RADIATIVE COOLING WITH THERMOELECTRIC GENERATOR FOR POWER GENERATION

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A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Mechanical)

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April 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

Radiative cooling thermoelectric generator (RC-TEG) is an energy harvesting device that utilizes radiative cooling and thermoelectric technology to convert the temperature difference between the hot and the cold sides of the thermoelectric module into electricity. They offer a sustainable method for power generation, but their widespread adoption is hindered by the challenge of low energy conversion efficiency due to the small and unstable temperature difference across the thermoelectric generator. This study addresses the challenge of low energy conversion efficiency in TEG modules for power generation. The objective of this research is to design a simple prototype of RC-TEG for power generation, analyze its energy conversion efficiency, and compare the performance of TEG modules with and without radiative cooler coating, as well as with different radiative cooler coatings. A comprehensive study on RC-TEG, energy conversion efficiency, and radiative cooler coatings was conducted to achieve these objectives. A prototype was developed and investigated for the impact of radiative cooler coatings on energy conversion efficiency through experimental studies. The experimental findings demonstrated that applying radiative cooler coatings has positively enhances the power generation. Specifically, utilizing both cool weather white paint and silicon dioxide coating, the highest power output of 0.1080 mW (0.051 W/m^2) is generated with a radiative cooling module area of 0.0021 m^2 as well as with a conversion efficiency of 0.34 % at a figure of merit of 0.71 and a differential temperature of 8.2 K, surpassing other conditions investigated. With that, these results highlighted the potential of RC-TEG to advance in sustainable and reliable power generation technology.

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LIST OF SYMBOLS / ABBREVIATIONS

Al_2O_3	Aluminium oxide
$BaSO_4$	Barium sulphate
$CaCO_3$	Calcium carbonate
GHGs	Greenhouse gases
IEA	International Energy Agency
PEA	Polyethylene aerogel
PRC	Passive radiative cooling
RC-TEG	Radiative cooling thermoelectric generator
rpm	Revolutions per minute
IR	Thermal infrared
S	Seebeck coefficient
SE	Selective emitter
SERI	Solar Energy Research Institute
SiO_2	Silicon dioxide
TEG	Thermoelectric generator
TiO_2	Titanium dioxide
η	Efficiency of TEG modules
σ	Electrical conductivity
T	Mean temperature
T_C	Temperature of cold side of TEG
T_H	Temperature of hot side of TEG
K	Thermal conductivity
ZT	Figure of merit

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

With the ever-increasing global population and the relentless progress of technology, the utilization of energy has surged to unprecedented heights. According to ENERGY WATCH (2021), the demand for electricity in Malaysia is predicted to increase from 18,808MW in 2020 to 24,050MW by 2039 as shown in Figure 1.1. Additionally, on a larger scale, the global total energy consumption is predicted to rise by a staggering 48% by 2040 based on the US Energy Information Administration. This is due to the combination of population expansion as well as economic growth in developing nations (ENERGY WATCH, 2021). The stability of the environment is seriously threatened by climate change as most of the global energy output is relying on non-renewable energy sources. Energy is generated primarily by the fossil fuels like coal, oil, and gas on a global scale. These fossil fuels remain a major energy source, with around 83% of the world's annual energy consumption still coming from these fossil fuels. As a result, the Earth's natural carbon cycle may be impacted by excessive emissions of carbon dioxide into the atmosphere, which eventually leads to climate change due to the rise of the greenhouse effect. If this practice continues, the ecosystems as well as the living things on Earth such as wildlife and human will all suffer due to the warming effect caused by a rise in greenhouse gases (GHGs) in the atmosphere (Terrapass, 2022).

Due to their limited and depleting availability as well as possessing harmful impacts on the environment, fossil fuels continue to be an unsustainable source of energy. Thus, the demand for eco-friendly and sustainable energy sources like solar, tide as well as wind has increased. In order to ensure the average global surface temperature is only within an increment of 2°C, these renewable energy sources play a vital role in the reduction required in GHG emissions between now and 2050 (Gielen, et al., 2019). However, the majority of these renewable energy sources are dispersed unevenly over the globe in both time and space. For example, solar energy is not available at night, while tidal energy is only available near the coast. Hence, the idea of producing electricity using radiative cooling and outgoing heat radiation has gained popularity recently (Zhao, Pei and Raman, 2020). To make use of the temperature differential brought on by radiative cooling, the application with the use of a thermoelectric generator has been proposed. Regardless of the availability of any natural or artificial energy source, this power generation can produce electric energy whenever and wherever it is needed (Xia, et al., 2019).

