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Analysis of Emissivity Effects on Subterranean Heat Transfer for Thermoelectric Power Generation

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Abstract

This research explores the impact of heat sink dimensions and surface emissivity on thermoelectric energy harvesting (TEH) system performance. Finite element models were developed to simulate a TEH system embedded in pavement. The model was partially submerged into the pavement. Only the top plate is exposed at the same level as the asphalt pavement surface to allow the harvest of thermal energy from the sunlight. The bottom plate is connected to the heat sink structure to achieve a temperature difference (ΔT) between the top and bottom plate. Generally, higher ΔT will generate a higher thermoelectric output voltage. Hence, an analysis of the heat sink's length and the influence of emissivity in heat transfer is conducted to improve the output of temperature difference. The study focused on optimizing heat sink length and emissivity to maximize temperature difference (ΔT) between the hot and cold sides of the thermoelectric generator. Simulation results guided the construction of a prototype, which was subsequently field-tested. Experimental data confirmed a significant 133% enhancement in ΔT compared to previous studies, validating the positive influence of heat sink design parameters on TEH system output.

1. Introduction

For long-term environmental sustainability, renewable energy sources must be secured. The depletion of fossil fuels and the negative consequences of their burning need the development of alternative green energy sources. The ability to generate green electrical energy by harvesting energy from asphalt pavements has shown promising results [1]. One of the significant visible elements of civil engineering infrastructure is asphalt pavement. They cover nearly 6 million lane-km in the United States alone. Several recent research endeavors have focused on tapping into the energy contained in them. Some of these attempts include gathering mechanical energy influenced by traffic, for example, utilizing piezoelectric technology and mechanical systems, while others involve directly harvesting energy from temperature difference (ΔT) in the asphalt pavement. Capturing unwanted energy and transforming it into usable forms, such as electric energy, can result in sustainable transportation infrastructure systems that lessen society's reliance on fossil fuels and, in the end, turn pavements into new renewable energy sources. The gathered energy might be used to power pavement health monitoring equipment, roadside or traffic lights, infrastructure sensors, and communication systems, among other things. Therefore, there is a lot of interest in and work put into researching how to successfully collect energy from pavements [2–5] .

Numerous studies have lately been performed to evaluate the potential of generating green energy from highways. One source of wasted energy is the induced vibration and strains caused by passing automobiles on the pavement surface. Piezoelectric transducers were created to recover surplus energy from pavement vibrations [6], [7]. Placing thermoelectric generators (TEGs) into the pavement structure is another method of harvesting thermal energy from asphalt pavement. The temperature differential created by solar radiation received by the pavement surface can be turned into electric energy with TEG. The Seebeck effect allows TEG to convert heat into electrical energy [8–11]. TEGs provide several advantages, including ecologically friendly energy, the absence of moving mechanical components, and reduced maintenance needs [12, 26]. Generally, the temperature gradients between the hot and cold sides influence the quantity of power produced by TEGs. TEG harvesting designs can take advantage of this thermal gradient and sustain it over time [13]. For example, providing an effective cooling mechanism for supplying low temperature at the TEG's cold side will significantly impact the system's performance [14]. Based in all the literature search, the studies summarized into three themes:

Technology Performance and Optimization [4],[15]: A central theme is the empirical evaluation of technology. Jiang et al. [4] provide a concrete, quantitative benchmark (0.4V at ΔT=15°C), establishing a performance baseline. Khamil et al. [16] build on this by directly comparing Thermoelectric Coolers (TECs) and Thermoelectric Generators (TEGs), introducing a crucial finding that TECs may outperform TEGs in specific (lower temperature) environments. This comparative analysis is a significant contribution to the field.

System Configuration and Feasibility [5, 12, 25]: These studies zoom out from the module-level to the system-level. Wang et al. [5] focus on the engineering configurations within the asphalt pavement itself, while Gholikhani et al. [17] provide a broader economic and practical feasibility analysis, concluding that the technology is advanced enough for "self-sustaining roadside power." This moves the discussion from "if it works" to "how to implement it effectively."

Fundamental Heat Transfer Principles [18], [19]: These entries are critical as they address the underlying physics governing the system's efficiency. Acikgoz et al. [18] study radiative heat transfer, a key mechanism for heat gain or loss in pavements. Jalaal et al. [19] delve into the complex temperature dependence of surface emissivity—a material property directly influencing radiative heat transfer. Their findings which shown a slightly increased temperature and prominent improvement in temperature readings are fundamental to optimizing the heat source for the thermoelectric modules.

