THERMOELECTRIC OUTPUT ENHANCEMENT USING AN ALUMINIUM TUBE AS PCM- BASED STORAGE FOR THERMOELECTRIC ROAD HARVESTING

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

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DEDICATION

This study is wholeheartedly dedicated to my beloved parents, who have been my source of inspiration and gave me strength when thought of giving up, who continually provide their moral, spiritual, emotions and financial supports. To my supervisor who share a lot of advice, knowledge, and encouragement to finish this study. And lastly, I dedicated this thesis to the Almighty God, thank you for the guidance, strength, power of mind, protection and skills and giving a healthy life.

ABSTRACT

Due to the enormous amount of waste heat produced by asphalt pavement, road thermal energy harvesting has gained more attention in recent years. In this project, a thermoelectric energy harvesting system (TEH) that utilized the heat from the surface of asphalt pavement is studied. This thesis aimed to design new TEHs with phase change material (PCM) as cold storage to retain subterranean cooling by simulation and experimentally. The design model consisted of an asphalt base holder to hold the asphalt, a top plate for heating, and a bottom plate for cooling. The top plate is exposed on the asphalt surface to harvest heat from sunlight, and the bottom plate is submerged into the pavement. The bottom plate is then connected to the H-shape cooling element, and both cylinder tubes are filled with PCMs. The heat transfer analysis for the TEHs is performed using Finite Element Analysis (FEA) simulation and validated with an experimental investigation. Two types of PCM are used, PCM RT 25 and paraffin wax, PCM RT 30. Results indicate that PCM RT 30 outperforms PCM RT 25, yielding a higher temperature difference. The average generated output voltage is 1.2V with a temperature difference of 20.16°C for PCM RT 30. At the same time, RT 25 achieves only 0.9V with a temperature difference of 14.2°C. Consequently, utilizing PCM RT 30 enables charging 5F supercapacitors to reach 3.8V within 2.50 hours, marking a significant achievement in this study.

ABSTRAK

Disebabkan oleh jumlah besar sisa haba yang dihasilkan oleh turapan asfalt, penuaian tenaga haba jalan telah mendapat lebih perhatian dalam beberapa tahun kebelakangan ini. Dalam projek ini, sistem penuaian tenaga termoelektrik (TEH) yang menggunakan haba dari permukaan turapan asfalt dikaji. Tesis ini bertujuan untuk mereka bentuk TEH baharu dengan PCM sebagai storan sejuk untuk mengekalkan penyejukan bawah tanah melalui simulasi dan eksperimen. Model reka bentuk terdiri daripada pemegang asas asfalt untuk memegang asfalt, plat atas untuk pemanasan, dan plat bawah untuk penyejukan. Plat atas terdedah pada permukaan asfalt untuk menuai haba daripada cahaya matahari, dan plat bawah ditenggelami ke dalam turapan. Plat bawah kemudiannya disambungkan kepada elemen penyejuk bentuk H dan kedua-dua silinder diisi dengan PCM. Analisis pemindahan haba untuk TEH dilakukan menggunakan simulasi Analisis Unsur Terhad (FEA) dan disahkan dengan penyiasatan eksperimen. Dua jenis PCM digunakan, PCM RT 25 dan lilin parafin, PCM RT 30. Keputusan menunjukkan bahawa PCM RT 30 mengatasi PCM RT 25, menghasilkan perbezaan suhu yang lebih tinggi. Purata voltan keluaran yang dijana ialah 1.2V dengan perbezaan suhu 20.16°C untuk PCM RT 30, manakala RT 25 hanya mencapai 0.9V dengan perbezaan suhu 14.2°C. Akibatnya, menggunakan PCM RT 30 membolehkan pengecasan superkapasitor 5F mencapai 3.8V dalam masa 2.50 jam, menandakan pencapaian penting dalam kajian ini.

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Also, I want to express our utmost gratitude toward my project supervisor, Dr. Khairun Nisa Binti Khamil, for her guidance, time, and ideas in this project. I could only complete this project with her support and guidance.

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LIST OF SYMBOLS AND ABBREVIATIONS

TEG	-	Thermoelectric Generator
TEHs	-	Thermoelectric Energy Harvesting system
PCM	-	Phase Change Material
DT	-	Temperature Difference
FEA	-	Finite Element Analysis
TES	-	Thermal Energy Storage
DOE	-	Design of Experiment
NIDAQ	-	National Instrument Data Acquisition
FEA	-	Finite Element Analysis
MPPC	-	Maximum Power Point Collector
RT	-	Rubitherm
DP	-	Design Point
VTEG	-	Thermoelectric Generator Voltage
VBOOST	-	Booster Voltage
AVG	-	Average

CHAPTER 1

INTRODUCTION

This chapter gives an overall overview of the project, which includes the problem statement, objective, the scope of the project and the importance of the study.

1.1 Project Overview

The application of thermoelectric devices for energy harvesting, namely in road infrastructure, has attracted considerable interest because of its capacity to transform dissipated heat into valuable electrical energy. The current work presents a new method to improve thermoelectric output by using an aluminium tube as a storage system based on phase change material (PCM) in thermoelectric road harvesting. The incorporation of phase change materials introduces a dynamic aspect to energy storage, enabling effective heat regulation and enhanced thermoelectric efficiency.

What precisely is the concept of energy harvesting? In his 2020 paper, H. Akinaga [1] asserted that minuscule quantities of dissipating energy could be harnessed and utilized as accessible electrical energy from the surrounding environment. As he describes it, energy harvesting is a technology that collects renewable energy from the environment to restore or replace energy storage devices without interrupting the regular operation of the application. Thermoelectric energy harvesting is a technique that involves the production of electrical energy by exploiting temperature variations. This technology has undergone extensive research for several decades. It possesses numerous potential uses, such as waste heat recovery, power production for remote sensors, and cooling and heating systems. Thermoelectric energy harvesting operates on the fundamental principle of the Seebeck effect, which asserts that a voltage is produced when there is a disparity in temperature across a substance.

Many cities, as well as states, are developing ambitious sustainable energy plans [2]. Various surveys have shown that we waste at least 70% of our primary energy, which dissipates as waste heat. H. Akinaga [1] surveyed that the temperature of the dispersing heat voted mainly was below 100 degrees Celsius. Besides that, Peninsular Malaysia has a tropical climate with high humidity and a distinct monsoon season.

The region experiences two monsoon seasons, the Northeast Monsoon from October to March and the Southwest Monsoon from April to September. The Northeast Monsoon brings in cold and dry air from the Northeast, while the Southwest Monsoon brings warm and wet air. The average temperature in Peninsular Malaysia is between 75-90°F (24-32°C), with high humidity throughout the year. Average annual rainfall varies depending on location, with the east coast receiving more rain than the west coast during the monsoon season. These meteorological parameters have a significant impact on local agriculture and the economy.

The high solar radiation throughout the year in Malaysia is advantageous for harnessing thermal energy. Malaysia's sunny and tropical climate, coupled with its clear skies, enables the efficient operation of solar thermal energy systems. Moreover, Malaysia's elevated temperatures and humidity levels can be harnessed to generate energy through the utilization of geothermal systems.

Given the advantages mentioned earlier, Malaysia can generate significant profits by harvesting thermal energy. What is the process of harvesting it? The text discusses the many techniques for extracting thermal energy from asphalt pavement. It specifically explores the possibility of implementing a Thermoelectric Energy Harvesting system (TEHs) that incorporates a thermoelectric generator (TEG). It is an excellent method for generating an independent power supply for different IoT devices by harnessing and converting a small amount of heat energy into electrical power, increasing its effectiveness.

1.2 Problem Statement

A novel approach to harvesting waste thermal energy that can be transformed into power is the thermoelectric generator (TEG). Nevertheless, the poor efficiency of the thermoelectric materials and the requirement for a significant temperature differential across the TEG device limit the performance of TEGs [3]. One way to boost TEG performance is to utilize phase change materials (PCMs) as thermal storage to increase the temperature gradient. This is because PCM is excellent for thermal regulation applications since it can keep and maintain a consistent temperature even during a phase change [4].

Furthermore, when the sun and convection between them heat, the ambient temperature near the heat sink diminishes, and the temperature on the cold side of the TEG can rise quickly [5]. TEG's shortcomings stem from this issue, which prevents the module from operating to its maximum potential. Maintaining or enhancing the convection between the sides is essential since TEG primarily depends on the heat transfer between the cold and hot sides.

Since DT is proportional to output voltage, the H-shape element at the subterranean level was able to attain high temperatures and high output voltages in an earlier study [6]. However, the production changes irregularly because of the sun's shifting irradiance. Studies conducted by [7] and [8] have demonstrated how adding PCM improves the output voltage. However, it uses a TEG, which is only effective at temperatures above 100°C [9]. According to [10], the asphalt reading in Malaysia only drops below 65°C. There is yet to be a study using black painted top plate and PCM to boost the thermoelectric output. This is because black surface has higher surface emissivity.

1.3 Objective

The objectives of this project are:

1. To model the effect of the aluminium tube as a PSM-based storage to enhance thermoelectric output using finite element analysis (FEA).
2. To optimize the design structure of the prototype using design of experiment (DOE) in Ansys Simulation
3. To validate Ansys optimization simulation in field testing.

1.4 Scope of Work

This project is separated into two different areas. The first phase of the study focuses primarily on simulating the TEHs. In contrast, the second part involves conducting experiments using a physical model. The data from both stages is compared for validations.

<u>PSM I</u>

a) Collect related articles on TEHs and PCM and then analyze the data.
b) Simulate design using a cross-platform finite element analysis, solver, and multi-physics simulation software called Ansys Engineering Simulation Software.
c) Obtain preliminary data and findings on PCMs.
d) Optimization using Design of Experiment (DOE) to get the suitable geometry before field experiment.

PSM II

a) Students will be exposed to the sun during the daylight experiment for data gathering.
b) Experimental work on testing two types of Phase Change Material (PCM): PCM RT 25 and PCM RT 30.
c) Experimental using super capacitor to store the voltage using the best PCM results.

1.5 Project Significant

I. It can be implemented on the asphalt pavement along the freeway.
II. The output power obtained can be used for multiple applications, such as streetlights or traffic lights.
III. It can be utilized to charge super capacitor, a storage for electrical energy.

1.6 Chapter Outline

Chapter 1: This chapter gives an overall overview of the project, which includes the problem statement, objective, the scope of the project and the importance of the study.

Chapter 2: This chapter aims to examine the literature review conducted in previous research. Comprehension is necessary for the successful completion of this research, and it is crucial to locate materials and publications pertaining to the subject matter. This chapter discusses phase change materials, thermoelectric generators, asphalt pavement energy harvesting systems, and finite element analysis.

Chapter 3: This chapter covers the suggested approach for this project, which comprises the methods that will be implemented to produce the best possible results. The significance of applying the proper technique will determine and identify the project's flaws. This chapter includes the project's model, simulation, and experimental steps.

Chapter 4: This chapter portrays the preliminary results of the simulation from the Ansys Engineering Simulation Software and the results from the field testing using the physical model of the TEH system.

Chapter 5: This chapter synthesizes the key findings of the research, highlighting its achievements and implications for both field experiment and simulation contributions. The limitations and areas for improvement are acknowledged, providing insights into potential constraints and factors that may have influenced the study.

CHAPTER 2

BACKGROUND STUDY

The objective of this chapter is to examine the literature review conducted in previous research. Comprehension is necessary for the successful completion of this research, and it is crucial to locate materials and publications pertaining to the subject matter. This chapter discusses phase change materials, thermoelectric generators, asphalt pavement energy harvesting systems, and finite element analysis.

2.1 Thermoelectric Generator (TEG)

A thermoelectric generator (TEG) transforms thermal energy into electrical energy. They operate based on the Seebeck effect, which asserts that one end is heated when two dissimilar metals are connected. At the same time, the other is cooled, a voltage is produced between the two ends. Thermoelectric generators (TEGs) utilize this principle to transform thermal energy into electrical energy. Thermocouples are composed of multiple dissimilar metals that are interconnected.

One side of the TEG is subjected to a heat source. In contrast, the other side is cooled, generating voltage and current across the thermocouple. Thermoelectric generators (TEGs) are devoid of mechanical components and necessitate very little upkeep, rendering them a dependable and enduring power source. It finds application in diverse fields, such as power sensors, medical devices, and remote communication equipment.

Figure 2.1: Peltier TEG Module GL-II Series [27]

TEG is highly eco-friendly since it does not generate emissions or pollution while in operation. They generate electricity by directly converting heat using the Seebeck effect without combustion or other polluting processes. Furthermore, Thermoelectric Generators (TEG) are devoid of moving components and have only minimum upkeep, diminishing the ecological consequences associated with their manufacturing and disposal. Nevertheless, thermoelectric generators (TEGs) typically exhibit a low conversion efficiency, resulting in substantial heat energy dissipation throughout the conversion procedure. This can provide a drawback when employing TEG for power generation to a significant degree.

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

S = Seebeck's Coefficient [μV/K]

ΔV = Thermovoltage [V]

ΔT = Temperature Difference [K]

The Seebeck effect is the occurrence of a phenomenon when two dissimilar metals are connected, and one end is subjected to heating while the other end is subjected to cooling. The temperature gradient creates an electric potential between the two terminals, which can be used to provide electrical energy. The Seebeck effect is essential for functioning thermoelectric generators (TEGs).

In a TEG, an array of thermocouples, pairs of dissimilar metals joined together, are used to convert heat to electricity. Thermocouples are connected in series and parallel to create a thermoelectric module. One end of the module is attached to the heat source, and the heat sink cools the other. The heat source causes a temperature gradient across the module, which produces a voltage and current across the thermocouple. This current can power the device or be stored in the battery. The Seebeck coefficient, which measures the voltage produced per unit temperature difference, and the properties of the thermocouple material used in the TEG determine the efficiency of the TEG. This theory provides the foundation for utilizing temperature differentials within the asphalt to generate electricity through the thermoelectric effect, which will be discussed in the sub-chapter.

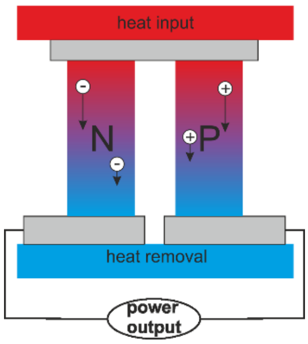

Figure 2.2: Illustration of the Seeback effect [28]

2.1.1 TEG in Energy Harvesting System at Asphalt Pavement

TEGs can convert heat into electricity in energy harvesting systems on asphalt pavements. During summer, asphalt pavement can reach high temperatures, and this heat can be captured and converted into electricity using a TEG.

In such systems, the TEG is embedded into the asphalt surface and connected to a heat sink, usually a layer of gravel or coolant-soaked water pipes. As vehicles pass over the pavement, they heat the TEG, which generates electricity. The heat sink then cools the TEG, completing the thermoelectric cycle. The electricity generated can be used to power lights, traffic signals, and other road infrastructure or be stored in batteries for later use.

TEGs are ideal for energy harvesting on asphalt pavements because they have no moving parts and require minimal maintenance. In addition, they can operate in a wide temperature range, making them ideal for the high temperatures generated by the sun on asphalt.