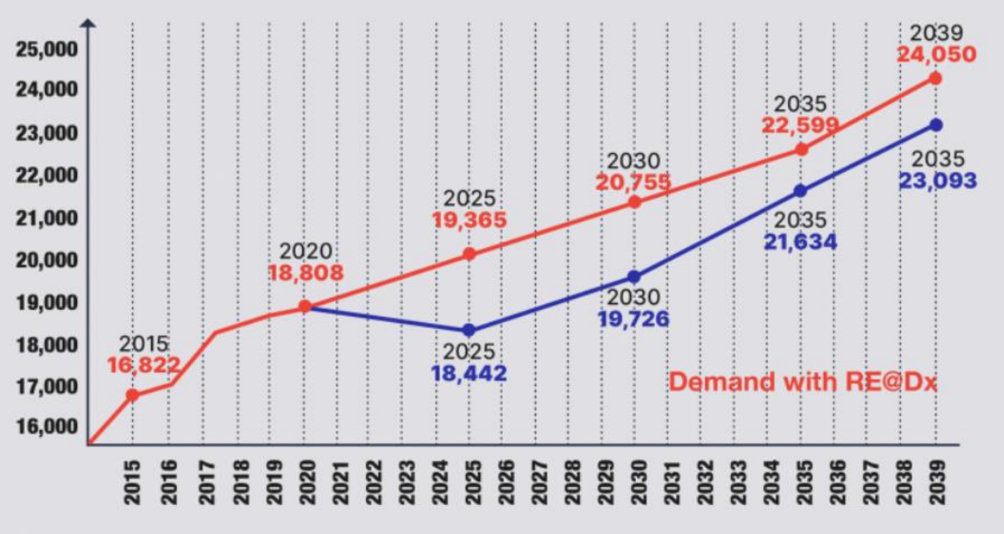

Figure 1.1 Projection of electricity demand in Malaysia from 2021 to 2309 (ENERGY WATCH, 2021)

1.2 IMPORTANCE OF THE STUDY

The reliance on non-renewable energy sources such as fossil fuels has posed significant environmental challenges including the production of greenhouse gases which eventually lead to global warming. The need to search for sustainable and effective energy solutions is growing due to the rapid rise in global energy consumption. In response to this need, the development of radiative cooling thermoelectric generator (RC-TEG) offers a possible solution by utilizing temperature difference to generate power. By conducting a comprehensive analysis of energy conversion efficiency as well as comparing the power generation performance with different radiative cooler coatings, this research aims to provide valuable insights towards the development of more efficient and reliable RC-TEG.

1.3 PROBLEM STATEMENT

Majority of the societies rely significantly on non-renewable resources, particularly for their energy needs. Fossil fuels are thought to account for around 80% of the energy used in the world (Dhir, 2022). One of the most significant environmental problems related to the use of fossil fuels is the production of GHGs, which contribute to global warming as well as threads related to climate change. In order to meet the global growing demand for energy and to reduce environmental issues, renewable energy has gained popularity. However, the generation of power is frequently interrupted when energy is being harvested from nature (Ishii, Dao and Nagao, 2020) and it is still difficult to produce electricity both during the day and at night without using energy storage (Tian, et al., 2020).

With that, radiative cooling thermoelectric generator (RC-TEG) has gained interest as a viable source for power generation due to the growing demand for sustainable and efficient energy solutions. This innovative system harnesses the temperature differential between the thermoelectric generator to produce electricity, offering the potential for clean and renewable energy production. However, the output performance is severely reduced by the small and unstable temperature difference across the TEG modules (Liu, et al., 2023). Therefore, the widespread adoption of RC-TEG poses a challenge due to the low conversion efficiency of harvested thermal energy into usable electricity. To overcome this obstacle and pave the way for their broader integration into the energy landscape, concerted efforts must be directed towards enhancing the efficiency and performance of RC-TEG. Only by addressing these efficiency limitations, the potential of RC-TEG as a reliable, eco-friendly, and economically viable power generation technology can be fulfilled, and thereby facilitating their widespread adoption as well as contributing to a greener future.

1.4 AIM AND OBJECTIVES

The proposed project aims to address the problem of poor energy conversion efficiency rate of radiative cooling thermoelectric generator. To promote the widespread adoption of radiative cooling thermoelectric generator as a sustainable and efficient power generation solution, the following objectives are designed to achieve the goal.

