued to absorb heat from the cold surface until the end of the charging cycle, delaying the reduction in the temperature difference between the two surfaces. The heating cycle was terminated at the end of 420 minutes. The same procedure used in the first experiment was also followed in the second experiment, and the heat source acting on the hot surface of the TEG module was removed and replaced by a fan. As shown in Figure 5-b), at the beginning of the discharging cycle, the cold surface (indicated in blue) became the part of the TEG module with the highest temperature, and the hot surface (indicated in red) became the coldest part of the module. As in the charging cycle, the discharging cycle also consisted of two phases. In the pre-

sensible cooling section, the PCM acted as the heat source for the system and released its stored heat to the cold surface of the TEG, which took 120 minutes. Then PCM-2, whose temperature decreased to the phase transition temperature, began to change phase (solidify) and remained in the phase change region until the end of the experiment.

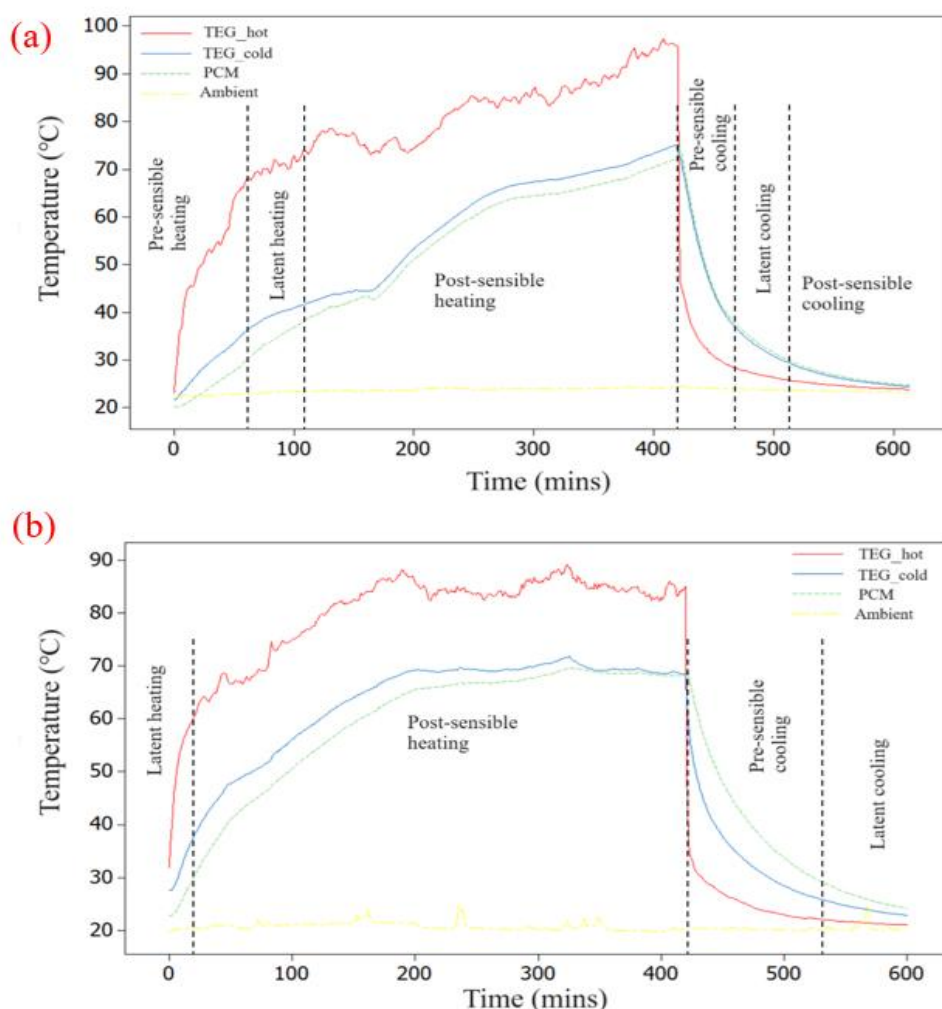


Figure 5. Thermal results of the system. a) PCM-1, b) PCM-2.

