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An analysis of phase change material for subterranean cooling of the thermoelectric energy harvesting system at asphalt pavement

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ABSTRACT

This study proposes a novel thermoelectric harvester design for asphalt pavements, incorporating thermoelectric generators and phase change material. Through simulation and experimentation, a system was developed *using* PCM as a cold storage unit to maintain subterranean cooling. The design comprises an asphalt base holder and top and bottom plates for heat capture and dissipation, respectively. The exposed top plate harvests solar heat, while the submerged bottom plate connects to an H-shaped cooling element and a PCM container. This configuration leverages subterranean cooling and facilitates a significant temperature difference between the TEG plates. Consequently, the experiment observed a maximum attainable temperature difference of 42.22°C with PCM compared to 14.39°C without PCM, translating to a threefold increase in charging efficiency, as demonstrated by a 5 V supercapacitor fully charged within 2.6 h. This novel TEG design offers a promising approach for self-sustainable energy harvesting from asphalt pavements.

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KEYWORDS
Asphalt pavement harvesting; thermoelectric energy harvesting; thermoelectric generator; subterranean cooling; phase change material

Nomenclature

PCM	phase change material
TEHs	thermoelectric energy harvesting systems
DT or ΔT	temperature difference
TEG	thermoelectric generator
S	Seebeck's coefficient
ΔV	thermovoltage
m	mass
C_P	heat storage capacity
T_1	lower (initial) temperature
T_2	upper (final) temperature
Cs	specific heat capacities in a solid state
C_1	specific heat capacities in a liquid state
T	temperature
T_M	melting temperature
k	thermal conductivity in a liquid state
ks	thermal conductivity in a solid state
ρ_{TM}	density of melting temperature
VOC	open circuit voltage from TEG
VBOOST	boost voltage fro
PMC	power management circuit
T_a	surface area of the Top plate Temperature
T_b	ambient temperature
ε	emissivity coefficient
σ	Stefan–Boltzmann constant

1. Introduction

Sustainable societies with strong economies require reliable energy sources. Non-renewable sources are limited by depletion, inefficiency and the generation of waste heat and toxic gases. To achieve environmental sustainability and longevity, research has focused on renewable and clean energy alternatives. Researchers offered a promising solution with the discovery of thermoelectric materials (Singh et al. 2022) and some developed a hybrid energy harvester; thermo-magneto-pyroelectric energy generator (TMPyEG) designed to continuously harvest waste heat and convert it into electric energy where it has outperformed conventional thermoelectric energy harvesting devices using a soft magnetic material and a pyroelectric material (PMN-PZT) to generate electricity from low-grade waste heat (Choi et al. 2023). Despite the primary focus of thermoelectric research being on material property enhancement and hybridisation of the harvester, thermal management of the device is often overlooked. Effective thermal management is crucial for harnessing waste heat from road pavements. Studies by Benrazavi et al.(2016) have shown that urban asphalt surface temperatures can peak at approximately 60.4°C between noon and 3:00 pm, leading to a power generation temperature setting of less than 65°C (Benrazavi et al. 2016). The heat stored in asphalt roads makes them ideal for thermoelectric energy harvesting. Our previous research at UTeM demonstrated that the inclusion of asphalt in the system significantly affected

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temperature distribution, with a 24.39% increase in temperature difference compared to a system without asphalt (Khamil, Mohd Sabri, and Yusop 2020a). However, high surface heat can impact the temperature differences in the Thermoelectric Module (TEM), leading to reduced output voltage and ineffective heat dissipation.

Thermoelectric conversion efficiencies, as noted by Sajid, Hassan, and Rahman (2017), depend on the cold side temperature of the TEG cooling system. Phase Change Material (PCM) is not only cost-effective but also exhibits high latent heat and efficiency (Sajid, Hassan, and Rahman 2017; Venkatesan and Venkata Ramanan 2022). Current research, as reviewed by Luo et al. (2022), is focused on PCM heat absorption and cooling at high temperatures, but more investigation is needed on PCM heat storage at low temperatures (Luo et al. 2022). M. De Falco, Salvatori, and Zaccagnini (2021) proposed a system comprising a two-stage storage tank containing a heterogeneous mixture of an organic PCM and water, which can rapidly and uniformly solidify the PCM, storing cold energy as latent heat (De Falco, Salvatori, and Zaccagnini 2021). When using a cold storage heat preservation box, the quantity of PCM filled, as noted by Xiaofeng and Xuelai (2021), is a critical factor influencing the effective temperature range within the structure (Xiaofeng and Xuelai 2021). However, the extent of this influence when submerged at a subterranean level remains unclear. The latent heat effect of PCM-based storage at the underground level is yet to be explored. Li et al. (2021) demonstrated that PCM is used to store latent heat to manipulate and stabilise the hot-side temperature of the thermoelectric module, enhancing thermal conductivity and accelerating heat dissipation (Li et al. 2021). However, the influence of the amount of PCM used on the system structure's heat conduction was not further elaborated. Therefore, a further evaluation of a model/system that comprises the PCM that can absorb and retain the temperature for the cooling structure in (Khamil et al. 2021) to preserve the subterranean's cool temperature for the cold side of TEM thus, generating a high-temperature difference (DT) and high-power generation.

