# AN ANALYSIS OF PHASE CHANGE MATERIAL (PCM) FOR SUBTERRANEAN COOLING OF THERMOELECTRIC ENERGY HARVESTING SYSTEM AT ASPHALT PAVEMENT

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# UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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2022

## **DECLARATION**

I declare that this report entitled "Analysis of Phase Change Material (PCM) for Subterranean Cooling of Thermoelectric Energy Harvesting System (TEHs) at Asphalt Pavement" is the result of my own work except for quotes as cited in the references.



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21<sup>st</sup> June 2022

# APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with

Honours.	UTeM
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Date:	21 JUNE 2022

### DEDICATION

I dedicate this project to God Almighty Allah my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. He has been the source of my strength throughout this program. I also dedicate this work to my mom, my family, who has encouraged me all the way. Not to forget, my beloved partner whose encouragement has made sure that I give it all it takes to finish that which I have started. My supervisor, who has encouraged me attentively with her fullest and truest attention to accomplish my work for this Bachelor's degree.

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### ABSTRACT

Thermoelectric generator (TEG) has offered a promising clean energy solution where it has persistently improved. In this project, a thermoelectric energy harvesting system (TEHs) that utilized the heat from the surface of asphalt pavement is studied. This thesis aimed to design a new TEHs with PCM as cold storage to retain subterranean cooling by simulation and experimentally. The design model consisted of asphalt base holder to hold the asphalt, top plate for heating, and 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 a container filled with PCM with melting point of 30°C. Simulation and experiments were conducted to investigate the PCM's effects at TEG's output voltage. Furthermore, the best-selected model was used to study the charging capabilities of the TEHs on two 5F supercapacitors in series. From both simulations and experiments, it was discovered the new TEHs with

PCM incorporation able to reach temperature difference (DT) 42°C with 1.5V opencircuit voltage. This gives an increment of over 170% more than a design without PCM incorporation. The 5F supercapacitors were successfully charged within 2 hours from 1.5V This project offers a new perspective for self-sustainable TEHs design that can be used for various purpose.

### ABSTRAK

Penjana termoelektrik (TEG) telah menawarkan penyelesaian tenaga bersih yang sangat menjanjikan di mana ia telah bertambah baik secara berterusan. Dalam projek ini, sistem penuaian tenaga termoelektrik (TEHs) yang menggunakan haba dari permukaan turapan asfalt dikaji. Tesis ini bertujuan untuk merekabentuk sistem TEH baharu dengan PCM sebagai storan sejuk untuk mengekalkan penyejukan bawah tanah secara simulasi dan eksperimentasi. 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 tenggelam ke dalam turapan. Plat bawah kemudiannya disambungkan kepada elemen penyejuk yang berbentuk H dan bekas

yang diisi dengan PCM dengan takat lebur 30 darjah Celsius. Ini memberi kelebihan penyejukan bawah tanah kepada sistem dan mencapai perbezaan suhu tinggi antara plat atas dan bawah TEH. Simulasi dan eksperimentaso telah dijalankan untuk menyiasat kesan PCM terhadap voltan keluaran TEG. Tambahan pula, model pilihan terbaik digunakan untuk mengkaji keupayaan pengecasan TEH pada dua superkapasitor 5F secara bersiri. Daripada simulasi dan eksperimentasi, didapati TEH baharu dengan gabungan PCM mampu mencapai perbezaan suhu (DT) 42°C dengan voltan litar terbuka 1.5V. Ini memberikan peningkatan 170% lebih daripada reka bentuk tanpa penggabungan PCM. Kapasitor super 5F berjaya dicas dalam masa 2 jam dari 1.5V hingga 3.3V Projek ini menawarkan perspektif baharu untuk reka bentuk TEH lestari sendiri yang boleh digunakan untuk pelbagai tujuan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

- MPPC : Maximum Power Point Collector
- NIDAQ : National Instrument Data Acquisition
- TEG : Thermo-electric Generator
- TEHs : Thermo-electric Energy Harvesting system



# **CHAPTER 1**

## **INTRODUCTION**



This chapter briefly explains the introduction of the project, problem statements on why the project is conducted. Other than that, this chapter also gives clarifications on the objectives and scopes of the project and along with its commercialization potential.

#### **1.1** Introduction of the Project

Research and development of sustainable energy harvesting technology began in the early twenty-first century. Since then, various energy harvesting technologies have evolved, matured, and even been successfully turned into hardware prototypes for extending the operating lifetime of low-power electronic devices such as mobile phones, smart wireless sensor networks, and other low-power electronic devices. What exactly is energy harvesting? In 2020, H. Akinaga [1] wrote in his paper that tiny amounts of dissipating energy can be harvested and used as available electric energy from the environment around us. According to him, energy harvesting is a technology that gathers freely accessible renewable energy from the surrounding environment to replenish or put consumed energy back into energy storage devices without disturbing or even stopping the application's usual functioning. Progress in sustainable energy harvesting technologies research is still intact and continuous, thanks to the earlier knowledge and experience gained over a decade ago. These technologies are maturing, and strong synergies with certain application sectors are forming. It is an interesting method that has the potential to generate renewable and clean energy while also enhancing the sustainability of infrastructure. The evidence can be seen through the increasing development of photovoltaic panels, solar thermal, geothermal, and other similar solutions to harvest the ambient energy. This project deliberated on harvesting thermal energy.

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 was mostly below 100 degrees Celsius. Additionally, Farahani

and her team [3] made an analysis of meteorological parameters in Peninsula Malaysia. They stated that the climate features a tropical rainforest climate where it experiences a dry and hot season and a rainy season. The dry and hot season occurs when seasonal winds from southwest Sumatra, Indonesia, blow and move towards the west coast of Peninsular Malaysia, and are blocked by the Titiwangsa Mountain Range. The temperature can reach up to 40 °C but mostly varies from 23 °C to 32 °C. Aside from having hot and humid temperatures, Malaysia also seems to have a decent road length of the freeways. As of 2021, PLUS updated that the North-South Express (NSE) is the longest expressway in Malaysia with a total length of 748 kilometers running from Bukit Kayu Hitam in Kedah near the Malaysia. The highway connects numerous major cities and towns in western Peninsular Malaysia, serving as the peninsula's "backbone.". It provides a faster alternative to the old federal route, thus reducing traveling time between various towns and cities.

Given all of these advantages, Malaysia can highly make a profit by harvesting those thermal energies. How can it be harvested? Abundant methods for harvesting heat energy from asphalt pavement were reviewed multiple times and this project entertained the idea of using a Thermo-electric Energy Harvesting system (TEHs) which utilizes the function of a thermoelectric generator (TEG). It is one of the best ways on gaining traction as a method for providing an independent power supply for various IoT devices, which may gather and transform the minute energy of such heat into electrical power. A TEG module can brilliantly convert heat flux or temperature difference directly into electrical energy. This occurrence is called Seebeck effect. Alas, there are some flaws to this device.

