PERFORMANCE ANALYSIS OF A SOLAR THERMOELECTRIC GENERATOR(STEG) SYSTEM WITH SPRAY COOLING

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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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2020

DECLARATION

I declare that this report entitled "PERFORMANCE ANALYSIS OF A SOLAR THERMOELECTRIC GENERATOR(STEG) SYSTEM WITH SPRAY COOOLING" is the result of my own work except for quotes as cited in the references.

Signature :

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Date : 26 JUN 2020

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.

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ABSTRACT

Investors worldwide have paid greater attention to this emerging industry in recent years. In many cases, this has translated into rapid renewable energy commercialization and considerable industry expansion. Thermoelectric Generators (TEGs) provide a very special opportunity for the society to overcome world energy consumption issue by providing clean and renewable energy to human. This research proposes the utilization of spray cooling as a good method to be applied in involving the STEG systems. Plus, a TEG design with a spray cooling system are developed to power up a mobile phone charger and an algorithm designed for the temperature sensor connected with microcontroller to detect the temperature of the cold side of TEGs. Eight TEGs are used to build the prototype, with series of electrical and thermal configurations. LTC3105EDD boost converter is used to boost the output of TEGs. A 100F supercapacitor is used to store harvested energy. The spray cooling will start to spray when the temperature of the cold side reached a certain temperature. Finally, the efficiency achieved is 11.45%

ABSTRAK

Pelabur di seluruh dunia memberi perhatian yang lebih besar terhadap industri baru ini dalam beberapa tahun kebelakangan. Dalam banyak kes, ini telah diterjemahkan ke dalam pengkomersialan tenaga boleh diperbaharui yang cepat dan pengembangan industri yang besar. Penjana termoelektrik (TEG) memberikan peluang yang sangat istimewa bagi masyarakat untuk mengatasi masalah penggunaan tenaga dunia dengan memberikan tenaga yang bersih dan boleh diperbaharui kepada manusia. Penyelidikan ini mencadangkan penggunaan penyejukan semburan sebagai kaedah yang baik untuk diterapkan dalam melibatkan sistem STEG. Selain itu, reka bentuk TEG dengan sistem penyejukan semburan dikembangkan untuk menghidupkan pengecas telefon bimbit dan algoritma yang dirancang untuk sensor suhu yang disambungkan dengan mikrokontroler untuk mengesan suhu sisi sejuk TEG. Lapan TEG digunakan untuk membina prototaip, dengan rangkaian konfigurasi elektrik dan terma. LTC3105EDD boost converter digunakan untuk meningkatkan output TEG. Supercapacitor 100F digunakan untuk menyimpan tenaga yang dituai. Penyejukan semburan akan mula disembur apabila suhu bahagian sejuk mencapai suhu tertentu. Akhirnya, kecekapan yang dicapai adalah 11.45%.

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LIST OF SYMBOLS AND ABBREVIATIONS

TEG	-	Thermoelectric Generator
DC	-	Direct Current
RF	-	Radio Frequency
PV	-	Photovoltaic
TEC	-	Thermoelectric Cooler
STEG	-	Solar Thermoelectric Generator
F	-	Farad
V	-	Volt
A	-	Ampere
W	-	Watt
IC	-	Integrated Circuit
TSES	-	Thermally Series Electrically Series
TSEP	-	Thermally Series Electrically Parallel
TPES	-	Thermally Parallel Electrically Parallel
TPEP	-	Thermally Parallel Electrically Series

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CHAPTER 1

INTRODUCTION

This chapter will provide an overview about the project where there is an explanation on the project objectives and problem statement. The scope statement of the project is included in this chapter to state the range of work the project covers and will not cover. A thesis statement is also included at the end of this chapter to provide an overview of each chapter in this thesis

1.1 Background Study

Over the past decades, research and efforts have investigate harvesting ambient environmental energy owing to the rapid-growing worldwide energy consumption. To sustain development of human civilization, the search for renewable and clean energy with lesser carbon emission is urgent. The growth in electricity consumption, the search for clean energy without greenhouse gas emissions and large hydrocarbon costs have led to the pursuit for fresh clean and renewable sources [1]. A track, which is a usable source, is the recovery of waste heat generated in industry through processes such as solid waste combustion, geothermal energy, power plants or car exhaust[2]. In this process, temperature values ranging from 360 to 1,000 K are reported in the literature for these heat sources [3]. Thermoelectric power generation, for example, is a promising way to achieve efficient waste energy harvesting. Due to their advantages of compact structure, high reliability, no vibration and direct electric energy conversion [4]. Thermoelectric generators (TEGs) provide a very special opportunity for the society to overcome world energy consumption issue by providing clean and renewable energy to human.

As a dependable future effort, solar photovoltaic electricity era have been extensively employed. On the other hand, the STEG Converts photovoltaic energy to electricity by first converts it into heat through the potential difference of a TEG. A TEG system are able at once transform warmness into electrical energy by using the thermoelectric effect besides without using reactions of chemical or any components of mechanical [5]. TEG overall performance often rely on homes of material of thermoelectric and difference of temperature of the cold side and the hot side of the device [6]. Extant studies regarding STEG structures have commonly targeted on strength technology overall performance barring accounting for the strength fed on by means of cooling structures [7]. Results suggested in these research, thus, do not precisely described the real STEG system's performance, specifically those functioning beneath the concentration ration of high, whereby lots of power are fed on by cooling down the temperature of the cold side. More interest ought to be diverted closer to developing higher efficiency cooling techniques to facilitate by reducing in cooling obligations while improving the STEG generating performance [8].

From all the method of cooling, Spray cooling as an effective technique commonly used due to its various advantages, such as lower pressure rate, high coefficient of heat transfer, no sub-cooling including null heat transfer tolerance for reference to the heating surface [9] However, spray cooling has still not been used in systems of STEG. Plus, the fact that the current studies structures of STEG, the leg of thermoelectric, are often kept fixed. The thermoelectric leg 's structure and physical parameters have a huge impact on the performance and operating parameters of power generation [10]. Therefore, the design and physical properties of STEG models need to be further investigated to promote the growth of better TEG-system designs.

1.2 Objective

This project is set out to:

1. Design a TEG with spray cooling method to power up a mobile phone charger
2. Investigate the efficiency of power generated by the TEG with spray cooling compared with TEG with water-cooling method
3. Conduct an experimental test rig to analyze TEG system in terms of efficiency and output power

1.3 Problem Statement

Nowadays, the usage of Thermoelectric Generator (TEG) is widely used in research and in the industries. But on the contrary, plenty of energy are being wasted on bringing down the temperature of the TEG's cold side because most of the studies uses the water-cooling method. Plus, the design of a TEG system are have a big impact on the output. The physical and structure of the TEG have a big contribution on the performance generating power and operation parameters. Moreover, the usage of water-cooling method has been proved that it has various disadvantages which it has high water usage, low coefficient of heat transfer, and have thermal contact resistance with reference to the heating place. Furthermore, the recovery of spray-water may be greatly enhanced by using spray cooling in a closed-loop system, thus counteracting the large use of cooling water.

1.4 Scope of Work

This project required three major hardware circuitries to develop the final product; the Thermoelectric Generator (TEG) circuit, the microcontroller Arduino Uno will be used and will connected with the spray cooling circuit, the LTC3105EDD circuit booster and 100F supercapacitor circuit that will be connected with the output. The temperature sensor relates to the microcontroller which is powered up by the harvested energy from the TEGs. The temperature sensor is responsible to read the temperature of the TEG.

Note that this project attempts to power up a spray cooling circuit. The spray cooling used is a budget plug and play spray cooling system which will work easily with a microcontroller. It is made up of simple spray nozzle that will blast out water from the nozzle. The spray cooling will turn on when the temperature sensor detects an abnormal temperature that is programmed in the microcontroller. The temperature sensor that will be used is thermocouple which have an accuracy of 0.5°C to 5 °C. However, they operate across the widest temperature which is from -200°C to 1750 °C.

Also, the circuit booster used is LTC3105EDD. This is a boost or step up converter that will produce an output voltage of 5V on the paper but in a test, it can produce 4.98V-5V at peak and it offers high power efficiency maximum of 92%.

1.5 Thesis Structure

The remainder of this thesis is structured into FIVE (5) chapters as follows:

Chapter 2 presents the theoretical background of this project which include the usage of Thermoelectric Generator (TEG) including with the microcontroller technology and the usage of spray cooling system. Chapter 3 describe the research of methodology including hardware design and development, hardware sensors placement, and mechanical system of this project. Chapter 4 is mainly focused on the hardware design of the spray cooling system attached with the TEG system, the software design for the microcontroller parts and the output of the TEG system. Finally, Chapter 5 discusses the conclusion from analysis.

CHAPTER 2

LITERATURE REVIEW

This chapter covers the overview of the problems brought by batteries and why thermal energy harvesting can be the ideal solution to battery problems. Also, theories of thermoelectric generator and spray cooling are covered in this chapter, including the working principle and working operation. The past study of thermoelectric generator projects is reviewed and discussed. Other main component that are used in this project such as booster circuit, microcontroller and temperature sensor are analysed, in terms on their functionality and the efficiency of the power generate by the thermoelectric generator are also analysed.

2.1 Background Study

In this day and age, renewable energy is being studied more frequent as the global warming issues are becoming more critical compared to for the past ten years ago. The study of photovoltaic cell, hydroelectric generator, geothermal generator and others have shown that the renewable energy have really bright future to replace the non-renewable energy such as fossil fuels, coal, gas and oil. As a technology that been widely used such as photovoltaic cell it is the frequent reliable power generator in the industry. Solar thermoelectric generator (STEG) on the other hand will generate electricity by converting solar heat energy into electricity using effect of thermoelectric without using any reaction of chemical or any mechanical component. [11]. TEG has been widely known for its clean energy conversion technology for harvesting of waste heat into useful electricity [10]. According to the Seebeck effect, the electricity produced by the thermoelectric generator is directly proportional to the temperature gradient between the hot and cold junction, which in contact with the environment [12]. The STEG have many advantages of using it as it is soundproof, free from pollution, compact, wear-free, portable, and technology that is long-lasting [13], the system of STEG has discover various application in industry as it is contain lots of waste heat including photovoltaic, exhaust of automobile, LED and waste heat from industrial. STEG properties play a big role in generating electricity, the material that is used to make the TEG show differences when generating electricity and the temperature difference between the hot and cold sides of the module [14].

However, studies show that STEG is only focused on the performance to generate electric but did not focused on the strength by cooling structures [15]. While on the other hand, recent study shows that the real performance of STEG system that operates on high concentration rations shows that the power produce by the STEG system are wasted on bringing down the the cold side temperature of TEG. The efficiency of TEG could be improved by increasing the merit figure of thermoelectric materials or the temperature difference between the hot and cold side [2]. In TEG system, the concentration ration of solar collector and cooling system played very big role in generating power of TEG. The percentage of efficiency of STEG system can obtain around 5% at concentration ratio of small as reported [10]. On the other study by Li analysed that the effect of ratio of concentration, surrounding temperature and speed of wind on the power generation of TEG systems. He showed that STEG that is equipped with a heat pipe system could attain output that is higher compared to regular STEG system occupied in a similar area [16]. While Sun [17] proposed a model of simulation to estimate the performance of system of STEG daily. The research indicates that existing maximum external resistance will produce maximum daily generating power while by using a cooling system as reported by Fernanda et al[18] the STEG system of output power are connected to heat loss by the cold side. According to Chen [19] it analysed that the output power of TEG system would increase by applying a water cooling technique in STEG system compared to using heat sink technique.

2.2 Energy Harvesting

Energy harvesting is the acquisition and transformation into electrical energy of small power from the surrounding or person that would otherwise be lost as heat, light, noise, vibration or movement. In other word energy harvesting is called micro energy harvesting as it would only produce a small amount of electrical energy in milli voltage unit. Well, there are plenty of ways to scavenge or harvesting energy in the environment such as solar, mechanical, temperature, Radio Frequency (RF) and other method. Energy harvesting equipment's quality and ability strongly depend on the efficiency and basic properties of the materials[20]. Although producing larger scale energy that can be renew like wind turbines is similar in theory, the value of production of energy is much lower, usually being few watts to tens of micro watts. Energy storage can be used as an alternative to batteries, or at least to improve them. While low-cost batteries contain limited quantities of energy and require frequent repair or charge up. Battery disposal is also a problem to the environment, and, despite the proliferation of autonomous systems, this problem can only increase.

Up to now, energy harvesting has focused on the development of discrete devices that can generate electricity from kinetic energy. Energy harvesting quality is essentially related to the quantity and existence of the energy source in the system. The knowledge of process limitations and the complexity of source of energy must be detect in early stage when designing a harvesting energy solution. Usually, custom-made design for devices for each appliable source in traditional kinetic energy harvesting and there are seldom applications that provide simple solution.