In this literature review describes the previous and current attempts to address the issue with thermoelectric energy harvesting at asphalt pavement. Khamil et. a1. (2021) presented an experimental investigation on the influence of conduction shape factor in subterranean cooling for a thermoelectric energy harvesting system at asphalt pavement [3]. The paper highlighted the thermal distribution evaluation of multiple diameters of the aluminum rod as a cooling element and examines the optimum designs for the surface heat absorption method using the aluminum plate in the road thermoelectric energy harvesting system (RTEHs). However, the paper only focuses on the optimum designs for the surface heat absorption method using the aluminum plate in the road thermoelectric energy harvesting system (RTEHs). Therefore, my study will focus on how to increase the temperature difference between hot plate and cold plate by using aluminum tube with PCM- based storage.

Besides that, Quintáns et. al. (2020) stated that the development of a thermoelectric energy harvesting system that utilizes daily ambient temperature variations and water-stored energy [11]. To enhance the efficiency and effectiveness of thermoelectric energy harvesting. In Quintáns et al. (2020), the focus is on using water as a thermal storage medium to smooth out daily temperature variations and improve energy harvesting over time. In my project, the focus is on using PCM-based storage to enhance the temperature gradient across the thermoelectric generator and improve power output.

Khamil et. al. (2020) presented high cooling performances of H-shape heat sink for thermoelectric energy harvesting system (TEHs) at asphalt pavement [12]. The paper highlighted the design of a thermoelectric energy harvesting system (TEHs) that converts the waste heat from the surface of asphalt pavement into useful electrical energy. However, the paper only focuses on use aluminium plate and rod to be cooling module Therefore, my study will focus on and upgrade the cooling method by using PCM-based storage in the aluminium tube to increase the temperature different and generate more energy.

Furthermore, Khamil et. al. (2020) stated that thermoelectric energy harvesting system (TEHs) at asphalt pavement with a subterranean cooling method" [13]. The paper highlighted the effects of the heat conduction using different shape structures in the subterranean level. However, the paper only focuses on using two types of cooling elements, which is a cylindrical rod and flat bar Therefore, my study will focus on adding the third cooling elements using aluminium rod instead of steel rod and using Phase Change Material (PCM).

Lim et. al. (2020) stated that qpplication of a phase change material to a thermoelectric ceiling radiant cooling panel as a heat storage layer. The paper highlighted to propose and obtain a workable design of a phase change material integrated thermoelectric radiant cooling panel (PCM-TERCP) through numerical and experimental investigations of thermal performance [14]. Therefore, my study will approach different ways to use PCM as a cooling agent to hold the temperature longer to increase the temperature different between top plate and bottom plate to generate and harvest more energy. Both studies highlight the potential of using a PCM to enhance the efficiency and performance of thermoelectric systems. The use of a PCM in thermal energy storage can help maintain a constant temperature and enhance the temperature gradient across the thermoelectric module, which can lead to an increase in power output.

Seyed Amid Tahami et. al. (2019) has developed a new thermoelectric approach for energy harvesting from asphalt pavement [7]. The paper is highlighted for its innovative design of a thermoelectric generator system that generates electricity by utilizing the heat gradient between the pavement surface and the soil beneath it. However, the research mainly focuses on the system's effectiveness, which is enhanced by adding a phase-changing heat sink to its cooling module. The improved prototype is a potential independent power source for the South Texas setting. Therefore, this study will focus on systems consisting of heat collectors, thermal electricity generators, cooling modules, and some simulations using finite element analysis to establish their ideal design.

Lastly, Amid Tahami et. al. (2021) presented that evaluation of a roadway thermoelectric energy harvester through FE analysis and laboratory tests [15]. The design, construction, and evaluation of a better thermoelectric energy system prototype for harvesting heat from road pavements were highlighted in the research. The most promising prototypes were designed, built, and tested in laboratories to determine their potential for power harvesting after being simulated using Finite Element (FE) analysis. The research, however, was solely concerned with deciding how geometric design affected how effectively the invention transferred heat over seven hours of summer sunlight in South Texas. FE analysis was used to simulate the plan, and the project was simulated using FE analysis. Therefore, my study will focus on FE analysis used in the system development process to simulate designs and look at how they function in terms of thermal conductivity.

2.2 Phase Change Material (PCM)

A phase change material (PCM) is a material that can absorb or release large amounts of energy during a phase change, such as melting or solidification. Power is stored in the form of latent heat, which is the heat required to change the phase of a substance without changing its temperature. This makes PCM useful for thermal energy storage, as it can store large amounts of heat during a phase change, which can then be released over time as the material solidifies. Common examples of PCMs include paraffin wax, salt hydrates, and eutectic alloys. It is used in many applications, including building insulation, cooling, and thermal energy storage for renewable energy systems such as solar thermal power plants. Besides that, PCMs are latent heat thermal energy storage materials that use their chemical bonds for the storage and release of energy [30].

In addition, Thermal Energy Storage (TES) is a widely employed technique for storing energy. TES can be categorised into two primary classifications. The first type of heat storage is sensible heat storage, while the second type is latent heat storage. The augmentation of energy resulting from the application of heat to a substance is depicted in Figure 2.3 as elaborated by reference [29]. The illustrated process involves sensible heating in regions A-B, C-D, E-F, and G-H, as well as latent heating in regions B-C, D-E, and F-G. The specific heat of a material during phase transition can be integrated with the temperature difference to determine the total energy stored per unit weight. In order to store the same amount of energy as latent heat transfer, a greater quantity of medium is necessary for sensible heat transfer.

These two options are not technically feasible due to the small latent heat in solid-solid transition and the need for a large volume for liquid-gas transformation.

Additionally, when referring to energy storage through solid-liquid transformation, we specifically mean the storage of energy in a higher density form that operates at a constant temperature, using phase change materials (PCM). For this experiment, PCM RT 25 and PCM RT 30 were used.

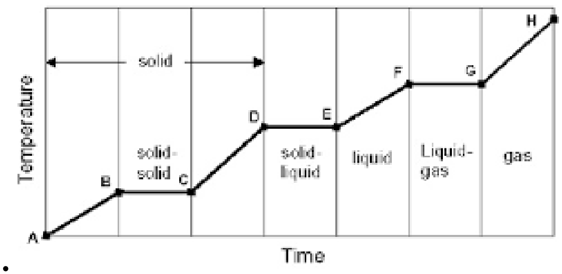

Figure 2.3: Temperature versus Time diagram for heating of a PCM [29]

2.2.1 TEHs with PCM as Thermal Storage

A preliminary overview of previous work on thermoelectric energy harvesting with phase change materials during thermal storage is reviewed. Therefore, this section discusses relevant literature related to this project's scope.

Kun Du et al. (2018) reviewed the application of phase change materials in cooling, heating, and power generation in different temperature ranges [16]. The paper highlights the latest research on phase change materials (PCM) and their applications for heating, cooling, and electricity generation according to their operating temperature range from (-20 °C to +200 °C). However, this paper only focuses on the various phase change materials used in each temperature range, their performance, methods to improve heat transmission, environmental impact, and economic analysis. Therefore, this study will focus on improving the operational efficiency of PCM storage for heating and cooling applications depending on the specific application used in the project.

Guangyao Wang et al. (2017) stated that harvesting environmental thermal energy using solid/liquid phase change materials [17]. The study emphasizes cycling the phase change material through the temperature differential and converting a portion of the energy the phase change material receives throughout its melting process into mechanical or electrical power. However, this research solely investigates the theoretical and experimental viability of employing solid/liquid PCM to capture ambient thermal energy associated with slight temperature changes.

Xinzhong Liao et al. (2020) stated that investigation of a double-PCM-based thermoelectric energy harvesting device using temperature fluctuations in an ambient environment [18]. A new double-PCM-based thermoelectric energy-harvesting device based on temperature variations in the surrounding environment is proposed to enhance device performance. A double-PCM-based device has been created and tested for three days in a setting with a wide temperature range (0–40°C). However, based solely on numerical and experimental findings, the research only compares the average output power performance of the single-PCM-based and the double-PCM-based thermoelectric energy-harvesting devices. Therefore, my study will focus on demonstrating the operation of electrical equipment at various times and locations, as well as the thermoelectric energy harvesting device built on a double PCM.

Wei Zhu et al. (2018) presented the multi-parameter optimization design of thermoelectric harvester based on phase change material for space generation [19]. Simulation and experiment validated that selecting PCM with an appropriate melting temperature is critical for temperature control by balancing the heat storage and release process, increasing power production. The paper, however, focuses solely on the total energy and high-grade energy output of PCM thermal storage and aircraft-specific thermoelectric generator (TEG) modules. Therefore, my study will focus on the finite element analysis method for the appropriate melting temperature to increase the output power.

Jianhui Mao et. al. (2020) showed an enhancement of power generation of a thermoelectric generator using phase change material [20]. The research highlighted a thermoelectric generator (TEG) with embedded phase change material (PCM) to gather waste heat energy. This TEG module contains a volume of molten carbonate salt within a cuboid polydimethylsiloxane (PDMS) body. However, this paper will focus on contrasting the performance of TEGs with and without PCM, focusing exclusively on the effect of integrated PCM on TEG performance. As a result, this research will focus on findings demonstrating how TEGs with PCM may attain the output voltage and longer energy harvesting duration compared to similar values without PCM.

Leland Weiss et al. (2018) stated operational enhancements for small-scale thermal energy storage devices [21]. The emphasized research examines how thermal energy storage works on millimeter scales, both in terms of fabrication and performance. Paraffin wax, which is inexpensive and widely available, is used as the primary thermal storage substance, and it stores energy by undergoing phase transformation from solid to liquid states. However, the investigation in this study is limited to two methods for designing and describing small-scale thermal energy storage (TES) devices. Therefore, my research will focus on an improvement of a design-based process to integrate capillary heat pipes with waxes and materials-based systems in which the hexagonal boron nitride (h-BN) nanomaterials.

Hafiz Muhammad Ali (2019) has presented applications of combined/hybrid use of heat pipe and phase change materials in energy storage and cooling systems [22]. The research emphasized that phase change materials (PCM) have outstanding heat storage qualities and have tremendous promise for latent heat energy storage, waste heat recovery, and heating and cooling systems. Heat pipes (HP) are among the most popular types of heat transfer equipment because they can transfer heat isothermally over short and long distances. However, the article only focuses on systems that improve thermal performance and efficiency by combining PCM with heat pipes (HP). Therefore, this study will focus on the overall efficiency of PCM, heat storage, and emission rate to improve significantly with HP integration.

Unlike Khattari et. al (2022) studied on the validity of using PCM in a controlled cooling ceiling integrated into a ventilated room. The goal of this study is to investigate the energy and thermal benefits of employing PCM in a ventilated room with three Moroccan climates representing three different Köppen-Geiger climate types [23]. The cooling power is adjusted to keep the temperature of the indoor air within a restricted range, ensuring thermal comfort without wasting energy. Simulations were run in a turbulent and transient flow regime using a UDF, using real variable 23 ambient temperature. This is also utilized to manage the cooling power based on the temperature of the ceiling and the temperature of the inside air. The use of paraffin C13 as a PCM in cooling ceilings in Fez and Ifrane climates was shown to be beneficial, with energy savings of 17.07 percent and 16.30 percent, respectively. It was also discovered that utilizing paraffin C13 reduced energy usage by only 02.23 percent in Marrakech's climate, and as a result, it is considered insufficiently useful for this sort of environment. Hence, the summary of the related literature review that useful for this project are tabulate in Table 2.3.

2.3 Table of Summary

Table 2.1: Summary of Literatures Review

Reference	Year	Title	Summary Method
[3]	2021	The influence of conduction shape factor in subterranean cooling for a thermoelectric energy harvesting system atasphalt pavement.	The thermal distribution evaluation of multiple diameters of the aluminum rod as a cooling element. producing the highest temperature difference (DT) of 15.19°C. Generate volage 0.682V.
[11]	2020	The development of a thermoelectric energy harvesting system that utilizes daily ambient temperature variations and water-stored energy	Provides a detailed analysis of the system's performance under different operating conditions, providing insights into how to optimize the energy harvesting process.
[12]	2020	High Cooling performances of H-shape heat sink for Thermoelectric Energy Harvesting system (TEHs) at Asphalt Pavement.	H-shape element in subterranean cooling in order to achieve a high-temperature difference (ΔT). Temperature difference (DT) of 23°C. Generate volatge 1.02V
[13]	2020	Thermoelectric energy harvesting system (TEHs) at asphalt pavement with a subterranean cooling method.	Different shape structures in the subterranean level. DT of 7.95°C with 0.32 V output voltage.
[14]	2020	Application of a phase change material to a thermoelectric ceiling radiant cooling panel as a heat storage layer	A novel approach to enhancing the performance of thermoelectric ceiling radiant cooling panels by applying a phase change material (PCM) as a heat storage layer
[7]	2019	A new thermoelectric approach for energy harvesting from asphalt pavement	A thermoelectric generator system that generates electricity by utilizing the heat gradient between the pavement surface and the soil beneath it.

[15]	2021	Evaluation of a roadway thermoelectric energy harvester through FE analysis and laboratory tests	The design, construction, and evaluation of a better thermoelectric energy system prototype for harvesting heat from road pavements
[16]	2018	A review of the application of phase change materials in cooling, heating, and power generation in different temperature ranges	Latest research on phase change materials (PCM) and their applications for heating, cooling, and electricity generation according to their operating temperature range from (-20 °C to +200 °C).
[17]	2017	Harvesting environmental thermal energy using solid/liquid phase change materials	The study emphasizes cycling the phase change material through the temperature differential and converting a portion of the energy the phase change material receives throughout its melting process into mechanical or electrical power.
[18]	2020	Investigation of a double-PCM-based thermoelectric energy harvesting device using temperature fluctuations in an ambient environment	A new double-PCM-based thermoelectric energy-harvesting device based on temperature variations in the surrounding environment is proposed to enhance device performance. A double-PCM-based device has been created and tested for three days in a setting with a wide temperature range (0–40°C).
[19]	2018	The multi-parameter optimization design of thermoelectric harvester based on phase change material for space generation	Temperature control by balancing the heat storage and release process, increasing power production. Simulation and experiment validated that selecting PCM with an appropriate melting temperature.

[20]	2020	An enhancement of power generation of a thermoelectric generator using phase change material	A thermoelectric generator (TEG) with embedded phase change material (PCM) to gather waste heat energy. This TEG module contains a volume of molten carbonate salt within a cuboid polydimethylsiloxane (PDMS) body.
[21]	2018	Operational enhancements for small-scale thermal energy storage devices	The highlighted research focuses on millimeter-scale thermal energy storage using paraffin wax. The study explores fabrication and performance, leveraging the inexpensive and readily available wax to store energy through solid-to-liquid phase transformation.
[14]	2019	Applications of combined/hybrid use of heat pipe and phase change materials in energy storage and cooling systems	The article only focuses on systems that improve thermal performance and efficiency by combining PCM with heat pipes (HP).
[23]	2022	CFD study on the validity of using PCM in a controlled cooling ceiling integrated in a ventilated room	Using a UDF, simulations were run in a turbulent and transient flow regime, using real variable 23 ambient temperature. The use of paraffin C13 as a PCM in cooling ceilings in Fez and Ifrane climates was shown to be beneficial, with energy savings of 17.07 percent and 16.30 percent, respectively.