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#### **1.2 Problem Statements**

There are a few problems with the previous research on TEHs at asphalt pavement [4]. Firstly, the ambient temperature can easily give impact to the small-scaled TEG module. Environmental factors such as cloudiness, dryness, sunshine, wind, rain and even the asphalt itself can influence the heat conducted to the system. There are seemingly high possibilities that these factors can badly reduce the output voltage of the TEG when weather is not in the good term.

Second, the temperature on the cold side of the TEG can rises rapidly when the ambient temperature around the heat sink is heated by the solar and the convection between them decreases [5]. This problem brings TEG to the downside as it does not let the module working to its fullest. Since TEG mainly relies on the heat flux between the cold side and the hot side, it is crucial to maintain or improve the convection between the sides.

To add, a straight-up physical model construction would lead to high-cost consumption and the generalizability of much-published research on this issue is problematic. To avoid, this TEHs will be simulated using Finite Element Analysis (FEA). FEA is used to help simulate physical phenomena while allowing for the optimization of components as part of the design process of a project. In this project, COMSOL Multiphysics software will be used similarly in [4].

#### **1.3** Objectives of the Project.

The objectives of this project are:

- a) To design a new TEHs with PCM as cold storage to retain subterranean cooling by simulation and experimentally.
- b) To analyze the latent heat effect of a PCM to increase output voltage of TEG.
- c) To investigate the charging capabilities using new TEHs with PCM subterranean cooling.

#### **1.4** Scopes of the Project

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This project is divided into two sections. The first section mainly focuses on the simulation of the TEHs. This is where the model of the TEH is designed and simulated to predict the thermal response conditions before commencing it into an actual experiment. Moving on to the next stage, the experiment or field testing with the physical model. The data from both stages is compared for validations.

### PSM INVERSITI TEKNIKAL MALAYSIA MELAKA

- a) Collects related articles on TEHs and PCM then analyzes the data.
- b) Simulate design by using a cross-platform finite element analysis, solver, and multi-physics simulation software called COMSOL.
  - i. To predict thermal response conditions before commencing into an actual experiment.
- c) Obtain preliminary data and finding on PCM.
  - i. A sufficient latent heat

- ii. A suitable fusion temperature
- iii. A sufficient volume

#### PSM II

- a) Validation of the simulations.
- b) Students will be exposed to the sun during the daylight experiment for data gathering.
- c) Experimental work on testing the Phase Change Material (PCM).

#### **1.5** Expected Outcome

ALAYS

- I. COMSOL prototype model simulations.
- II. A prototype of TEHs at asphalt pavement with PCM.
- III. A better, cost-effective architectural design of TEHs that can generate high power using a subterranean cooling approach.
- 1.6 Applications & Commercialization Potential

Thermoelectric energy has a vast range of applications in various fields like; electricity generation, refrigeration, air conditioning, particular heating/cooling, biomedical devices, etc. due to its simple construction and mechanism, portability, require DC supply to run, etc. With this project, it can be implemented at the asphalt pavement along the freeway. The output power obtained can be used for multiple applications such as streetlights, traffic lights or even for charging small storage cells. Based on [5], the electricity cost can be saved up to RM592 per year if H-shaped TEHs are employed. The upgraded TEHs with PCM could save way more than the said number.

### **1.7 Project Significant**

- I. It can be implemented at 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 supercapacitor, a storage for electrical energy.



## **CHAPTER 2**

### LITERATURE REVIEW



the energy harvesting systems at asphalt pavement. The chapter includes thermoelectric generator, phase change material, and finite element analysis.

#### 2.1 Thermoelectric Generator (TEG)

#### 2.1.1 Concept of a TEG

A thermoelectric generator (TEG) has offered a promising clean energy solution where it has persistently improved [7]. Global energy shortage, environmental pollution, and climate change are the most urgent challenges mankind has ever faced. The hope of future energy security lies in the economical, efficient, and clean use of existing energy, as well as the development of new energy sources. For this to end, environmentally friendly collection and use of clean energy have been explored by industries from different perspectives.

Now, what actually is a TEG? Thermo-Electric Generators are devices that can transform heat flux into electrical power and vice versa. In simple terms, whenever there is a temperature difference, this device can convert it into electrical energy. These semiconductors operate based on the thermoelectric effect also known as Seebeck effect. As there are no moving parts, these devices are particularly simple to manufacture and upkeep. These generators also have a great deal of potential for exploiting waste heat. The manufacturing of thermoelectric modules is done by coupling two conjugate p-type and n-type doped semiconductor materials in an optimized manner. Figure 1 illustrates an example of the TEG module.



Figure 1 : Peltier TEG Module GL-II Series [33]

Rohit and his team [7] studied the performance along with the principle of thermoelectric generation. The thermoelectric generator works on the principle of the Seebeck effect which is shown in Figure 2 and Equation 1. When two junctions are formed by joining two dissimilar materials maintained at different temperatures, a voltage of the order  $\mu$ V/K is generated. The materials used here are called thermoelectric materials. The selection of these materials is based on their properties like thermal conductivity, electrical conductivity, Seebeck coefficient, etc.

$$S = -\frac{\Delta V}{\Delta T} = \frac{V_{hot} - V_{cold}}{T_{hot} - T_{cold}}$$
(1)

S = Seebeck's Coefficient  $[\mu V/K]$ 

 $\Delta V =$  Thermovoltage [V]

 $\Delta T$  = Temperature Difference [K]

The amount of power generated by the TEG depends on the temperature difference between the opposite faces of the TEG. When one surface is maintained at a higher temperature heat gets conducted to the other surface which reduces the temperature difference. Hence a heat exchanger needs to be designed to maintain low temperature on the other face. The way how simple and effective this device is, has led to numerous researchers to study and find ways to make it more beneficial to our technologies. Specifically, TEHs at asphalt pavement.



#### Figure 2 : Illustration of the Seebeck effect [34]

#### 2.1.2 TEG in energy harvesting system at asphalt pavement.

Energy harvesting reclaims otherwise dissipated or wasted energy and is a highly sustainable power generation approach. While energy harvesting technology has successfully been explored in countless electronics and mechanical systems applications, its application to roadway pavements is currently in its infancy. Since asphalt pavement is a huge storage of solar energy, pavement energy harvesting technology promises a significant breakthrough in attaining renewable energy at a massive scale [8]. The specific attributes of harnessing energy from pavements are:

- a) The size of roadways is massive, and hence, a relatively large amount of energy can be collected,
- b) There are exist various types of available energy sources, e.g. geothermal, solar, mechanical, etc.,
- c) Long-distance power transmission is not necessary because the collected electrical energy can be consumed in place by traffic facilities.