2. Principles of thermoelectric effect and energy storage

2.1. Concept of thermoelectric generator (TEG)

Thermoelectric generators (TEGs) can transform heat flux into electrical power and vice versa. In simple terms, whenever there is a temperature difference, these can convert it into electrical energy. These semiconductors operate based on the thermoelectric effect, also known as the Seebeck effect. As there are no moving parts, these devices are particularly needed for manufacture and upkeep. These generators also have a great deal of potential for exploiting waste heat. The manufacturing of thermoelectric modules is done by coupling two conjugate p-type and n-type-doped semiconductor materials in an optimised manner. The thermoelectric generator works on the principle of the Seebeck effect (Rohit et al. 2017), which can be referred to in Equation (1).

$$S = \frac{\Delta V}{\Delta T} \tag{1}$$

When two junctions are formed by joining two dissimilar materials maintained at different temperatures a voltage. The materials used here are called thermoelectric materials and the selection of these materials is based on their properties like thermal conductivity, electrical conductivity, Seebeck coefficient, etc. Hence, for TEGs, increasing the DT across the hot and cold sides is crucial for maximising power output. Temperature variations can increase the ΔT in TEGs by raising the hot side temperature (within material limits) or lowering the cold side temperature through active cooling or favourable ambient conditions. However, it's important to consider material limitations and heat transfer efficiency to ensure optimal and safe operation of the TEG. Yu and Li 2024; Yu and Song 2023 try to overcome the low efficiency of TE devices by using the Seebeck effect by directly connecting two types of phase change materials with different conductivities and different phase transition temperatures, hence a stable electrical energy output would be feasible enough even without the TE device itself. However, in this study, we have carefully selected the TE device that we'll use as mentioned in (Khamil et al. 2020b) and focused on harvesting energy from asphalt pavement. Several studies utilised TEGs for harvesting thermal energy from asphalt pavement (Datta, Dessouky, and Papagiannakis 2017; Jiang et al. 2018; Lin et al. 2021; Rahman, Hamja, and Chowdhury 2013). Their work emphasised the efficiency of using TEGs to harvest thermal energy from asphalt and solar radiation. However, the flaw of TEGs is that the temperature difference between the hot side and cold side of the TEG is it is easily influenced by the temperature variation. To fix this problem, PCM will be added to retain subterranean cooling on the TEHs. In this study, TEG used APH-127-10-25 from European Thermodynamics (European Thermodynamics 2014).

2.2. PCM as an energy storage

Alternative energy can be created in a variety of ways, one of which is energy storage. In addition to conserving energy, energy storage reduces the variance between supply and demand and enhances the accuracy and reliability of energy supply. The idea of this paper is to add PCM for acting as a cold storage and help the cold side of the TEG to retain the temperature. This idea has been practised in many of the previous works (De Falco, Dose, and Zaccagnini 2015; Duan 2021; Khattari et al. 2022; Lin et al. 2021; Murali et al. 2021; Rahman, Hamja, and Chowdhury 2013; Reddy, Venkataramaiah, and Lokesh 2014; Sun et al. 2022; Vikneswaran, Pasupathy, and Arumuganainar 2014; Zalba et al. 2003; Zhang et al. 2010; Zhao and Tan 2014). They utilised PCM as energy storage for cooling purposes of their work. PCMs are latent heat thermal energy storage materials that use their chemical bonds for the storage and release of energy (Madruga 2023; Tk and Raj 2018). A new method of PCM as produced by (Yu et al. 2018) shows a graphene-embedded form of PCM which can enhance both the shape stability and thermal conductivity of the resulting PCM composite. Sensible heat storage occurs when energy is stored or released by increasing or decreasing the temperature of the storage substance, accordingly. The amount of thermal energy stored is determined by

Equation in (2).

$$Q = m \int_{T1}^{T2} C_P \Delta T \quad (2)$$

3. System concept

The configuration of the TEHs at the asphalt pavement model has been built, as shown in Figure 1 where the dimensions of the system model are listed in Table 2. This model consists of a thermoelectric generator (TEG) module sandwiched between two aluminium plates, which are the top (hot side) and bottom (cold side) plates. The bottom part is submerged in the asphalt with three rods. There is a soil layer below the asphalt layer to replicate the asphalt pavement design.

The conductivity of the PCM is relatively small. An extra structure should be used to improve the internal thermal conductivity of the PCM, particularly so the parts far from the contact face work effectively (Zhang et al. 2010). The thickness of the PCM container is around 0.2 cm which may enhance heat transfer efficiency and mitigate the low conductivity of the PCM (Salunkhe and Shembekar 2012). On the other hand, (Khamil et al. 2021) used an H-shape heat sink for their TEHs. With both papers as references, this project plans to combine and improvise these methods by welding an aluminium plate in between two H-shape structures with diameters of 1.25 in.. Two cascaded TEGs used are APH-127-10-25 from European Thermodynamics, will be placed in between the top plate and bottom plate. The PCM used in this project, Salt Hydrate type: Calcium Chloride Hexahydrate ($CaCl_2 \cdot 6H_2O$), will be placed in a container at the bottom plate of the TEHs to retain the ambient temperature of the bottom plate, as shown in Figure 1. The heat transfer analysis for the TEHs will be performed using COMSOL Multiphysics simulation and will be validated with an experimental investigation.

4. Methodology

4.1. Finite element analysis (FEA)

COMSOL Multiphysics software was used to design and simulate the prototype of the model. A variety of methods were used to access TEH simulation. To perform the thermal performance of the defined building element, 3D geometry was employed, while a time-dependent study was chosen to satisfy the non-steady nature of the problem. The material and properties used for this simulation were portrayed in Table 1 taken from the previous study (Khamil, Mohd Sabri, and Yusop 2020a) while Table 2 depicts the dimensions of the prototype.

From the chosen dimensions, the model was designed and constructed using a 3D model tool in COMSOL Multiphysics software. The final technical drawing to simulate this model is shown in Figure 2. From the top, the TEG was sandwiched between the top plate and the bottom plate which were 1 mm aluminium plates. Attached under it was a container for PCM placement and connected to the 10 cm H-shaped heatsink. The model considers three ambient boundary conditions. The ground temperature at 10-centimetre depth is assumed to be constant at 27°C, representing the average water temperature.