Hence, in these study aims to augment the electrical output of a thermoelectric energy harvester. This will be achieved by engineering a rod-based structure to improve heat flow, with its performance evaluated across a range of geometric parameters. A key focus is analyzing the role of surface emissivity in radiative heat transfer to maximize the temperature differential between the generator's hot and cold plates. The project will employ finite element analysis (FEA) using COMSOL Multiphysics to model and simulate these thermal phenomena.

Symbol	Description	Unit
α	absorptivity	-
h_{conv}	convection coefficient	W
ε	Emissivity	-
σ	Stefan-Boltzmann constant	$W/m^2.K^4$
T	Absoulte Temperature	K
k	Thermal Conductivity	$W/m.K$
A	Surface Area	m^2
ΔT	Temperature Difference	°C
q	Heat emission/conduction/radiation	W

2. Hardware and Software Design of The System

2.1 Finite Element Analysis (FEA) Modeling

The geometry for the 3D FEA model needs to accurately represent all components mentioned to ensure fidelity in heat transfer analysis and there are plenty of software that able to help to simulated the 3D modelling [20], [21], [29].

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Pavement Domain: This consists of two primary, large-volume layers: the top Asphalt Layer and the underlying Soil Layer (subgrade). These domains must be large enough horizontally and vertically to ensure that external boundary conditions do not artificially influence the TEG results.

TEHs Internal Structure: This precisely defined sub-assembly includes:

- TEG Module: The central component, modelled as a thin cuboid, requiring distinct material properties and physics coupling (if the electrical output is solved).
- Top (Hot Side) and Bottom (Cold Side) Aluminum Plates: Plates of defined thickness and area, sandwiching the TEG.
- Three Aluminum Rods: Cylindrical heat sinks attached to the bottom plate and submerged into the asphalt/soil. These components are geometrically distinct to apply the specific "black painted" surface condition.

Material Assignment: Each domain (Asphalt, Soil, Aluminum Plates, Aluminum Rods, TEG) must be assigned its specific in Table 1 for transient analysis [20]. For this project, COMSOL were used to designed Thermoelectric Energy Harvesting system (TEHs) for the simulation, as shown in Fig. 1.

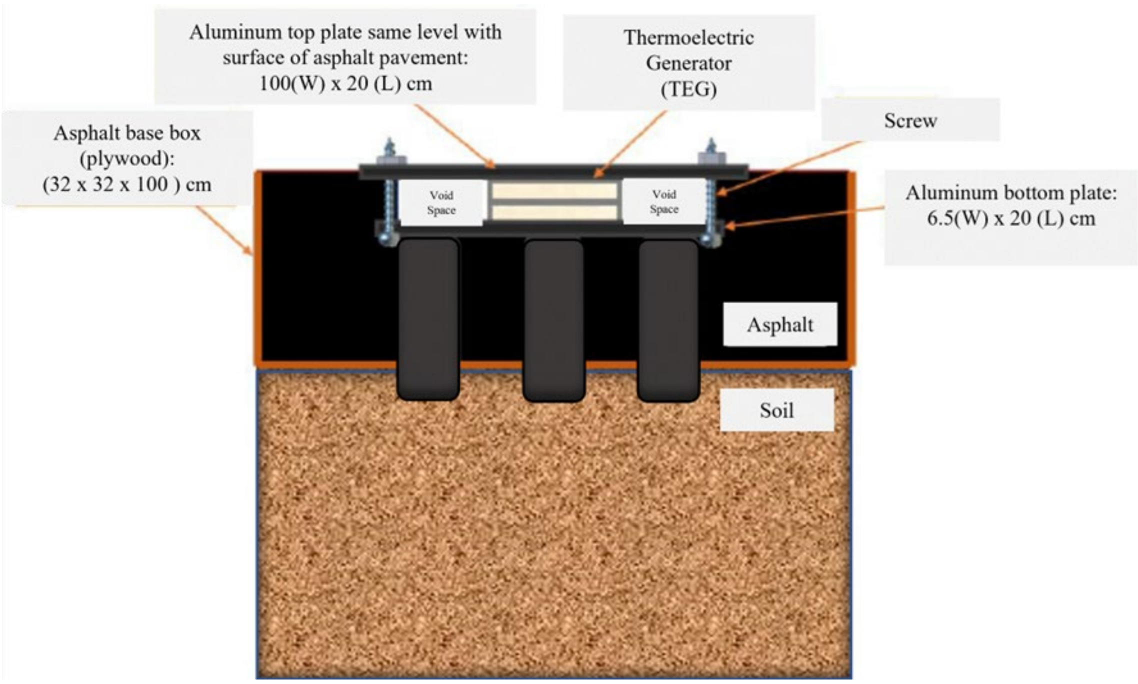

Fig. 1 *Cross Section view of TEHs model*

This model consists of a TEG module between two aluminum plates, the top (hot side) and bottom (cold side) plates. The bottom part was submerged into the asphalt with three rods. A soil layer below the asphalt layer replicates the asphalt pavement design. Table 1 shows the material used and its properties in the simulation, and Table 2 shows the size dimension for the models used in this simulation design as displayed in Fig. 2.