1. To design a radiative cooling thermoelectric generator prototype that can be used for power generation.
2. To analyse the energy conversion efficiency rate of radiative cooling thermoelectric generator.
3. To compare the power generation performance of radiative cooling thermoelectric generator with the use of different radiative cooler coatings.

1.5 SCOPE AND LIMITATION OF THE STUDY

The scope of this study focusing on developing a practical radiative cooling thermoelectric generator (RC-TEG) prototype to analyse the energy conversion efficiency. Hence, to maximize the energy conversion efficiency of the TEG modules, this study will involve exploration and a comparison of power generation capabilities of TEG modules under variance conditions such as in the absent of radiative cooler coating and with the use of different radiative cooler coatings.

However, the limitation of this study is the dependence of the RC-TEG prototype on weather-conditions. In this study, the experiments are conducted on two separate days. Therefore, the variations in weather conditions between these days may result in differences in the temperatures measured on both the hot side and cold side. Eventually, these differences in the temperatures measured can influence the voltage generated by the TEG modules, which potentially impact the overall performance of the RC-TEG.

1.6 CONTRIBUTION OF THE STUDY

This study aims to contribute to the growing body of research on sustainable and effective energy for power generation, which is increasingly important due to the environmental impact caused by non-renewable energy sources as well as the rapid rise in global energy demand. The findings of this study may inform future research efforts aimed at developing more efficient and sustainable energy generation solutions. By designing the RC-TEG prototype and analyzing the energy conversion efficiency of the TEG modules under various conditions, this study may offer a foundation for further optimization of RC-TEG to enhance their efficiency and reliability. With the understanding of RC-TEG technology, this study may promote a wider adoption of RC-TEG as a sustainable and efficient power generation solution, thereby addressing the increasing energy demands as well as reducing the environmental impact associated with conventional energy generation methods.

1.7 OUTLINE OF REPORT

This project report comprises several key chapters with each dedicated to different aspects of the project. First of all, the general introduction of the study is covered in Chapter 1, along with the importance of study, problem statement, aim and objectives, scope and limitations as well as the contribution of the study. Moving forward, literature review related to thermoelectric generator, radiative cooling as well as the studies done by previous researcher is conducted and is presented in Chapter 2. Next, Chapter 3 provides a comprehensive breakdown of the experimental study framework, which also comprise of the work schedule, materials required, details of the designed prototype, experimental setup as well as the formula for evaluating the energy efficiency of TEG modules. Subsequently, Chapter 4 showcases the experimental results obtained and followed by an in-depth discussion. Finally, conclusion of this study is drawn in Chapter 5, along with recommendations that could help improve future work that is similar to this study.

CHAPTER 2

LITERATURE REVIEW

2.1 BRIEF INTRODUCTION TO THERMOELECTRIC GENERATOR

Today, the rising need for electricity, depletion of fossil fuel availability, global warming as well as environmental threats are the most well-known problems faced by humans. Based on a recent assessment by the International Energy Agency (IEA), the energy sector is now responsible for nearly three-quarters of the global greenhouse gas emissions, and a significant shift in energy supply as well as conversion is essential in achieving net zero global CO_2 emissions by 2050. Due to this, numerous research on energy systems has concentrated on increasing the effectiveness of current systems as well as developing new systems with higher efficiencies and flexibility in utilizing renewable sources (Tohidi, Ghazanfari Holagh and Chitsaz, 2022). One of the research areas is on thermoelectric generators (TEG) for power generation.

Thermoelectric materials and thermoelectric modules are the two primary parts of a TEG. There are two categories of thermoelectric materials which are n-type and p-type. The electron content of p-type materials is deficient, whereas the electron content of n-type materials is abundant (Electrical4U, 2023). A typical TEG is made of a sandwich that implements an array of n-type and p-type semiconductor legs as demonstrated in Figure 2.1. The legs consist of either antimony telluride or bismuth telluride pellets. A parallel thermal connection and a series electrical connection are made by strapping the legs together. For electrical insulation and good thermal conductivity, aluminium oxide ceramic is typically used for the top and bottom of the module (Scansen, 2011). Also, thermoelectric module consists of a hot side and a cool side.