In pavement engineering, energy harvesting technology becomes a focal point of interdisciplinary research. Jiang et al [8] claimed that by far, research on energy harvesting from road pavement has focused on the following aspects portrayed in Table 1.



No.	Aspects	Description	
1	Piezoelectric techno	By embedding piezoelectric materials in the pavement structure, a portion of generated from tire-road interactions can be converted into electric energy.	f the mechanical energy
2	Photovoltaic technol	Using solar panels to replace traditional asphalt and concrete materials on p absorb the solar radiation and transform it into electric energy.	paved roads, which will
3	Thermoelectric technology	By laying thermoelectric generators (TEGs) inside or outside the pavement stru energy absorbed by the road surface can be converted into electric energy.	cture, part of the thermal
	U	VERSITI TEKNIKAL MALAYSIA MELAKA	

## Table 1 : Technologies on energy harvesting from road pavement.

Compared with piezoelectric and photoelectric modes, pavement thermoelectric technology has its superiorities despite the currently low efficiency. The thermal energy absorbed by road surfaces can be directly converted into electric energy without changing pavement materials and structures. On the one hand, the heat transition can reduce plastic deformation caused by rising temperature within asphalt pavement in hot weather, and thus prolong the service life of the road. On the other hand, through the diversion of heat from the road surface, the urban heat island effect which is caused by the heat absorption and storage inside the asphalt pavement can be mitigated [8].

As mentioned, over the past decade, most research in TEHs at asphalt pavement has emphasized the use of TEG. Samer and his team [9] have studied the development of a thermoelectric energy harvesting prototype for asphalt pavement roadways. Their study was based in South Texas where the asphalt pavement surface temperature in the summer is as high as 55°C due to solar radiation. Soil temperatures below the pavement, however, are roughly 51 constants (i.e., 27°C to 33°C) at relatively shallow depths (15 cm). Their prototype absorbed heat from the pavement surface and transfers it to a TEG module implanted in the subgrade at the pavement shoulder's edge. They got the outcome of a 64mm x 64mm TEG prototype which is capable of generating an average of 10 mW of electric power continuously over a 58 period of 8 hours, for the weather conditions encountered in South Texas.

With similar objectives, Wei and his teammates [10] succeeded in creating an RTEG with the output voltage around 0.4 V by asphalt mixture slab (300 mm  $\times$  300 mm by size), when the temperature difference between the road surface and ambient air was 15 degrees Celsius in winter. While in summer, the output voltage was about 0.6 V to 0.7 V, with a temperature difference of 25 degrees Celsius to 30 degrees

Celsius. This means that some 160 kWh of energy can be obtained in 8 hours from a road of 1 km in length and 10 m in width.

Song et al [11], studies went with several objectives which were to investigate the key factors affecting the energy conversion efficiency, to derive optimal mechanical and circuit configurations, and to compose a thermoelectric energy harvesting system tailored for the pavement application. The results indicate that the controlling of the heat transfer from the pavement to the thermoelectric generator is central to effective thermoelectric energy harvesting. Among the tested thermoelectric systems, the best device configuration yielded 42 mW; about 26 times higher power than the default case in this study. The main purpose of this study is to investigate the various factors that could affect the efficiency of the energy harvesting system. It does not use PCM while the student's project does.

Khamil et al, [4] reviewed thermoelectric energy harvesting systems (TEHs) at asphalt pavement with a subterranean cooling method. Their study goes with a couple of objectives which were to investigate the effects of the heat conduction using different shape structures in the subterranean level and to take advantage of subterranean cooling. The results have provided the first evidence that the structure of the cylindrical road gave an optimum temperature difference for the proposed TEHs for direct implementation to Malaysia's road.

The idea of TEHs itself is brilliant, but this system can still be improvised with the help of certain materials. For this project, the TEHs will be coupled with Phase Change Material (PCM) for subterranean cooling.

#### 2.2 Phase Change Material (PCM)

#### 2.2.1 Fundamental of PCM

Alternative energy can be created in a variety of ways, one of which is energy storage. In addition to conserving energy, energy storage reduces the variance between supply and demand and enhances the accuracy and reliability of energy supply.

Thermal Energy Storage (TES) is one of the most commonly used methods of energy storage. TES can be classified into two main categories. First is sensible heat storage and second is latent heat storage. The increase of energy from the heating of a substance is shown in the Figure 3 discussed by [12]. The process displayed includes sensible heating, in regions A-B, C-D, E-F, and G-H, and also latent heating in B-C, D-E and F-G regions. The total amount of energy stored per unit weight is equal to the summation of integration for the specific heat of material in phase transition with temperature difference. For sensible heat transfer, a larger amount of medium is required to store the same amount of energy as that of latent heat transfer.

Due to small latent heat in solid-solid transition and the requirement of large volume for liquid-gas transformation- these two options are not technically viable. Furthermore, as energy storage in the case of solid-liquid transformation is of higher density and operates at a constant temperature as PCM we will only mean energy storage through this transformation.



Figure 3 : Temperature versus Time diagram for heating of a PCM [12].

PCM mainly depends on latent heat storage, while storage through sensible heat relies on a change in the temperature of materials. Thermal energy storage through PCM is capable of storing and releasing energy in large quantities. The holding and releasing of energy depend on the change in phase of the materials. Practical experiments have shown that a major reduction in storage volume can be attained through PCM compared to sensible heat storage.

PCMs are latent heat thermal energy storage materials that use their chemical bonds for the storage and release of energy [36]. Sensible heat storage occurs when energy is stored or released by increasing or decreasing the temperature of the storage substance, accordingly. The amount of thermal energy stored is determined by the material's temperature change, mass, m (kg), and heat storage capacity, Cp (kJ / kg °C), and can be stated as in Equation 2 where, T1 and T2 denotes the lower (initial) and upper (final) temperature levels between which the storage system is operating.

$$Q = m \int_{T1}^{T2} C_p \Delta T$$
<sup>(2)</sup>

When PCMs reach the temperature at which they melt, they absorb a large amount of energy without getting heated. PCMs, solidify and release energy when the surrounding temperature drops. Though in a sense every material is a phase change material, in energy storage we call PCM only those materials which possess certain characteristics for energy storage. Phase change materials for energy storage should have high thermal conductivity and large latent heat. Additionally, the melting point of the substances should lie within a realistic range of application; materials should be chemically stable and should melt congruently with least supercooling. Chemically, the materials also must be non-toxic and non-corrosive.

Financially, PCMs should be available and very cost-effective. According to the research done over the last few decades- types of paraffin, salt hydrants, fatty acids, and sugar alcohols are suitable for usage as Phase Change Materials though none of those materials possess all the properties of an ideal PCM.