In terms of solar and light energy harvesting; theoretically, devices with solar cells can work forever without the need for batteries. Photovoltaic cells or, in short, PV modules are a group of connected electrical cells. To convert sunlight into electrical energy to power a device, they can be put in a device. The main challenge of solar harvesting, however, is that the sun does not shine all the time because of the weather could not be predicted. Plus, the temperature of the sun is not always constant as it always changes over time. For example, during the night there will be low ultraviolet and cloudy days, making auxiliary light sources not always available. Therefore, this kind of self-power is not reliable. Normally, this can be done by storing the energy produced in the battery to provide electricity when there is no light. It can monitor one or more charging functions by using the energy generated by one or both of solar power cell and the battery. To control the switching circuitry, a programmable controller is used, selectively couples one or both of solar cell and the battery to power the load. Based on Couch et al, the battery and/or solar cell charges a super capacitor, selectively coupled by the controller, which is then controlled selectively to power the charge. The ultimate result is that solar energy is only available outdoors, and in daytime it is not a reliable and convenient way to harvest energy.

In addition to the above two energy harvest methods, where a mechanical stress is applied to materials such as quartz, Rochelle salts and bulk ceramic materials can produce little electricity between solid dielectric surfaces [24]. Fundamentally, individuals call this as the piezoelectric impact. The artistic is known to be costly to create and are restricted in size. Plus, it requires hostile to breaking and re-authorization structures. Likewise, piezoelectric materials are created as square and the squares of piezoelectric materials are unbending, weak and substantial. The other downside is piezo earthenware production have a generally low yield power [25]. Since the RF gathering is incapable, and both sunlight based module and piezoelectric module must be utilized under the presence of sun and development/stress separately, the main most ideal approach to reap vitality for electronic gadgets, for example, remote sensor hub is through collecting heat vitality. It is either somewhat or completely, by utilizing the regular temperature distinction between the human body and the surrounding temperature to deliver power for persistent activity of the remote sensor hub.

2.3 Material of Thermoelectric (Seebeck and Peltier Effect)

As shown in Figure 2.1, a thermoelectric module is essentially a circuit containing thermoelectric materials producing electricity. Although many types of efficient thermoelectric materials are available, under standard waste heat recovery conditions, not all are able to operate as a unit.

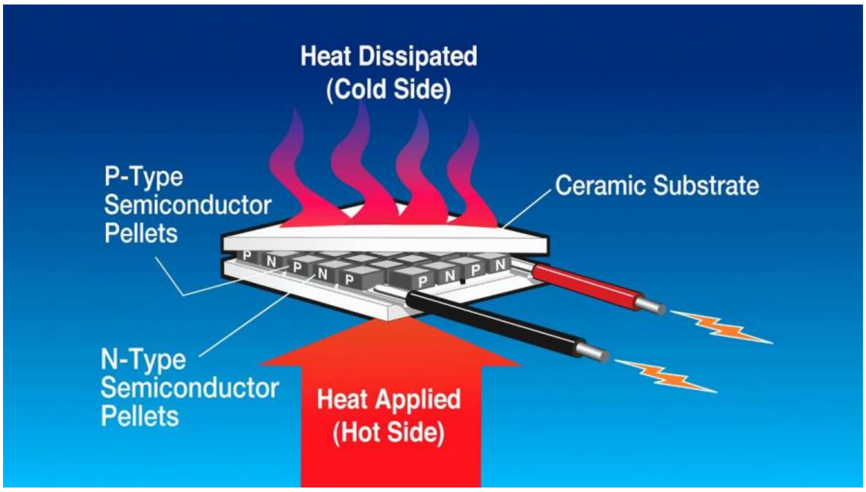

Figure 2.1 Example of Thermoelectric Module

There are two criteria that must be met by a thermoelectric unit, which are stresses and strains that are thermally induced and mechanical fatigue. This is because the thermoelectric module must function at a very high temperature gradient for power generation and must also endure a large number of thermal cycles. The thermoelectric module's physical design will affect its effectiveness. Design technology is very important to join a thermoelectric module. The p and n-type materials, as already known, form a thermoelectric "couple," but do not form a p-n junction. They must have high coefficient and properties that are tightly controlled. The element type p and n must be designed in the module in such a way that they are series thermally and in series electrically. Therefore, internal cabling, as well as junctions and materials that will work under harsh mechanical conditions, is mandatory. [21]Seebeck effect was found in year 1821. It is discovered that two different metals have different temperature at the joints; a so-called thermos- current and thermos-electromotive force will exist as the corresponding current and electromotive force.

Increasing the temperature gradient between the two joints will increase the voltage difference. The proportional constant related to the intrinsic property of the material is defined as the Seebeck coefficient. For materials like metals, the coefficient is relatively low, approximately around 0 μ V/K. Meanwhile, for semiconductor, the coefficient is larger, which is around ± 200 μ V/K. The Seebeck coefficient general equation is given as

$$\alpha = \frac{-\Delta V}{\Delta T} \quad (2.1)$$

Equation 2.1: Seebeck Coefficient General Equation

In this equation, ΔV is the voltage difference and ΔT is the temperature difference between the two sides. The negative charge of electron and conventions of current flow is the reason for the negative sign. The dominance of electrons (n-type) will produce negative Seebeck coefficient while dominance of holes (p-type) will produce positive Seebeck coefficient. Both p-type and n-type materials are required for the current flow in a device.

2.4 Thermoelectric Generator

Thermoelectric Generator Module is no different compared with thermoelectric module because it uses Seebeck effect. A commonplace TEG module is built by a quantities of p-type and n-type thermoelectric components, which associated thermally equal however electrically in arrangement, and sandwiched between two fired layers as appeared in Figure 2.2 so as to accomplish a thermo-incited capability of a couple of volts to control little electronic gadgets, engines, or to charge a battery[22]. It is essential to be sandwiched between clay layers to maintain a strategic distance from hamper the metal interconnects and to ensure a decent warm trade with the encompassing.

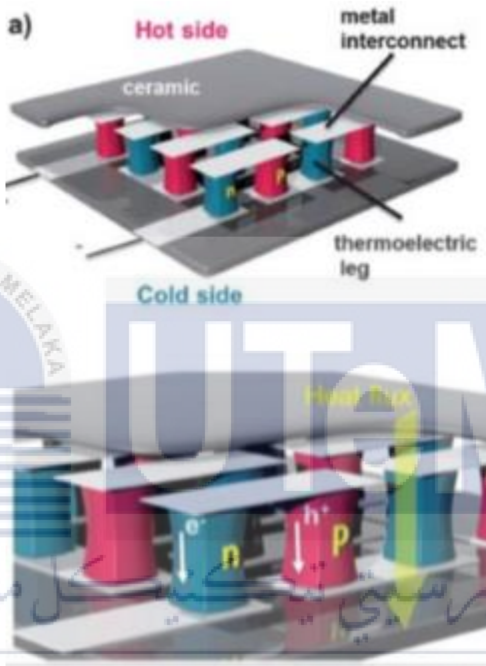

Figure 2.2 Schematic diagram of Thermoelectric Module

A device which called Thermoelectric Generator(TEG) that could produce electricity current, or power from only temperature difference between the hot side and the cold side of the surfaces of TEG. The thermoelectric matter must be an electro-conductive or able to conduct electricity and able to produce significant Seebeck to produce enough and efficient power generation of thermoelectric[23]. Usually, the value of Seebeck coefficient could be small as only μV/K for metals to as large as mV/K for insulator of electricity. Warming one finish of a thermoelectric material makes electrons move from hot to cold end. At the point when the electrons move to the virus side from the hot side, it creates current. The electric flow is straightforwardly relative to the temperature angle. The more current produce, the more force is created.

2.5 DC to DC Booster

Although there are many boost converters available and relatively easy to design but because the power generated from TEGs is staggeringly low, it is a challenge to operate any boost converter as a start-up voltage. Based on [20], the researchers from AGH University of Science and Technology had used an ultra-low power DC-DC converter to boost up the power harvested from TEGs. The converter used is based on the LTC3108 circuit. Based on their research, the most suitable converter is LTC3108 because it offers the lowest input voltage for start-up, which is 20 mV for no load start-up and 40 mV in operation, due to the thermoelectric generator's internal resistance will match the DC-DC boost converter's input resistance[24].

In the experiment, one of their goals are also to determine the Seebeck voltage's relationship to thermal resistance. Their findings show that the Seebeck output voltage is strongly influenced by TEG's attachment to the body. Essentially, when the thermal resistance is reduced to 25 K / W, the converter could only turn on. Their experiment result on relationship of Seebeck voltage vs thermal resistance is shown in Figure 2.3.

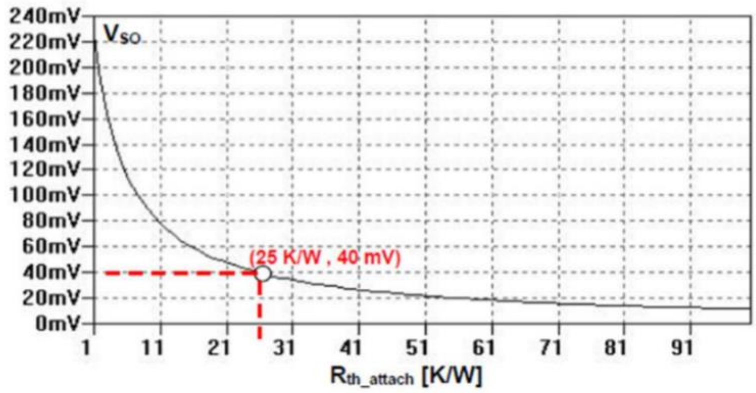

Figure 2.3:Seebeck Voltage Against Thermal Resistance

Eventually, using LTspice they tried to reduce the thermal resistance in the simulation to 25 K / W. Their simulation experiment is successful, and it has been shown that LTC3108 can operate with 40 mV voltage input. Figure 2.4 shows one of the outputs of the converter, VLDO, which will regulate at 2.2V.

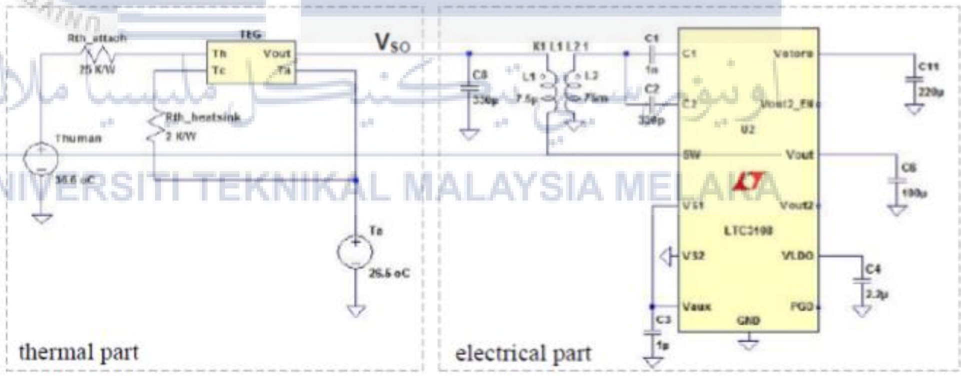

Figure 2.4: Setup for combined simulations with boost-up voltage *converter*

While the researchers managed to use LTC3108 to boost the ultra-small voltage from TEGs to 2.2 V, they are still challenged to maintain the output voltage from LTC3108 due to the fact that thermal equilibrium is easily reached without further TEG thermal condition. Therampilly J. J. in 2012. From California Polytechnic State

University the investigation into a prototype human warmth harvester, which was heat harvesting for battery charging, had carried out quite similar research.[25] The warm side of TEG is connected to the oil-filled Altoids container in which oil absorbs and maintains the heat for longer periods of time in the project to create a continuous heat source. The Peltier's warmer side is linked to a heat sink to dissipate heat to the surrounding area to keep the cooler side cool to maintain a temperature difference. The Peltier cell used in this senior project is TEC1-12706. The TEG output is connected to the Ultralow Voltage StepUp Converter and Power Manager (LTC3108) DC-DC converter used for the peltier unit. The converter's output is then used for battery or cell phone charging. However, because of the difficulty in maintaining a constant difference in temperature, the energy acquired from the peltier module really varied. For a temperature difference of 25 °C, the Seebeck voltage starts around 3 V and reduces to rapidly diminishes due to rapid heating of heat sinks.

Several researchers from the Tyndall National Institute in Ireland are carrying out further research. The research focuses on the thermoelectric energy harvesting method using human body heat to power wearable electronics and on proposing an effective power management device for use [26]. We can only generate 100 mV from the human body by putting multiple TEGs on the human arm and wrist. The experiment's ambient temperature gradient and human arm is also about 5 ° C. Additionally, they also use the LTC3108 circuit as the ultra-low voltage boost converter. The converter output is used for portable electronics with low power. The boost converter's final output is about 0.278 mW, which is enough of a wireless sensor node. Their LTC 3108 report shows that it can run at least 30 mV. According to them, the converter yield is increased by 24 percent efficiency, 75 percent from the dc-dc converter stage and 18 percent average end-to-end efficiency.