2.4 Summary

This study aimed to enhance the effectiveness of thermoelectric road harvesting by investigating the utilization of an aluminium tube as a storage system based on phase change material (PCM). The literature review emphasized the critical role of efficient energy storage in thermoelectric systems. Incorporating the aluminium tube and utilizing its phase change material (PCM) capabilities exhibited superior thermoelectric output compared to conventional approaches. This strategy not only enhances the capability to store energy but also aligns with objectives related to sustainability. The study significantly contributes to the area by providing vital insights that might inform future research on enhancing the efficiency and feasibility of road thermoelectric energy generation.

CHAPTER 3

METHODOLOGY

This chapter covers the suggested approach for this project, which comprises the methods that will be implemented to produce the best possible results. The significance of applying the proper technique will determine and identify the project's flaws. This chapter includes the project's model, simulation, and experimental step.

3.1 Project Development Flow.

Figure 3.1 will be used as a visual reference throughout the development of this project. Initially, Objective 1 is the process that involves reading an article or journal to learn more about similar initiatives. Then, defining the project's problem and objective. Then, determine the optimal method for designing and simulating the model. Lastly, collect the data using simulation and do an analysis. After obtaining the result from simulation analysis, the optimization of the design will begin to see what optimum result. So that the objective 2 achieved. For objective 3, the construction of physical model will begin to conduct experimental. Finally, collect the data from experimental to analyze and compare the result between simulation and experimental.

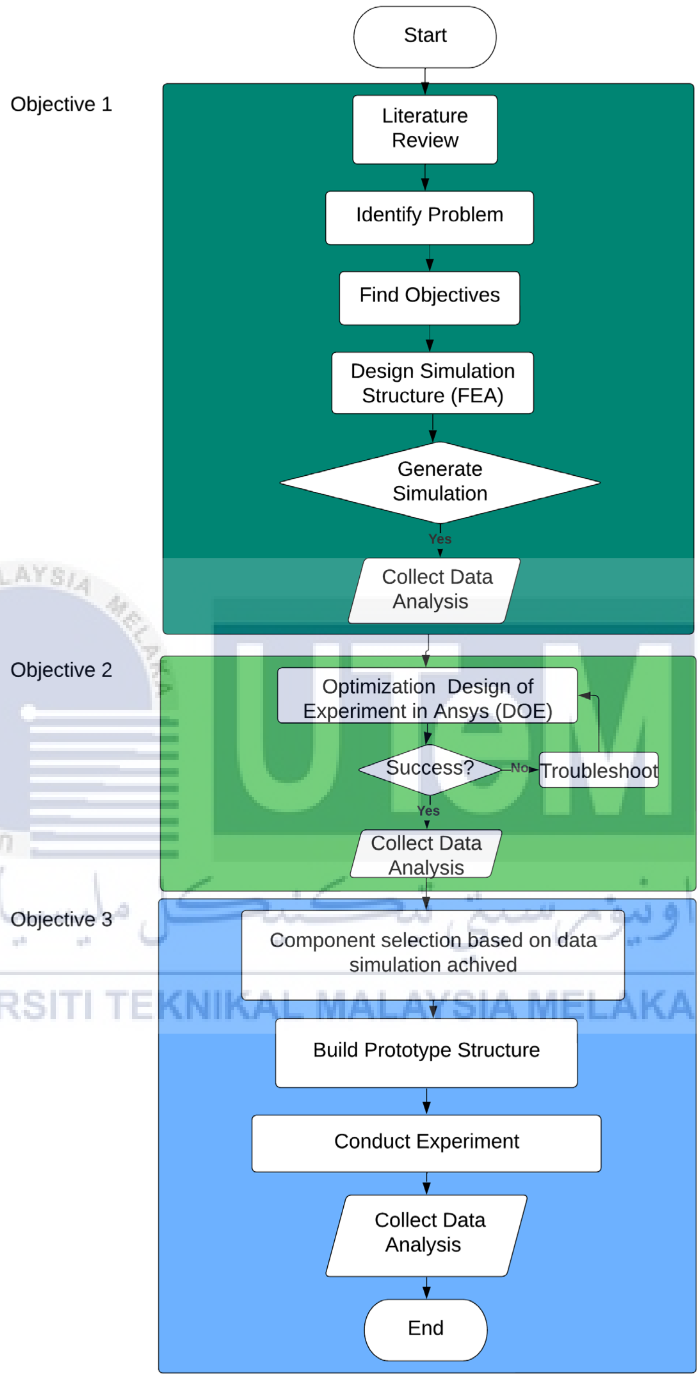

Figure 3.1: Flowchart Project Development Flow

3.2 Finite Element Analysis (Ansys Engineering Simulation Software)

TEHs usually evaluate the performance of thermoelectric materials and devices used in the system. This includes measuring the thermal conductivity, electrical conductivity, and Seebeck coefficient of the material, as well as the power output and efficiency of the device. System components' thermal and electrical properties, such as heat capacity and thermal conductivity, should also be characterized. Referring to Figure 3.2 below, Ansys Engineering Simulation Software can also be used to model system performance. These simulations can help predict system performance under different operating conditions and aid in system design and optimization.

Finite Element Analysis (FEA) is a computational method that can simulate and analyze complex systems by dividing them into more minor, finite elements. In the context of TEG, FEA helps model and optimize the performance of this device, which converts temperature gradients into electrical energy. When phase change materials (PCM) are incorporated into the system, FEA can aid in understanding the heat transfer dynamics and optimizing the design for efficient energy harvesting on asphalt pavement. These advancements will lead to improvements in energy conversion technology.

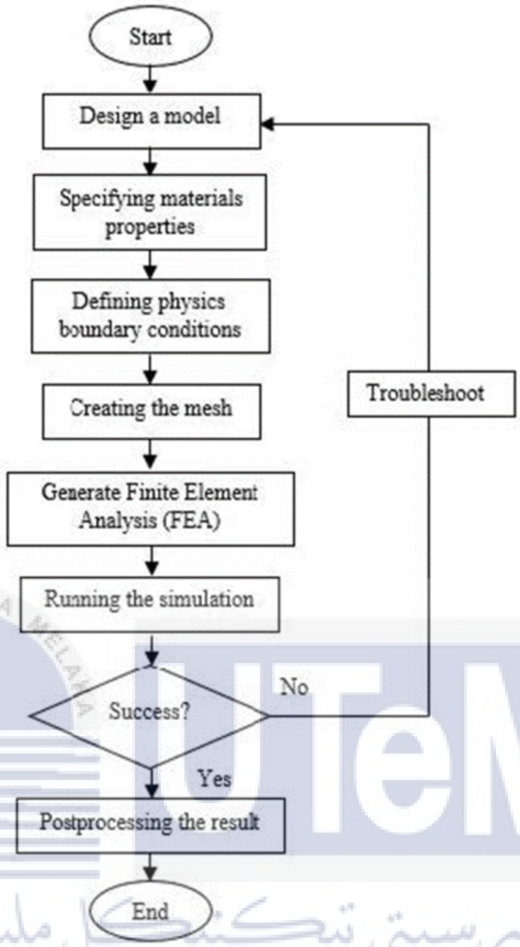

Figure 3.2: Flowchart Finite Element Analysis

3.3 Optimization in Design of Experiment (Ansys Enginnering Simulation Software)

Design of Experiments (DOE) is a branch of applied statistics that deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of a parameter or group of parameters. The process involves planning and executing experiments to determine the individual and interactive effects of various factors that can influence the output results of measurements. Besides that, it is used to identify the factors that affect the output of a process to optimize the process by adjusting the input variables. So that, it can minimize the number of experiments required to achieve the desired result.

3.4 Model of the Project

Commence by generating a preliminary outline or 2D depiction of the model to aid in conceptualizing the general form and dimensions of the model. Next, construct the model by employing 3D geometry to generate fundamental shapes and structures, such as blocks and cylinders. Proceed with the construction of the model, enhancing and elaborating it by incorporating specific material features. After the model is finished, a time-dependent analysis is conducted to execute the model.

The proposed design [13] based on Figure 3.3 concept involves the direct exposure of the top aluminium plate to the asphalt surface, with its edge in direct contact with the asphalt. The thermoelectric cooling (TEC) [24] was positioned between the top aluminium plate and the bottom aluminium plate. Prior research has extensively confirmed the use of the cooling element method, whereby an H-shaped configuration was formed through the fusion of an aluminium plate with two cylindrical tubes with a radius of 19.5 mm.

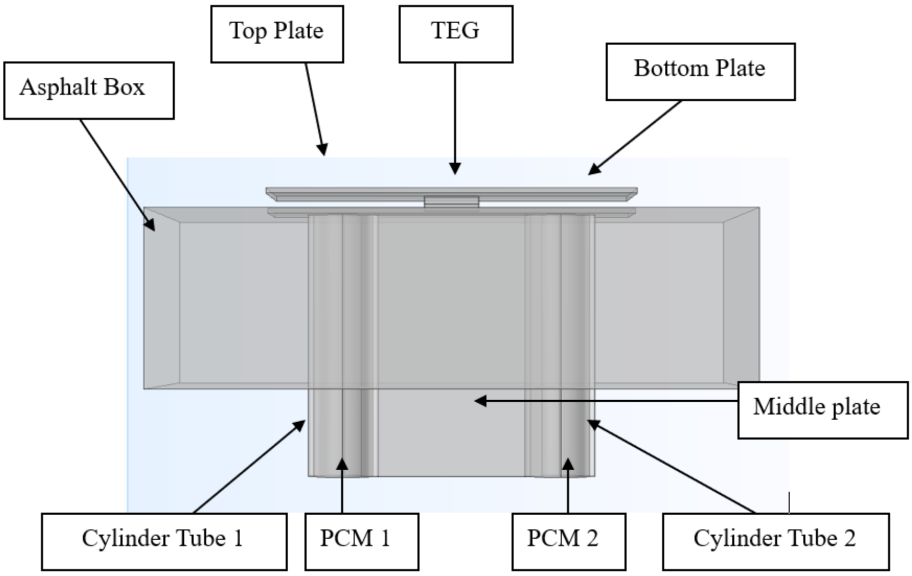

Figure 3.3: Simulation model TEHs at Asphalt Pavement

Figure 3.4: Isometric view of the model [13]

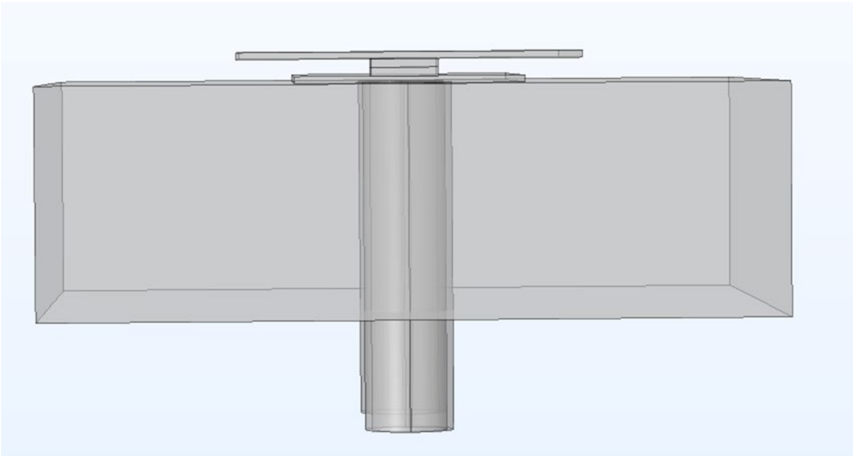

Figure 3.5: Side view of the model

Table 3.1: Dimensions of Simulation Model

Type	Dimension (mm)
Bottom Plate	60 x 200 x 3
Middle Plate	153 x 100 x 3
Cylindrical Tubes	Radius 19.5, Height 153
TEG Module	3 x 3 x 0.5
Top Plate	100 x 200 x 3
Asphalt	300 x 300 x 100

Table 3.2: Materials and Properties of the Simulation Model

Material	Density (kg/$mm3$)	Heat Capacity (J/(kg.K))	Thermal Conductivity (W/(m.k))	Electrical Conductivity (S/m)	Latent Heat (kJ/kg)
Aluminium	2.7	900	222	3.77E+07	-
Alumina	2820	896	138	3.03E+07	-
Asphalt	2.24	900	0.8	-	-
PCM RT 25	770	0.2	1500	-	230
PCM RT 30	880	0.2	2000	-	170

3.5 Setup of the project for Field testing.

There are 5 parts of experiment for this project which continued one after another.

I. Model with clear surface top plate and PCM RT 25.

II. Model with black painted surface top plate and PCM RT 25.

III. Model with clear surface top plate and PCM RT 30.

IV. Model with black painted surface top plate and PCM RT 30.

V. Charging Supercapacitor using the model with black painted surface top plate and PCM RT 30.

Each of these studies were completed over a period of 3 days, with a total of 2.5 hours dedicated to each day. The entirety of the acquired data was retained and subjected to analysis. The chosen model was physically manufactured according to the diagram shown below.

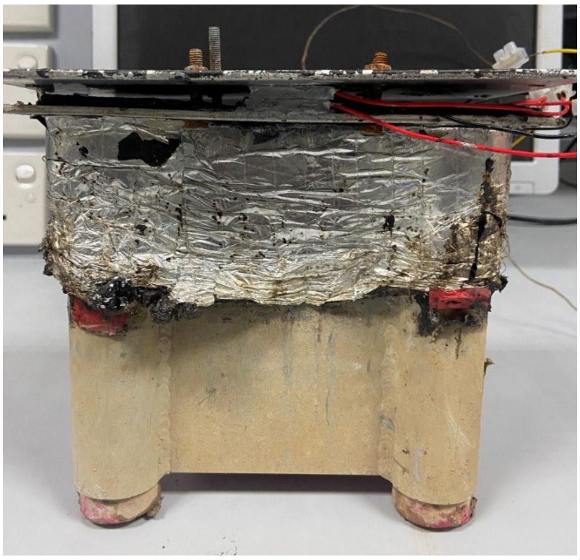

Figure 3.6: The H-Shaped Heat Sink Physical Model

The experimental model of the project consists of an aluminium plate, as shown in Figure 3.6. The minimum required thickness for an H-shape heat sink made of aluminium is 3 mm. Aluminium will undergo melting and become unwieldable when its size is less than 3 mm.

3.5.1 Physical Model Embedded in Asphalt

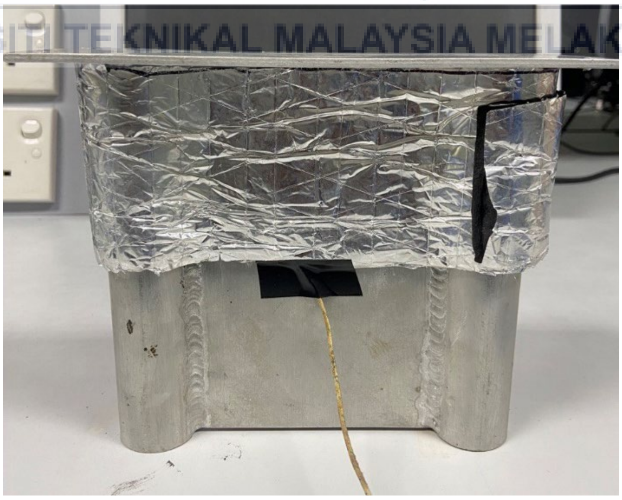

Figure 3.7: H-Shaped Heat Sink Tape with K-Type Thermocouple at Middle Plate and with Insulation Foam.