The surrounding air temperature varies sinusoidally throughout the day due to combined free and forced convection (wind) at exposed surfaces. A bulk heat transfer coefficient of 20 W/(m⊃2·K) is applied to these surfaces using a *Convective Heat Flux* boundary condition. Lastly, radiative heat transfer between exposed faces is modelled using pre-computed greybody radiative view factors.

4.2. Simulation for phase change material

At the temperature where a material undergoes a phase change, its ability to store heat resembles a very concentrated function,

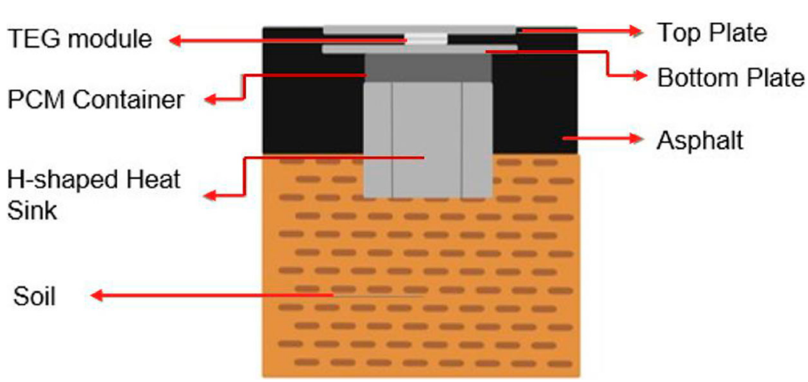

Figure 1. Illustration of thermoelectric energy harvesting system (TEHs).

Table 1. Material and properties of the model.

Material	Heat capacity (J/(Kg.K))	Thermal conductivity (W/m.K)	Density (Kg/m^3)	Electrical conductivity (S/m)	Latent heat (KJ/Kg)
Aluminum	900	222	2.7	3.774e^7	–
Alumina	896	138	2820	3.030e^7	–
Soil	800	1.59	1430	–	–
Asphalt	900	0.8	2.24	–	–
PCM: $CaCl_2 \cdot 6H_2O$	2000	0.2	880	–	170

Table 2. Dimensions of the thermoelectric energy harvesting system (TEHs).

Type	Dimension (cm)
Cylindrical rod	Radius (1.588) Height (10)
Top plate	15 × 20 × 0.3
Bottom plate	15 × 20 × 0.3
Middle plate	0.3 × 14.176 × 10
TEG module	3 × 3 × 0.5
Asphalt	32 × 32 × 10
Soil	32 × 32 × 20
PCM container	10 × 20 × 0.2

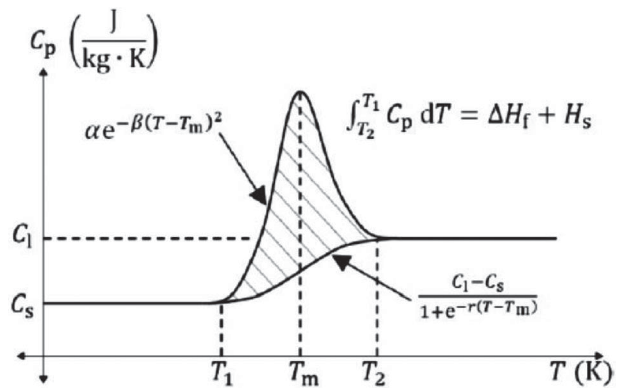

Figure 3. Approximation of specific heat capacity for phase change simulation.

similar to a sharp spike. There are numerous researchers who used Multiphysics simulation and numerical modelling before working on the experiments (Khamil et al. 2021; Venkatesan and Venkata Ramanan 2022). In modelling work using COMSOL by (Kheirabadi and Groulx 2014), the specific heat capacity values of a phase change material (PCM) were replaced with a smooth curve, as shown in Figure 3.

This curve includes two parts: a sigmoid curve that shows how the heat capacity changes from solid to liquid and a bell-shaped curve (Gaussian) representing how heat capacity increases during the phase change. To ensure accuracy, a critical condition: the integral (a mathematical concept) of the heat capacity within a specific temperature range must equal the combined energy needed for the material to change phases. Additionally, the heat capacity values before and after this temperature range must match the heat capacities of the solid and liquid forms of the material. The resulting heat capacity of a material undergoing a phase change using Equation 3.

$$C_P = C_S + \frac{C1 - C_S}{1 + e^{-r(T-T_m)}} + \alpha e^{\beta(T-T_m)^2} \quad (3)$$

In the context of this study, the coefficients α and β are determined through numerical methods to fulfil specific integral requirements and the value denoted as r is computed following Equation 4.

$$r = \frac{10}{\Delta T} \quad (4)$$

The thermal conductivity of a material that undergoes a phase transition experiences a straightforward shift from one thermal conductivity value to another at the critical melting temperature. To encapsulate this behaviour, a sigmoid function, as illustrated in Equation 5, was employed for modelling purposes.

$$k = k_s - \frac{k_s - k_1}{1 + e^{-r(T-T_m)}} \quad (5)$$

In this context, *ks* and *k* represent the thermal conductivities of the material when it is in solid and liquid states, respectively. Furthermore, the density of the PCM was kept constant, equivalent to its density at the melting temperature, denoted as $\rho_{TM.}$

4.3. Field testing and experimental work

With the results obtained from the simulation, this project proceeds to field testing where multiple experiments are conducted. There are four parts of the experiment for this project which continued one after another.

I. Model without PCM.
II. Model with PCM.
III. Model with PCM and black painted top plate.
IV. Charging Supercapacitor using the model.