2.6 Temperature Sensor (LM35)

The temperature sensor is a system that detects temperature bypass variations. The data sheet of the LM35 specifies that these ICs are precise IC temperature sensors whose output voltage is directly proportional to the temperature of Celsius. Therefore, the LM35 has a benefit over linear temperature sensors measured in Kelvin, since the 7user is not needed to deduct a significant constant voltage from its output in order to obtain convenient Centigrade scaling[27]. The LM35 does not need any external calibration or trimming to provide standard accuracies of ±1⁄4 ° C at room temperature and ±3⁄4 °C over a maximum temperature range. In this task, this sensor is used to measure and read room temperature.

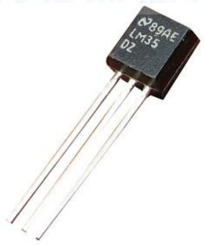

Figure 2.5: Temperature Sensor LM35

By referring to table 2.1, it shows the characteristic for the Temperature Sensor LM35.

Table 2.1 Characteristic of Temperature Sensor LM35

Parameter	Description
Supply Voltage	4 to 30 Volt
Temp. Range	-55 to +150 ˚C
Accuracy	±2 ˚C
Output	+10mVolt/ ˚C

2.7 Supercapacitor

Supercapacitors are gadgets equipped for overseeing high force rates contrasted with batteries. In spite of the fact that supercapacitors give hundred to numerous multiple times higher force in a similar volume [28], they cannot store a similar measure as batteries do, which typically lower than 3 until 30 times [29]. This application makes supercapacitors in which force blasts is require, however high vitality stockpiling limit is not specified. Supercapacitors can likewise be incorporated inside a ESS which battery based to decouple the force and vitality attributes of ESS, along these lines improving the estimating while at the same time fulfilling the force and vitality necessities, and most likely growing its long line.

The force yield of supercapacitors compared different which is low than electrolytic capacitors yet could achieve around 10 kW kg^{-1}. Then again, their specific vitality is a few significant degrees higher than the one of capacitors [30]. These gadgets are intriguing in light of the fact that the hole is fill between aluminum electrolytic capacitors and batteries, which is fit for putting away a lot of vitality, yet do not offer densities of high power (1 kW kg^{-1}) because of their stockpiling instrument.

Accordingly, it is critical to take note of that supercapacitors cannot exclusively be released very quickly, yet in addition be charged in such a brief timeframe period. This is a significant benefit for vitality.

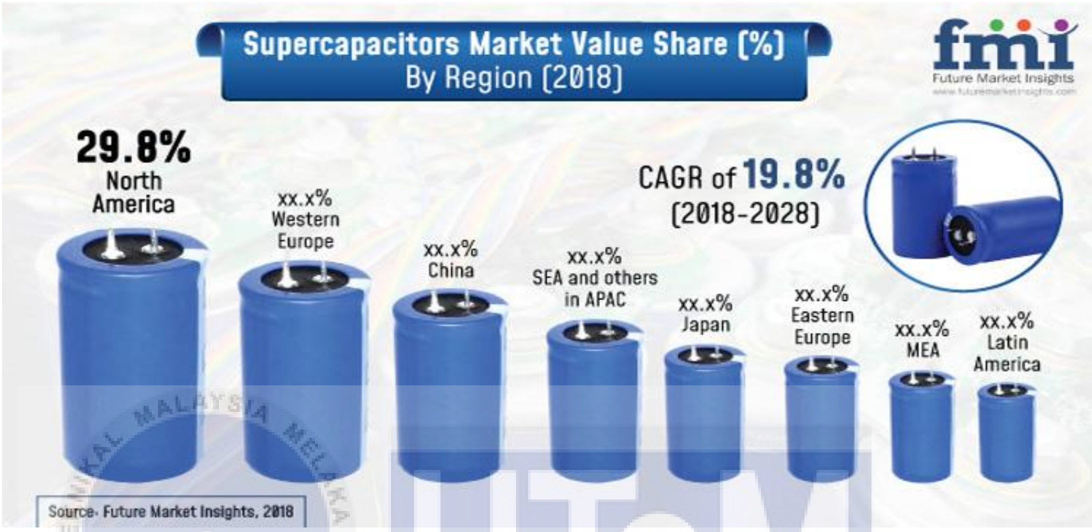

Figure 2.6 Example of supercapacitors in market

2.8 Summary

This chapter covers the background study of energy harvesting, and the component that will use for this project. The theories and background study of energy harvesting is covered in this chapter. There are a few reaping strategies other than warm collecting, for example, photovoltaic and piezoelectric is talked about. Their individual disservices additionally shrouded in this part. Other than that, hypotheses of thermoelectric material, for example, Seebeck and Peltier impacts are examined. Moreover, past generally comparative works from different scientists with respect to the field, parts and techniques utilized in this undertaking is basically examined. It is discovered that utilizing TEG to gather body heat creates moderately little vitality/power (around μW) which cannot for driving any electronic gadgets, at any rate not for an extremely significant time-frame or required a lot of TEGs associated in arrangement. The best lift converter to help the voltages straightforwardly from TEGs is the LTC3105EDD. It can help from a few milli-volt to selectable voltages, for example, 3.3V and 5V.

CHAPTER 3

PROJECT METHODOLOGY

This chapter specifically discusses on the methods implemented to complete this project. It describes how this project had been carried out to achieve the project objectives. This chapter also covers the explanation of the overall project methodology and the development of the prototype stage by stage in details. Besides that, all the components used to build the prototype is explained in detail regarding on their functionality and working principle. The steps of how each component is implemented to the prototype are also covered in this chapter.

3.1 Project Planning

To finish this venture in time, a task arranging is made since guarantee that the undertaking gained ground and stream easily as indicated by plan. Undertaking arranging is typically executed at the underlying phase of the venture, for the most part with the assistance of Gantt diagram. Gantt diagram causes specialist to plan and remain on track for venture fruition. Essentially, a Gantt outline underlines two kinds of period, which are arranging time and the task running time. Before this undertaking began, a lot of Gantt diagram wanted to be the guide all through this task improvement.

3.2 Overview Project Methodology

This project requires three major hardware circuitries to develop final prototype: the thermoelectric generator circuit, the boosting circuits, and the spray cooling circuit. TEG circuitry involves usage of four pieces of 40 x 40mm TEGs connected in electrically series and thermally series. The purpose of the configuration is like this is to get the possible maximum output from the TEGs. By referring to Figure 3.1 it shows the overview of the project.

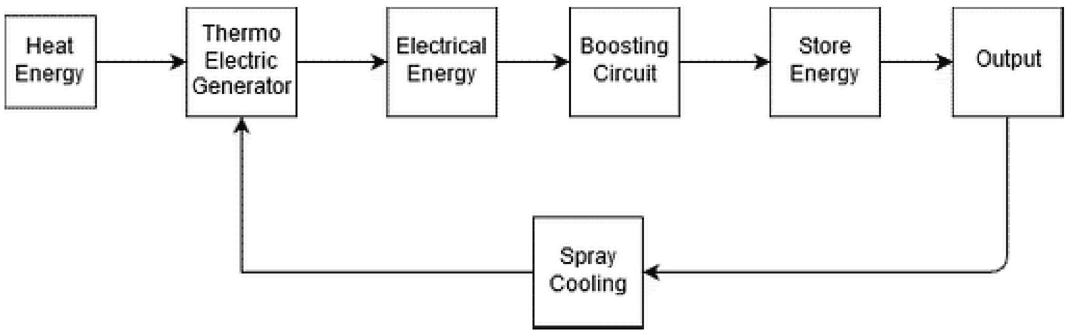

Figure 3.1 Overview Project

An early experiment is made to compare the TEGs thermal configurations versus the output voltage. An ice is used to replace the spray cooling at the cold side of the TEGs to make sure to get the maximum output. An ultra-low DC to DC boost converter, LTC3105EDD is used to boost tens to hundreds of millivolts from the TEGs to 5V. The boosted voltage from TEGs is stored in a supercapacitor and use to power up Mobile Phone Charger. Since most microcontrollers is powered up under minimum voltage of 3.3 V, a power bank will be used to power up the microcontroller.

One must understand the relatively small energy extracted from the TEGs, particularly when the thermal gradient is high. Thermoelectric generators ' output energy is about microwatts, hundreds of millivolts and tens of milliamps. A microcontroller cannot be powered directly from TEGs. The ultra-low boost converter LTC3105EDD is therefore used. The LTC31055EDD will improve output voltages of 3.3 V, and 5 V to a minimum of 20 mV. As already known, no matter how the voltage is improved, power will never be increased. The current is decreased when the voltage is increased and vice versa. That is why the charges can never be driven directly from the LTC3105EDD. Even though the voltage is controlled at 3.3 V, the current is extremely small, at multiple microamps. Therefore, in the event, the supercapacitor is used. The LTC3105EDD's entire power is contained in a supercapacitor. Supercapacitor is chosen before the battery because it has a low resistance of the equivalent series (ESR). It can generate massive power and it can be powered faster than batteries. The downside is that, depending on the load, it also discharged easily. This provides sufficient energy to turn on the loads when the supercapacitor is fully charged. The mobile phone charger is operated at least 3.3 V. Thus, if it is connected directly from the supercapacitor, the length of time the loads are on is limited. As the supercapacitor will quickly discharge and the time limit for charging the phone are very limited.

3.3 Thermoelectric Generator

There are plenty of models of thermoelectric generators available in the market right now. However, since the designed prototype is an armband, a small thermoelectric generator is used so that it is more convenience, small, light and suitable for the surface of the wearer's arm. The model of thermoelectric generator that is used for the prototype is TEC1-12706 from Thermonamics Company. The dimension of the TEC1-12706 is 40 mm x 40 mm x 3.9 mm. This model has seventy-one couples and it is a single stage module designed for cooling and heating up to 100 C^{o}.

From the datasheet, the maximum voltage converted from the temperature gradient is 17.2 V at 50ºC between the hot and cold plate of the TEC1-12706. Meanwhile the maximum current generated is 6.1 A. This module's max. power is 66.7 W. Ultimately, this model's AC resistance is around 2.2Ω. TEC1-12706 model is made up of Alumina (Al2O3, white 96 percent) for its ceramic content and for its solder tinning, it is made up of Bismuth Tin (BiSn).

The fundamental highlights of this model are that it has no moving parts, no clamour and strong state. Additionally, it has a conservative structure, smaller than usual and light in weight. Clearly, it is natural benevolent and RoHS agreeable. This model offers exact temperature control and extraordinarily solid in quality and superior. Generally, this model is executed as temperature stabilizer, CPU cooler and logical instrument, photonic and clinical frameworks, laser cooling and CCD sensor. For this undertaking, the physical contact from human body is utilized as the warmth source at the hot plate of TEG and encompassing temperature is utilized at the cool side of the TEG surface. A reasonable heatsink is utilized at the cooler plate to scatter heat from the TEG.

Hypothetically, more TEGs associated in arrangement will deliver more force, however that is additionally relying upon how the TEGs game plan is done, particularly when the warm setup is thought about. Figure 3.2 depicts the thermoelectric generator that is used for the prototype.

Figure 3.2 Example of TEGs

A thermoelectric generators thermal configuration experiments are done before choosing the right configuration to build the prototype. The purpose of the experiments is to know the difference of the output voltage of TEGs. The configuration of the TEGs are determine by Thermally Series and Electrically Series, Thermally Parallel and Electrically Series, Thermally Series Electrically Parallel, Thermally Series and lastly Thermally Series and Electrically Parallel. The testing of configuration is done by placing two TEGs on a hot plate and set it on the regular temperature of sunlight which is around 30 ºC -50 ºC. The schematic diagram for the testing of configuration of TEGs be in Figure 3.2.