Firstly, a K-Type thermocouple is necessary for temperature measurement in beneath cooling systems. The K-Type Thermocouple tape is displayed on the Middle Plate in Figure and on the Bottom Plate in Figure 3.7. Thermal insulation from the asphalt is achieved by using insulation foam. It aids in preventing the H-shaped Heat Sink from receiving heat transfer from asphalt.

Figure 3.8: Asphalt Shape to Place the Subterranean Cooling System

The next step is to prepare a 300mm x 300mm x 100 mm wooden box with asphalt inside. Then embedded, the physical model was into the asphalt.

3.5.2 TEG Placement

To ensure the heat transfer is performed in a proficient way, each side of the TEG was bounded using 4 M6 bolts and nuts between top plate and bottom plate.

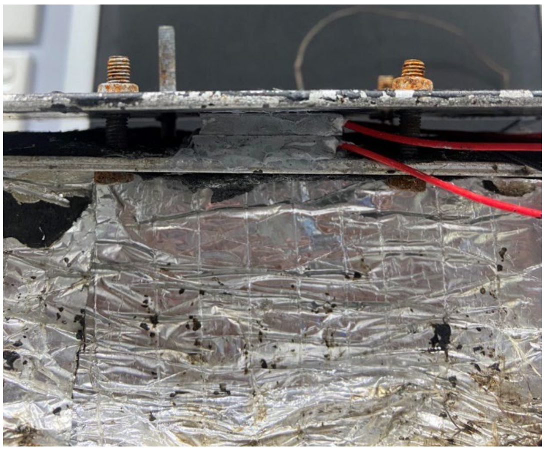

Figure 3.9: Bolts and Nuts to Hold the TEG in place.

3.6 Data Collection

Two kinds of data were collected for this study: the model's temperature and the TEG's open circuit voltage. A few devices have been utilized to aid in the collection of data which are Pico data logger for measuring temperature and National Instrument Data Acquisition (NIDAQ) device for measuring voltage (VTeg). In Figure 3.10 are basic equipment to prevent heat from the sun which, a parasol and box serve as desk to place a laptop.

Figure 3.10: Data collection setup in field testing

Figure 3.11: Project installation on the ground

3.6.1 Pico Data Logger TC-08 with Thermocouple

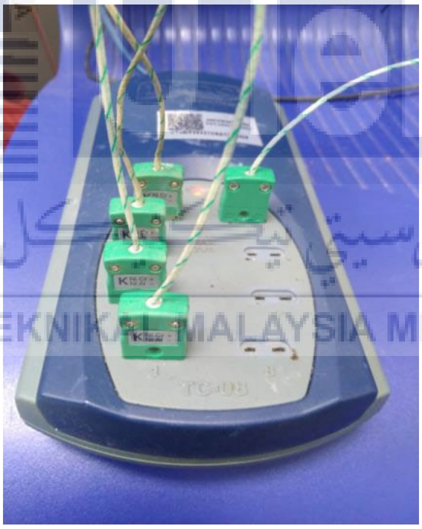

Figure 3.12: Pico Data Logger TC-08 with K-Type Thermocouple

The TC-08 thermocouple data recorder is a device that records temperature readings. It can work with K-Type thermocouples installed on the top plate, PCM thermal storage, bottom plate, middle plate, and asphalt. The TC-08 thermocouple data recorder can evaluate a wide temperature range using any thermocouple with a miniature thermocouple connector. Pico data logger offers a wide selection of high-quality thermocouples for any need. It is an 8-channel thermocouple data logger that can utilize all standard thermocouple types with a temperature range of -270 to 1820 °C (the temperature range is dictated by the thermocouple used). The built-in Cold Junction Compensation (CJC) circuit can measure the ambient temperature, which functions as the 9th available channel. Temperature readings can be taken in a brisk and detailed way with the help of the TC-08 thermocouple data recorder.

3.6.2 LTC3105EDD with MPPC

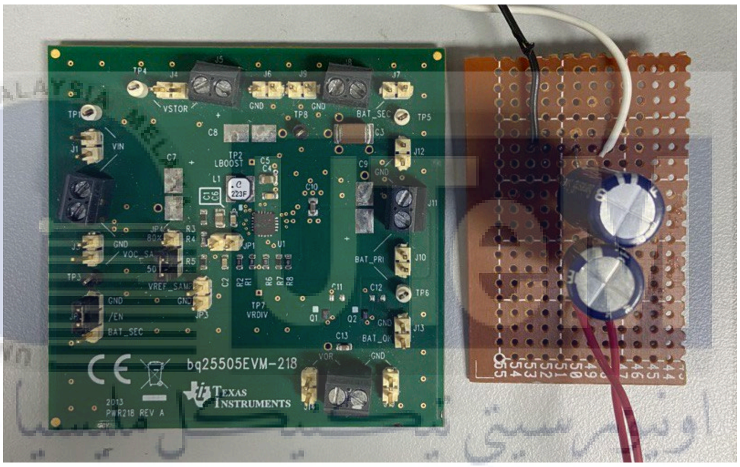

Figure 3.13: LTC3105EDD Step-up Converter and Super Capacitor

Measuring the voltage across the open circuit of the TEG would not yield a dependable reading. Hence, the boost module utilized in this system corresponds to the apparatus depicted in Figure 3.13. The LTC3105 is a high-efficiency step-up DC/DC converter capable of operating at input voltages as low as 225 mV. The device can work immediately using low-voltage, high-impress alternative power sources such as TEG, solar, and fuel cells. This is made possible by its 250mV start-up power and the inclusion of an integrated maximum power point controller (MPPC). Introducing a user-configurable maximum power point control (MPPC), set point can enhance the energy output obtained from different power sources. The utilization of the new automatically adjusting peak current in the Burst Mode function improves efficiency and reduces the voltage ripple of the converter in all operational conditions. The LTC3105 requires an input voltage ranging from 0.2V to 5V and can provide an output voltage of 5.25V with a maximum output power of 100mA. This is compatible with any energy harvester that generates a small amount of voltage and current, enabling it to power a low-power device autonomously. These tools were utilized for data collection during field testing. Subsequently, the following chapter will delve into the acquired outcomes.

3.6.3 NI Multifunctional Data Acquisition Card USB 6001

Figure 3.14: National Instrument Data Acquisition Device

A National Instrument Data Acquisition device was utilized in order to capture and monitor the output voltages, as depicted in Figure 3.14. This NI Multifunction I/O Devices built for computer-based systems combine analogue, digital, and counter/timer capability in a single device. Multifunction I/O devices provide a variety of I/O with different channel counts, sample rates, output rates, and other features. Other capabilities are included to accommodate a wide range of measurement needs.

These devices are suitable for a variety of applications. Laboratory automation, research, and design verification are just a few examples of industry applications. The DAQExpress interactive measurement software is supplied and allows for quick hardware setup and data collection. The integrated NI-DAQmx driver allows for comprehensive measurement and visualization customization. A range of supported programming languages are used to create automation applications.

3.7 Summary

The purpose of the research was to improve the effectiveness of thermoelectric road harvesting by employing phase-change material (PCM)-based aluminium tube storage. The study utilized a comprehensive methodology, integrating computational simulations and empirical investigations. Actual tests comprised developing and testing the aluminium tube PCM-based storage in real-world situations, while computer simulations assisted with estimating and optimizing the system's theoretical performance. Simulation and experimentation results verified that this strategy greatly increases thermoelectric output. Combining these two techniques not only enhances the comprehension of the suggested system but also establishes a foundation for real-world uses, enhancing the efficiency of thermoelectric energy harvesting from roadways.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter portrays the preliminary results of the simulation from the Ansys Engineering Simulation Software and the results from the field testing using the physical model of the TEH system.

4.1 Simulations Finite Element Analysis (FEA)

The simulations separated into 2 types which are:

i. Model with PCM RT 25

ii. Model with PCM RT 30

4.1.1 Comparison of Simulations PCM RT 25 and PCM RT 30 Results.

Figure 4.1 and 4.2 below shows the results obtained from the result of the model tested for 2.5 hours of simulation using Thermal Transient in the Ansys Engineering Simulation Software, with solar irradiance set based on an external radiation source.

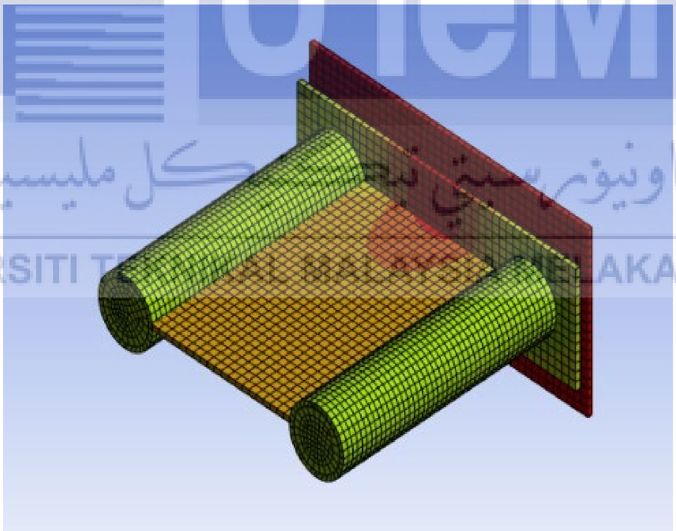

Figure 4.1: The Temperature Flow in Model RT 25

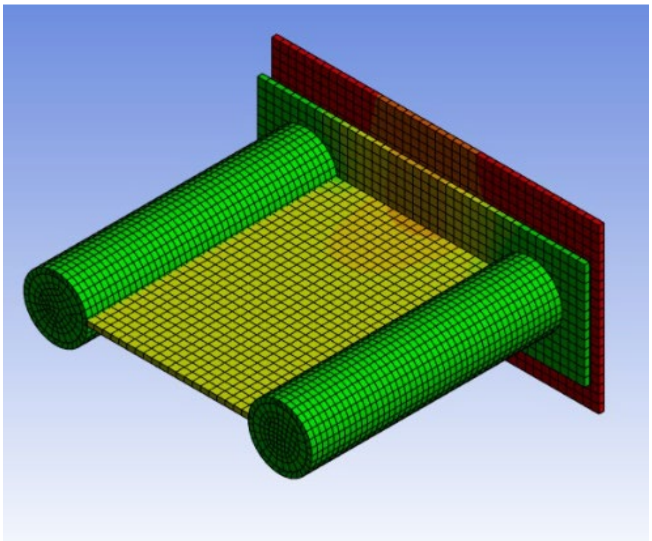

Figure 4.2: The Temperature Flow in Model with PCM RT 30

The results from simulation of the TEHs with PCM RT 25 and PCM RT 30 were compared and analyzed based on Table 4.1.

Table 4.1: Summary Temperature Each Sides and Temperature Difference both Simulations

Type of PCMs	Duration (s)	Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	DT (Top Plate & Cylinder 1&2) (°C)
PCM RT 25	0	25.4	25.4	25.4	25.4	25.4	0
	7200	61.8	54.8	52	43.1	43.1	18.7
PCM RT 30	0	25.4	25.4	25.4	25.4	25.4	0
	7200	63.8	56.1	50.9	39.8	39.8	24.0

From the simulation of the model, the results indicate that utilizing and the use of the PCM RT 30 is more significant temperature difference after two hours simulation than using PCM RT 25 shows in Table 4.1. Before verifying these results in field experiment, optimization for the size of top plate, both cylinders and PCMs in DOE carried out to see the most suitable and efficient geometry of the model.

4.1.2 Optimization in Design of Experiments (DOE)

4.1.2.1 Optimization for Model with PCM RT 25

Table 4.2: Optimization in DOE for Model with PCM RT 25

Name	Top Plate width x length (mm)	Cylinder 1 (mm)	Cylinder 2 (mm)	PCM 1 (mm)	PCM 2 (mm)	Top Plate Maximum Temperature (°C)	PCM Maximum Temperature (°C)	DT Top plate & PCM (°C)
DP 0	200 x 100	19.5	19.5	16.5	16.5	61.7	44.5	17.2
DP 1	210 x 110	20.0	20.0	17.0	17.0	60.4.	44.5	15.9
DP 2	220 x 120	21.0	21.0	18.0	18.0	57.9	44.5	13.4
DP 3	230 x 130	22.0	22.0	19.0	19.0	57.0	44.5	12.5
DP 4	240 x 140	23.0	23.0	20.0	20.0	56.7	44.5	12.2
DP 5	250 x 150	24.0	24.0	210	21.0	56.1	44.5	11.6

According to the Table 4.2, Design Point 0 (DP 0) had the highest temperature difference (DT), which was 17.2°C. In addition, DP 5 represents the minimum DT, which is 11.6°C. According to the theory of surface area to volume ratio, objects with larger surface areas can dissipate more heat. This is due to the fact that a greater surface area offers increased capacity and locations for heat transfer, whether it be heat loss or heat gain, depending on the surrounding conditions [13]. So that, DP 0 is the most suitable and efficient measurement of the top plate, both cylinders and both PCMs to conduct field experiment than other design points.

4.1.2.2 Optimization for Model with PCM RT 30

Table 4.3: Optimization in DOE for Model with PCM RT 30

Name	Top Plate width x length (mm)	Cylinder 1 (mm)	Cylinder 2 (mm)	PCM 1 (mm)	PCM 2 (mm)	Top Plate Maximum Temperature (°C)	PCM Maximum Temperature (°C)	DT Top plate & PCM (°C)
DP 0	200 x 100	19.5	19.5	16.5	16.5	61.7	38.1	23.6
DP 1	210 x 110	20	20	17	17	60.4	38.1	22.3
DP 2	220 x 120	21	21	18	18	57.9	38.1	19.8
DP 3	230 x 130	22	22	19	19	57.0	38.1	18.9
DP 4	240 x 140	23	23	20	20	56.7	38.1	18.6
DP 5	250 x 150	24	24	21	21	56.1	38.1	18

Moving to optimization for model with PCM RT 30, same as Table 4.3, the DP 0 is the most efficient in term of measurement of the model to generate the most DT between top plate and PCM. Hence, DP 0 dimensions will be chosen for field experiment.