Each of these experiments was conducted for three days with five hours committed per day. All of the data collected was

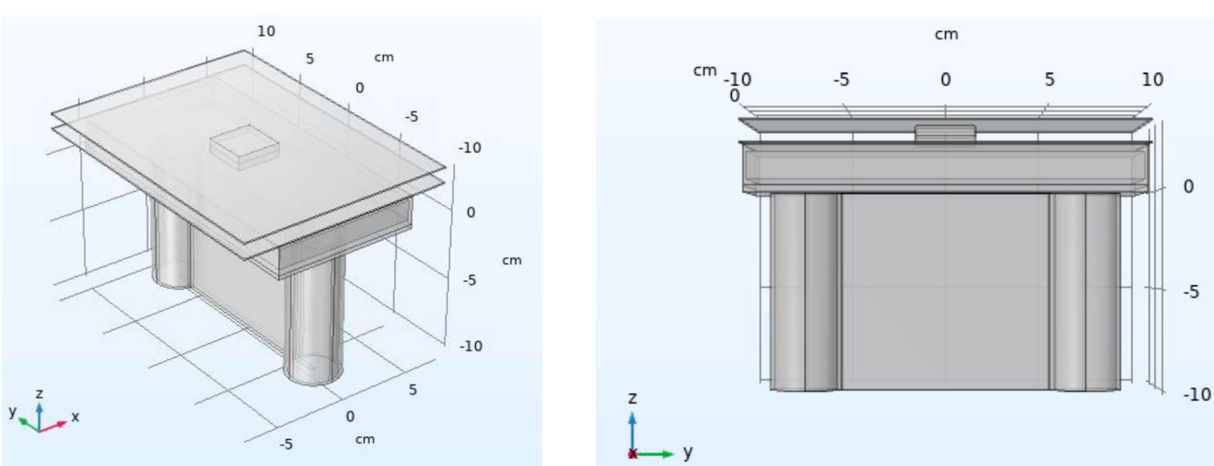

Figure 2. Isometric view of the designed model in COMSOL Multiphysics.

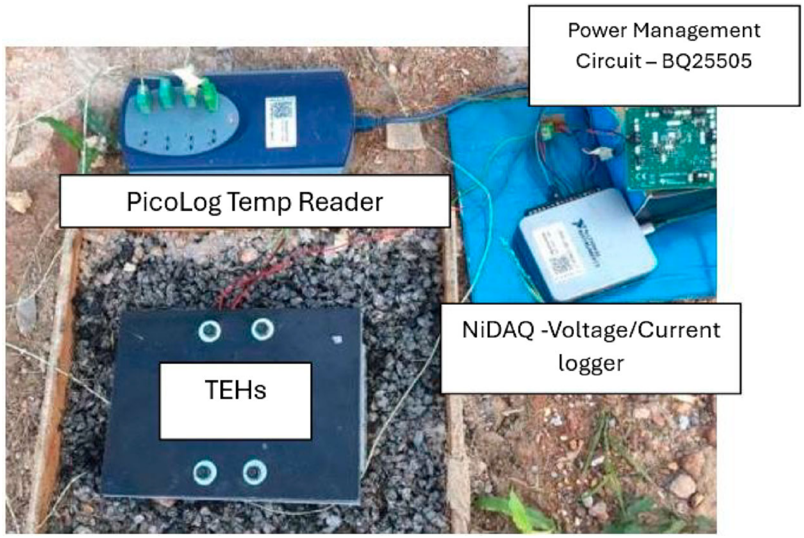

Figure 4. Model set-up for field testing.

stored and analysed. Figure 4 illustrates the setup model for the field testing. Pico TC-08 USB Thermocouple Data Logger, NI Data Acquisition Card USB 6001 and Power Management circuit were used to aid this project for data collection. There were two types of data collected which were the output voltages from the TEG denoted as open circuit voltage, VOC and the temperature of this prototype. Power management circuits provide a boosted output voltage - VBOOST (from the thermoelectric generator) to maximise power extraction for efficient energy harvesting applications.

5. Results and discussions

5.1. Finite element analysis results

For this project, the simulations were focused on the temperature difference between the top plate (hot side of the TEG) and the bottom plate (cold side of the TEG). The comparisons for both of the simulations can be referred to Table 3. From the table, it was found that with PCM, the temperature differences were greater compared to the absence of the PCM. This can be related to the theory (refer to Equation 2), where PCM can act as energy storage and provide better temperature differences as portrayed in Figure 5. The simulation of heat transfers shows that after 5 h, the highest temperature for the top plate which is supposed to be exposed to solar radiation can be around 50–60°C. For this project, the simulations were focused on the temperature difference between the top plate (hot side of the TEG) and the bottom plate (cold side of the TEG). The comparisons between both simulations can be referred to in Table 3.

Table 3. Temperature variation for the simulation of the TEHs with and without PCM.

	PCM	Asphalt (°C)	Middle plate (°C)	Bottom plate (°C)	Top Plate (°C)	DT (°C)
Min	With	24.41	24.34	24.40	24.40	2
	Without	28.76	26.45	25.22	26.58	2
Max	With	58.43	26.54	32.57	63.27	31.74
	Without	58.43	29.94	38.11	60.69	22.58
Avg.	With	54.17	25.24	31.74	58.93	27.19
	Without	53.96	27.98	27.41	58.40	22.56

Table 3 presents comprehensive comparative results for both simulation scenarios. When compared to scenarios without the PCM, analysis of the data from Table 3 shows that temperature differentials are notably increased when PCM is present. The top plate, which is purposefully exposed to direct solar radiation, reaches a peak temperature of between 50 and −60°C after five hours, according to the heat transfer simulations used in this study. The simulation work done for this research project focused primarily on examining the temperature difference between the top plate, which represents the hot side of the thermoelectric generator and the bottom plate, which represents the cold side of the TEG. This observation can be attributed to the theoretical foundation, as delineated in Equation 2, wherein phase change material (PCM) is recognised for its capacity to serve as an energy reservoir, thereby contributing to the generation of more pronounced temperature differentials.