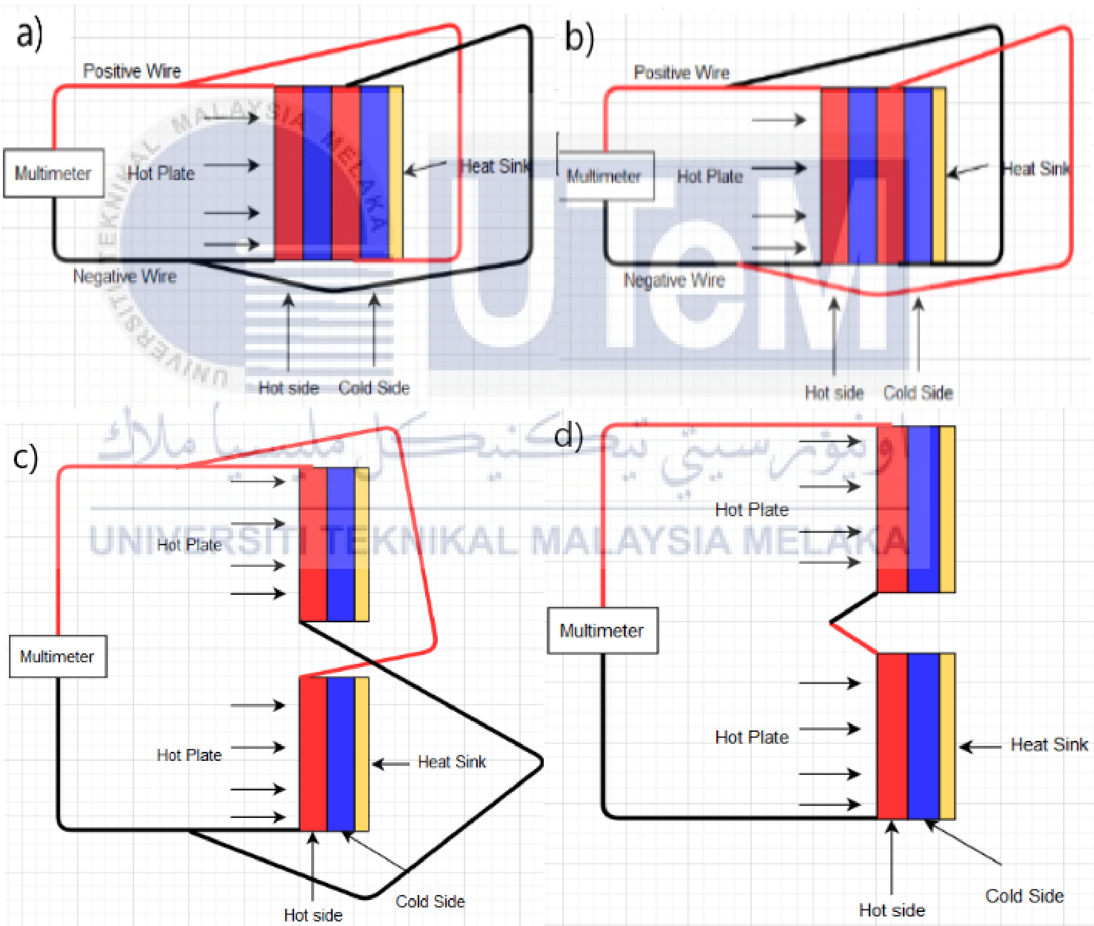

Figure 3.3 Configuration of TEGs

Figure 3.3 above shows that a) Thermally Parallel Electrically Parallel b) Thermally Parallel Electrically Series c) Thermally Series and Electrically Parallel d) Thermally Series Electrically Series.

These experiments are vital because the output voltage of the TEGs is used to trigger the LTC3105EDD boost converter, where it needs a minimum of 200mV to 5V to start up. After the test run is done, a final decision on building the prototype was decided. A configuration of Thermally Series and Electrically Series is chosen because it will produce the highest output voltage. A total of eight TEGs are used to make the prototype. All the eight pieces of TEGs are place on a wooden board and connected electrically series. Plus, all the TEGs are also connected in thermally series. This is so that it can produce sufficient output voltage and output power. The prototype is illustrated as in Figure 3.4. The full picture of the prototype is shown in figure 3.5 and figure 3.6

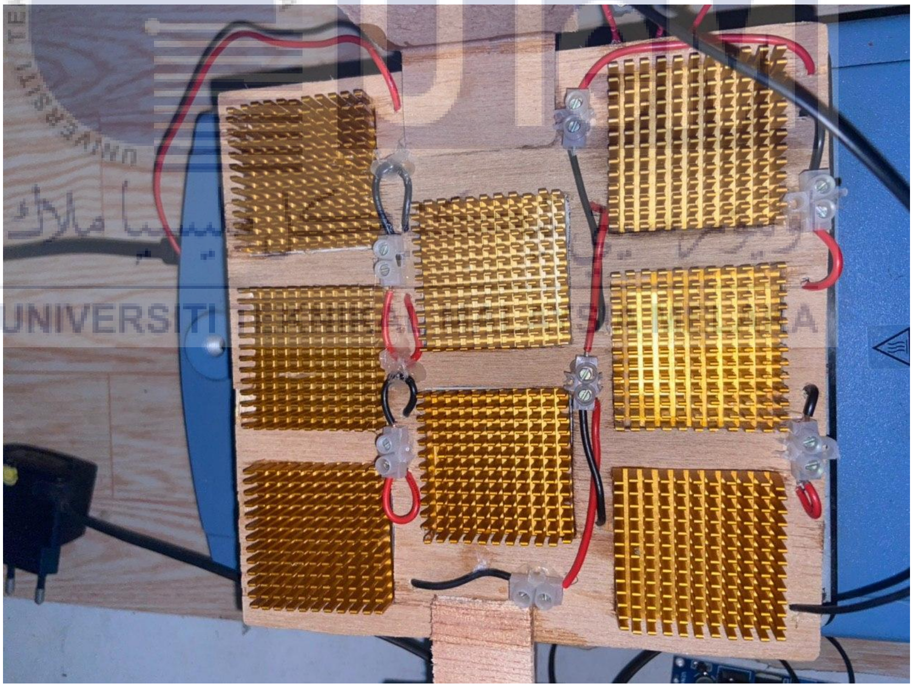

Figure 3.4 Arrangement of TEGs in electrically series and thermally series

The first part of the project shows that the TEG are arranged in thermally series and electrically parallel. The output will connect to the LTC3105EDD.

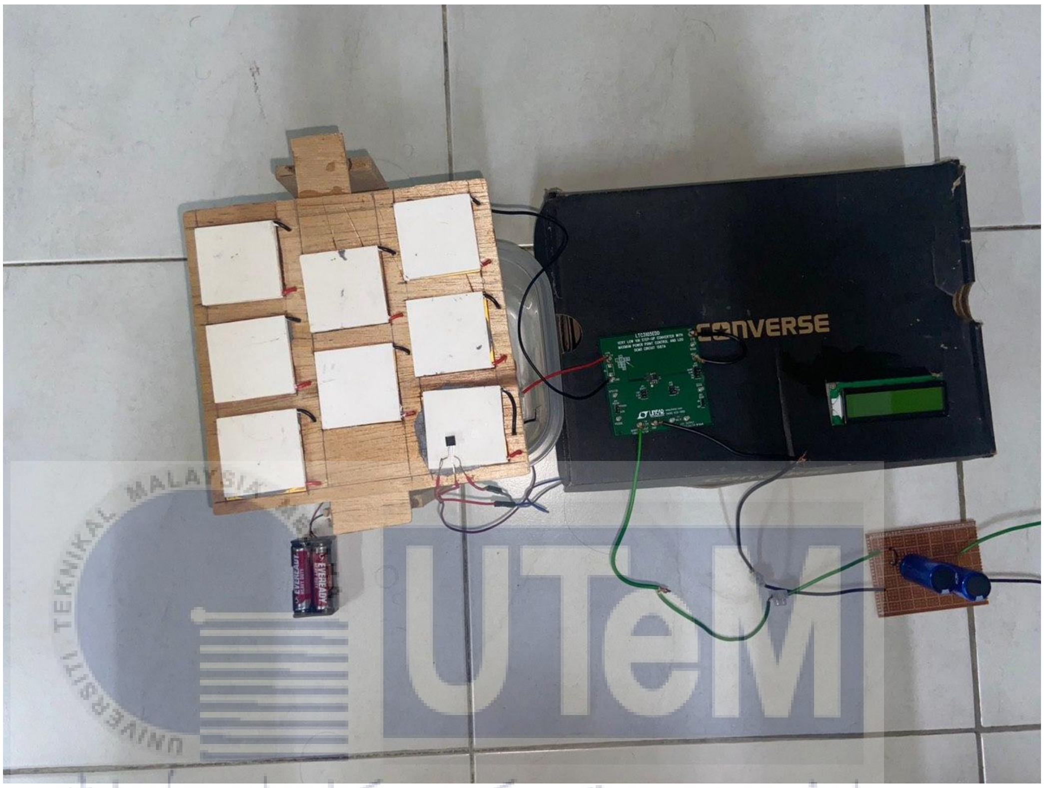

Figure 3.5 The first part of prototype which is the TEG connected with the LTC3105EDD and output goes into supercapacitor

The second part of the prototype is for the output of the system, the output will connect to the supercapacitor and it will connect with the usb that will charge the mobile phone.

Figure 3.6 The second part of prototype which the output of supercapacitor goes into the 5V usb converter and the output will go into the mobile phone

A heat sink is applied at the cold side of the TEGs. There are plenty of heat sinks on the market, but the thicker base heat sink is a safer option to dissipate heat faster and avoid the TEGs to achieve thermal equilibrium. As for the prototype, a 40 x 40 x 20 mm heat sink is used. The base of the heat sink is 4 mm. Figure3.7 shows the heat sink used for the prototype. The heat sink will be attached to the cold side of the TEGs.

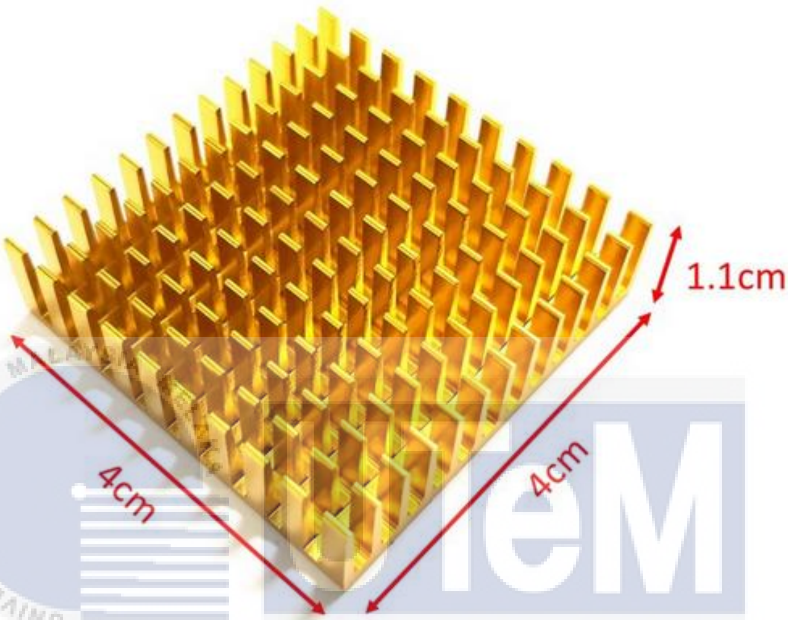

Figure 3.7 Heat sink used for the prototype

A thermal joint compound was used in between the TEGs and the heat sink to make it stick together. The thermal joint was used to eliminate gaps of air and spaces between the surface of the cold side of TEGs and the heat sink. It was also used to maximize the heat transfer from the hot side of the TEGs to the cold side of TEGs. The thermal joint use was the 30G CPU Heatsink Thermal Paste. Figure 3.8 below shows the thermal joint, or the thermal paste used.

Figure 3.8 Thermal paste compound

The thermal paste is not an adhesive compound. So, to assure that the TEGs and the heat sink are stack together, the thermal paste was used. After the prototype was built, another experiment was done to obtain the output voltage of the prototype and to check the functionality of the prototype.

3.4 Charging of Supercapacitor

The prototype is tested at outdoor by exposed it to the sunlight. Next, the prototype will try to store the energy to the 100F supercapacitor. The prototype is placed at outdoor so that it is exposed to the sunlight temperature which 30 °C-40 °C. The experiment is conducted to investigate the charging time for the supercapacitor by the LTC3105EDD boost converter. A calculation is made for the charging time for the supercapacitor. The calculation will be shown in Chapter 4.

Figure 3.9 Supercapacitor arranged in series

3.5 Spray Cooling System

The prototype for this project uses the spray cooling system as the cooling method for the system. The result for this project will compare the spray cooling method and the water-cooling method. The spray cooling part are including the Arduino, battery, relay and water pump. The Arduino act as the microcontroller to read the temperature data received from the hot side of the TEGs and the cold side of the TEGs. The temperature sensor is used to detect the temperature for the TEGs. The temperature sensor will read the temperature of the cold side, and if the temperature of the cold side reached more than 35 °C, it will send signal to Arduino and the Arduino will the signal to relay to turn on the relay so that the connection of the batter and the water pump are close and the water pump will start to spray the heat sink. This method is used because it is the main objective of the project. The spray cooling system will stop to spray when the temperature of the Cold Side of the TEGs reached less than 25°C. The flow of the system is shown in flowchart below as in figure 3.10.