Given the complexity and varying scales of the geometry—from the bulk pavement down to the thin TEG module—the *Mesh Strategy* would employ an adaptive approach, utilizing a fine, highly structured mesh in critical regions like the TEG and the rod surfaces to accurately capture high thermal gradients, while transitioning to a coarser tetrahedral mesh in the far-field bulk asphalt and soil domains to manage computational cost.

The **Boundary and Initial Conditions** are crucial for simulating the realistic heat transfer environment. The **Initial Condition** at *t = 0* would set the entire model to a uniform starting temperature, typically a mean ground temperature. The top surface of the asphalt receives the most complex boundary conditions:

Solar Flux Profile is modelled as a time-dependent heat flux input,

$$q_{solar} = \alpha . I(t) \quad (1)$$

where *I(t)* is the transient solar irradiance and α is assumed high for dark asphalt. Simultaneously, the top surface loses heat via **Convection**:

$$q_{conv} = h_{conv}(T_{surface} - T_{ambient}) \quad (2)$$

These requiring time-dependent functions for both the ambient temperature, $T_{ambient}$ *(t)* and an assumed or calculated convection coefficient h_{conv}. Finally, surface **Radiative Model** loss is accounted for via the Stefan-Boltzmann law using the high emissivity of the asphalt surface:

$$q_{rad} = \varepsilon\sigma(T^4{}_{surface} - T^4{}_{ambient}) \quad (3)$$

For the subterranean structure, the "black painted" rod surfaces are assigned a high emissivity for the internal **Radiative Model**, even though the heat transfer to the surrounding soil is primarily dominated by **conduction** as stated, which is governed by Fourier's law:

$$q_{cond} \propto kA\ (\Delta T/L) \quad (4)$$

Which emphasizing the importance of k in the aluminum rods and the surrounding asphalt/soil materials. The external side and bottom boundaries of the overall soil domain would be typically treated as **thermal insulation** to simulate an infinitely large environment. These models were built to analyze heat sink's length and emissivity's influence on heat transfer [18], [22]. *Equation* (5) represents heat emission, q_{em}, from an object with a surface area of A and a temperature of T.

$$q_{em} = \varepsilon\sigma A T^4 \quad (5)$$

Table 1 *Material properties for this model design* [23]

Material	Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)	Density (kg/m³)	Electrical Conductivity (S/m)
Aluminum	900	222	2.7	3.774e7
Alumina	896	138	2820	3.030e7
Soil	800	1.59	1430	-
Asphalt	900	0.8	2.24	-
Polyethylene Foam	374	0.022	100	-

Table 2 *The dimension of the model*

Type	Dimension (m)
Cylindrical Rod	Radius (1.59) Height (1)
Top Plate	Design (1 x 2 x 0.03)
Bottom Plate	0.65 x 2 x 0.03
TEG Module	0.3 x 0.3 x 0.045
Asphalt	3.2 x 3.2 x 1
Soil	3.2 x 3.2 x 1