5.2. Field experiment results

This study employed a four-phase sequential experimental design. In the first phase, the model's performance was evaluated without the inclusion of a phase change material (PCM). Subsequently, the model with PCM was examined before the application of black paint to the upper plate. The selection of the optimal design was based on its efficacy in charging a supercapacitor. The experiment was conducted during April–May, which coincides with the peak temperature season in Malaysia.

5.2.1. Incorporating phase change material (PCM)

5.2.1.1. Without PCM. In Figure 6, D1, D2 and D3 represent the experimental days, corresponding to Day 1, Day 2 and Day 3, respectively. Similarly, Figure 7 shows DT_D1, DT_D2 and DT_D3 which correspond to the temperature difference of the experiment days. As seen, the highest VOC and VBOOST are 0.39 and 1.28 V, respectively, on Day 2 and Day 3. Concurrently, the highest DT is 14.39˚C on the third day. It can be seen the trends of all three days are similar. Figure 7 illustrates a temporal trend

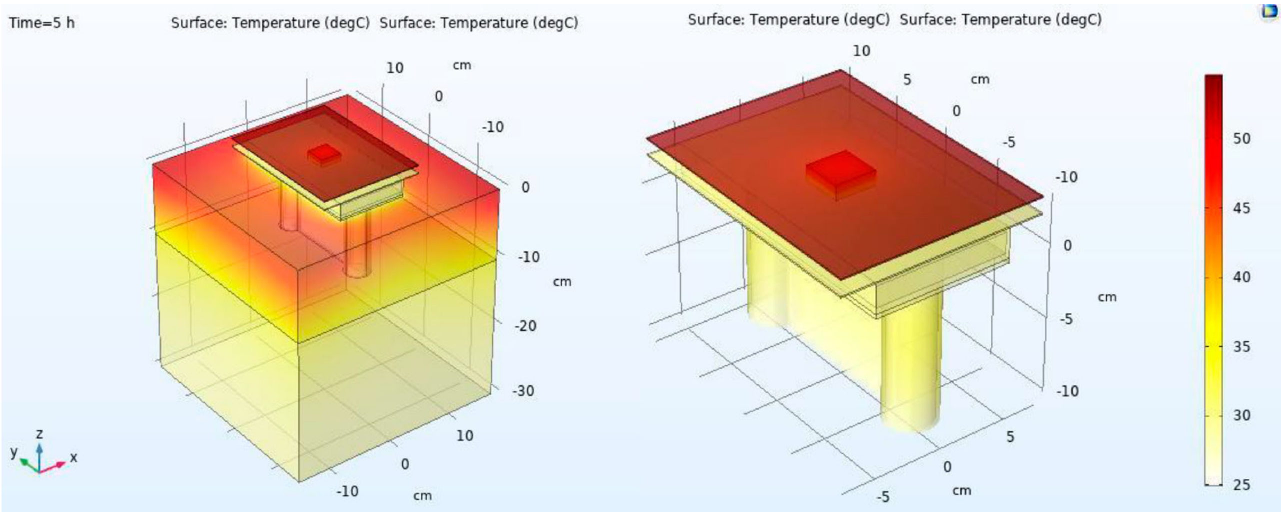

Figure 5. Finite element analysis (FEA) simulation results for TEHs.

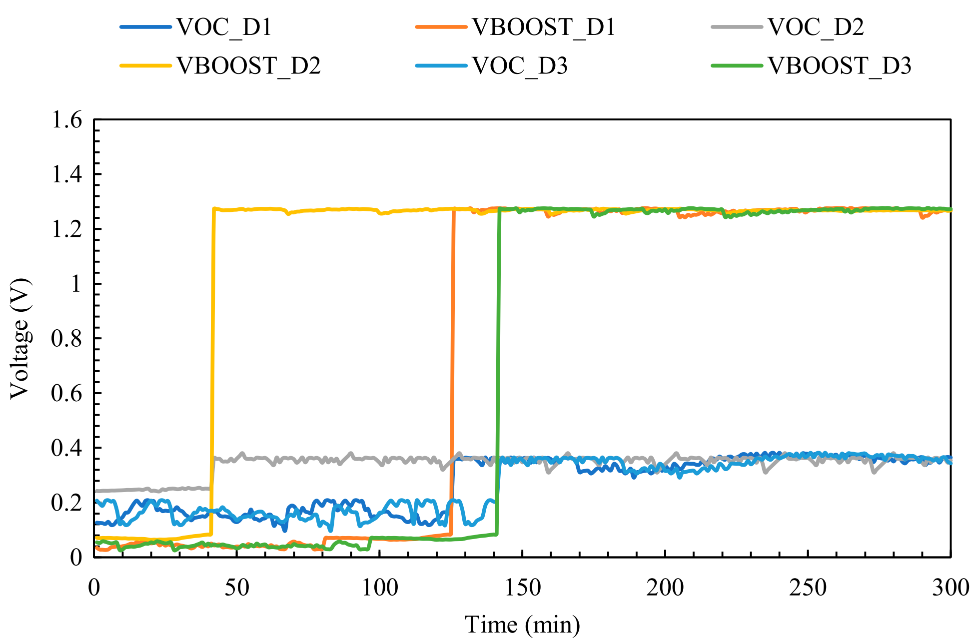

Figure 6. Comparison of open circuit voltage and boosted voltage in TEHs without PCM.

in the DT across the TEHs for 5 hours. Notably, DT appears to begin at a higher value and subsequently decrease throughout the day. This observation suggests a potential correlation with ambient temperature, which may decline as the day progresses, reaching a minimum of around 5–6 pm (Benrazavi et al. 2016). Consequently, the decreasing ambient temperature could be influencing the DT experienced by the TEHs.