Serial	Manufacturer	Temperature	KA No. of listed
		Range (°C)	PCM
1	EPS	-114 to 164	61
2	Rubitherm	-3 to 100	29
3	Cristopia	-33 to 27	12
4	TEAP	-50 to 78	22
5	Doerken	-22 to 28	2
6	Climator	-18 to 70	9

Table 2 : PCM and its manufactures.

#### 2.2.2 PCM as a thermal cooling medium

Thermal energy storage and phase change materials (PCMs) in particular, have been the main topic in research for the last 20 years, but although the information is quantitatively enormous, it is also spread widely in the literature and is difficult to find [13]. There is a large volume of published studies created by brilliant researchers, describing the role of PCM as thermal storage or energy storage. Rahman [14] stated that Thermal Energy Storage (TES) through the usage of Phase Change Materials (PCM) is one of those approaches through which alternative energy can be generated; which not only reduces the variance between supply and demand but also increases the stability of energy supply in addition to energy conservation. Their study described the realistic applications of PCM and their financial feasibilities. Though the durability of PCMs over numerous cycles can be questionable, encapsulation significantly increases their efficiency and resilience. Successful and efficient storage of solar energy through PCM can be highly beneficial to take the implementation of renewable energy to the next level.

De Falco and his teammates [15] reviewed a cold storage system using PCM properties. Their study aimed to store cold energy using the solidification latent heat of PCMs and implement an innovative heat exchanger system in the storage unit. They also seek to gain high power both in charge and release phases. They managed to develop and test a 5-kWh prototype, together with some experimental results, demonstrating the technology application potentialities. At the end of their test on the prototype, the thermal power exchanged between the primary and secondary circuits amounts to 75% of the total power absorbed by the storage unit. The cold storage system is suitable for domestic applications (typical in/out primary circuit temperature

= 7-12°C) since it can store cold energy at 5.5°C. This shows that PCM is fitting as thermal storage.

Lokesh [16] did a parametric study on phase change material-based thermal energy storage systems. The usage of phase change materials (PCM) to store the heat in the form of latent heat is increased because a large quantity of thermal energy is stored in smaller volumes. In the present experimental investigation, sodium thiosulphate pentahydrate is employed as a phase change material and it is stored in stainless steel capsules. These capsules are kept in a fabricated tank and hot water is supplied into it. The effect of the mass flow rate of heat transfer fluid at 4 lit/min and heat transfer fluid inlet temperature at 60°C is more on charging time when compared to other. Hence, it is concluded that higher flow rates and higher inlet temperatures of heat transfer fluid are recommended.

Agbossou [17], did a study that demonstrates a way of using micro-energy to improve macro-energy production smartly. With the prototype self-powered temperature sensing system, it can respond to the target temperature every two minutes when the input solar radiation is around 900W/m2. The results of the autonomous temperature monitoring show that with a simple cooling system and with the harvested micro-energy, one can increase the performance of a PV panel (10% of voltage increase with ambient thermal loading in autumn). This study focuses on smart cooler PV for countries with four seasons.

Arumuganainar [18], made a thermal presentation of two-phase congested thermosyphon in the submission of determined thermoelectric dominance producer using PCM thermal storage. Their study aimed to evaluate the thermal presentation of the proposed system, which is a CTEG system that works with passive cooling to achieve invariable cooling. The thermal presentation of the concentrated thermoelectric generator utilizing two phases close thermosyphon as heat transfer device has been investigated mathematically. TPCT has been exposed to be a useful heat transporting machine due to simple structural creation and it can be without problems bent to fit and join between the CTEG structure and PCM thermal storage. A two-phase closed thermosyphon is used as a heat transporting device to transfer excess heat from the heated TEG part to the frozen PCM storeroom reservoir to heat the luggage compartment. This study however does not use asphalts.

Tan [19], reviewed the experimental evaluation of a prototype thermoelectric system integrated with PCM (phase change material) for space cooling. A simplified analytical model for the thermoelectric module has been adopted to investigate the theoretical performance characteristics of the modules. The experimental test in a reduced-scale chamber has achieved a 7-degree Celsius temperature difference between "indoor" and "outdoor" environments and realized an average cooling COP (coefficient of performance) of 0.87 for the thermoelectric cooling system, with the maximum cooling COP of 1.22. Another comparison test for the efficacy of the PCM heat storage unit shows that 35.3% of electrical energy has been saved from using PCM heat storage. The setup only used a single fan and the chamber was used with a piping system.

By drawing on the concept of PCM in thermal cooling, Weng [20] and G. Murali [21] claimed that PCM is suitable for cooling strategies in Battery Thermal Management systems (BTMs). In Jingweng's study, his team aimed to compare the thermal behaviors of battery thermal management modules with different protocols and ambient temperatures to determine the applicability of PCM cooling strategies in
different operating conditions. The constant-current mode produces a reduced temperature fluctuation range but a greater temperature, according to the findings. It reduces the cooling effect of PCMs and speeds up their failure, especially in hightemperature situations. With constant current mode, the PCM cooling technology fails at 1518 s at 54.0 °C in a 45 °C environment, whereas it fails at 2969 s at 44.1 °C in a 35 °C environment. This team proposed a novel PCM cooling structure combining copper-plate-enhanced heat pipe with PCM to promote secondary heat dissipation, whose cooling performances are evaluated between forced convection and natural convection after their findings. For Murali, his study begins with the development of a Hybrid Thermal Management System that works in conjunction with PCM to AALAYSI improve the cooling performance of the BTMS. He pointed out that even in some circumstances of big battery modules/packs, liquid cooling alone is insufficient for cooling. As a result, PCM-based liquid cooling systems are built to perform better. Furthermore, some of the thermal conductivity enrichment approaches for PCM are covered (e.g., the use of thermally conductive particles, cellular foams, and encapsulation). Various essential parameters influencing system performance, such as cell spacing, PCM mass, PCM thickness, specific heat capacity, and thermal conductivity, are evaluated in his research investigations.

Unlike Jinweng and Murali, Khattari [22] studied on the validity of using PCM in a controlled cooling ceiling integrated into a ventilated room. The goal of this study is to look into the energy and thermal benefits of employing PCM in a ventilated room with three Moroccan climates representing three different Köppen-Geiger climate types. The cooling power is adjusted to keep the temperature of the indoor air within a restricted range, ensuring thermal comfort without wasting energy. Using a UDF, simulations were run in a turbulent and transient flow regime, using real variable

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. With a similar concept, Xiaoqin Sun, Yuan Zhang, Kun Xie, Mario A. Medina [23] did a parametric study on the thermal response of a building wall with a phase change material (PCM) layer for passive space cooling. Heat flux reductions were used to investigate the effects of six parameters. Outdoor AALAYSI air temperature, indoor air temperature, insulation level, PCM layer thickness, PCM layer position within the wall cavity and PCM phase transition temperature were all taken into consideration. At the end of their findings, they claimed that the indoor air temperature is adjusted at 24°C, the PCM phase transition temperature should be in the range of 27°C - 31°C for better results during space cooling.