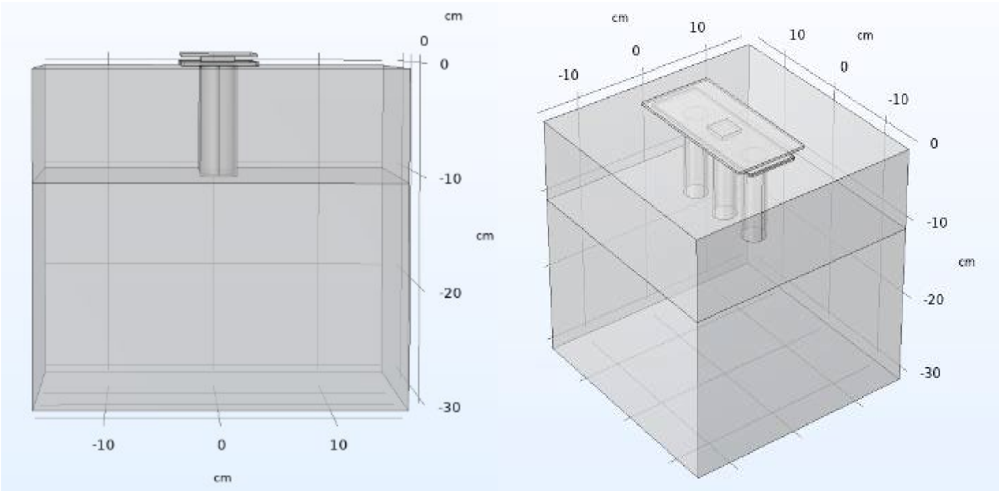

Fig. 2 *TEG module on asphalt pavement model*

The research will warrant a better understanding of the emissivity effect in subterranean level with the use of shorter rods than the one reported in the previous study [15].

2.2 Experimental Setup

For the experimental setup, the main structure of the model was built, as shown in Fig.1. To ensure a close contact for the TEG, the top and bottom plate holes are drilled and tighten with screws as presented in Fig.3.

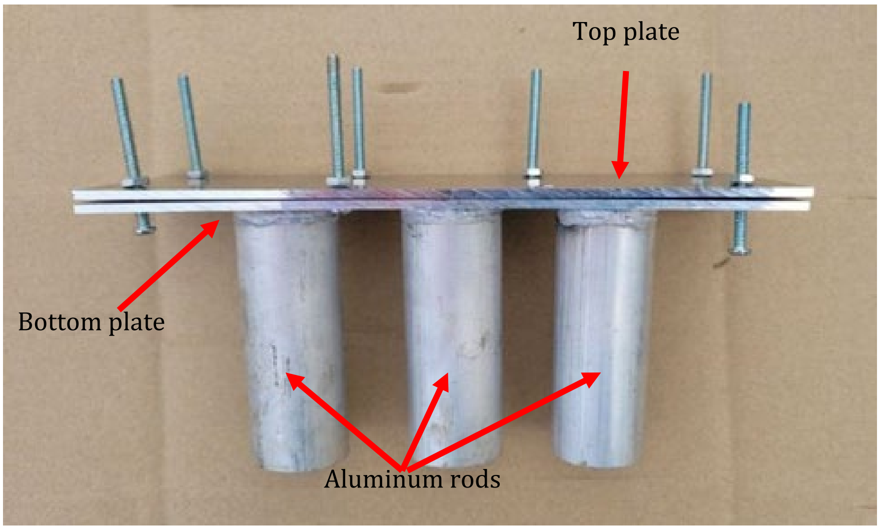

Fig. 3 *The main structure of the design model without TEGs*

A plywood simulation box with the dimension of (32 x 32 x 10) cm was built and filled with asphalt. In the middle of the box, the prototype model is submerged with the top plate adjusted to be of the same level as the asphalt, as seen in Fig. 4. This simulation box's purpose is to replicate the asphalt pavement condition.

Two TEGs were used in this project and were connected in a cascaded arrangement as used by previous studies by Khamil et al. [15],[24]. The cascaded method will increase the voltage output because the thickness of the TEG will influence the voltage parameter. In between the top plate and bottom plate, TEG was placed and screwed to make a close contact with the plates [16]. The glass fibre K- type thermocouple was attached to the top plate, bottom plate, asphalt, and rods so that measurement of temperature can be done on the surfaces of the structure, the soil and the ambient. Then, the asphalt box is submerged into the soil and left for one day for the soil to set. As can see in Fig. 4, the top plate is exposed to sunlight for harvesting energy from the sunlight, and the bottom plate is submerged with a cooling element of cylindrical rod. The cooling element takes advantage of subterranean cooling to distribute the heat and cool the cold side of the TEG. This setup will lead to the temperature difference between both plates.

Fig. 4 *The main structure was placed in the middle and filled with asphalt at the same level with top plate*

3. Results

3.1 FEA's Result

Designated computational models with the dimension of the top plate of 100 x 200 mm are simulated. There are two designs: one with black paint and another one is without black paint. Both designs were simulated with 10 cm length of rod. Design with the highest temperature differences will be chosen for field testing and compare with 30 cm length of rod in previous study [15] to study the analysis of heat sink's length. The black painted and non-painted model were investigated to study the influence of emissivity. The heat properties defined in this simulation setup are according to the Malaysia's ambient temperature. The period for this simulation was set for 5 hours. The thickness of the asphalt layer is 10 cm, a dimension defined according to the Malaysian Public Works Department's standard specification for road works. Then, a 20cm soil layer was designed below the asphalt layer. The dimensions were defined to follow the real dimension in the experiment. So, it will help this simulation obtain closer output results with real conditions. The simulations were tested between non-painted and painted rods (high emissivity), and the results are presented in Table 3, where the temperature points are taken according to the placement of the temperature sensors in the real experimental setup and are denoted in the table as Asphalt, Top plate, Bottom rod, and ΔT.