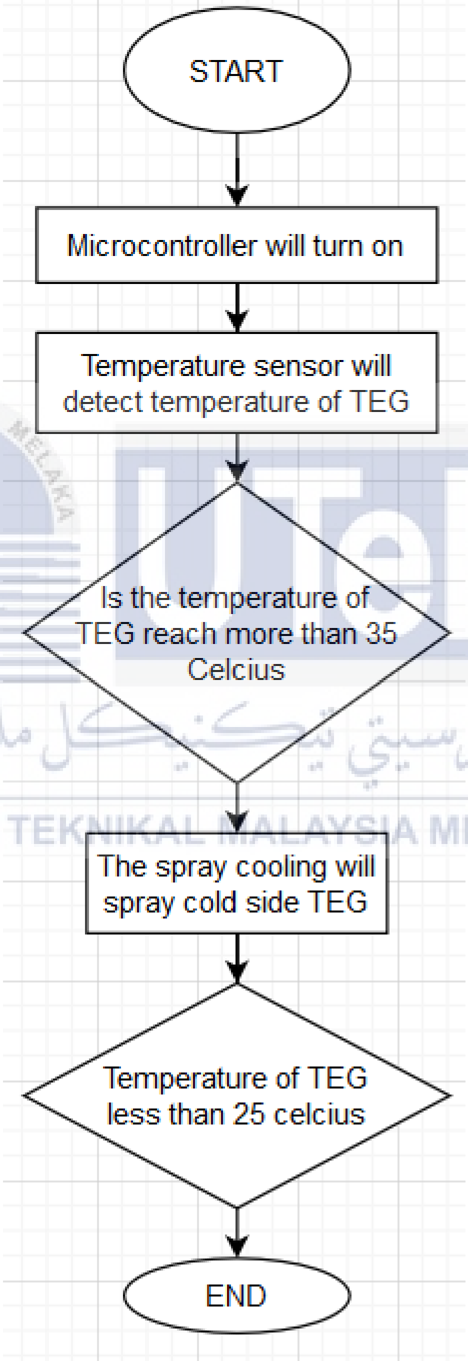

Figure 3.10 Flowchart the spray cooling system

In figure 3.11 it shows the spray that is used to spray the cold side of the TEGs. The spray will be triggered when the temperature of the cold side of the TEGs reach more than 35°C and it will stop when the temperature reached less than 25°C.

Figure 3.11 Spray Cooling

CHAPTER 4

RESULTS AND DISCUSSION

This chapter will include all the obtained results, including the output voltage analysis from different configuration of the thermoelectric generators before the prototype is built, thermal gradient of the thermoelectric generators during experiment conduction and the output voltage of the thermoelectric generator from the prototype that is built. Also, this chapter will cover the simulation results from the LTC boost converter and the comparator circuit. Furthermore, all the results obtained from the final prototype is provided in this chapter. The output result of each component used in the prototype is shown in this chapter. Lastly, the result of testing whether the final prototype is improving battery life is provided.

This chapter will describe the result of each part separately. The first part will be table and graph of configuration of TEG with using two TEGs until 8 TEGs. The next part of this chapter will discuss the best configuration to be use for the TEGs system. Next, it will analyse the result of the spray cooling system which include the efficiency of the TEGs system with spray cooling. Last part will compare the result of the spray cooling system and the water-cooling method.

4.1 Thermal Accumulation

This part is to select the best configuration of TEG to get the higher output voltage. The setup of configuration of TEGs is divided into four group which is Thermally Series Electrically Series, Thermally series Electrically Parallel, Thermally Parallel Electrically Series and Thermally Parallel Electrically Parallel. The test is made by using hot plate as the heater for the hot side of TEGs. The reading is taken three times and the result shown are the average of observation. Only two TEGs is used to develop this result. The result is shown below:

Thermally Series and Electrically Series

Table 4.1 shows the result of reading for the Thermally Series and Electrically Series configuration. The result obtained is quite high in temperature difference because it uses ice as the coolant for the temperature at the cold side of TEG.

Table 4.1: Thermally Series and Electrically Series configuration

Temperature(°C) (Hot plate)	Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage
30	32	27	5	0.14V
35	34	28	6	0.2V
40	40	30.4	9.2	1.25V
45	43	30.3	12.7	1.71V
50	49	30.1	18.9	2.75V

Thermally Series and Electrically Parallel

Table 4.2 shows the Thermally Series and Electrically Parallel configuration. The result obtain is slightly low compared with the Thermally Series and Electrically Parallel because of the electrically parallel configuration.

Table 4.2: Thermally Series and Electrically Parallel Configuration

Temperature(°C) (Hot plate)	Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage
30	34	29	5	1.04V
35	35	29	6	1.85V
40	40	33.1	6.9	2.10V
45	43	31.3	11.7	2.45V
50	49	37.8	11.2	2.41V

Thermally Parallel and Electrically Series

Table 4.3 shows the result for the Thermally Parallel and Electrically Series configuration. The result for this configuration is the not as high as the thermally series and electrically series as the Two TEGs are stacked together and the transfer heat coefficient are very low due to thermally parallel.

Table 4.3:Thermally Parallel and Electrically Series Configuration

Temperature(°C) (Hot plate)	Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage
30	30	26	4	0.358V
35	35	30	5	0.554V
40	40	26.5	13.5	1.35V
45	43	30.3	12.7	1.85V
50	49	32	17	2.15V

Thermally Parallel and Electrically Parallel

Table below shows the thermally parallel and electrically parallel configuration. The result for the configuration is the lowest output voltage because all the configuration used are parallel which thermally in parallel and electrically in parallel.

Table 4.4: Thermally Parallel and Electrically Parallel Configuration

Temperature(°C) (Hot plate)	Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage
30	30	24.5	5.5	0.79V
35	35	23	12	1.14V
40	40	29	11	1.15V
45	43	29	14	1.35V
50	49	34	15	1.87V

Based on figure 4.1 it can be show that the highest output voltage and temperature difference are the Thermally Series and Electrically Series (TSES) and the lowest output voltage are Thermally Parallel and Electrically Parallel (TPEP).

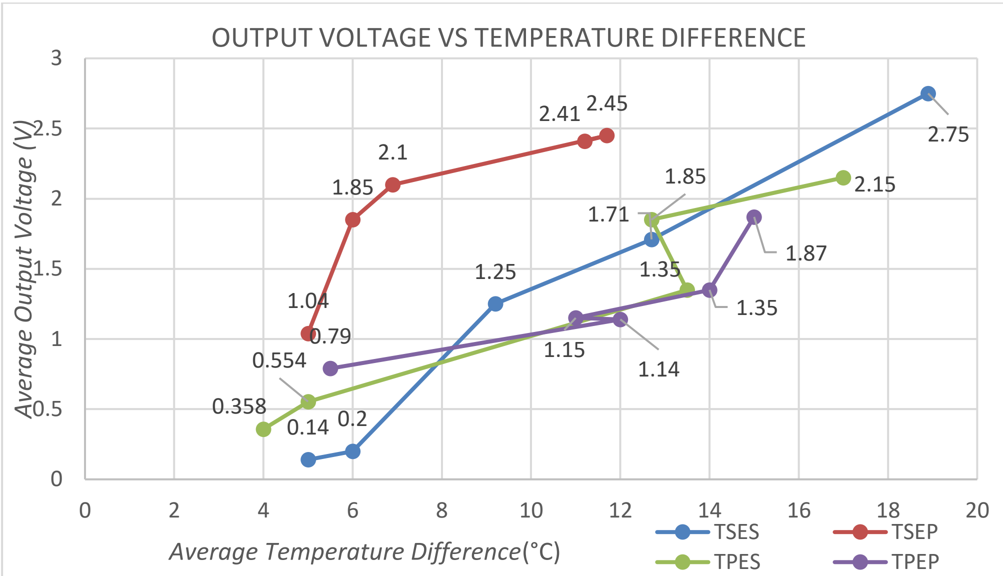

Figure 4.1: Graph of Output Voltage VS Temperature Difference

Based on this experiment it shows that there is large difference of the TEGs will produce difference of output voltage. It can be deduced that the output voltage is higher if use thermally series and electrically series. This happened because the large surface area that get continuous heat will generate higher voltage output based on the observation. Refer to the concept of Seebeck Effect, the TEGs devices will produce electricity if there is temperature difference between the hot side and cold side of the TEG. The data above are based on the average reading, the data is taken three consecutive times and average is calculated after that and the data displayed at the table and graph are the average data for the voltage output, and temperature difference.

4.2 TEG Analysis

There is test that have been done to observe the output voltage of TEGs. This test is made to observe the output voltage of the TEGs that will generate electricity that will be able to turn on the Maximum Power Point Tracker (MPPT) LTC3105EDD. The temperature for the hot plate has set to 30°C to 40°C. The test is done by taking the data for three repeated times and the temperature reading, temperature difference and the output voltage are the average result that is obtained. The test is also done to find out the best number of TEGs that could maintain and power up the MPPT.

4.2.1 Two TEGs

Table 4.5: Two TEGs connected electrically series and thermally series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
32	20	12	1.61
34	25	11	1.75
36	23	13	1.94
38	22	16	2.27
40	21.3	18.7	2.48

Based on table 4.5 above it shows that the temperature difference of the 2 TEG. In this table show the gradually decreasing of the temperature because of the temperature of surrounding are only at 26°C, so the temperature decreased easily. The temperature show that the output voltage produce based on the temperature difference in are shown in table 4.5.

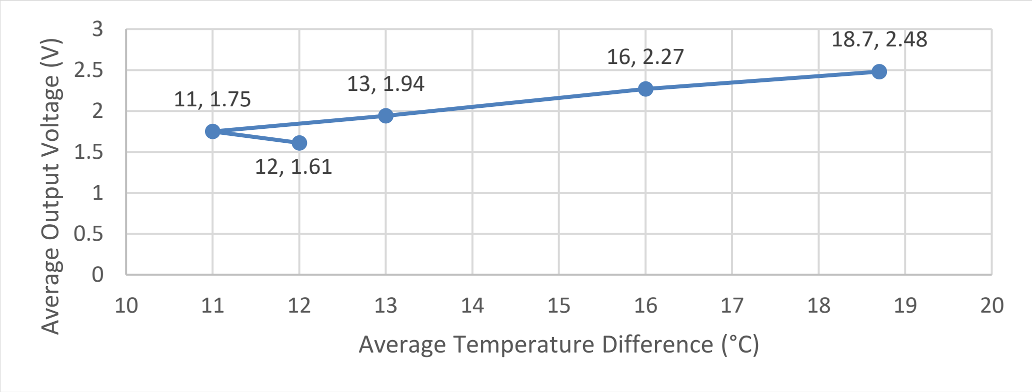

Figure 4.2 Graph Output Voltage VS Temperature Difference

Based on the result it shows that the voltage produce for 2 TEGs are range around 1.61V to 2.48V but this result is obtain by putting ice on the cold side of the TEGs so the temperature difference is quite high. The reading is taken three times for every temperature set by the hot side. So, the reading of the cold side is taken three times, the temperature difference is calculated for three times and the output voltage is taken three times. The displayed result on the table and graph are the average result. One of the reasons why the result is taken three times as it is to avoid error reading and to achieve higher accuracy of reading taken. Based on Figure4.2, between the point of 12°C and 11°C there are quite weird data, this is because the reading is taken three times and the average reading are like the data displayed.

4.2.2 Three TEGs

Table 4.6 Three TEGs Connected Electrically Series and Thermally Series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
32	22	10	2.78
34	19	16	3.75
38	23	15	3.54
40	18	22	4.23
44	16	28	4.58

Based on table 4.6 result show that the higher out voltage that will produce for 3 TEG is around 4.58V at 44°C of hot side temperature and the lowest of output voltage is 2.78V at 32°C hot side temperature. For the 44°C the temperature difference is 28°C and produce 4.58V.