Related to the topic, Juan Duan [24] investigated a novel heat sink made of phase change material (PCM) and metal foam (porous) that is utilized to cool concentrator photovoltaic (CPV) at a sun concentration ratio (CR) of 20. The impacts of varied porosities (80 percent, 90 percent, 100 percent) and heights (H = 0.5x, 1.0x, 2.0x, 3.0x) of PCM-porous systems on boosting the electric efficiency of CPV modules are numerically examined. When compared to pure PCM as a heat sink, the results suggest that metal foam with high thermal conductivity embedded in PCM with high latent heat can considerably improve the cooling effect of CPV. He also argued that the height of PCM-porous is another factor to influences the cooling effect and electric efficiency of the solar cell. In Weisan Hua's [25] review related to the PCM

heat sink, he stated that according to studies, the higher the heat transfer efficiency, the closer the heat sink is to the heat source. As a result, it has been suggested that directly integrating PCM into the chip be considered as an enhancement called embedded cooling. The placement of the PCM was then explained that it will be put inside a container. The container is made up of a container wall and a lid, and the PCM is placed within. The container is usually made of alumina (ceramic) or copper. The shape of the container may be quite irregular if the PCM is not integrated with the module components to enhance the volume of the PCM as much as possible. Using 3D printing technology to create the container is a fantastic option right now. To prevent the PCM from leaking once it has been filled, the container wall and lid must



# Table 3 : Summary of Literature Studies on PCM as thermal cooling.

Ref.	Type of PCM	Latent Heat (kJ/kg)	Melting Temp. (degC)	Conclusion
[20]	A commercial solid paraffin wax	123.8	15.2	A novel PCM cooling structure coupling copper-plate-enhanced heat pipe (HP) with natural convection and forced airconvection is proposed with experimental verification to fix the PCM cooling failure.
[26]	Graphene oxide- modified silica gel	174.4	44	This graphene oxide shows better cooling performance, so it is used to increase thermal conductivity and helps the transfer of heat accumulated in the battery pack to the tubes more efficiently.
[22]	Paraffin C13 PCM	189	22	The suitability of using the paraffin C13 PCM was demonstrated in simulations resulting incooling power savings reaching an energy perspective of 17.07 percent.
[23]	Paraffin-based PCM, octadecane CH3(CH2)16CH3)	140 NIVER	27 Siti te	For better results during space cooling, it was observed that the PCM phase transition temperature should be in the range of 27 °C - 31 °C when the indoor air temperature was set at 24 °C.
[24]	RT70HC	260	69	The cooling effect of PCM-porous systems directly influences the electric efficiency of the solar cell. According to the systematical discussion about the cooling effect of the PCM- porous system, it can give a comprehensive understanding of the merits and demerits of this PCM-porous system.
[25]	RT35HC	240	34	The PCM cooling container is made up of a container wall and a lid, and the PCM is placed within. The container is usually made of alumina (ceramic) or copper.

#### 2.3 COMSOL Multiphysics as FEA platform for thermal studies

PCM-assisted heat pipe cooling system for the thermal management of an LTO cell for high-current profiles was studied by Hamiredza and his team. The concept of a passive thermal management system (TMS) for electric vehicles is presented in their research [27], which includes natural convection, heat pipe, and phase change material (PCM). The PCM is an organic paraffin wax from Shanghai Tianlan New Material Technology Co., Ltd with a melting temperature of 30 °C, which is ideal and effective for the recommended operating temperature range of the Li-ion cells. Although PCM has a low thermal conductivity, it can compensate with embedded heat pipes. COMSOL Multiphysics®, a commercial computational fluid dynamics (CFD) software, is used to solve mathematical models. With an acceptable error range, the simulation results are confirmed against experimental data. When compared to natural convection, heat pipe and PCM-assisted heat pipe cooling systems reduced maximum cell temperature by 17.3 percent and 40.7 percent, respectively.

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Erhan Akyol [28] did an experimental and numerical investigation of heat transfer in a channel with multiple phase change materials (PCMs). COMSOL finite element modeling software was used to investigate the thermal performance of an airphase change material (PCM) unit used in free cooling applications in this study. The impact of air inlet temperature, velocity, and PCM configuration on the air-PCM unit's efficiency was explored. Experiments were carried out on a PCM unit, which is a channel with PCM plates inside and one side exposed to medium air. Other than Akyol, Mahmoud [29] also chose RT25HC as PCM in his study of a novel enhanced conduction model for predicting the performance of a PV panel cooled by PCM. The mathematical models in this study are programmed and solved by COMSOL Multiphysics. The system of equations is adapted using Heat Transfer Physics for all domains and Laminar Flow Physics for the PCM domain in CFD modeling. The study covered, PCM domain aspect ratio (H/L) of two to eight, inclination angles of 0° to 90°, PCM thickness 10–40 mm, and melting temperature of 25 and 26.6 °C. More on works of literature on the usage of COMSOL in PCM thermal cooling, Barbara [30] claimed that the commercial finite element method (FEM) code COMSOL Multiphysics ® 5.5 was used to create a 2D model of the radiant floor arrangement. The model was calibrated in both the steady and transient states using experimental data, and it was then utilized to examine various configurations and thermal properties. The size of the finite elements was set to be fine for the area close to the PCM containers and coarse for the area far away from them to minimize numerical errors and speed up the computation.

 Table 4 : Summary of Literature Studies on COMSOL as FEA platform for PCM thermal cooling.

No.	Ref.	Type of PCM	Melting	Latent	Thermal
U	NIVERSI	TI TEKNIKAL	Temp. MALAY	Heat SIA MELA	Conductivity
			(degC)	(kJ/kg)	(W/m.K)
1	[27]	Organic Paraffin	30	220	0.4
		Wax			
2	[28], [29]	RT25HC	24	230	0.3
3	[30]	S27	27	185	0.54
4	[31]	Paraffin	35	181	16.6
		Graphite			
5	[32]	RT35	33	160	0.2

# **CHAPTER 3**

## **METHODOLOGY**

In this chapter, the research methodology of the project will be explained as well

as its detailed description. The model of the project, the usage of COMSOL Multiphysics Software and details on how the field testing worked also will be included in this chapter.

## 3.1 Research Methodology Flow Chart of the Project



**Figure 4 : Flowchart of the Project.** 

#### **3.2** Detail Description of The Research Methodology

This test is widely available and has been used in many investigational studies. Case studies have been long established in previous years to present a detailed analysis of the thermoelectric energy harvesting system. For this project, the flow of the process shown in the Figure will be followed thoroughly.