Table 3 *FEA's result between non-painted with painted rods*

Item	Point of temperature	Max (°C)	Min (°C)	Average (°C)
Non – Painted	Asphalt	67.92	33.1	50.51
(ε = 0.2)	Top Plate	41.96	26.88	33.42
	Bottom Rod	26.87	26.85	26.86
	ΔT	15.09	6.03	10.56
Painted	Asphalt	75.29	26.94	69.11
(ε = 0.94)	Top Plate	56.49	24.41	51.97
	Bottom Rod	28.47	24.4	27.96
	ΔT	28.02	6.01	17.02

The high emissivity of ε = 0.94 is assigned to the asphalt surface and the black-painted aluminum rods to maximize radiative heat transfer (emission/absorption), while the low emissivity of ε= 0.2 is used for bare/oxidized aluminum plates where heat transfer is dominated by conduction. Thus, presented in Table 3, buried painted rods have the highest ΔT compared to non-painted with an average of 24°C temperature difference. The maximum ΔT shows an immense increase of 60% between the non-painted and painted rods.

As seen in Fig. 5, the top plate is fully heated from the solar while the painted rods submerged in asphalt still maintain an average of 27.92°C. Hence, this 10 cm long painted rod model proves the role of radiation and conduction as presented by the emissivity theory of Stefan-Boltzmann law and the conduction theory of Fourier's law, as shown earlier in *Equations* (4) and (5). The heat is received by the rod from the top surface, increasing the rod's temperature. Painted rod offers better ability to absorb and emit radiation energy. As the temperature of the rod increases, emission increases too. This led to an increased release of heat to the soil. The quick action of heat absorption and released by the heat sink (the rod) encourages heat transfer for the process. Based on *Equation* (5), the cold rod will encourage heat conduction between the top and the bottom of the rod as well as between the rod and the soil. In Khamil et al. [24], the experiment uses a rod that was 30 cm long [15]. The results gave an average ΔT of 7.44°C. In comparison, this research shows that a 10 cm long painted rod is able to generate a higher temperature difference with an average ΔT of 24.02°C. This is consistent with *Equation* (4) where shorter rod reduces the heat resistance and therefore better heat transfer can be achieved. With a shorter length, the heat can disperse much faster, increasing the ΔT. Hence, the 10 cm painted rod will be tested in field testing.

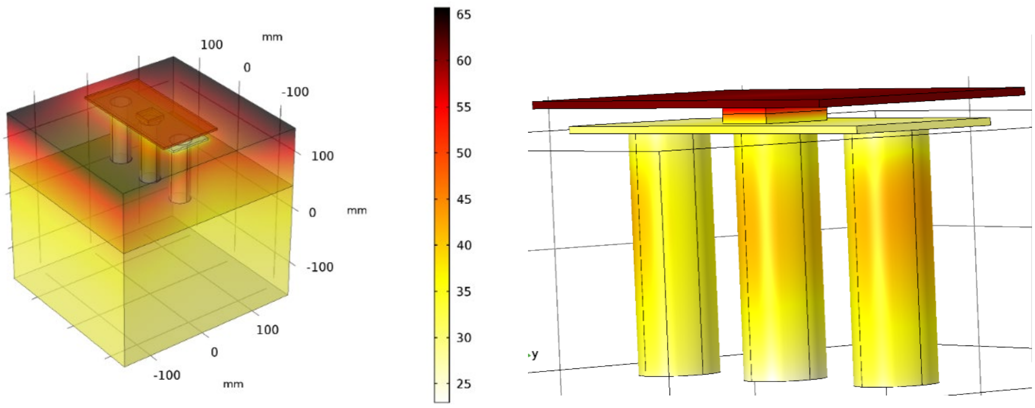

Fig. 5 *Finite Element Analysis result for painted rods*

3.2 Field Testing Results

The experimental results were collected for 5 hours or 18000 seconds (12 pm to 5 pm GMT+8), both temperature and voltage output were measured simultaneously. Picolog data logging software is used for temperature data collection to obtain the results. DAQExpress companion software is used for voltage output, and experiments were conducted 3 times to check the output consistency and choose the best data among them.