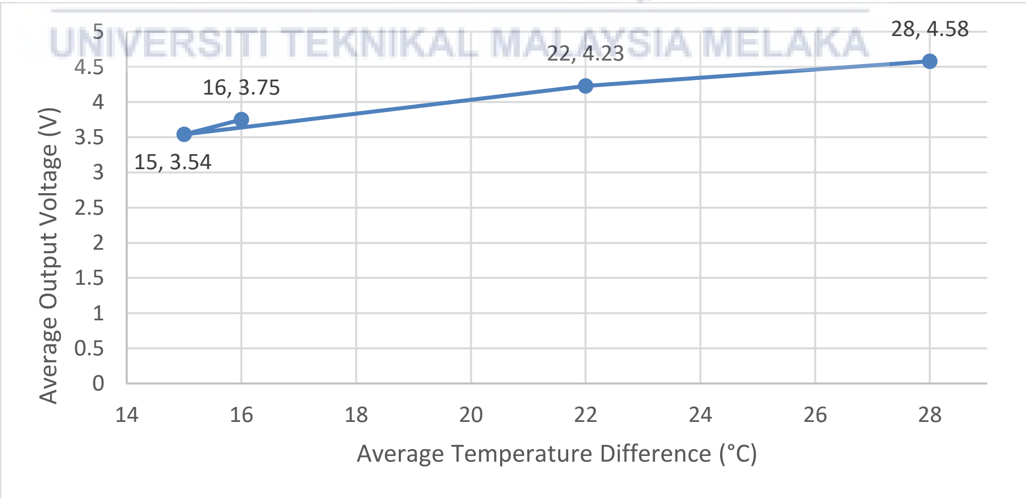

Figure 4.3: Graph Output Voltage VS Temperature Difference

Based on the result it shows that the voltage produce for 3 TEGs are range around 2.78V to 4.58V but this result is obtain by putting ice on the cold side of the TEGs so the temperature difference is quite high. The reading is taken three times for every temperature set by the hot side. So, the reading of the cold side is taken three times, the temperature difference is calculated for three times and the output voltage is taken three times. The displayed result on the table and graph are the average result. One of the reasons why the result is taken three times as it is to avoid error reading and to achieve higher accuracy of reading taken. Based on Figure4.3, between the point of 16°C and 15°C there are quite weird data, this is because the reading is taken three times and the average reading are like the data displayed.

4.2.3 Four TEGs

Table 4.7 Four TEGs connected in series and thermally series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
30	28	2	0.28
32	28	4	0.32
35	29	5	0.36
38	33	5	0.468
40	32	8	1.03

Based on Table 4.7 show that the highest output voltage that will produce for 4 TEG is around 1.03V at 40°C of hot side temperature and the lowest of output voltage is 0.28V at 30°C hot side temperature.

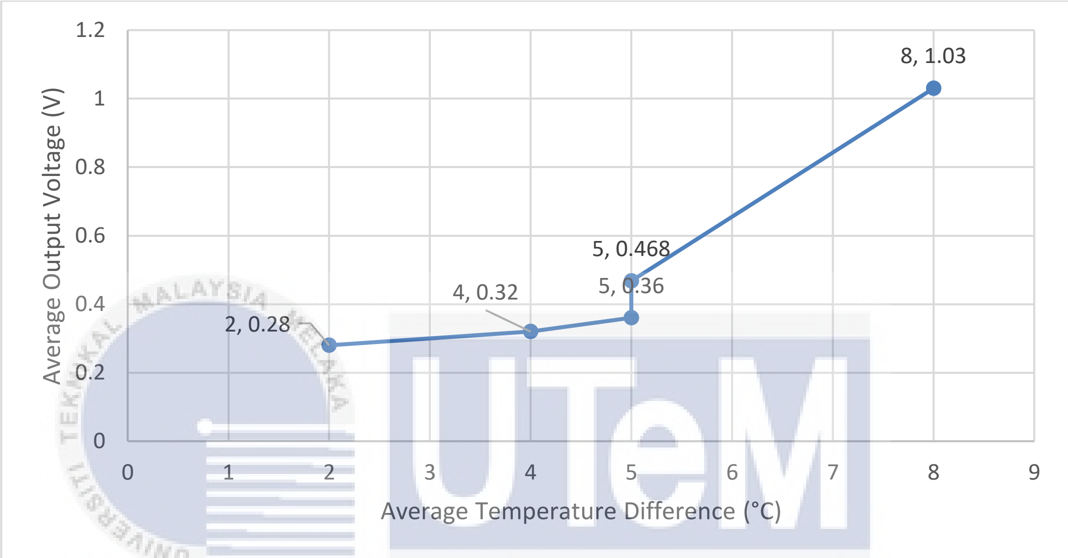

Figure 4.4: Graph Output Voltage VS Temperature Difference

Based on the result it shows that the voltage produced for 4 TEGs are range around 0.28V to 0.576V. This result is very different with the previous result because the cold side is not cold with ice but cold by only using heat sink. As for the 35°C and 38°C temperature of hot side it achieved the same temperature difference but different in output voltage. This is due to the average reading that are taken during the analyzing of the configuration.

4.2.4 Five TEGs

Table 4.8: Five TEGs connected in series and thermally series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature Difference(°C)	Output Voltage(V)
30	28	2	0.48
33	29	4	0.75
36	31	5	0.95
38	35	3	1.23
40	36	4	1.58

Based on the result for the table 4.8 it shows that the highest output voltage is 1.58V which appeared at the 40°C of temperature at hot side. While the lowest output voltage are shown at 0.48V which is at 30°C of hot side.

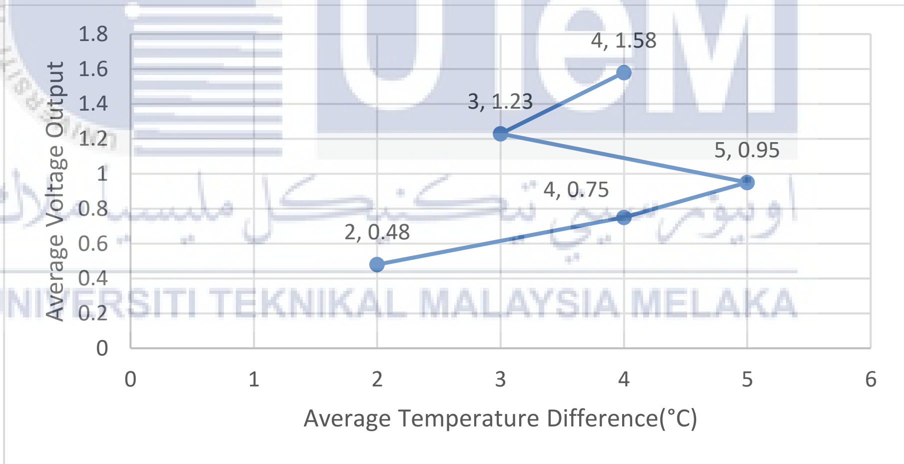

Figure 4.5 Graph Output Voltage VS Temperature Difference

Based on the result it shows that the voltage produced for 5 TEGs are range around 0.48V to 1.58V. This result is very different with the previous result because the cold side is not cold with ice but cold by only using heat sink. The result from the graph are shaped zig-zag at 0.95V to 1.23V, this happen because of the temperature difference of 1.23V are lower than 0.95V. Basically this is all due to the average value achieved during the reading taken, the result of temperature difference for 1.23V have a large gap so it produce 3°C of temperature difference and that is the average temperature difference and the average output voltage.

4.2.5 Six TEGs

Table 4.9: Six TEGs connected in series and thermally series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
30	28	2	1.21
32	29	3	1.35
35	32	3.5	1.54
37	33	4	1.78
40	35	5	2.01

Based on table 4.9 show that the higher out voltage that will produce for 6 TEG is around 2.01V at 40°C of hot side temperature and the lowest of output voltage is 1.21V at 30°C hot side temperature

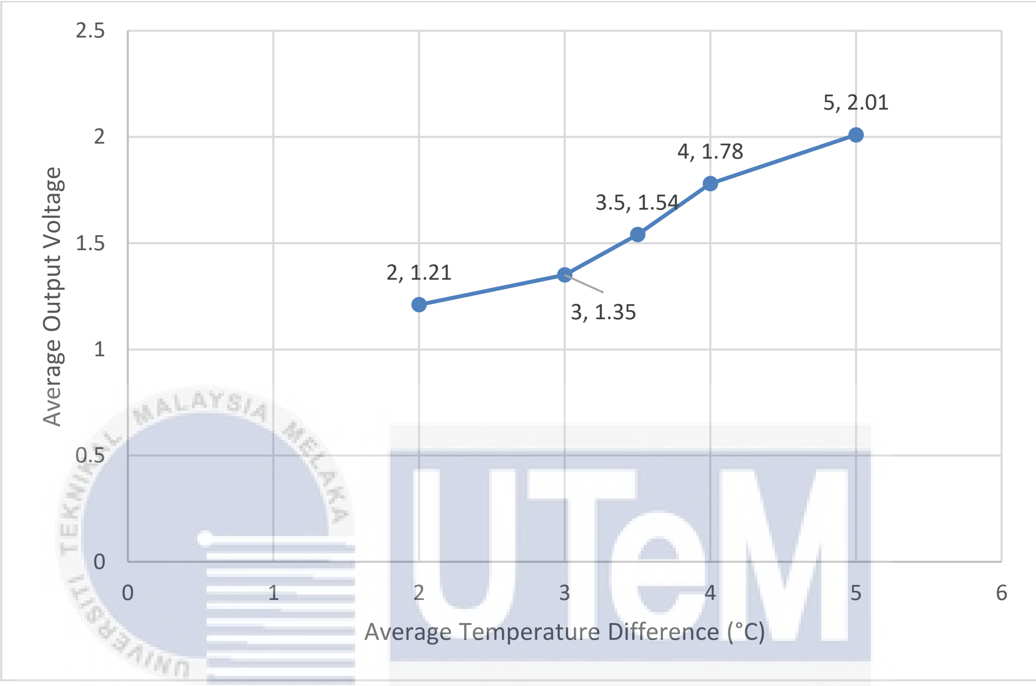

Figure 4.6 Graph Output Voltage VS Temperature Difference

Based on the figure 4.6 it shows that the voltage produced for 6 TEGs are range around 1.21V to 2.01V. The result of the graph shows that it is linearly increase as the temperature difference between the hot side and the cold side of the TEGs increases.

4.2.6 Seven TEGs

Table 4.10 Seven TEGs connected in series and thermally series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
30	28	2	1.58
32	29	3	1.62
35	32	3	1.71
37	34	3	1.82
40	35	5	2.21

Based on table 4.10 show that the highest output voltage that will produce for 7 TEG is around 2.21V at 40°C of hot side temperature and the lowest of output voltage is 1.58V at 30°C of hot side temperature.

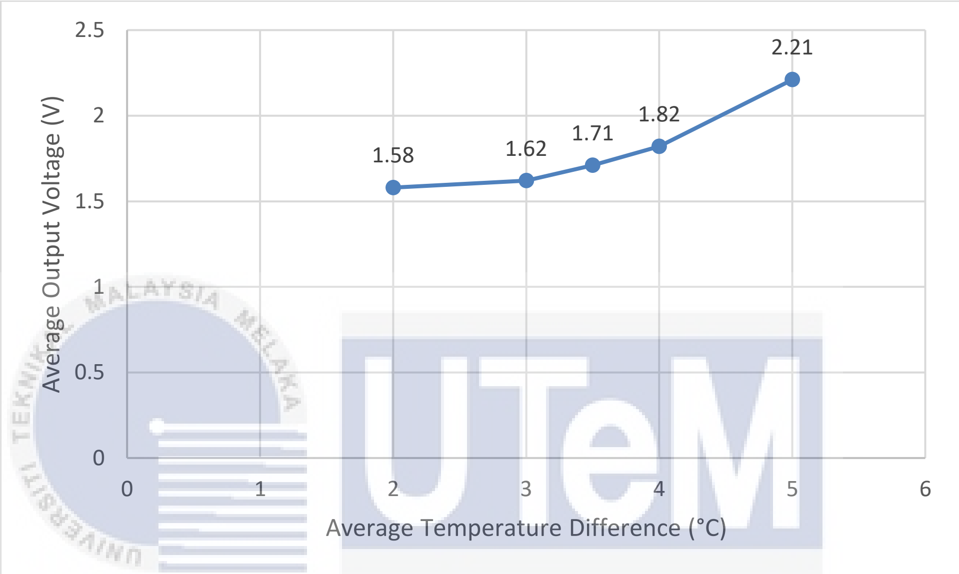

Figure 4.7 Graph of Temperature Difference vs Output Voltage

Based on the figure 4.7 it shows that the voltage produced for 7 TEGs are range around 1.21V to 2.01V. The result for the graph shows that the higher the temperature difference between the hot side and cold side of TEGs the higher the output voltage. Although the consistency of the data is very low, the result that show are logically approved as the higher difference of temperature, the higher the voltage output. The reading of the temperature difference is sometimes near to each other but the output voltage vary closely to each other this is because the value shown in the graph are average result obtain by taking the reading three times.

4.2.7 Eight TEGs

Table 4.11: Eight TEGs Connected Thermally Series and Electrically Series

Temperature(°C) (Hot Side)	Temperature(°C) (Cold side)	Temperature difference(°C)	Output Voltage(V)
30	27	3	1.69
33	29	4	1.81
36	31	5	2.32
38	32	6	2.89
40	33	7	3.05

Based on table 4.11 show that the highest output voltage that will produce for 8 TEG is around 3.05V at 40°C of hot side temperature and the lowest of output voltage is 1.69V at 30°C of hot side temperature.