First of all, background research is about exploring the general idea of interests which are in this case, PCM and TEHs. Related data was collected and certain calculations have been analyzed. Secondly, a model of the prototype was designed using Finite Element Analysis (FEA) called COMSOL Multiphysics. Next, during data simulation, various input has been simulated to meet the project's objective. Input data were from latent heat, PCM properties, and dimensions. Meanwhile, troubleshooting is necessary to gain the best results. After the best and proper simulation has been gained, the result will be analyzed and data will be evaluated to find several conclusions of the research.

In this PSM II, this project continued to construct a physical model using the prototype's material proposed. Later, the functionality of the prototype will be tested in real-time, and any data results will be recorded during prototype testing. Data of both simulation and experimental will be compared to see any changes or differences. If the prototype does not work well, the problems must be solved first before continuing the last part. At the end of this project, a fully functional prototype will be expected and the presentation will be carried on by the end of the semester.

#### **3.3** Use of COMSOL Multiphysics

The conductivity of the PCM is relatively small. An extra structure should be used to improve the internal thermal conductivity of the PCM, particularly so that the parts far from the contact face work effectively [6]. While on the other hand, [5] used an H-shape heat sink for their TEHs. With both papers as references, this project planned to combine and improvise these methods where an aluminum plate will be welded in between two 1.25 in. of diameters H-shape structures. Two cascaded thermoelectric modules (TEM), APH-127-10-25-S, will be placed in between the top plate and bottom plate. The PCM which for this project, Calcium Chloride Hexahydrate (CaCl2 · 6H2O) will be placed in a container at the bottom plate of the TEHs to retain the ambient temperature of the bottom plate. The heat transfer analysis for the TEHs is performed using COMSOL Multiphysics simulation and will be validated with an experimental investigation.

#### **3.4** Model of the Project

A variety of methods were used to access TEHs simulation. To perform the thermal performance of the defined building element, 3D geometry was employed, while a time-dependent study was chosen to satisfy the non-steady nature of the problem.

Material	Heat	Thermal	Density	Electrical	Latent
	capacity	Conductivity	$(kg/m^3)$	Conductivity	Heat
	(J/(kg.K))	(W/(m.k))	-	(S/m)	(kJ/kg)
Aluminum	900	222	2.7	3.774e7	-
Alumina	896	138	2820	3.030e7	-
Soil	800	1.59	1430	-	-
Asphalt	900	0.8	2.24	-	-
CaCl2 ·	2000	0.2	880	-	170
6H2O					

 Table 5 : Material and Properties of the model.

Туре	Dimension (cm)
Cylindrical Rod	Radius (1.588)
	Height (10)
Top Plate	15 x 20 x0.3
Bottom plate	15 x 20 x 0.3
Middle Plate	0.3 x 14.176 x 10
TEG module	3 x 3 x 0.5
Asphalt	32 x 32 x 10
Soil	32 x 32 x 20
PCM Container	10 x 20 x 2

 Table 6 : Dimensions of the model.



Figure 5 : Isometric view of the model.







Figure 7: Side view of the model.

With the designed model using the COMSOL Multiphysics Software, this project is proceeded to a field testing where multiple experiments are conducted.

### **3.5** Setup of the Project for Field testing.

There are 4 parts of experiment for this project which continued one after another.

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

Each of these experiments were conducted 3 days with 5 hours committed per day. All of the data collected were stored and analyzed. The design of the selected model was constructed physically as the following figures.



Figure 8 : The basic physical model of the project made of aluminum plate.

Figure 8 shows the H-shaped heat sink structure which attached to the empty PCM container. Two TEGs, soldered in series, are sandwiched in between top plate and bottom plate as in Figure 9 and 10.





Figure 10 : Bolts and nuts to secure the TEG.

To ensure the heat transfer is performed in a proficient way, each side of the TEG were bounded using 4 M6 bolts and nuts. Then, the model was submerged into an asphalt box for a couple days before it was planted into the soil as in Figure 11 and 12.



Figure 11 : Model was left to set for a couple of days.



Figure 12 : The model is ready for experiment

## 3.6 Data Collection

Two types of data were taken for this study. One for the temperature of this model and another one for the open circuit voltage from the TEG. There a few devices that has been used to assist the data collection.

#### 3.6.1 Pico TC-08 USB Thermocouple Data Logger

This device in Figure 13 played important role as the Data Logger for the temperature recordings. It worked along with K-Type thermocouple, Figure 14, that were placed on the top plate, bottom plate, middle plate and asphalt. The TC-08 thermocouple data recorder can be used to assess a wide range of temperatures with any thermocouple that has a modest thermocouple connector. Pico has a vast assortment of thermocouples that are ideal for any application. It's a thermocouple 32 data logger with 8 channels. With a temperature range of –270 to +1820 °C (The temperature range is determined by the thermocouple being used), all standard thermocouple types are supported. As a 9th channel, the built-in Cold Junction Compensation (CJC) circuit can be used to measure ambient temperature. With the TC-08 thermocouple data recorder, temperature measurements will be quick and comprehensive.



Figure 13 : Pico Data Logger [37]



Figure 14 : K-Type thermocouple [38]

#### 3.6.2 NI Multifunctional Data Acquisition Card USB 6001

Moving on to the data collection for the output voltages. It was recorded and monitored with by using National Instrument Data Acquisition device as in Figure 15. 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 visualisation customisation. A range of supported programming languages are used to create automation applications.



#### Figure 15 : National Instrument Data Acquisition device [39]

### 3.6.3 LTC3105EDD MPPC

The open circuit voltage from the TEG alone is not good enough to be taken. Therefore, this device in Figure 16 will act as the booster for this system. The LTC3105 is a high-efficiency step-up DC/DC converter that can work with input voltages as low as 225mV. Due to a 250mV start-up capability and an inbuilt maximum power point controller, it is feasible to operate immediately from low voltage, high impedance alternative power sources such as solar cells, TEGs (thermoelectric generators), and fuel cells (MPPC). A user programmable MPPC set point enhances the amount of energy generated from any power source. Thanks to a revolutionary self-adjusting peak current, the Burst Mode function improves converter efficiency and output voltage ripple under all working conditions. The AUX powered 6mA LDO provides a regulated rail for extra microcontrollers and sensors while the main output is charging. [pdf baru] claimed that LTC3105 requires a low input voltage ranging from 0.2V to 5V and able to produce voltage of 5.25V with output current of 100mA. This IC is suitable to use with any energy harvester which produce very low voltage and current to power up a low power autonomous device. These were the equipment that were utilized to gather data during the field testing. The results will be explained on the next chapter.



# **CHAPTER 4**

## **RESULTS AND DISCUSSION**



### 4.1 Simulations

The simulations divided into 2 types which are:

- i. Without PCM
- ii. Without PCM

## 4.1.1 Graphics for the Heat Transfer

Figure 17 depicted the heat conduction applied on this model after 5 hours of simulation using COMSOL Multiphysics software.