4.2 Field Experiment Result

In the experiment, temperature and voltage output are tracked for 2.5 hours, or 9000 seconds (12 pm to 2.30 pm GMT+8). The temperature data is collected using the PicoLog TC-08 data logger system, which yields the findings. For voltage output, the National Instrument DAQExpress companion software is used. To ensure the consistency of the results, each experiment was carried out for a duration of three days. This was done by conducting the experiment multiple times, which aids in discerning whether the observed data was an anomaly or indicative of the norm. The experiments have 5 parts of results which consists of:

I. Model with clear surface top plate and PCM RT 25.

II. Model with black painted surface top plate and PCM RT 25.

III. Model with clear surface top plate and PCM RT 30.

IV. Model with black painted surface top plate and PCM RT 30.

V. Charging Supercapacitor using the model with black painted surface top plate and PCM RT 30.

4.2.1 Part 1: Experiment Result for Model with clear surface top plate and PCM RT 25.

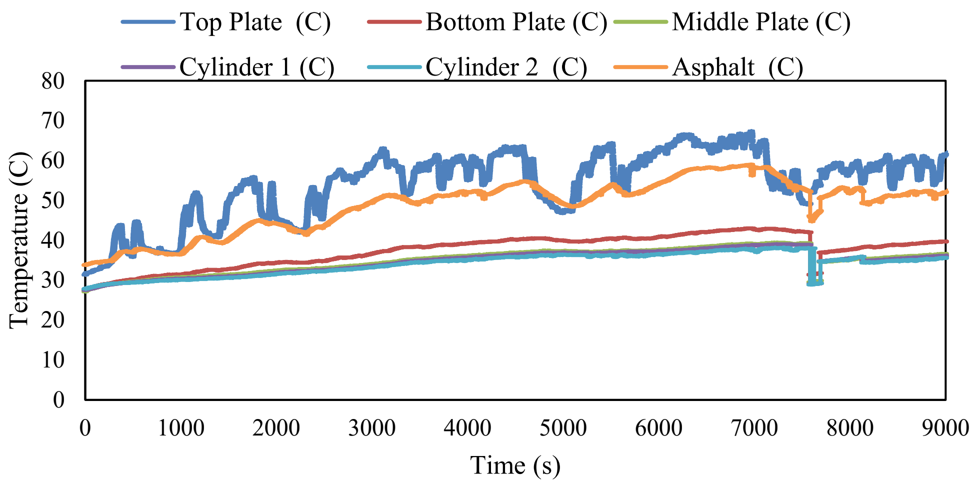

Figure 4.2: Temperature Whole Model for Day 1 Part 1

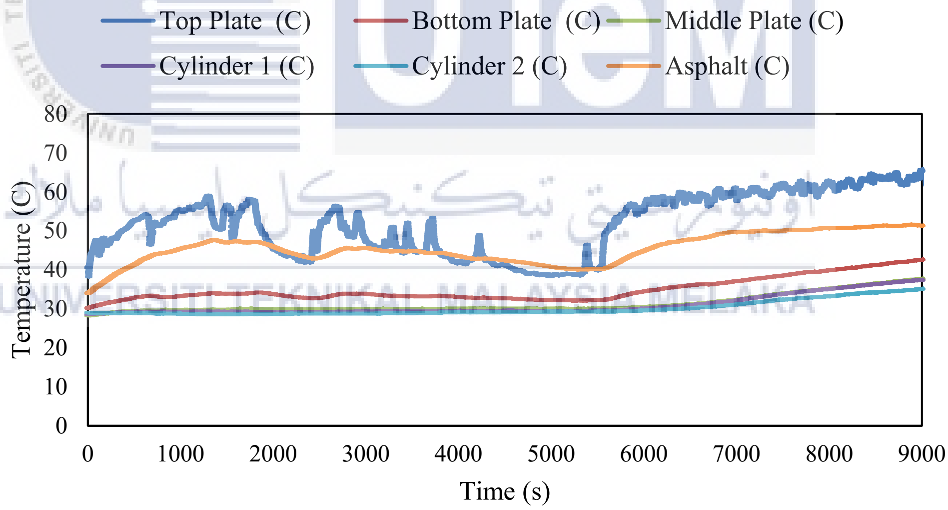

Figure 4.3: Temperature Whole Model for Day 2 Part 1

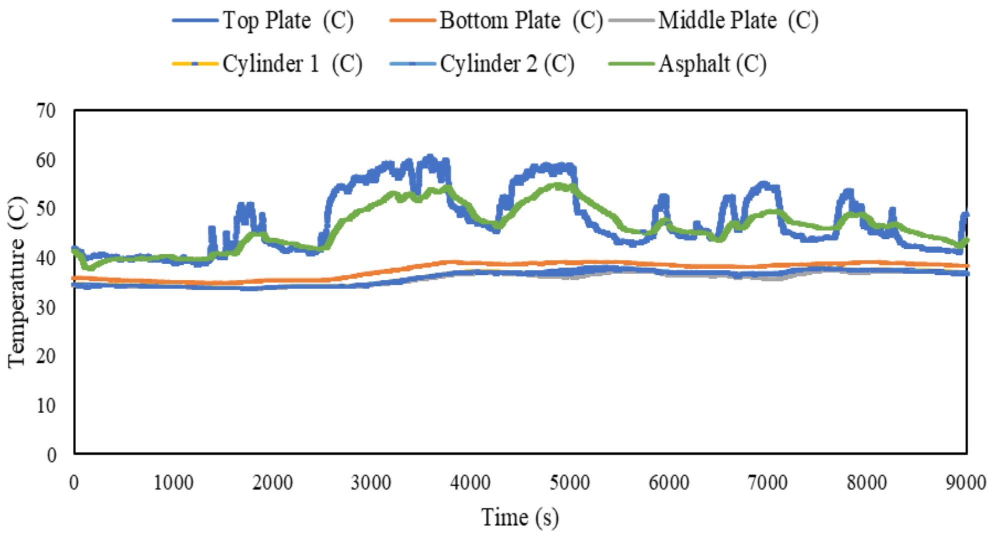

Figure 4.4: Temperature Whole Model for Day 3 Part 1

Table 4.4: Average Temperature for Whole Model for Three Days

	Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	Asphalt Avg (°C)	DT Avg (Top Plate & Cylinder 1&2) (°C)
Day 1	54.3	31.4	30.7	30.3	30.3	53.7	24
Day 2	47.6	30.5	30.1	31.3	31.3	38.2	16.3
Day 3	51.4	34.7	33.7	33.9	33.9	47.4	17.5

Figures 4.3 until 4.5 show the readings of TEHs that were obtained utilizing a clear surface top plate and PCM RT 25. Every day of the experiment is covered by these readings. Table 4.4 shows that Day 1 is the most efficient of the other two days due to its average DT of approximately 24°C, which suggests that TEG can produce higher voltage more efficiently. The K-Type thermocouple is connected to the exterior

surface of the cylinder rather than the PCM, which results in the collection of the DT temperature between the upper plate and cylinders. Both cylinders tubes presumably function as a subterranean cooling system. The average daily temperature on Days 2 and 3 is below 18°C due to the day's partly cloudy weather.

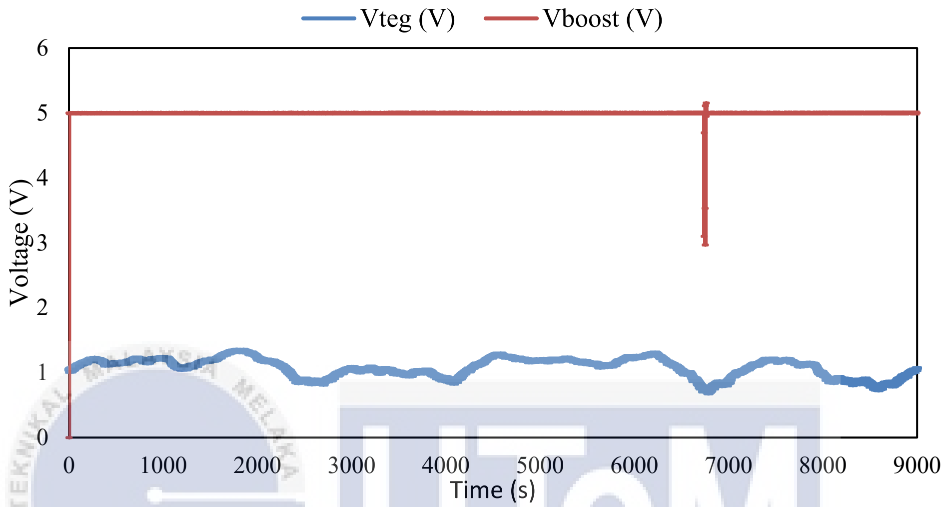

Figure 4.5: VTeg and VBoost for Day 1 Part 1

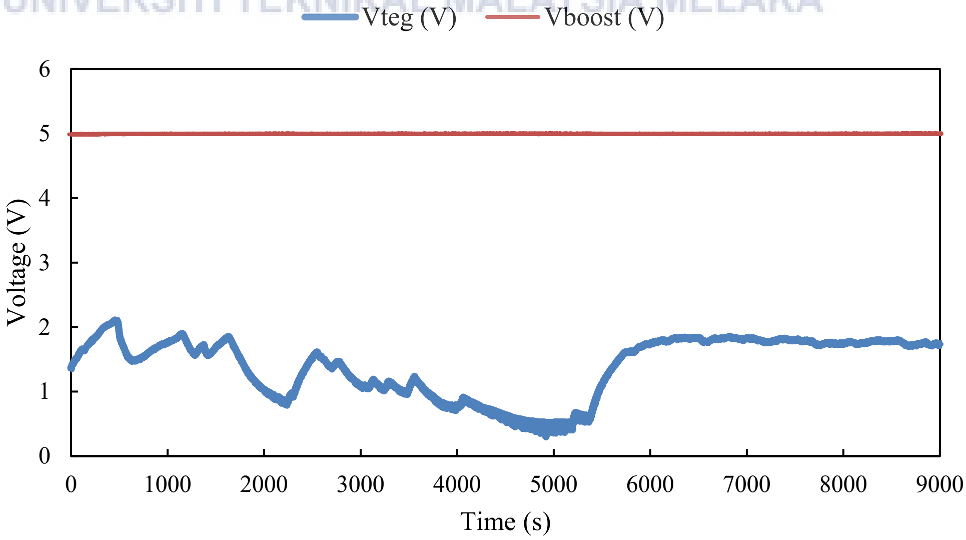

Figure 4.6: VTeg and VBoost for Day 2 Part 1

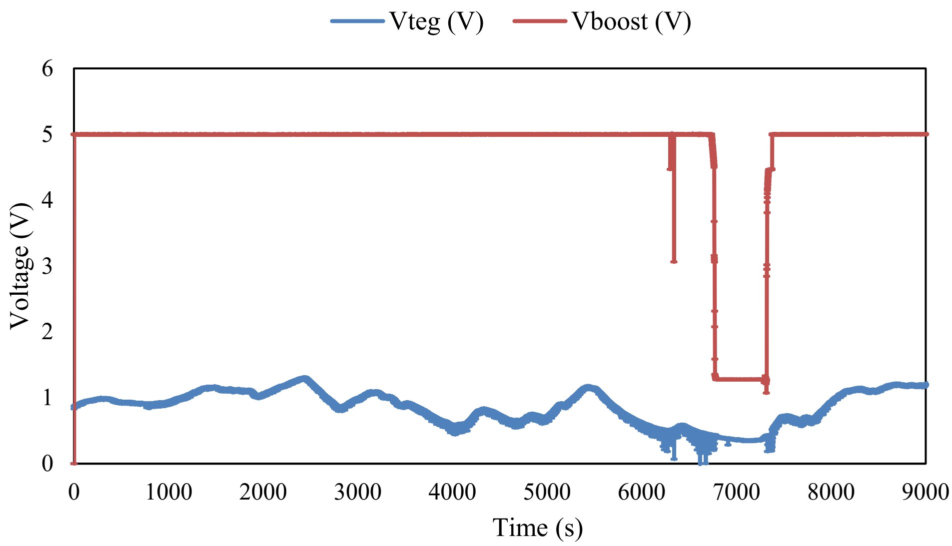

Figure 4.7: VTeg and VBoost for Day 3 Part 1

The output voltages from the TEG are illustrated in Figures 4.6 to 4.8. The average Voltage TEG (VTeg) on Days 1, 2, and 3 was 1.0 V, while the average Voltage Booster (Vboost) was approximately 4.8 V. The unstable voltage booster readings for approximately one thousand seconds on day three, however, suggest that the weather will be marginally cloudy and erratic.

Table 4.5: Average VTeg and VBoost for Three Days

	VTeg Avg (V)	Vboost Avg (V)
Day 1	0.9	4.9
Day 2	1.3	5.0
Day 3	0.8	4.7

The highest average VTeg and Vboost were 1.3V and 5.0 on Day 2 according to Table 4.5. The lowest average VTeg and Vboost was in Day 3 which is only generated average about 0.8V and 4.7V. Therefore, the clear surface top plate is not suitable because has low surface emissivity and PCM RT 25 is unsuitable as PCM thermal storage temperatures are extremely high.

4.2.2 Part 2: Experiment Result for Model with Black Painted Surface Top Plate and PCM RT 25.

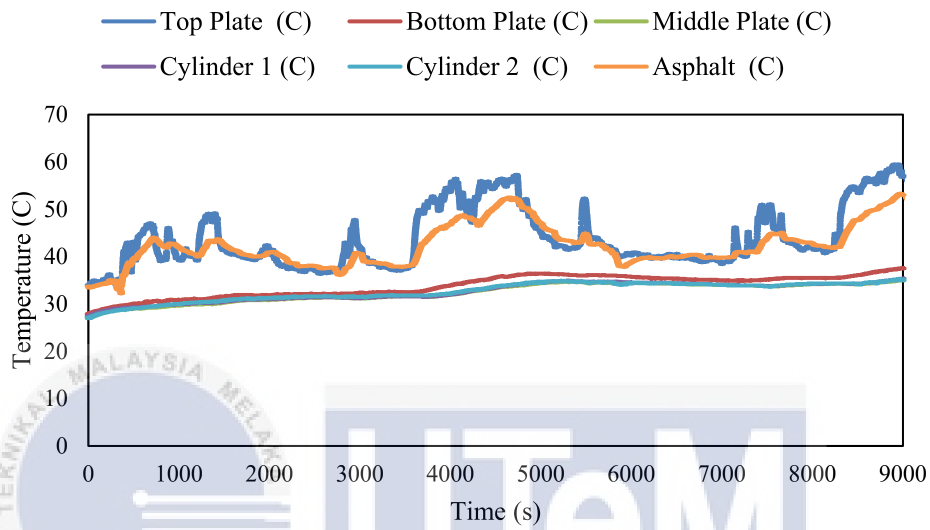

Figure 4.8: Temperature Whole Model for Day 1 Part 2

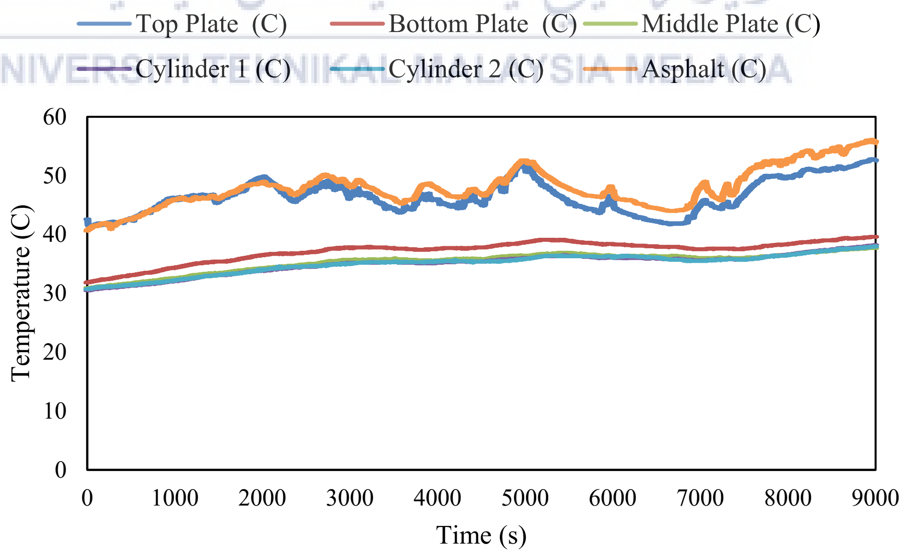

Figure 4.9: Temperature Whole Model for Day 2 Part 2

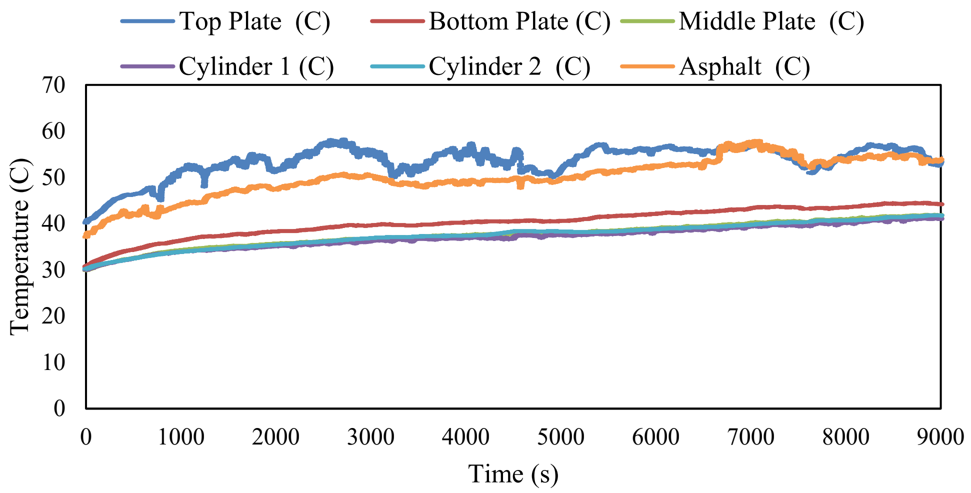

Figure 4.10: Temperature Whole Model for Day 3 Part 2

Table 4.6: Average Temperature for Whole Model for Three Days

	Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	Asphalt Avg (°C)	DT (Top Plate & Cylinder 1&2) (°C)
Day 1	49.8	33.2	32.7	30.1	30.1	48.2	19.7
Day 2	55.7	35.2	33.9	34.4	34.4	53.1	21.3
Day 3	56.3	36.1	34.7	32.9	32.9	55.9	23.4

Figures 4.9 to 4.11show the readings of TEHs that were obtained utilizing a black painted surface top plate with PCM RT 25. Table 4.6 shows that Day 3 is the most efficient of the other two days due to its average DT of approximately 23.4°C. The average daily temperature on Days 1 and 2 is slightly below Day 3 but shows consistency among three days experiment.