Table 4 shows the comparison between the results of simulation and experiment as shown in Fig. 6 and Fig. 7. There is some error in the experiment because of the environmental and the physical factors, but the discrepancy for the average results is still less than 20%.

Table 4 *Comparison between simulation and experimental results for 10cm painted rod*

	Top Plate (°C)			Bottom Rod (°C)			ΔT (°C)		
	Max	Min	Average	Max	Min	Average	Max	Min	Average
Simulation	56.49	24.41	51.97	28.47	24.4	27.96	28.02	6.01	17.02
Experimental	67.53	32.75	45.72	46.85	26.37	32.01	35.85	6.38	13.96
% Error	20%	34%	12%	65%	8%	14%	28%	6%	18%

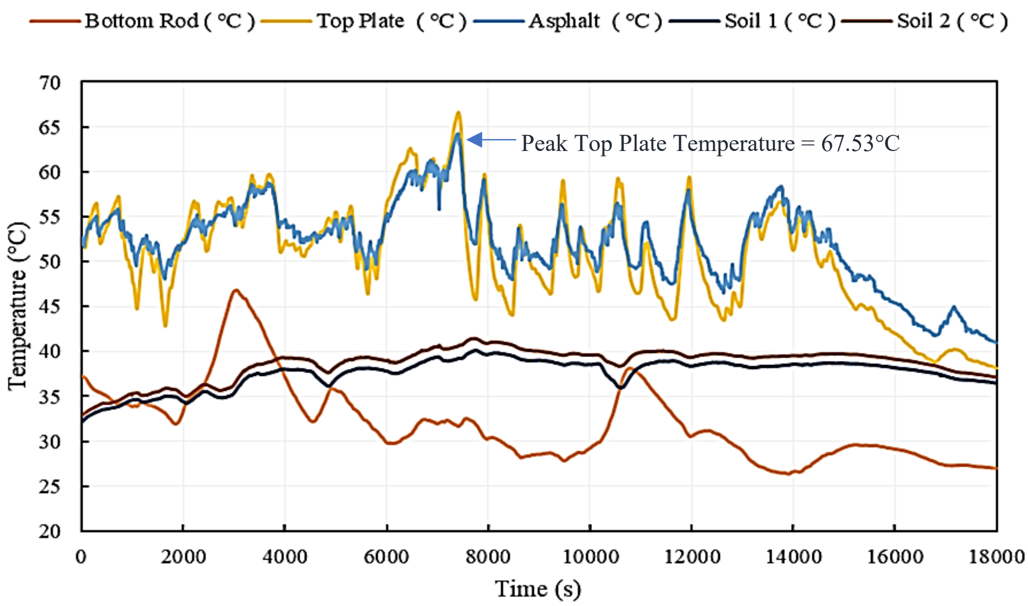

Fig. 6 *Temperature data for 10cm with black painted rods*

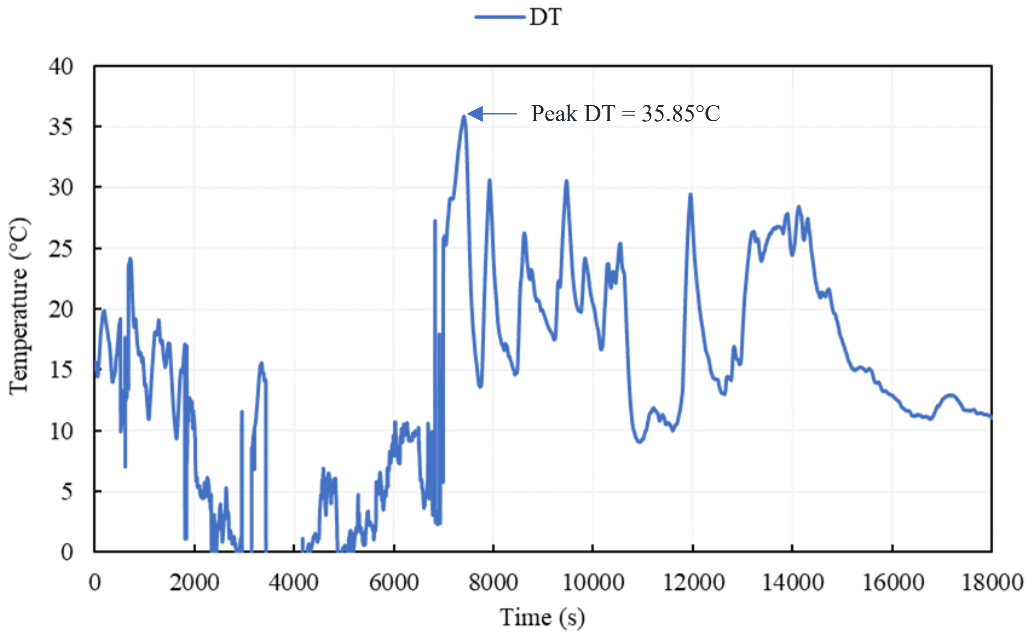

Fig. 7 *Field testing result for temperature difference for 10cm painted rod*

In Fig.6, the comparison tells us that there is a profound thermal damping effect as heat propagates from the exposed surface down into the subsurface where the Top Plate and Asphalt layers, being on or near the exposed surface, exhibit high-amplitude, rapid fluctuations (transients). This indicates they are strongly coupled with the boundary conditions—primarily solar radiation (heating) and convection/radiation to the atmosphere (cooling). While in the subsurface layers; the Soil 1 and Soil 2 layers show significantly lower average temperatures and remarkably stable, low-amplitude profiles. The pavement structure and upper soil layers are acting as a massive thermal buffer or thermal mass.