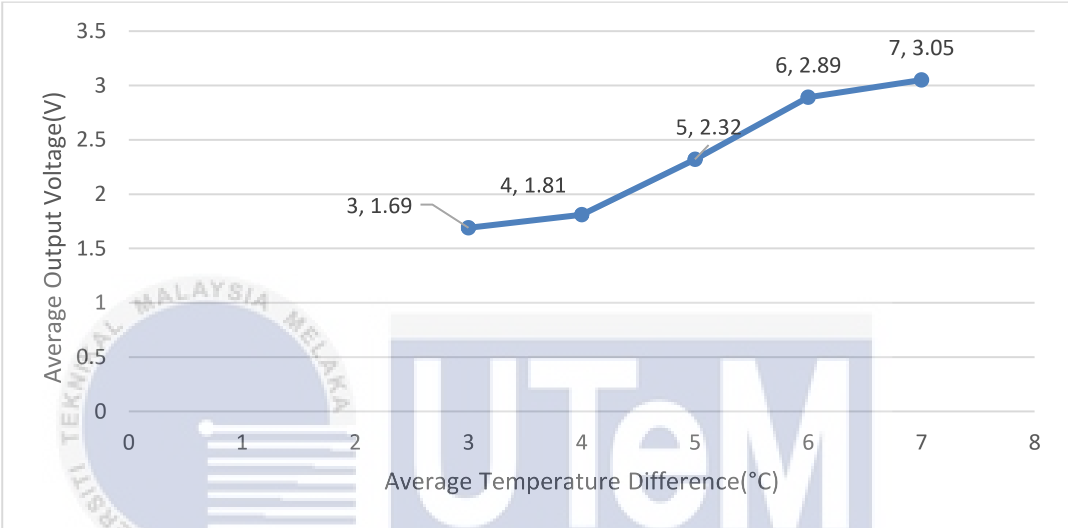

Figure 4.8: Graph of Temperature Difference vs Output Voltage

Based on the result it shows that the voltage produced for 8 TEGs are range around 1.21V to 2.01V. The result for the graph is slightly increased compared with the 7 TEGs graph, this is because the temperature are almost the same and the cooling system efficiency getting lower as the number of TEGs increase. So, by using 8 TEGs it can produce sufficient voltage to support the prototype.

4.3 Efficiency of System

After all the results and data are obtained, the calculation part which is the efficiency are done. This is done to investigate the efficiency of the system. Based on the Minghui, it stated that the net output of efficiency of the spray cooling system should be approximately 9.9% higher compared with the water-cooling method at a ratio of 10 where C =100[1]. So, based on the calculation for efficiency, the project must obtain the power output first and then the calculation for the efficiency could be done. Based on the equation 4.1, the value of output power is done.

The output power for eight TEGs is used as the data for eight TEGs are the highest output voltage. The input power and output power can be calculated by using Equation 4.1 below,

$$P_{in} = Input\ Voltage \times Input\ Current \quad (4.1)$$

Equation 4.1 Power Equation

$$P_{in} = 3.05V \times 115.53mA = 0.352W$$

The output voltage and output current of the eight TEGs are shown above. As for the output power, it is taken at the output of the supercapacitor which is before it goes into the charger of mobile phone. The output power is calculated as,

$$P_{out} = Output\ Voltage \times Output\ Current \quad (4.2)$$

Equation 4.2 Output Power Equation

$$P_{out} = 5V \times 4.8mA = 0.024W$$

The efficiency of the system can be calculated from Equation 4.2,

$$Efficiency, \eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (4.3)$$

Equation 4.3 Efficiency Equation

$$\eta = \frac{0.024W}{0.352W} \times 100\% = 6.818\%$$

The efficiency of the system is only about 6.818% it is relatively low but since there are many power loss from the component in the energy harvesting board such as the wire, the resistor from inside the booster and the internal resistor of the TEGs. The expectation from the reference is about 9.9%. So, for Eight TEGs the efficiency did not achieve the expected result. But, for the result for the average efficiency are different from the eight TEGs result. The calculation for the average efficiency can be calculated as below,

$$P_{in} = 2.352V \times 89.1mA = 0.2096W$$

$$P_{out} = 5V \times 4.8mA = 0.024W$$

$$Efficiency, \eta = \frac{0.024}{0.2096} \times 100\% = 11.45\%$$

The average efficiency is taken from the average reading of voltage output from the Table 4.11 above. The voltage output and current are calculated in average. So, when all the data above are in average, the efficiency are calculated in average. Based on the calculation, the efficiency of the system increased about 4.632%, and it could prove that based on the research it stated that the efficiency should be approximately around 9.9% compared with water cooling method.

As for comparison with the water-cooling method, this research showed that the water-cooling method could achieve 2.34% of efficiency [31]. This research showed that it uses the higher temperature which is 150°C - 230°C compared with this project which it uses only 30°C - 40°C. The research use gas stove as the heat source. Figure4.9 below shows the schematic diagram and the prototype of the project,

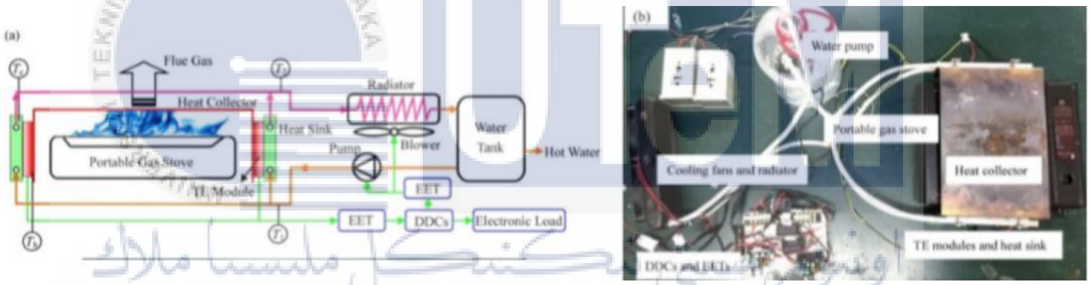

Figure 4.9 The schematic diagram of the project(A) and the prototype of the project(B)

Based on table4.12 below it shows the comparison of between two method which is the water-cooling method and water spraying method,

Table 4.12 Comparison with two method

	WATER COOLING METHOD	**SPRAY COOLING METHOD**
METHOD	Uses high temperature Eg: Gas stove	Uses temperature of sunlight
TEMPERATURE RANGE	150 °C -230 °C	30°C - 40°C
EFFICIENCY	2.34%	11.45%

Figure below shows the comparison between two method

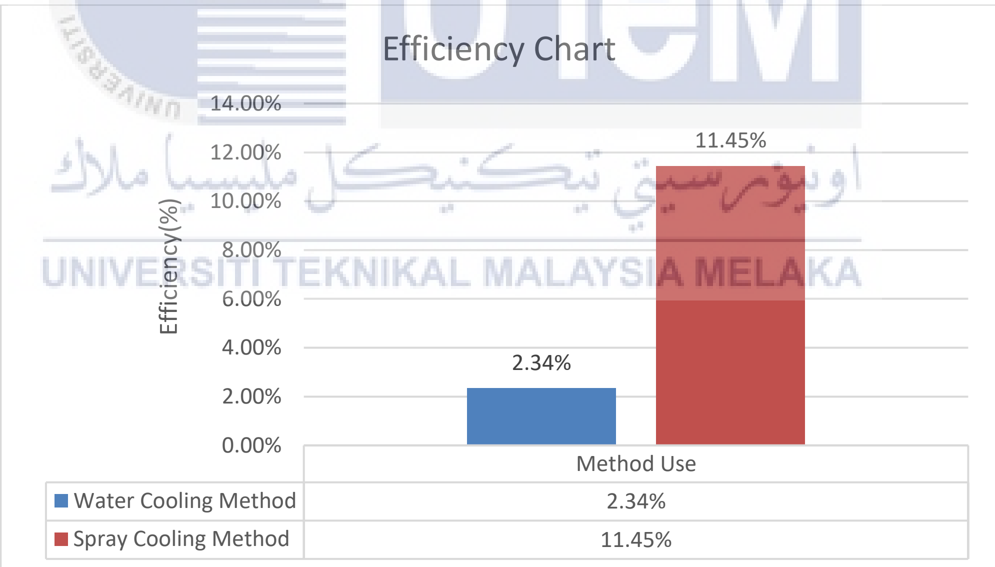

Figure 4.10 Chart of Efficiency between the two method

Figure 4.10 above shows the comparison of between the two method which is water cooling method and spray cooling method. Based on the chart above it can be conclude that the efficiency for the water cooling method is much greater compared with the water cooling method, the margin between the two efficiency's method are 9.11% and it is almost accurate according to the research above which it should be 9.9%

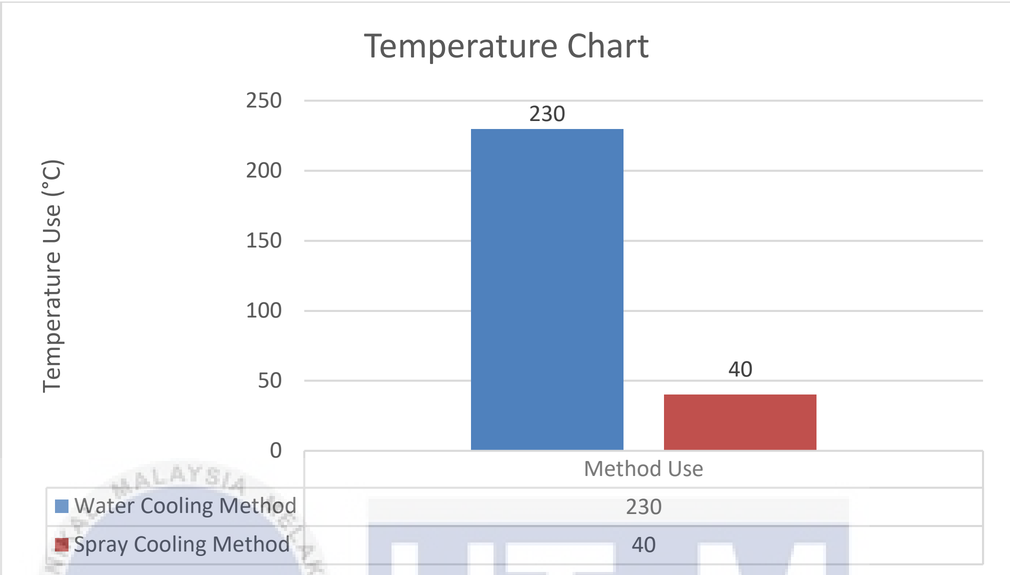

Figure 4.11 Chart of temperature between the two method

The Figure 4.11 above discussed about the comparison of temperature between the two method which is water cooling method and spray cooling method. It can be deduced by the water-cooling method uses very higher temperature compared with the spray cooling method which only uses very low temperature by using only 40°C while the water-cooling method uses 230°C.

Based on all the result above, we can conclude that although the water cooling method uses a very high temperature while the spray cooling method only uses the temperature of sunlight which is 30°C-40°C, the water cooling method only able to produce a very low efficiency which is only 2.34% which is very low compared with the spray cooling method which can produce 11.45%. This proved that the spray cooling method are much better compared with the spray cooling method.

4.4 Charging of Supercapacitor

After the TEGs voltage are regulated at 5V, the energy is stored in supercapacitor. As mentioned in Chapter 3, the supercapacitor used in the prototype are 100F. So, to fully charge the supercapacitor, it will take a lot of time. The time taken to fully charge the supercapacitor can show in the calculation shown in Equation 4.3 below

$$I_C = C\frac{dV}{dt}$$

Equation 4.4 Current from Capacitor

$$\frac{dV}{dt} = \frac{I_C}{C}$$

$$\frac{dV}{dt} = \frac{4.8mA}{100F}$$

$$\frac{dV}{dt} = 480\ \mu Vs^{-1}$$

$$t = \frac{V}{480\mu Vs^{-1}}$$

$$t = \frac{3}{480\mu Vs^{-1}}$$

$$t = 10416.67\text{seconds} = 2.89\text{ hours}$$

Based on the calculation, to charge the supercapacitor from 0V to 5V using LTC3105EDD, it took about 2.89hours. However, as it took too long to charge the supercapacitor, a power supply of 5V and 2A are used to fasten up the time taken to charge the supercapacitor to fully charge. Even if the supercapacitor is out of charge, the TEGs could charge it back but it will took a long time, so to get a faster it uses power supply to charge it and then it will connect to the full system of the project.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

This section provides a conclusion to the overall project including reflection on achieving the targets and overall product running. A potential recommendation is given at the end of this chapter for further development of this project.