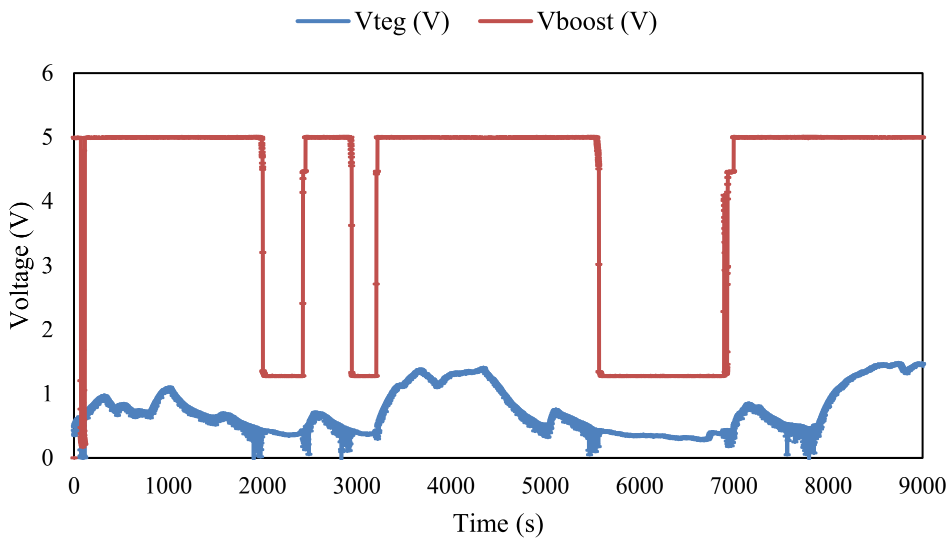

Figure 4.11: VTeg and VBoost for Day 1 Part 2

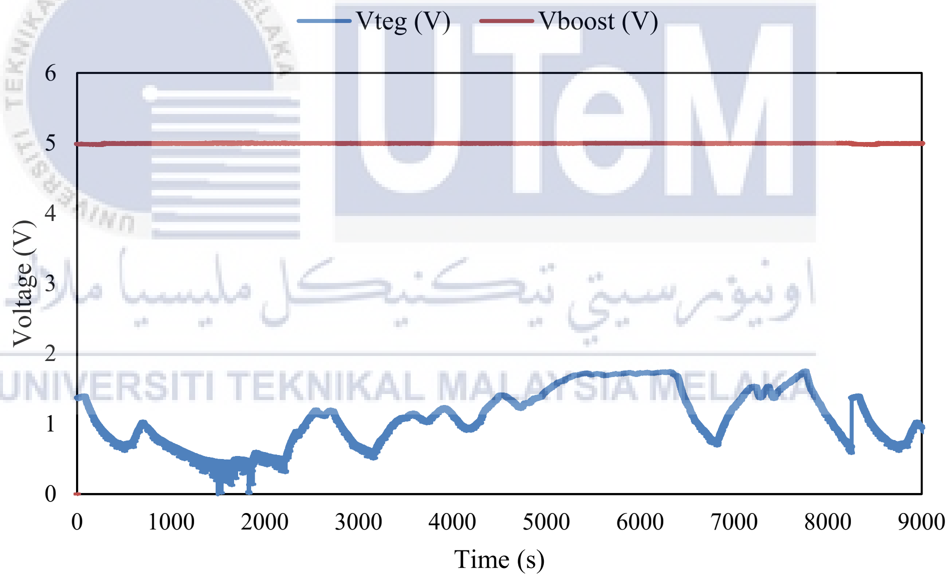

Figure 4.12: VTeg and VBoost for Day 2 Part 2

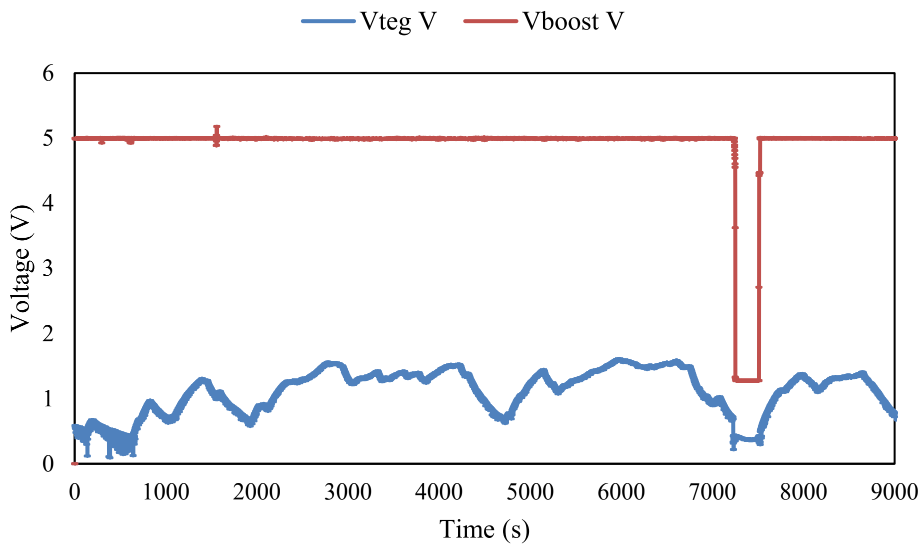

Figure 4.13: VTeg and VBoost for Day 3 Part 2

In Part 2 of the experiment, the output voltages from the TEG are illustrated in Figures 4.12 to 4.14. The average Open Circuit Voltage (Vteg) on Days 1, 2, and 3 was 1.2 V, while the average Voltage Booster (Vboost) was approximately 4.2 V. The unstable voltage booster readings especially in Day 1 because of the rainy day.

Table 4.7: Average VTeg and VBoost for Three Days

	VTeg Avg (V)	Vboost Avg (V)
Day 1	1.1	3.4
Day 2	1.2	5.0
Day 3	1.3	4.4

The highest VTeg was 1.3 V on Day 3 according to Table 4.7. The average second day's highest DT is 23.4 C. A summary of possible explanation for these results for PCM RT 25 with clear or black painted surface top plate are organic PCM. Typically, organic PCMs are derived from hydrocarbons or fatty acids. They offer a wide range of phase change temperatures and have relatively low melting points. However, organic PCMs may have a lower thermal conductivity, indicating that these materials may transfer heat less efficiently [25].

4.2.3 Part 3: Experiment Result for Model with clear surface top plate and PCM RT 30.

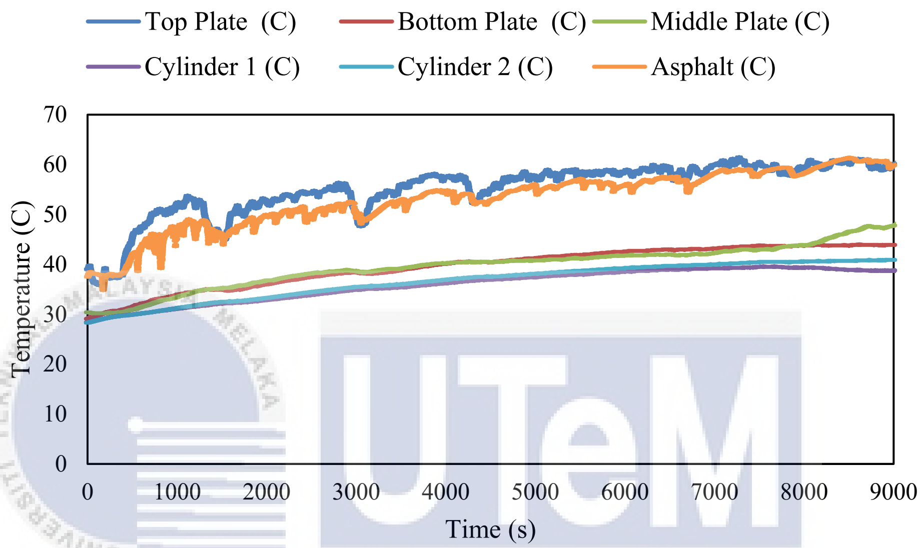

Figure 4.14: Temperature Whole Model for Day 1 Part 3

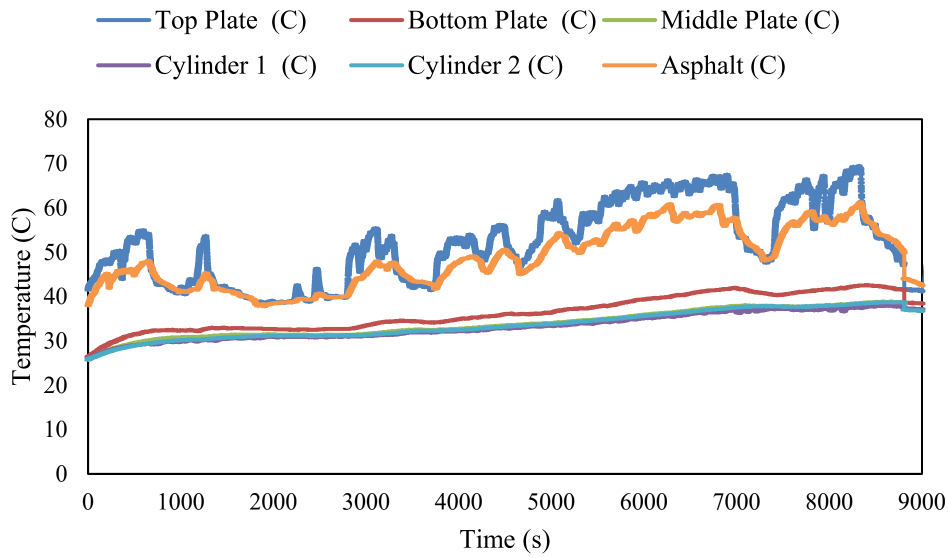

Figure 4.15: Temperature Whole Model for Day 2 Part 3

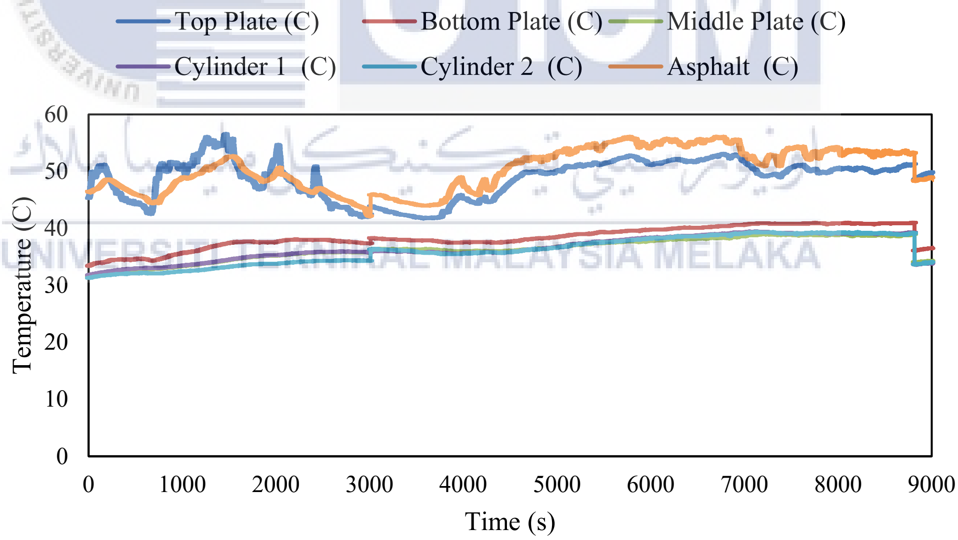

Figure 4.16: Temperature Whole Model for Day 3 Part 3

Table 4.8: Average Temperature for Whole Model for Three Days

	Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	Asphalt Avg (°C)	DT (Top Plate & Cylinder 1&2) (°C)
Day 1	50.3	35.7	35.1	33.1	33.1	50.8	17.2
Day 2	43.9	32.9	33	32.8	32.8	40.2	11.1
Day 3	47.5	36	34.7	29.9	29.9	45.6	17.6

Figures 4.15, 4.16, and 4.17 show the readings of TEHs that were recorded using black painted surface top plate with PCM RT30. These readings were displayed in the statistics. These readings pertain to each day of the experiment that was carried out.