Previously, it was mentioned that the electricity generation of the TEG module varied in direct proportion to the temperature difference between the two surfaces (cold and hot). Figure 6-a) shows the temperature difference between the both ends of the TEG and the voltage generation for both cycles. In the first part of the charging cycle, the temperature difference between the hot and cold surfaces increased. This is because PCM-1 absorbed heat from the cold surface, and the temperature increase was slower than that of the hot surface. In the phase change section, the temperature difference reached its highest value of 35.1 °C, and the highest voltage generation (0.89 V) was achieved. After the end of the phase change section, the temperature difference

gradually decreased, and as a result, the voltage generation also showed a decreasing trend. During the charging and discharging cycles, the system generated an average voltage of 0.58 V and 0.13 V, respectively. PCM-2, which was in the phase change region at the beginning of the experiment, absorbed heat from the cold surface, causing the temperature difference between the two surfaces to increase, and as a result, the voltage generation showed an increase. PCM-2, which then moved to the post-sensible heating region, continued to extract heat from the cold surface, maintaining the temperature difference within a certain range. In this region, the maximum temperature difference reached 23.4 °C, and the maximum voltage generation was measured at 0.7 V. The system generated an average voltage of 0.6 V in the charging region and 0.15 V in the discharging region (Figure 6-b).

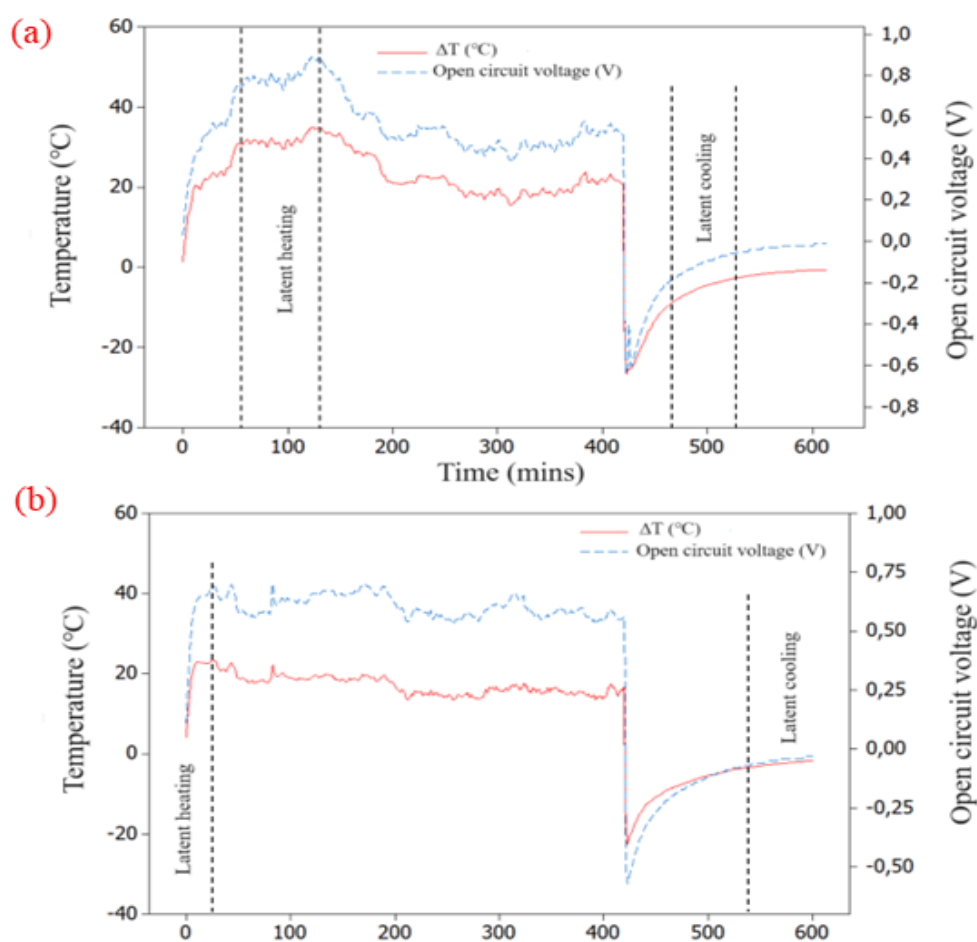


Figure 6. Temperature difference and Voltage generation. a) PCM-1, b) PCM-2.