5.1 Conclusion

To deduce all the overall project, it is proved that the project objectives have been successfully achieved. A TEGs system with spray cooling is successfully designed and developed, with the use of eight TEGs. The thermoelectric configuration had been successfully analyses and the result is greatly proved by taking the data more than one time which the data is taken three times. The configuration is set Thermally Series and Electrically Series, while the output voltage for the configuration are sufficient to go through the input of the LTC3105EDD so that the output could produce 5V. The LTC3105EDD function very well throughout the test rig of this project thus gives the great result for this project. The output of the dc booster which is the LTC3105EDD able to charge the supercapacitor for about 2.89 hours(theoretically) which is quite fast for an energy harvesting device to charge a 100F of supercapacitor. Furthermore, the objective of comparing the water cooling method and spray cooling method proved that the objective are achieved successfully which we could conclude that the spray cooling method are way better than the water cooling method which the spray cooling method have achieved 11.88% of efficiency while the water cooling method only able to achieved 2.34% of efficiency. So, based on the efficiency achieved it can be conclude that the energy needed to bringing down the temperature of the cold side are very minimal as we only need water pump to spray the cold side of the TEGs. Plus, the configuration also helped to achieve the greater result for this project.

5.2 Future Work Reference

There are several recommendations are listed to improve the designer of this spray cooling system. Firstly, the design for the spraying system could be improvise as the current system only could spray partially of the heat sink, so to improve the spray cooling system, the spray cooling should be able to spray all the heat sink evenly or the system could apply a spray mist as the spray mist require a lot of pressure from water pump and it would produce a colder water compared with current spray cooling system. Next, the heat source of the TEGs could use higher temperature as the higher temperature will produce higher output and higher efficiency will be produced. After that, for next future work reference it should discover the precise amount of water usage and the water pressure for the water pump needed to cool down the temperature of the cold side of TEGs. By doing the research about the amount of pressure needed and the amount of water needed it could precisely save the world and head towards the green technology vision. Lastly, they should research on the best component to replace the supercapacitor as the supercapacitor needed a lot of time to recharge and it also discharge very quickly

REFERENCES

[1] M. Ge, Z. Wang, L. Liu, J. Zhao, and Y. Zhao, "Performance analysis of a solar thermoelectric generation (STEG) system with spray cooling," *Energy Convers. Manag.*, 2018, doi: 10.1016/j.enconman.2018.10.016.

[2] D. Sun, L. Shen, Y. Yao, H. Chen, S. Jin, and H. He, "The real-time study of solar thermoelectric generator," *Appl. Therm. Eng.*, 2017, doi: 10.1016/j.applthermaleng.2017.03.075.

[3] Z. G. Chen, G. Hana, L. Yanga, L. Cheng, and J. Zou, "Nanostructured thermoelectric materials: Current research and future challenge," *Progress in Natural Science: Materials International*. 2012, doi: 10.1016/j.pnsc.2012.11.011.

[4] H. Ali, A. Z. Sahin, and B. S. Yilbas, "Thermodynamic analysis of a thermoelectric power generator in relation to geometric configuration device pins," *Energy Convers. Manag.*, 2014, doi: 10.1016/j.enconman.2013.11.029.

[5] W. L. Cheng, W. W. Zhang, H. Chen, and L. Hu, "Spray cooling and flash evaporation cooling: The current development and application," *Renewable and Sustainable Energy Reviews*. 2016, doi: 10.1016/j.rser.2015.11.014.

[6] H. Lv, G. Li, Y. Zheng, J. Hu, and J. Li, "Compact Water-Cooled Thermoelectric Generator (TEG) based on a portable gas stove," *Energies*, 2018, doi: 10.3390/en11092231.

[7] F. J. Disalvo, "Thermoelectric cooling and power generation," *Science*. 1999, doi: 10.1126/science.285.5428.703.

[8] M. Zebarjadi, K. Esfarjani, M. S. Dresselhaus, Z. F. Ren, and G. Chen, "Perspectives on thermoelectrics: From fundamentals to device applications," *Energy and Environmental Science*. 2012, doi: 10.1039/c1ee02497c.

[9] T. Caillat, J. P. Fleurial, G. J. Snyder, and A. Borshchevsky, "Development of high efficiency segmented thermoelectric unicouples," in *International Conference on Thermoelectrics, ICT, Proceedings*, 2001, doi: 10.1109/ict.2001.979888.

[10] A. Vargas-Almeida, M. A. Olivares-Robles, and P. Camacho-Medina, "Thermoelectric system in different thermal and electrical configurations: Its impact in the figure of merit," *Entropy*, 2013, doi: 10.3390/e15062162.

[11] S. J. Kim, J. H. We, and B. J. Cho, "A wearable thermoelectric generator fabricated on a glass fabric," *Energy Environ. Sci.*, 2014, doi: 10.1039/c4ee00242c.

[12] K. M. Powell, K. Rashid, K. Ellingwood, J. Tuttle, and B. D. Iverson, "Hybrid concentrated solar thermal power systems: A review," *Renewable and Sustainable Energy Reviews*. 2017, doi: 10.1016/j.rser.2017.05.067.

[13] D. N. Kossyvakis, C. G. Vossou, C. G. Provatidis, and E. V. Hristoforou, "Computational analysis and performance optimization of a solar thermoelectric generator," *Renew. Energy*, 2015, doi: 10.1016/j.renene.2015.03.026.

[14] H. B. Gao, G. H. Huang, H. J. Li, Z. G. Qu, and Y. J. Zhang, "Development of stove-powered thermoelectric generators: A review," *Applied Thermal Engineering*. 2016, doi: 10.1016/j.applthermaleng.2015.11.032.

[15] J. Pandit, M. Thompson, S. V. Ekkad, and S. T. Huxtable, "Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels," *Int. J. Heat Mass Transf.*, 2014, doi: 10.1016/j.ijheatmasstransfer.2014.05.030.

[16] J. H. Meng, X. D. Wang, and W. H. Chen, "Performance investigation and design optimization of a thermoelectric generator applied in automobile exhaust waste heat recovery," *Energy Convers. Manag.*, 2016, doi: 10.1016/j.enconman.2016.04.080.

[17] S. B. Riffat and X. Ma, "Thermoelectrics: A review of present and potential applications," *Applied Thermal Engineering*. 2003, doi: 10.1016/S1359-4311(03)00012-7.

[18] K. Y. Sudharshan, V. P. Kumar, and H. C. Barshilia, "Performance evaluation of a thermally concentrated solar thermo-electric generator without optical concentration," *Sol. Energy Mater. Sol. Cells*, 2016, doi: 10.1016/j.solmat.2016.05.033.

[19] Y. Zhao, S. Wang, M. Ge, Y. Li, and Z. Liang, “Analysis of thermoelectric generation characteristics of flue gas waste heat from natural gas boiler,” *Energy Convers. Manag.*, 2017, doi: 10.1016/j.enconman.2017.06.029.

[20] M. E. Demir and I. Dincer, “Performance assessment of a thermoelectric generator applied to exhaust waste heat recovery,” *Appl. Therm. Eng.*, 2017, doi: 10.1016/j.applthermaleng.2017.03.052.

[21] X. Gou, H. Xiao, and S. Yang, “Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system,” *Appl. Energy*, 2010, doi: 10.1016/j.apenergy.2010.02.013.

[22] C. Wu, “Analysis of waste-heat thermoelectric power generators,” *Applied Thermal Engineering*. 1996, doi: 10.1016/1359-4311(95)00014-5.

[23] Q. Cao, W. Luan, and T. Wang, “Performance enhancement of heat pipes assisted thermoelectric generator for automobile exhaust heat recovery,” *Appl. Therm. Eng.*, 2018, doi: 10.1016/j.applthermaleng.2017.09.134.

[24] S. Dwari and L. Parsa, “An efficient AC-DC step-up converter for low-voltage energy harvesting,” *IEEE Trans. Power Electron.*, 2010, doi: 10.1109/TPEL.2010.2044192.

[25] C. Lu, S. Wang, C. Chen, and Y. Li, “Effects of heat enhancement for exhaust heat exchanger on the performance of thermoelectric generator,” *Appl. Therm. Eng.*, 2015, doi: 10.1016/j.applthermaleng.2015.05.086.

[26] Z. Niu, H. Diao, S. Yu, K. Jiao, Q. Du, and G. Shu, “Investigation and design

optimization of exhaust-based thermoelectric generator system for internal combustion engine,” *Energy Convers. Manag.*, 2014, doi: 10.1016/j.enconman.2014.05.061.

[27] A. M. Shakhut, V. M. Lutkovskij, and N. N. Nikitin, “Temperature sensor,” *Prib. i Tekhnika Eksp.*, 1995, doi: 10.1007/978-3-642-41714-6_200437.

[28] A. González, E. Goikolea, J. A. Barrena, and R. Mysyk, “Review on supercapacitors: Technologies and materials,” *Renewable and Sustainable Energy Reviews*. 2016, doi: 10.1016/j.rser.2015.12.249.

[29] Y. Wang *et al.*, “Supercapacitor devices based on graphene materials,” *J. Phys. Chem. C*, 2009, doi: 10.1021/jp902214f.

[30] L. Zhang and X. S. Zhao, “Carbon-based materials as supercapacitor electrodes,” *Chem. Soc. Rev.*, 2009, doi: 10.1039/b813846j.

[31] H. Lv, G. Li, Y. Zheng, J. Hu, and J. Li, “Compact Water-Cooled Thermoelectric Generator (TEG) based on a portable gas stove,” *Energies*, vol. 11, no. 9, 2018, doi: 10.3390/en11092231.

APPENDICES

APPENDIX I

GANTT CHART

Project Planning
List the main activities for the proposed project. Specify the time period required for each activity

PSM 1 — 2019

Main Activity	Sep				Oct				Dec			
	1	2	3	4	1	2	3	4	1	2	3	4
Literature Review	X	X	X	X	X	X	X	X	X	X	X	X
Proposal Preparations	X	X	X									
Design for the TEG System				X	X	X	X	X	X	X		
Design for spray cooling system								X	X	X	X	X
Electronic Circuit Testing												
Data Analysis												
Thesis Writing				X	X	X	X	X	X	X	X	X
Thesis Submission												

PSM 2 — 2020

Main Activity	Jan				Feb				Mar				Apr				May				Jun			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Literature Review	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
Proposal Preparations																								
Design for the TEG System																								
Design for spray cooling system																								
Electronic Circuit Testing	X	X	X																					
Data Analysis	X	X	X	X																				
Thesis Writing	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
Thesis Submission															X	X								

Figure 5.1 Gantt Chart

APPENDIX II

PROGRAMMING CODE FOR SPRAY COOLING SYSTEM

```
#include <Wire.h>

#include <LCD.h>

#include <LiquidCrystal_I2C.h>

#define I2C_ADDR 0x27 //Define I2C Address where the PCF8574A is

#define BACKLIGHT_PIN 3

#define En_pin 2

#define Rw_pin 1


#define Rs_pin 0

#define D4_pin 4

#define D5_pin 5

#define D6_pin 6

#define D7_pin 7

//define variables for the LM35 temperature sensor

float temp1; //Define the temp float variable
```

```
float temp2; //Define the Fahrenheit float variable

int sensor = 0; // sensor middle pin on analog pin 0
int sensor2 = 1; //sensor analog pin 1

LiquidCrystal_I2C lcd(I2C_ADDR, En_pin,Rw_pin,Rs_pin,D4_pin,D5_pin,D6_pin,D7_pin);

void setup() {

lcd.begin (16,2); //Define the LCD as 16 column by 2 rows

//Switch on the backlight(Bawah ni)


lcd.setBacklightPin(BACKLIGHT_PIN,POSITIVE);

lcd.setBacklight(HIGH);

lcd.setCursor(0,0); //goto first column (column 0) and first line (Line 0)

lcd.print("Hot Side  = "); //Print at cursor Location

lcd.setCursor(0,1); //goto first column (column 0) and second line (line 1)

lcd.print("Cold Side = "); //Print at cursor location


pinMode (7, OUTPUT);
}
//Void loop I will read the temperature from the sensor1, and display it on the first row, then
//raed temperature from sensor2 and display it on the second row. The repeat the process every 5 seconds
void loop(){

temp1 = analogRead(sensor); //assigning the analog output to temp1
temp2 = analogRead(sensor2); //assign analog output to temp2

temp1 = temp1 * 0.48828125; //converting volts to degrees celsius ----- 0.48828125 = [(5V*1000)/1024]10
temp2 = temp2 * 0.48828125;

lcd.setCursor(11,0); //move the cursor to position 8 on row 1

lcd.print(temp1); //print the temperature in Celsius

lcd.setCursor(11,1); //move the cursor to position 8 on row 2
```

```
lcd.print(temp2); //print the temperature in Fahrenheit

if (temp2 > 35){
  digitalWrite (7, LOW);
}
else {
  digitalWrite(7, HIGH);
}
delay(500); //wait 1 seconds

}
```