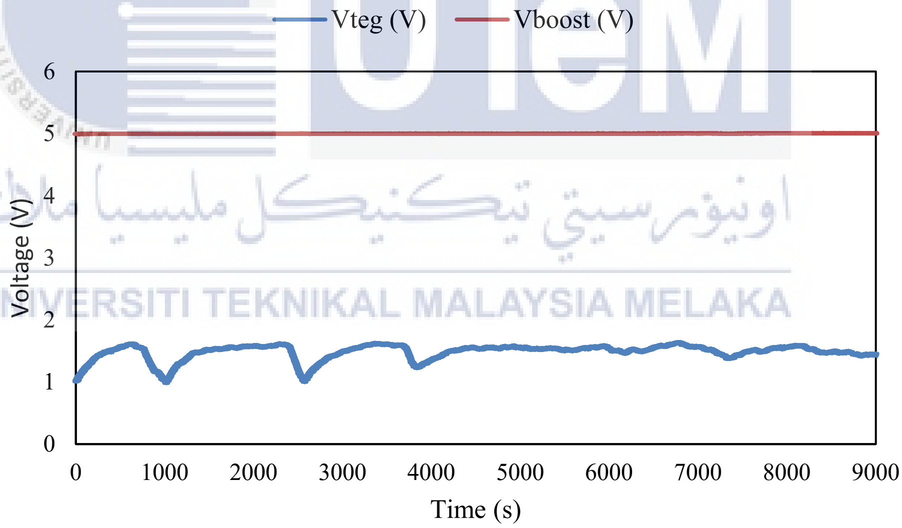

Figure 4.17: VTeg and VBoost for Day 2 Part 3

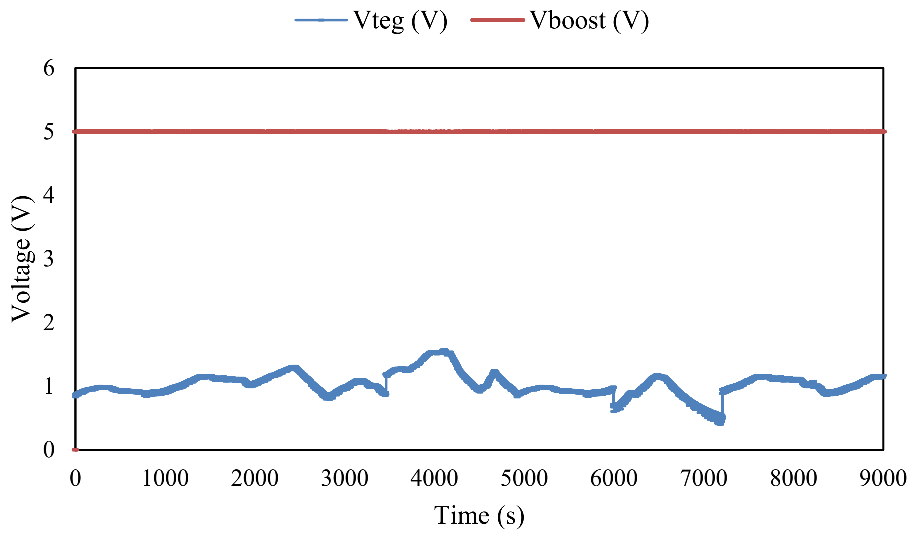

Figure 4.18: VTeg and VBoost for Day 2 Part 3

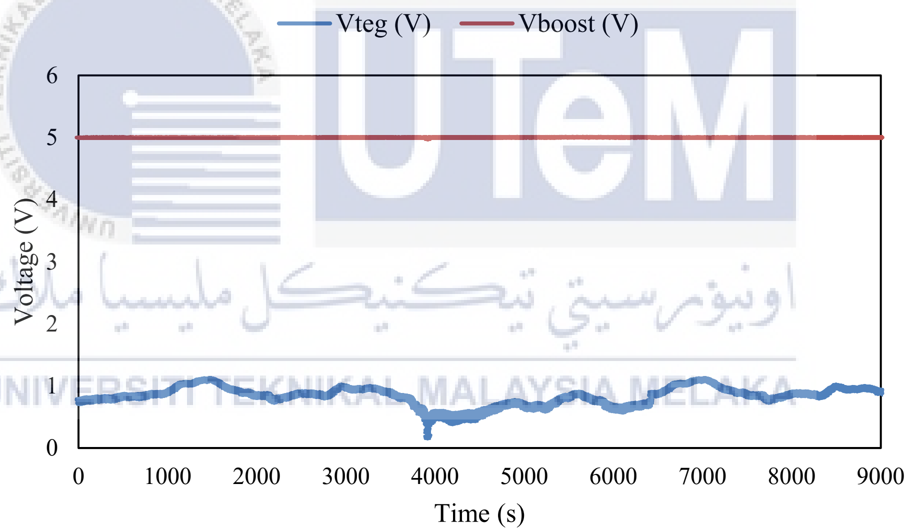

Figure 4.19: VTeg and VBoost for Day 2 Part 3

The third part evaluates the TEHs using the clear surface top plate with PCM RT 30 Melting Point within the thermal storage in both cylinders. The VTeg and VBoost for Days 1, 2, and 3 are depicted in Figures 4.18 to 4.20.

Table 4.9: Average VTeg and VBoost for Three Days

	VTeg Avg (V)	Vboost Avg (V)
Day 1	1.3	5
Day 2	0.9	5
Day 3	1.4	5

Table 4.9 shows that on Day 3, the highest average VTeg was 1.4 V. Additionally, every VBoost in these parts reaches the 5V maximum output. This is due to the favourable weather on those days. This section demonstrates that using PCM RT 30 is more efficient than PCM RT 25 in producing higher DT temperatures.

4.2.4 Part 4: Experiment Result for Model with black painted surface top plate and PCM RT 30.

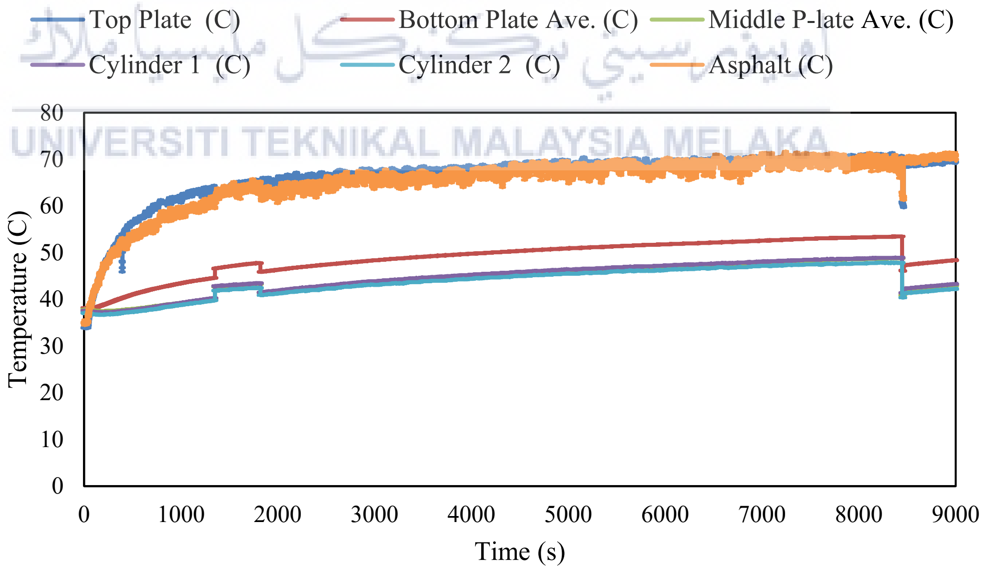

Figure 4.20: Temperature Whole Model for Day 1 Part 4

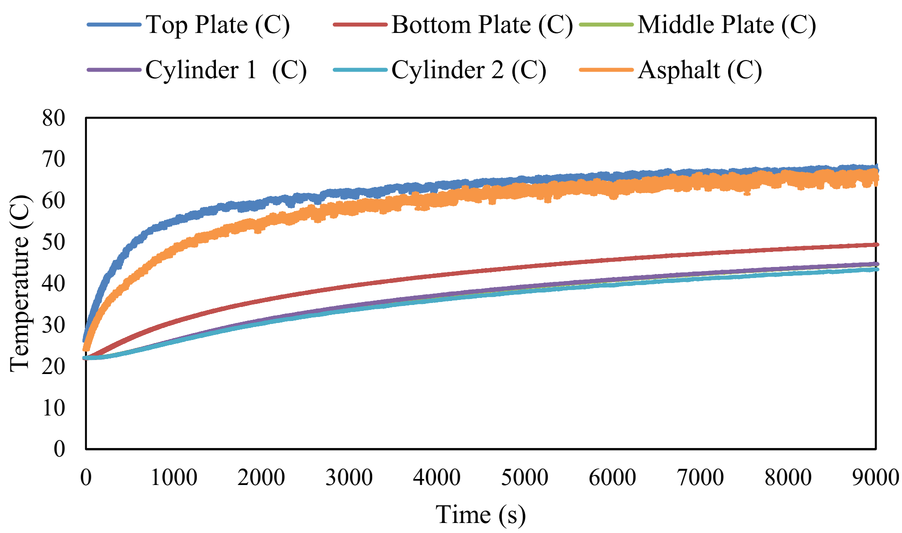

Figure 4.21: Temperature Whole Model for Day 2 Part 4

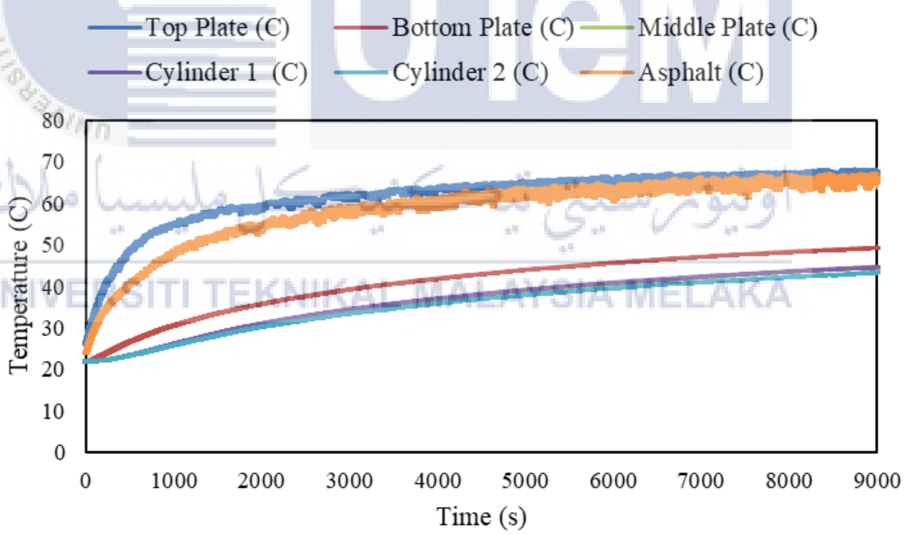

Figure 4.22: Temperature Whole Model for Day 3 Part 4

Table 4.10 : Average Temperature for Whole Model for Three Days

	Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	Asphalt Avg (°C)	DT (Top Plate & Cylinder 1&2) (°C)
Day 1	61.7	47.3	43.8	33.8	33.8	60.2	27.9
Day 2	58.3	38.9	35.3	32.6	32.6	58.7	25.7
Day 3	57.9	43.1	37.6	33.3	33.3	58.9	24.6

Figures 4.21 through 4.23 display the TEH results obtained using black painted surface top plate with the PCM RT 30. The statistics presented these readings. These readings apply to each day when the experiment is conducted.

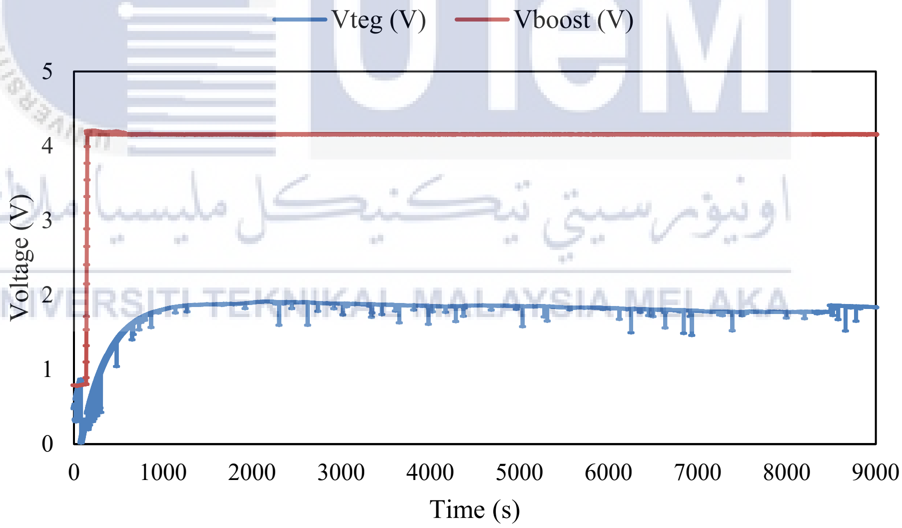

Figure 4.23: VTeg and VBoost for Day 1 Part 4

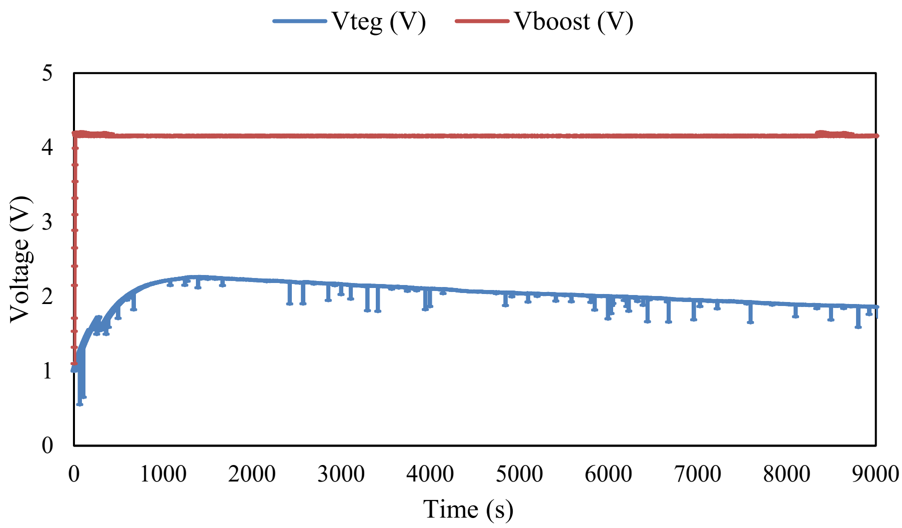

Figure 4.24: VTeg and VBoost for Day 2 Part 4

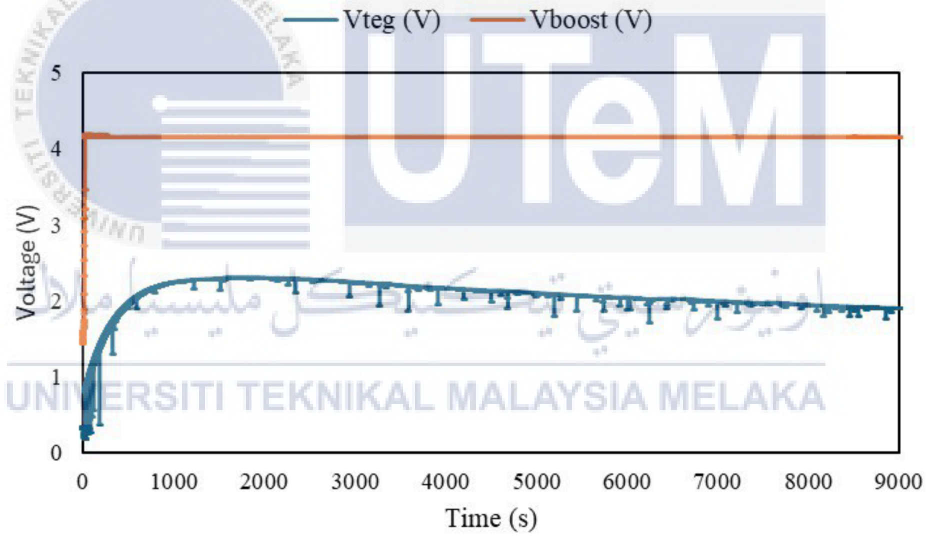

Figure 4.25: VTeg and VBoost for Day 3 Part 4

The fourth experiment assesses the TEHs using the black painted top surface with PCM 30 within the thermal storage in both cylinders. Figures 4.24 to 4.26 depict the increase and the consistent of the VTeg generated in those three days.