Despite being paraffin-based, the two PCMs exhibit distinct thermal behaviors due to their physical forms (wax versus powder). Because powdered PCM (PCM-1) has a larger surface area and better heat transfer properties, it has a higher thermal conductivity. This leads to a steeper

temperature gradient across the TEG during the charging cycle and faster heat absorption. Higher voltage and efficiency during this phase are a result of this.

The total thermal energy storage capacity of each PCM was determined using their measured masses and thermophysical characteristics to further support the observed differences in thermal and electrical performance. The combined sensible and latent heat capacity of PCM-1 (505.75 g) was roughly 96.1 kJ, whereas PCM-2 (1271.51 g) showed a significantly higher storage capacity of 295.0 kJ. Particularly during PCM-2's post-sensible and latent heating phases, this increased thermal energy storage capacity helped to sustain a more consistent temperature differential across the TEG surfaces, supporting continued voltage output.

Furthermore, Figure 7 demonstrates the power generation and the efficiency values of the system. The TEG module integrated with PCM-1 achieved 0.274 W of average power for charging and 0.031 W for discharging sections whereas it was 0.284 W and 0,03 W for charging and discharging sections respectively with PCM-2. The results are similar and in agreement with the literature [28,30,31]. The average theoretical maximum efficiency of the TEG-PCM-1 was found to be 1.11 % for charging and 0.30 % for discharging cycle. The average efficiency for TEG-PCM-2 was realised as 0.80 % and 0.31 % for charging and discharging cycles respectively. These efficiency values are similar to the reported efficiency of TEG [32].

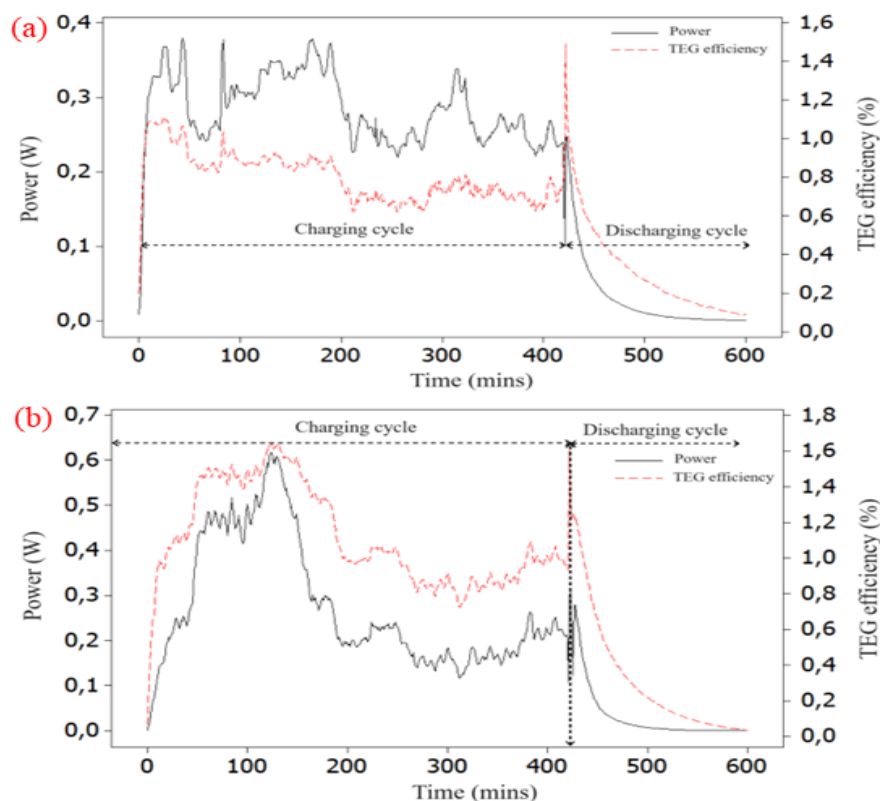


Figure 7. Power generation and efficiency of the TEG module. a) PCM-1, b) PCM-2.