Figure 17 : Graphic of the heat transfer of the model after 5 hours.

### 4.1.2 Comparison of Simulation Results

The results from simulation of the TEHs with and without the usage of PCM is compared and analyzed based on Table 7.

	Asphalt	Middle	Bottom	Top Plate	DT (C)
	(C)	Plate (C)	Plate (C)	(C)	
Min	24.41	24.338	24.402	24.406	2.004
	28.76	26.45	25.22	26.58	2.000289
Max	58.432	26.54	32.567	63.266	31.738
	58.432	29.94	28.113	60.687	18.453
Average	54.16725	25.23663	31.74035	58.92727	27.18692
	53.96082	27.98042	27.41177	58.39986	22.56325

#### Table 7 : Comparison of the simulation results.





From the simulations, it is found that TEH system with PCM has greater temperature difference compared to the one without PCM after 5 hours. To validate these results, experiments are made at a field during daytime.

#### 4.2 Field Testing

Temperature and voltage output are monitored for 5 hours or 18000 seconds (12 pm to 5 pm GMT+8) in the experiment. The results are obtained using PicoLog TC-08 data logger software for temperature data gathering. The National Instrument DAQExpress companion software is utilized for voltage output. Each experiment was conducted for 3 days to ensure the output consistency because by repeating an experiment more than once helps determine if the data was a fluke, or represents the normal case. The experiments have 4 parts of results which consists of:

- I. Without PCM
- II. With PCM
- III. With PCM and black painted top plate.
- IV. Charging Supercapacitor

### 4.2.1 Without PCM



Figure 18 : Open Circuit Voltage from TEG and Boosted Voltage from MPPC for the TEHs without PCM.

The first experiment is testing the TEHs without filling the PCM inside the container yet. The output voltages which are open circuit voltage from the TEG (VOC) and boosted voltage from the MPPC (VBOOST) were recorded for Day 1 (D1), Day 2 (D2) and Day 3 (D3) as portrayed in Figure 18. Meanwhile, Figure 19 shows its temperature difference (DT) corresponding to each day of the experiment.



**Figure 19 : Temperature difference for the TEHs without PCM in 5 hours.** 

Table 8 : Con	parison of data collected for 3 days experiment TEHs with	out
5	PCM.	

No.	KA		
<u>у</u> те	Min	Max	Average
VOC (V)	0.098257	0.381995	0.27254
سا ملاك	0.241093	0.38546	0.341058
	0.098257	0.382725	0.263405
VBOOST (V)	0.026678	1.276735 A ME	0.761456
	0.063757	1.274156	1.104597
	0.026678	1.276812	0.696682
DT (C)	0.783	11.865	4.495867
	2.565	12.207	8.670407
	0.25	15.848	7.23446

Day 1	Day 2	Day 3

Based on Table 8, the highest VOC and VBOOST are 0.39V and 1.28V respectively on Day 2 and Day 3. Concurrently, the biggest DT is 15.85°C on the third day.

### 4.2.2 With PCM



Figure 20 : Open Circuit Voltage from TEG and Boosted Voltage from MPPC for the TEHs with PCM.

The second experiment is testing the TEHs with filling the PCM inside the container. The output voltages which are open circuit voltage from the TEG (VOC) and boosted voltage from the MPPC (VBOOST) were recorded for Day 1 (D1), Day 2 (D2) and Day 3 (D3) as portrayed in Figure 20. Meanwhile, Figure 21 shows its temperature difference (DT) corresponding to each day of the experiment.



Figure 21 : Temperature difference for the TEHs with PCM in 5 hours.

 Table 9 : Comparison of data collected for 3 days experiment TEHs with

 PCM

ž S			
1) TE	Min	Max	Average
VOC (V)	0.26721	1.484527	0.530966
Mr. June	1.168722	1.499978	1.594943
	0.199822	1.45841	0.37893
VBOOST (V)	1.156147 ALA	3.292562 AKA	1.361351
	0.205948	3.020404	0.593587
	1.148409	3.300301	2.098776
DT (C)	4.939	25.999	12.94089
	8.732	42.221	30.37894
	5.703	31.031	21.1574

Day 1	Day 2	Day 3

Based on Table 9, the highest VOC and VBOOST are 1.49V and 3.3V respectively on Day 2 and Day 3. Concurrently, the biggest DT is 42.22°C on the second day.



#### 4.2.3 With PCM and black painted top plate.

Figure 22 : Open Circuit Voltage from TEG and Boosted Voltage from MPPC for the TEHs with PCM and black painted top plate.

The third experiment is testing the TEHs with the PCM filled inside the container and this time, the top plate was painted black. The output voltages which are open circuit voltage from the TEG (VOC) and boosted voltage from the MPPC (VBOOST) were recorded as portrayed in Figure 22. Meanwhile, Figure 23 shows its temperature difference (DT) corresponding to each day of the experiment. It also shows that when the top plate is painted with black, the heat was retained better compared to the nonpainted TEHs. This is due to the Stefan-Boltzmann Law, in Equation 3, that black surface can absorb can retain heat better than non-black surface.

$$Q = \varepsilon \sigma (T_a^4 - T_b^4) \tag{3}$$

Where Q is the heat flux,  $\varepsilon$  is emissivity,  $\sigma$  is the Stefan-Boltzmann constant and T is the absolute temperature in Kelvin.



Figure 23 : Temperature difference for the TEHs with PCM and black painted top plate in 5 hours.

 Table 10 : Comparison of data collected for 3 days experiment TEHs with

 PCM and black painted top plate.

X	2		
	Min	Max	Average
VOC (V)	0.3039	0.8056	0.5361
ملىسىا ملاك	1.1702	1.2983 بيوم سيم ب	2.0073
	0.1085	1.2757	1.0469
VBOOST (V)	0.0573	3.3022	2.7785
	0.2614	0.8095	0.5903
	1.1993	3.3257	2.4682
DT (C)	10.305	27.882	21.6912
	12.259	32.705	18.4965
	10.516	43.223	26.3623

Day 1	Day 2	Day 3

Based on Table 10, the highest VOC and VBOOST are 1.29V and 3.33V respectively on Day 2 and Day 3. Concurrently, the biggest DT is 43.22°C on the third day. From the collected results, it is clear that TEHs with PCM has better output voltage compared to the TEHs without PCM. Theoretically, referring to Equation 2, the bottom plate retained at low temperature aided by the PCM who acts as cold storage. By painting the top plate with black spray, the top plate seems to maintain the heat throughout the experiment due to the Stefan's Law in Equation 3. With PCM to retain the subterranean cooling and black top plate to retain the heat area exposed to sun, TEHs with PCM and black painted top plate was chosen to proceed for testing the charging capabilities of the new system.