Table 4.11: Average VTeg and VBoost for Three Days

	Vteg Avg (V)	Vboost Avg (V)
Day 1	1.7	4
Day 2	1.6	4.2
Day 3	1.7	4.1

According to Table 4.11, the days with the highest average VTeg were Day 1 and Day 3, with 1.7, followed by Day 2, with 1.6 V. On day one, the most significant recorded temperature difference was 27.6 °C. According to the obtained data, TEHs with PCM RT 30 melting point have higher output voltage than TEHs with PCM RT 25. The PCM thermal storage with PCM RT 30 retained at below 40 °C during the 2.5 hours of experiment aided by the black painted surface top plate. The black painted surface has absorbed heat than clear surface. These parts of the experiment were conducted in August. Because of that, the day was consistently hot during the experiment. Lastly, TEHs with black painted top surface with PCM RT 30 were chosen to test the new system's charging capabilities.

4.2.5 Part 5: Experiment Result for Charging Supercapacitor using the model Model with black painted surface top plate and PCM RT 30.

The last experiment used the TEHs with the blacked painted surface top plate with PCM RT 30 to charge two 5F 2.5V supercapacitors in series. Figure 4.27 depicts the temperature differential (DT) during the 2.5 hours of the day. Meanwhile, the output voltages, open circuit voltage from the TEG (VTeg), and boosted voltage from the MPPC (VBOOST) were recorded, as shown in Figure 4.28.

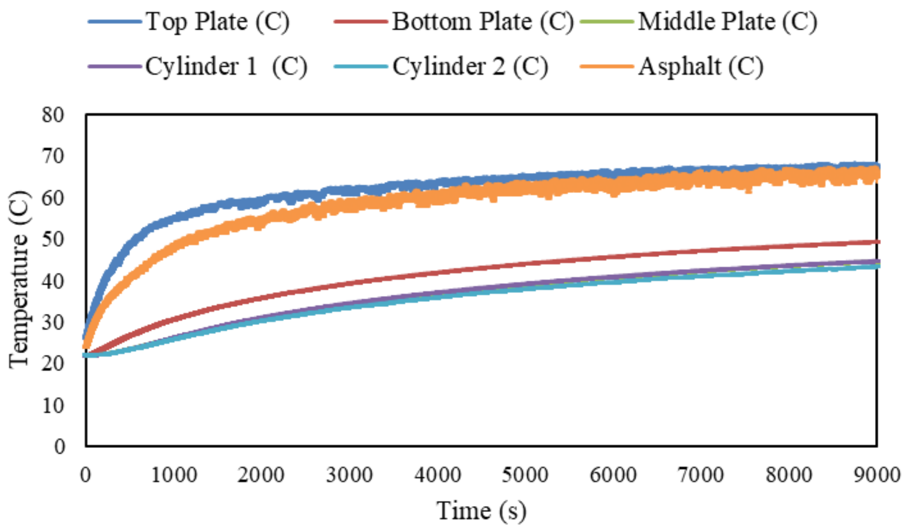

Figure 4.26: Temperature for TEHs with PCM RT 30 and black painted top plate when charging supercapacitor.

Table 4.12: Average Temperature for Whole Model

Top Plate Avg (°C)	Bottom Plate Avg (°C)	Middle Plate Avg (°C)	Cylinder 1 Avg (°C)	Cylinder 2 Avg (°C)	Asphalt Avg (°C)	DT (Top Plate & Cylinder 1&2) (°C)
59.7	36.7	34.9	34	34	57.9	25.7

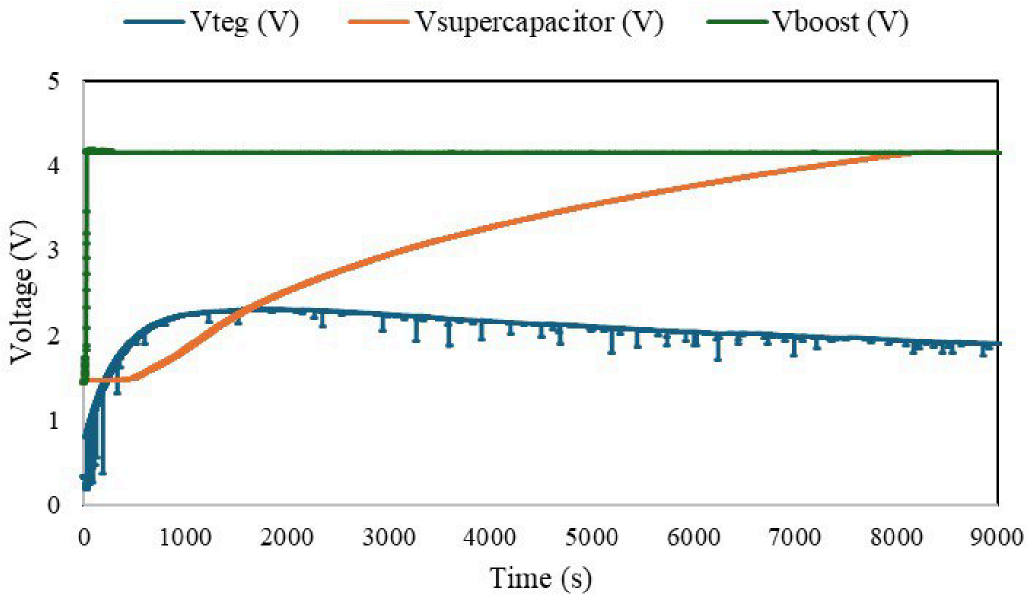

Figure 4.27: Open Circuit Voltage from TEG and Boosted Voltage from MPPC for the TEHs with PCM RT 30 and black painted top plate when charging supercapacitor.

Table 4.13: Data Collected for experiment to charge supercapacitor using the TEHs with and black painted top plate and PCM RT 30

Vteg Avg (V)	Vboost Avg (V)	VSuperCapacitor Avg (V)
2	4.3	3.1

One of the most important things learned from this study is that black painted surface top plate with PCM RT 30 was used to charge two 5F supercapacitors in series. The Boosted circuit is used to boost the voltage up to 4.2 V (Max) and used to charge the supercapacitor. and This study showed that about 3.1 V and 2.5 hours were needed to charge the supercapacitor in Table 4.13.

4.3 Findings of the experiment

Table 4.14 presents the comparison between the average result from the 3-day experiment and the simulation to validate the findings. It is evident from both tables that the experimental temperature differences are marginally greater than those predicted by the simulations. Equation 2 is used to compute the % error for experimental TEHs with PCM throughout the simulation.

$$Percent\ Error = \left| \frac{Experimental\ Value - Theoretical\ Value}{Theoretical\ Value} \right| \times\ 100\% \qquad (2)$$

Table 4.14: Comparison between Simulation and Experimental Results for TEHs with both PCMs.

Type of PCMs	Avg Simulation DT (°C)	Avg Experimental DT (°C)	Error (%)
PCM RT 25	18.7	21.4	14.4
PCM RT 30	24.0	26.0	8.3

The prime aim of this project is to design a better TEHs at asphalt pavement with greater performance of the TEG. Referring to Equation 1, the bigger the temperature difference between the cold side of the TEG, which in this experiment, is the bottom plate, and the hot side of the TEG, which is the top plate in this experiment, the greater the output voltage from the TEG. Compared with both PCMs, PCM RT 30 is better and more accurate than PCM RT 25.

Table 4.15: Comparison Both Analysis with PCMs and Previous Article [3]

Type of Method	Avg Simulation DT (°C)	Avg Experiment DT (°C)
PCM RT 25	18.7	21.4
PCM RT 30	24.0	26.0
Previous Article [3]	12.8	13.7

Hence, this proved that PCM does influence the TEHs to retain the subterranean cooling and produce greater temperature difference between the hot side and the cold side of the TEG. This is because, in theory, PCM can retain the cold side of the TEG by acting as cold storage. Besides that, compared with previous paper [3], the average both analysis is better than previous paper [3]. This is because the [3] used a solid cylindrical rod as the cooling system. So that, the DT cannot retain longer to generate voltage output.

4.4 Discussion

Two types of PCM are utilized, RT25 and PCM30 (paraffin wax). In comparison to PCM RT 30 with black painted surface top plate, PCM RT 30's average generated output voltage has attained 1.2V with a DT of 21.4°C, whereas PCM RT 25 with clear surface top plate was only capable of 1.0 V with a DT of 19.2°C. The other type is PCM RT 30, which is also composed of PCM with black painted surface top plate and can deliver the highest temperature difference and output voltage. The average output voltage has reached 1.6 V with a DT of 26.0°C, compared to 1.2 V with a DT of 15.3°C for clear surface top plate with RT 30. Both types of PCM, where PCM 25 is unsuitable for PCM thermal storage due to its lesser thermal conductivity, may transfer heat less efficiently, indicating that these materials may be less thermally conductive.

To explain between both PCMs, PCM RT 30, which consists of inorganic paraffin wax, is considered a more advantageous alternative as compared to PCM RT 25 organic due to its inherent benefits [25]. PCM RT 30's inorganic composition guarantees superior thermal conductivity, a critical element for effective heat transfer, and has a high melting point, boosting its stability in fluctuating temperature environments. Furthermore, the inorganic PCM RT 30 has exceptional temperature stability, a trait that greatly enhances its overall dependability. The combination of these qualities leads to an increased temperature difference (DT) in the system, resulting in the generation of greater voltages. On the other hand, PCM RT 25, being composed of organic materials, may exhibit lower thermal conductivity and stability. Hence, the research highlights the superiority of inorganic PCM RT 30 compared to organic PCM RT 25, emphasizing its capacity to provide higher voltage outputs and its general applicability for applications that demand strong and consistent thermal performance.

Besides that, for the types of surface top plate, emissivity is a fundamental notion that quantifies a material's capacity to release thermal radiation, and it performs a vital role in comprehending the interaction between surfaces and heat [26]. A black surface is regarded as more advantageous to a clear surface in terms of emissivity since it has an emissivity value of 1, meaning it emits thermal radiation at the highest possible rate. On the other hand, a transparent surface has a reduced ability to emit thermal radiation compared to a dark surface under same temperature conditions. This differentiation emphasizes the efficacy of black surfaces in emitting heat, rendering them very efficient in many applications that require thermal regulation. PCM 30 with metal foam was used to charge two 5F supercapacitors in series, which is one of the most significant findings from this study. This investigation revealed that the charging capabilities required approximately 3.3Vand can go up to 4.1V in over 2.5 hours.

4.5 Environment and Sustainability

Sustainability involves satisfying our own needs without compromising the potential of future generations to fulfil their own. This project presents an environmentally friendly technology that provides a fresh approach to designing self-sustainable TEHs. It may be utilized for several purposes and aligns with the seventh target of the United Nations' Sustainable Development Goals, which focuses on ensuring access to affordable and clean energy (SDG 7). The objective is to guarantee universal access to inexpensive, dependable, sustainable, and contemporary energy. There are five targets that must be accomplished by 2030 to reach this aim. There are a total of 6 indications that require measurement. Ensure widespread availability of contemporary energy, enhance the global proportion of renewable energy sources, and achieve a twofold increase in energy efficiency advancements. The two remaining objectives aim to facilitate access to research, technology, and investments in clean energy, as well as to enhance and improve energy services for developing nations. In essence, these objectives encompass ensuring inexpensive and dependable energy access, while simultaneously augmenting the proportion of renewable energy in the worldwide energy composition. The Thermoelectric Generator (TEG) employed in this project efficiently captures thermal energy from solar radiation, a sustainable and inexhaustible source, to generate electrical energy. This system is an integral component of environmentally friendly technology that does not produce any detrimental effects on its surroundings either during its application or its manufacture.

4.6 Summary

In conclusion, an in-depth analysis of both simulation and experimental data produced insightful findings for the study into thermoelectric output enhancement using an aluminum tube as a phase change material (PCM)-based storage system for thermoelectric road harvesting. The improved performance of the suggested system was anticipated by the simulation phase, which gave theoretical groundwork. Practical tests were then carried out to confirm these hypotheses, and the outcomes showed a significant increase in thermoelectric output. A complete comprehension of the suggested aluminium tube PCM-based storage strategy was made possible by the effective synergy between the simulated and experimental data. The results analyzed demonstrated the practical viability of this creative method in addition to confirming the system's ability to maximize thermoelectric output. The development of thermoelectric energy harvesting technology for road applications is greatly aided by an all-encompassing strategy that combines modelling and testing, opening the door to more effective and sustainable energy solutions.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

This chapter synthesizes the key findings of the research, highlighting its achievements and implications for both field experiment and simulation contributions. The limitations and areas for improvement are acknowledged, providing insights into potential constraints and factors that may have influenced the study.

5.1 Conclusion

To summarize, this study effectively resolved the problems specified in the problem statement about the efficiency limitation of thermoelectric generators (TEGs) and the requirement for a higher temperature gradient. The initial goal was accomplished through the utilization of finite element analysis (FEA) to simulate the effect of an aluminium tube as a storage medium based on phase change material (PCM) on improving thermoelectric output. The second objective is to enhance the prototype's design structure through the utilization of design of experiment (DOE) in Ansys Simulation, resulting in a system that is more efficient and effective. The third objective entailed verifying Ansys optimization simulations through field testing, so giving empirical verification of the model's practical relevance. The work effectively presented a technique to overcome the temperature gradient constraints of TEGs by using an aluminium tube as a storage solution based on PCM. The incorporation of Phase Change Material (PCM) successfully alleviated the temperature fluctuations caused by the sun's varying irradiance, leading to enhanced output voltage. This work successfully met its aims and proposed a potential approach to improve the thermoelectric output for road harvesting applications, thereby contributing to the progress of sustainable energy technology.

5.2 Future Plan

The prospects for thermoelectric energy harvesting are very attractive and offer significant potential. It is essential to determine the most suitable Phase Change Material (PCM) to achieve a substantially longer and more efficient temperature maintenance. In addition, the objective is to develop an Internet of Things (IoT) system capable of transmitting data via a smartphone or laptop display within the laboratory. This is particularly important due to the challenges of recording data during extremely hot weather conditions. Assessing the cost-effectiveness of thermoelectric energy harvesting systems is of utmost importance. Subsequent investigations ought to assess the expenses and advantages associated with various materials, designs, and plans to ascertain the most economically efficient choices.

Besides that, this model can be improved soon by developing a more effective step-up converter circuit to increase the open circuit voltage even when the TEG produces low voltage. Given that the current circuit is limited to boosting at approximately 250mV of TEG output voltage, it is desirable that future circuits will be capable of boosting at a lower threshold, preferably below 100mV. As a result, it can deliver a higher rate of boosted voltage from the TEG output and a faster rate of charging.

To summarize, there are numerous promising prospects for future advancements in the field of thermoelectric energy harvesting. By tackling the hurdles and researching novel materials, architectures, and systems, it is feasible to transform this technology into a substantial source of energy for global requirements.

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