This contrast demonstrates that the thermal diffusivity of the materials (pavement and soil) severely attenuates the high-frequency temperature swings from the surface, shielding the deeper ground. Hence, the rate of heat conduction is governed by Fourier's Law, which states that the heat flux, q_h is proportional to the temperature gradient, dT/dx.

$$q_h = -k\frac{dT}{dx} \tag{6}$$

A high-amplitude peak in the ΔT indicates a very large temperature difference across the measuring points. Since ΔT is the driving force for heat conduction, this signifies a very high rate of heat conduction (or heat flux) into the asphalt/soil mass at that moment. Essentially, the system is experiencing a rapid influx of energy, moving quickly down the high temperature gradient from the exposed surface layers (Top Plate/Asphalt) to the deeper, cooler layers (Soil). Before t=7000s, the temperatures are erratic and lower (around 45-55°C, suggesting intermittent cloud cover or hazy conditions are periodically blocking the sun. Around t=7000s, the temperature curves sharply rise to their maximum values. This strongly indicates the clouds cleared, allowing the full, direct intensity of solar radiation to impinge upon the surface, thus generating the massive temperature gradient ΔT that drives conduction.

When measured, the open-circuit voltage output from TEG is recorded at 1.6 volts. The voltage output from the TEG is boosted using LTC3105 and able to step up to 5V, which is suitable for any low-power electronic device. Even when there is a voltage drop from TEG, the LTC3105 is able to maintain the output voltage and decrease gradually. According to LTC3105, the board required a minimum of 250 mV from TEG to re-boost the voltage up to 5 volts, as presented in Fig. 8. Through simulation, the user is able to design and choose the right model for the prototype and achieve the desired output.