Thermoelectric generators can convert thermal energy to electrical energy without requiring the use of moving parts such as turbines (Jouhara, et al., 2021). This gives them significant benefits in terms of cheaper cost, great durability and reliability, as well as vast scalability (Astrain, et al., 2023). Due to the absence of vibration and noise during operation, TEGs are advantageous for the environment (Jouhara, et al., 2021). With that, it resulted in the development of TEG which utilizes thermal sources to produce electricity. However, the main disadvantage of TEG is the poor energy conversion efficiency, which is only about 3% for a temperature difference of 120 °C, compared to 10% for systems based on Organic Rankine Cycles for the same temperature difference (Astrain, et al., 2023). As a result, there has been a lot of interest in improving thermoelectric power generation such as to create innovative thermoelectric materials as well as to raise the differential temperature between the TEG ends to produce more electricity (Wang, et al., 2023).

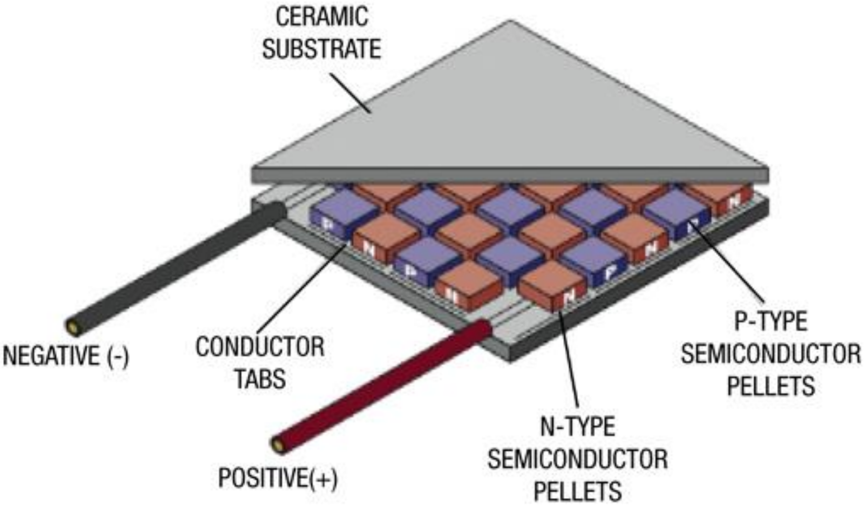

Figure 2.1: Structure of TEG module (Scansen, 2011)

2.2 WORKING PRINCIPLE OF THERMOELECTRIC GENERATOR

The thermoelectric effects such as Seebeck, Peltier, Thomson effect are the primary process that take place in a thermoelectric device. Thermoelectric effects are reversible processes that result in the direct conversion of heat and electrical energy. The physical transport characteristics of thermoelectric materials such as thermal and electrical conductivity, Seebeck coefficient, as well as the figure-of-merit for the efficiency of energy conversion are the main determinants of direct energy conversion (Enescu, 2019).

2.2.1 Seebeck Effect

The Seebeck effect occurs when a temperature gradient is created between two endpoints as shown in Figure 2.2. When a temperature differential is created, the energy level of the electrons at the hot end would be higher than that of the electrons at the cool end side. Due to the difference in energy level, the electrons at each end tend to go in the direction opposed to each other at different speed. Due to the faster moving electrons on the hot end side, potential difference between the two ends is created of which the DC voltage output is generated (Wat Electrical, 2021). The differential temperature of the device as well as the inherent thermoelectric properties of material will affect the electricity production of a TEG. With that, the material should have a low electrical resistivity to enhance charge carriers, as well as a low thermal conductivity to retain more heat, in order to maximize the amount of energy produced from a TEG (Ochieng, et al., 2022). The Seebeck effect only results in very small voltages. The voltage generated typically ranges from a few microvolts per Kelvin of temperature differential at the junction. Some devices can produce a few millivolts if the temperature differential is sufficiently large. The maximum deliverable current can be raised by connecting several of these components in simultaneously. It has been demonstrated that if a significant temperature difference is kept between the connections, these devices can produce a modest amount of electrical power (Vaidyanathan, 2019).