5.2.1.2. With PCM. Figures 8 and 9 show that the highest recorded VOC and VBOOST were 1.49 and 3.3 V, respectively, on Day 2 and Day 3. Simultaneously, the most prominent DT recorded was 42.22°C on the second day. Hence, it gives a significant of increase 27.91°C from the previous experiment which demonstrates a significant increase when compared to the model lacking PCM.

5.2.2. Black-painted top plate

Figures 10 and 11 depict the DT across TEHs with PCM and a black-painted top plate for 5 h. The top plate was painted black to further explore this model's characteristics, by exposing it to solar radiation. By referring to Figures 10 and 11, it becomes apparent that the highest VOC and VBOOST values were 1.29 and 3.33 V, respectively, on Day 2 and Day 3. Concurrently, the most substantial DT was recorded as 43.22°C on the third day. The results demonstrated a threefold increase compared to TEHs without PCM and an unpainted top plate.

The application of black spray paint to the upper plate is shown to effectively maintain heat throughout the experiment, in accordance with Stefan's Law, Equation 6.

$$Q = \varepsilon\sigma(T_a^4 - T_b^4) \quad (6)$$

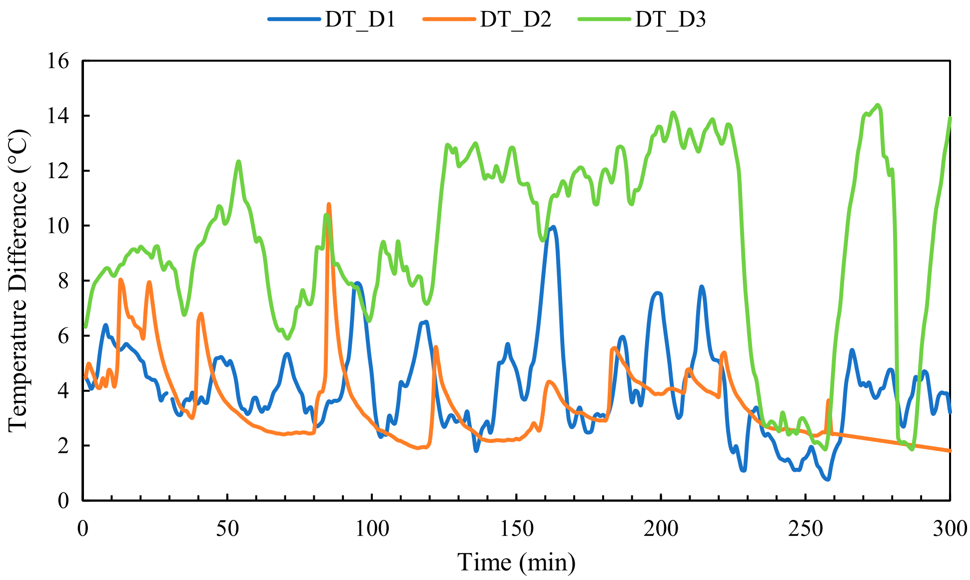

Figure 7. Temporal variation of DT in TEHs without PCM.

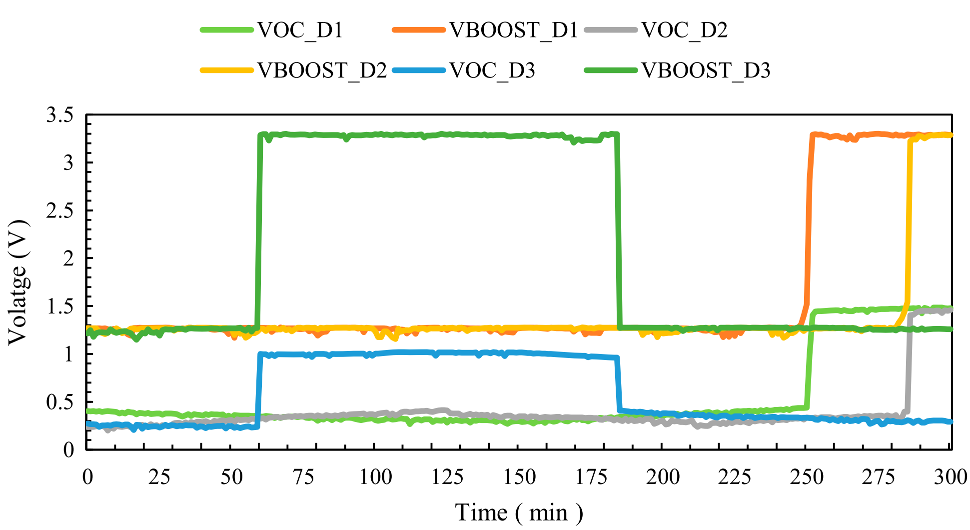

Figure 8. Comparison of open circuit voltage and boosted voltage in TEHs with PCM.

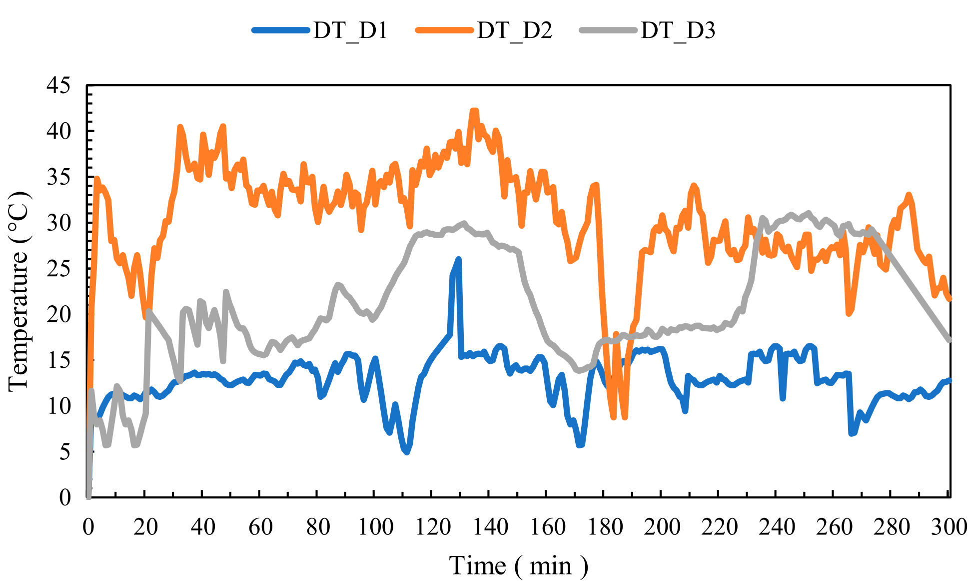

Figure 9. Temporal Variation of DT in TEHs with PCM.