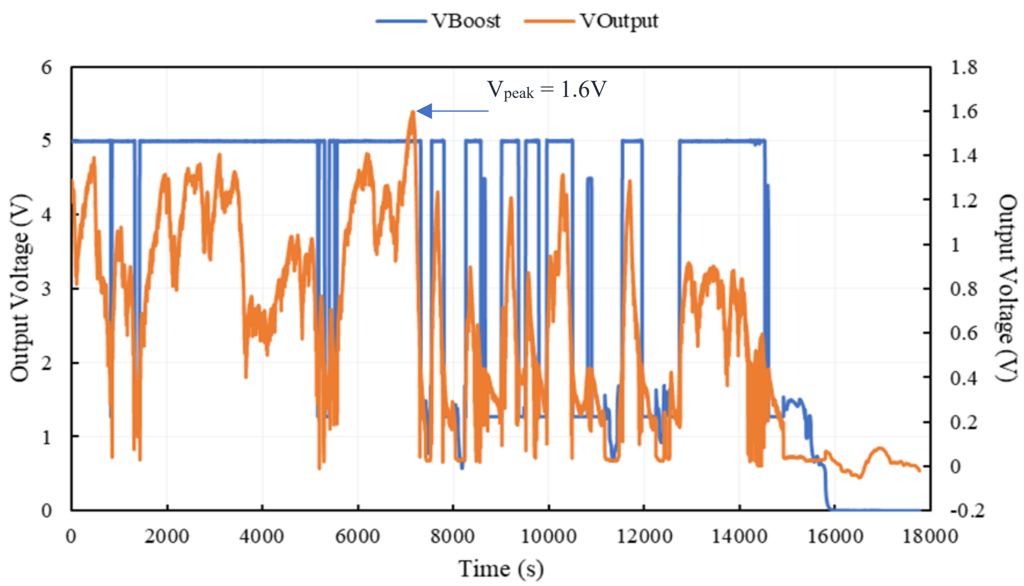

Fig. 8 *Voltage output from TEG AND MPPC for 10cm with black painted*

Based on the result, we can conclude based on previous designs of Thermoelectric Energy Harvesting systems (TEHs) in the [15] [23] [24] [27], highlighting their structural differences, maximum temperature gradients (ΔT), and maximum open-circuit voltage (V_{OC})

Table 5 *Summary of design configurations and its key design features*

Design Configuration	Key Design Features	Temperature Difference (ΔT)	Output Voltage (V_{OC})
Flat Bar [23]	Rectangular subterranean cooling structure	9.89°C	0.296 V
Single Cylindrical Rod (Rod A) [15]	22.23 mm diameter aluminum rod.	8.49°C	0.263 V
Single Cylindrical Rod (Rod B) [15]	25.4 mm diameter aluminum rod.	9.89°C	0.296 V
Single Cylindrical Rod (Rod C) [15]	31.75 mm diameter aluminum rod.	11.34°C	0.436 V
Triple Rod C (Original Plate) [15]	Three 31.75 mm rods; 60 x 200 mm top plate.	13.83°C	0.543 V
Triple Rod C (Large Plate) [15]	Three 31.75 mm rods; 100 x 200 mm top plate.	15.19°C	0.682 V
H-Shape Heat Sink [24] [27]	Aluminum plate welded between two 31.75 mm rods.	23°C	1.02 V
Optimized 10 cm Rod [Current Study]	Shorter length (10 cm) and black-painted surface ε=0.94).	35.85°C	1.6 V

Hence, the Table 5 gives an insight that optimal thermal performance is mostly determined by the geometry and shape factor, with rods showing superior heat transfer capabilities compared to flat bars due to a better surface area to volume ratio, which ensures a uniform distribution of heat. This effectiveness is further maximized with H-shaped rods, where a conduction shape factor S of 1.80 m is achieved, which is much larger than the 0.52 m of single rods. Besides shape, surface area and emissivity are key factors, such as increasing the size of the top plate to enhance the rate of radiation heat transfer according to Stefan-Boltzmann's Law, and applying black paint to enhance emissivity, with $\varepsilon = 0.94$, resulting in a 60% improvement in maximum temperature differential (ΔT). Furthermore, reducing the rod height from 30 cm to 10 cm improves thermal resistance, thereby ensuring quicker heat dissipation into the ground. To harness the energy generated, the systems are connected to a boost converter, such as the LTC3105 and BQ25505, which increases the raw voltage to a stable 5 V for powering wireless devices and lighting cities.

4. Conclusion

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

The first objective of this project is to design a realistic model of TEHs using finite element analysis (COMSOL) for heat transfer analysis. The different sizes of models were designed and simulated. Based on the higher temperature difference (ΔT) output, the best model design has been chosen for the prototype to build experimentally. The simulation method saved time and money when building the prototype experimentally. Secondly, to analyze the effect of the heat sink's length in heat transfer for both simulation and experimental. Thru simulation helped investigate the heat sink's length impact in terms of length. Then, to analyze the influence of emissivity in heat transfer using both simulation and experimental methods. This analysis proved that the influence of emissivity improved the temperature difference (ΔT) when compared with previous work.

As a result, the experiment evaluated the performance of a TEHs focusing on temperature difference and voltage output. Results indicate that a shorter heat sink length yields a higher temperature difference, aligning with simulation data. The TEG, producing an initial 1.6 volts, was successfully boosted to 5 volts using an LTC3105 converter. While experimental and simulated data showed general agreement, discrepancies within a 20% margin were observed due to environmental factors. Overall, the findings support the potential of the TEG system for low-power applications

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The contributions of all authors must be described in the following manner:

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Vikneswaran Gopala Krishnan and Khairun Nisa Khamil;* ***data collection:*** *Vikneswaran Gopala Krishnan;* ***analysis and interpretation of results:*** *Azdiana Md Yusoa, Mohd Faizul Mohd Sabri;* ***draft manuscript preparation:*** *All authors. All authors reviewed the results and approved the final version of the manuscript.*

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