Figure 24 : Open Circuit Voltage from TEG and Boosted Voltage from MPPC for the TEHs with PCM and black painted top plate when charging supercapacitor.

The last experiment is testing the TEHs with the PCM filled inside the container and the top plate was painted black to charge two 2.5V supercapacitor in series. The output voltages which are open circuit voltage from the TEG (VOC) and boosted voltage from the MPPC (VBOOST) were recorded for as portrayed in Figure 24. Meanwhile, Figure 25 shows its temperature difference (DT) for the 5 hours of the day.



Figure 25 : Temperature difference for the TEHs with PCM and black painted top plate when charging supercapacitor for 5 hours.

	Min	Max	Av
VOC(V)	0.220458	1.281894	0.858298
VBOOST(V)	1.737017	3.342478	2.653717
Supercapacitor(V)	0.976876	4.172149	3.050391
DT(C)	8.768	34.329	19.98032

 Table 11 : Comparison of data collected for experiment to charge supercapacitor using the TEHs with PCM.

Based on Table 11, the highest VOC and VBOOST are 1.28V and 3.34V respectively. It charged the supercapacitor up until 4.17V. Concurrently, the biggest DT for this experiment is 34.33°C with average of 19.98 °C.

### 4.3 Findings of the experiment

To validate the findings, both simulation and the highest result from 3-days of experiment were compared as shown in Table 12 and Table 13. From both tables, it shows that the temperature differences of experimental are slightly higher than the simulations. The percentage error for experimental TEHs with PCM over the simulation is calculated according toEquation 4.

% Error = 
$$\left| \frac{(Simulation - Experimental)}{Simulation} \right| x 100$$
 (4)

 Table 12 : Comparison between experimental results for TEHs without PCM.

4 12		1 <sup>1</sup>		
يسيا مالاك	Bottom Plate (C)	Top Plate (C)	DT (C)	
MinIVERSIT	25.2200 KAL M	26.5800 A MEL	2.0003	
	32.0600	36.4220	2.5650	
% Error	27.1200	37.0200	28.0900	
Max	28.1130	60.6870	32.7740	
	32.2760	43.3810	12.2070	
% Error	14.8100	28.5200	62.7500	
Average	27.4117	58.3998	22.5632	
	32.3210	40.3340	8.6704	
% Error	17.91	30.93	61.57	
Simulation Experimental				

	Bottom Plate (C)	Top Plate (C)	DT (C)	
Min	24.402	24.406	2.004	
	31.489	39.346	8.732	
% Error	29.04	61.21%	80.78	
Max	32.567	63.266	31.738	
	45.131	75.608	42.221	
% Error	38.57	19.50	32.91	
Average	31.7404	58.9273	27.1869	
	39.9636	70.2597	30.37894	
% Error	25.89	19.24	11.44	
Simulation Experimental				

Table 13 : Comparison between experimental results for TEHs with PCM.

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. In order to testify that this experiment did have improvement from the previous studies, for example in [4], the highest acquired DT was 15.19°C, so some calculations, Equation 5, were made to obtain the percentage of increase from it.

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, by theory, PCM can retained the cold side of the TEG by acting as cold storage based on Equation 2, resulting the system to maintain the temperature difference despite the cloudy weather. Likewise, comparing with the same paper, this project has and increment in term of charging capabilities using the new TEHs with 25.71% based on Equation 6. This has shown that this model has higher rate of charging compared to the previous study.



#### 4.4 Environment and Sustainability

Sustainability entails addressing our own demands without jeopardizing future generations' ability to meet their own. This project offers a green technology, a new perspective for self-sustainable TEHs design that can be used for various purpose and included in seventh goal in Sustainable Development Goals by United Nation, which is affordable and clean energy. It aims to ensure access to affordable, reliable, sustainable and modern energy for all. The goal has five targets to be achieved by 2030. There are 6 indicators that need to be measured. Universal access to modern energy, increase global percentage of renewable energy, double the improvement in energy efficiency. The remaining two targets are means of achieving targets which to promote access to research, technology and investments in clean energy, last, expand and upgrade energy services for developing countries. To simplify, these targets include access to affordable and reliable energy while increasing the share of renewable energy in the global energy mix. The TEG used in this project harvest thermal energy directly from solar radiation which is a renewable source to produce electrical energy. This system is a part of green technology that cause no harmful effect to its surrounding during application nor during its production.

## **CHAPTER 5**

## CONCLUSION

#### 5.1 Conclusion

Asphalt pavement thermoelectric energy harvesting systems (TEHs) are a promising energy source. Because asphalt pavements absorb more heat from the sun, they can capture the thermal energy and use it to generate clean energy. TEG energy harvesting design model enhancement. To get a consistent voltage output, TEG energy harvesting design model efficiency must be improved.

The main purpose of this project is to ameliorate the TEHs at asphalt pavement by using PCM as cold storage to retain the subterranean cooling. This project focuses in increasing the temperature difference (refer Equation 1) in order to have greater output voltage from the TEG. COMSOL Multiphysics software is used to simulate the system before proceeding to the field testing. Data has been analyzed between independent replicates in case of trends or observations from experiments.

Other than that, this thesis systematically analyzed on the latent heat effect of a PCM as cold storage during their phase transitions to increase the output voltage of the TEG. PCM was chosen as it can help in improving the temperature stability on its face and act as cold storage. Based on Table 8, without adding PCM to the system, the highest VOC and VBOOST are 0.39V and 1.28V respectively with the biggest DT of 15.85°C. However, when PCM was added to the system (refer Table 9), it is found that the highest VOC and VBOOST are 1.49V and 3.3V respectively on Day 2 with the biggest DT of 42.22°C. It is proven that PCM does affect the TEHs by theory (refer Equation 2) that it can store the heat energy and assist the system to retain the subterranean cooling. More, it is also found that by painting the top plate with black paint, aids the system to have better absorption of the heat from solar radiation due to Stefan Boltzmann Law (refer Equation3). It is proven by the experiment (refer Table 10), the highest VOC and VBOOST are 1.29V and 3.33V respectively with the biggest DT of 43.22°C. Last, this project thrived to investigate the charging capabilities using this new system at asphalt pavement with a success of 25.71% increment in the rate of charging (refer Equation 6), which took about 2.6 hours for the supercapacitor to be fully charged. All of the objectives have been met and there were few parts that improves from the previous studies, there were also a few parts that can be upgraded for more efficient system.

#### 5.2 Future Work

In the near future, this model can be improvised by innovating a better step-up converter circuit to boost the open circuit voltage even during low voltage produced from the TEG. Since the current circuit can only boost when the output voltage of the TEG is around 250mV, future circuit hopefully can boost lower than that, probably lower than 100mV. By this, it can provide a faster charging rate and higher rate of boosted voltage from the TEG output.
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