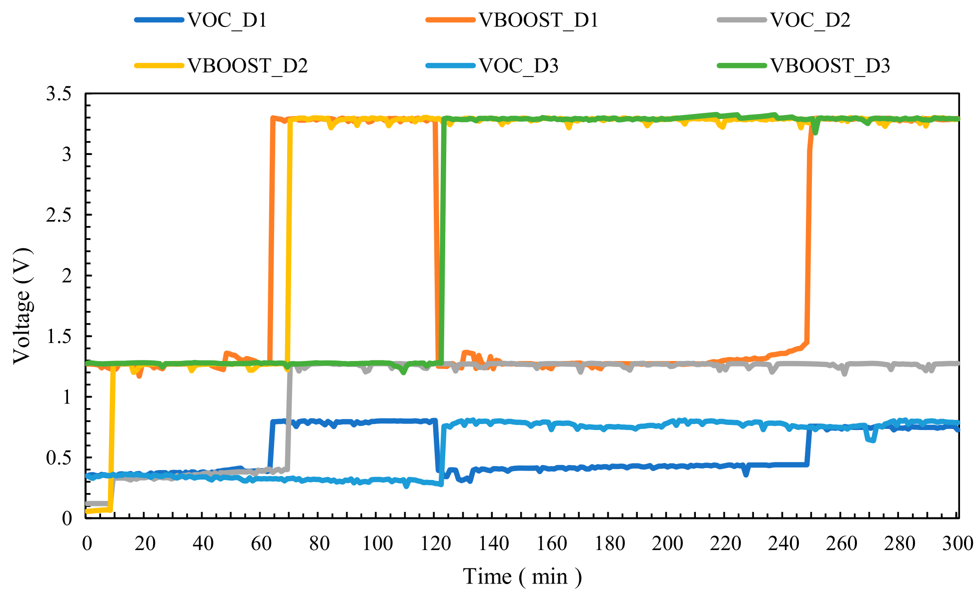

Figure 10. Comparison of open circuit voltage, boosted voltage, in TEHs with PCM and black painted top plate.

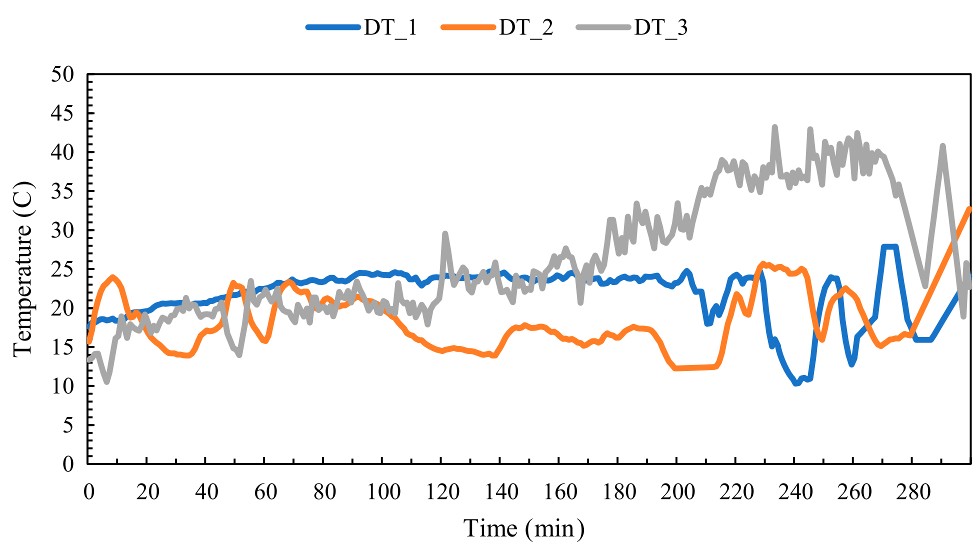

Figure 11. Temperature difference variation for TEHs with PCM and black top plate.

This law stipulates that black surfaces possess enhanced heat absorption and retention properties when compared to non-black surfaces. In this equation, Q represents heat flux, ϵ denotes the emissivity coefficient, σ represents the Stefan–Boltzmann constant and T signifies the absolute temperature in Kelvin. The emissivity value for black paint is noted as 0.93 compared to 0.09 for commercial Aluminium Sheets (Engineering ToolBox 2003). In simpler terms, black surfaces radiate heat away more effectively and efficiently than non-black surfaces at the same temperature. Considering the use of PCM for subterranean cooling retention and the implementation of a black-painted upper plate for enhanced heat retention in the area exposed to solar radiation, the TEHs featuring PCM and a black-painted upper plate were chosen to proceed with testing the charging capabilities of the novel system.

5.2.3. Charging supercapacitor

The model with PCM and black painted top was selected to charge two 2.5 V supercapacitors connected in series. The charging duration of this model was measured for 5 h to determine the time required to fully charge the supercapacitors. According to Figure 12, the maximum values of VOC and VBOOST were 1.28 and 3.34 V, respectively. The supercapacitor reached a voltage of 4.17 V.