Furthermore, the energy generated (E) by the TEG-PCM module is calculated using the equation of $E = \int_0^t P \cdot dt$. As a result, 6910.12 J of energy was generated by the TEG-PCM-1 module in 420 mins in the charging section whereas 344.18 J was made in 180 mins in the discharging section. On the other hand, TEG-PCM-2 module was able to generate 7157.75 J of energy in the charging section (420 mins) and 323.16 J in the discharging section (180 mins). This translates to a total energy generation of 7470.91 J for PCM-2, which is roughly 3% more than the 7254.30 J total energy generated with PCM-1.

5. CONCLUSION

A PCM combined with a TEG was designed, fabricated, and experimentally tested for the recovery of waste heat. The performance of two different paraffin-based PCMs under charging and discharging cycles was evaluated. The experimental setup demonstrated the generation of voltage, power output, and efficiency using waste heat. The charging process involved heating the TEG's hot side, while the cold side, attached to the PCM, absorbed heat, stabilizing the temperature gradient required for electricity generation. The discharging process was characterized by the release of stored heat by the PCM, which continued to generate electricity.

The following conclusions were drawn:

- The greater temperature differential ($\Delta T = 35.1^\circ\text{C}$) that PCM-1 maintained during the charging phase was the reason for its higher peak voltage (0.89 V vs. 0.7 V) and charging efficiency. On the other hand, PCM-2 offered more consistent performance throughout charging and discharging cycles due to its higher latent heat capacity (200–220 kJ/kg).
- PCM-1 showed higher peak thermal absorption rates resulting in a larger initial temperature difference during the charging phase. However, PCM-2 provided a steadier thermal output during discharging due to its higher latent heat capacity (200–220 kJ/kg).
- PCM-1 exhibited a more pronounced drop in both power output and efficiency after the phase transition was complete, while PCM-2 maintained a steadier output over time.
- PCM-1 achieved a maximum temperature difference (ΔT) of 35.1°C during charging, while PCM-2 reached 23.4°C . This indicates PCM-1 is more effective for systems requiring higher temperature gradients.
- The maximum voltage generated during the charging cycle was 0.89 V for PCM-1 and 0.7 V for PCM-2. During the discharging cycle, the average voltages dropped to 0.13 V for PCM-1 and 0.15 V for PCM-2.

- PCM-1 produced an average power output of 0.27 W during the charging cycle and 0.03 W during discharging. PCM-2 delivered a slightly higher power of 0.28 W in the charging cycle (a 3.6 % increase) and 0.029W during discharging.
- PCM-1 achieved an efficiency of 1.11 % in the charging cycle, while PCM-2 had an efficiency of 0.80 %. During the discharging cycle, efficiencies were comparable at 0.30 % for PCM-1 and 0.31 % for PCM-2.
- PCM-1 showed a higher energy generation per unit mass—14.34 J/g versus 5.87 J/g for PCM-2—despite PCM-2 producing a higher total energy output. In real-world applications where weight or volume is a constraint, this increased energy density might be advantageous.
- The reliability of the PCM-TEG integration approach was supported by the experimental results, which showed good agreement with previous studies in the literature [24–28] in terms of temperature profile, power output, and efficiency.

Furthermore, in the experiments, the maximum temperature of the hot surface of the TEG was kept below 100 °C. This value is within the temperature range required for safe operation of the TEG. However, PCM can be applied to the hot side of the TEG to take advantage of higher temperature applications. PCM will reduce the temperature of the hot side by storing the energy and can provide continuous electricity generation by giving the stored heat to the system when there is no heat source. Also, applying PCM on the hot side can reduce output voltage fluctuations which will provide voltage stability for electrical devices. To evaluate the practical economic viability of large-scale TEG-PCM systems, a thorough cost-benefit analysis taking into account the price, volume, and thermal characteristics of each PCM is recommended for future research. Further performance gains under variable heat source conditions might also be discovered by investigating the use of PCM on the hot side of TEG modules. Future research should also investigate how external load variation affect the TEG module's maximum power output. For practical use in waste heat recovery applications, it is important to match the external load to the internal resistance of the TEG system so that it can harvest energy in the best way possible.

NOMENCLATURE

PCM	Phase Change Material
TEG	Thermoelectric Generator
ZT	Dimensionless Figure of Merit

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Gökberk Karadirek: Writing - Original Draft, Methodology, Investigation

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CONFLICT OF INTEREST

There is no conflict of interest in this study.

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