The maximum attainable DT, as observed in Figure 13 in the present experiment, reached 34.33˚C, while the experiment yielded an average temperature of 19.98°C. The comprehensive charging duration for supercapacitors in this model was 2.6 h. In contrast, the study by (Haji Tugiman et al. 2023; Khamil et al. 2021) did not incorporate PCM in their methodology, resulting in a prolonged supercapacitor charging time of 3.5 h.

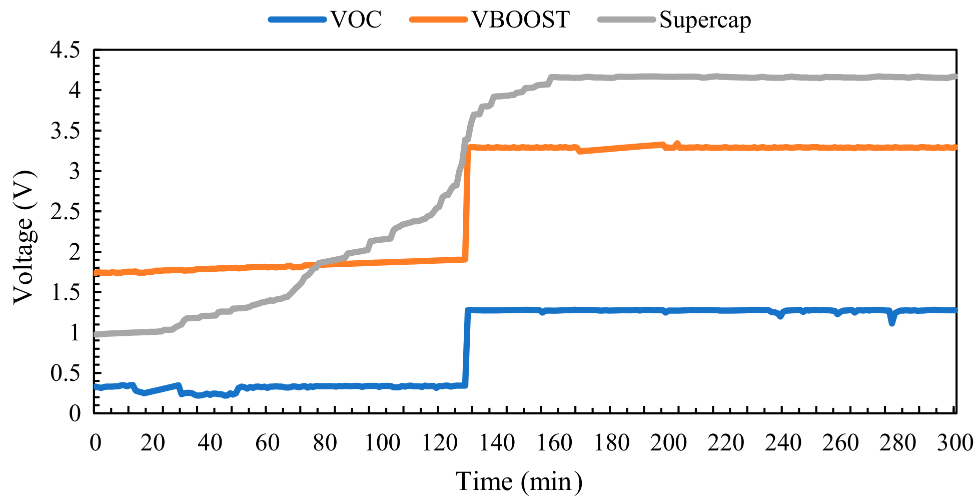

Figure 12. Open circuit voltage from TEG and boosted voltage from MPPC for the TEHs with PCM and black painted top plate when charging the supercapacitor.

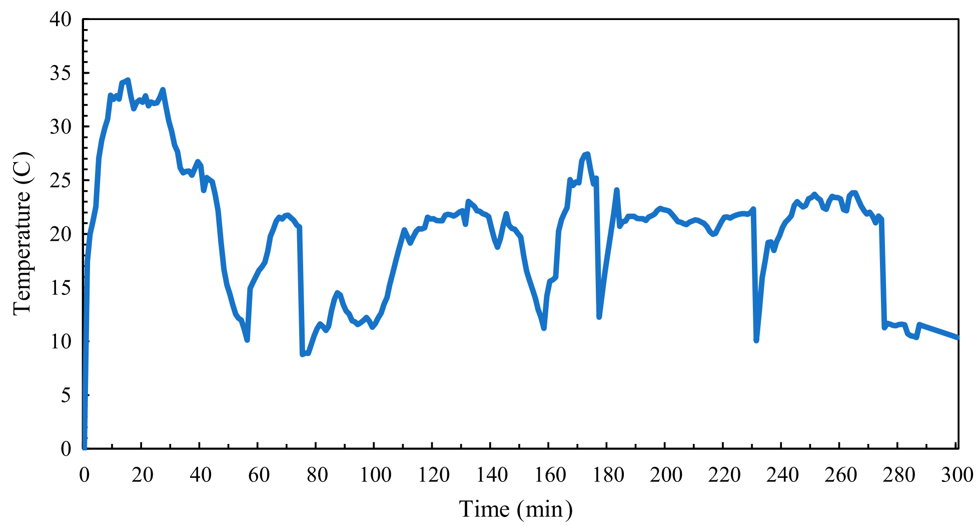

Figure 13. Influence of PCM and Black Paint on DT in TEHs while charging a supercapacitor.

This investigation has effectively enhanced the charging rate by three times. This enhancement is attributed to the incorporation of PCM as an energy storage medium, as mentioned in Equation (2), and the application of a top plate coating in Equation 6. These modifications have contributed to the amelioration of temperature differentials, thereby leading to an augmentation in the output voltage derived from the TEG which contributed to Equation 1. Using MATLAB/Simulink simulation (Khamil et al. 2020b), the thermoelectric energy harvesting efficiency calculated with given maximum hot and cold side temperatures is only around 12.05%.

6. Conclusion

The Thermoelectric Energy Harvesting system (TEHs) from asphalt pavement is a promising energy source. Asphalt pavements have a higher rate of heat absorption from the sunlight and thus can utilise that by harvesting thermal energy to produce clean electric energy. The improvement of TEG energy harvesting design model efficiency is important to get a stable voltage output.

A comprehensive analysis using finite element analysis (FEA) through COMSOL Multiphysics software and validated the findings with experimental data. The study explored the effects of various factors, including the presence of PCM, the length of the rod structure and the emissivity of the top plate, on heat transfer and temperature difference. Based on the simulation results, having PCM in the design increases the maximum DT by 40.5%. Experimentally, the inclusion of PCM significantly improved the system's performance, achieving a maximum temperature difference (ΔT) of 42.22°C compared to 14.391°C without PCM. The charging rate for supercapacitors was also enhanced by threefold, with a full charge achieved in 2.6 h. This further enhances the system by the influence of emissivity of the top plate which is painted black which improved the DT when compared with previous work. As a result, this concludes that the TEHs system is a promising approach for harvesting clean energy from asphalt pavements. The authors acknowledge the support of their institutions and funding sources for the research. The document also includes references to previous studies and contributions to the field.

Overall, the study demonstrates the potential of PCM-enhanced TEHs for sustainable energy harvesting from asphalt pavements, offering a method to capture and store thermal energy efficiently.

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