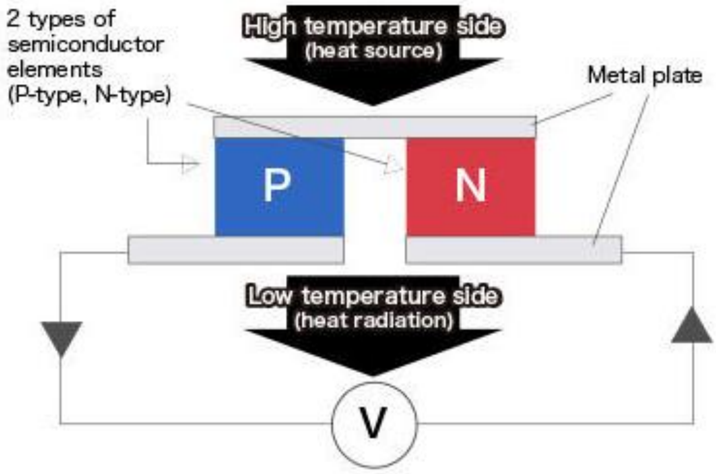

Figure 2.2: Seebeck effect (Kyocera Global, 2023)

2.2.2 Peltier Effect

The Peltier effect is the opposite of Seebeck effect, where heat is absorbed on one end and released at another end when current flows across a thermoelectric material (Aridi, et al., 2021), as shown in Figure 2.3. Peltier effect has led to the development of thermoelectric cooling devices, which are used in infrared detectors, central processing unit coolers as well as wine cellars (Ochieng, et al., 2022). The fundamental advantage of the Peltier effect is that it makes it possible to create cooling and heating systems without the use of moving parts. As a result, these systems operate silently are much less likely to break down than conventional coolers as well as heaters and therefore the need of maintenance is not required. In addition, the Peltier effect is typically applied effectively at a tiny scale, where conventional cooling methods are ineffective. However, a drawback of the Peltier effect is its extremely poor efficiency. Besides that, the heat generated by the circulating current itself, which is still large, contributes to the process of heat dissipation and causes a lot of energy consumption which makes it very expensive as well as limits its widespread deployment. Additionally, a short circuit might result from condensation if Peltier system components get too cold (Jouhara, et al., 2021).

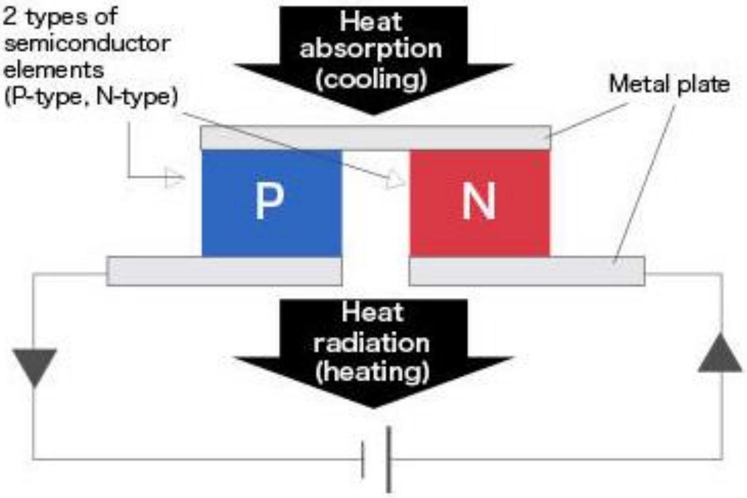

Figure 2.3: Peltier effect (Kyocera Global, 2023)

2.2.3 Thomson Effect

According to the Thomson effect, heat would be absorbed and evolved when a current travelled through the length of a conductive substance from the cold end to the other hot end or vice versa (Aridi, et al., 2021), as shown in Figure 2.4. The connection between the Seebeck and Peltier effects is made possible via the Thomson effect. Following the Seebeck and Peltier effects, it has been discovered that the Thomson effect has an impact on thermoelectric cooling as well as thermoelectric generating (Ochieng, et al., 2022).

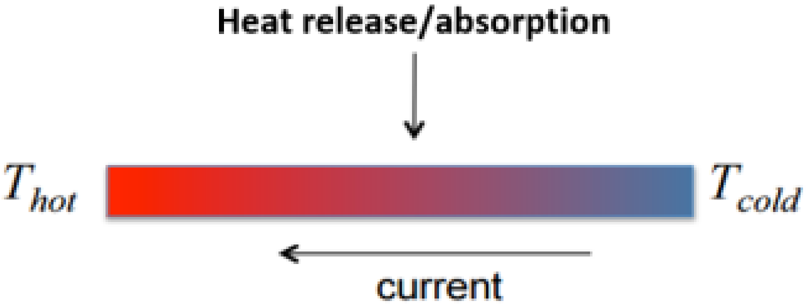

Figure 2.4: Thomson effect (Aridi, et al., 2021)

2.3 BRIEF INTRODUCTION ON RADIATIVE COOLING

Since the power generation of thermoelectric generator is derived from the difference in temperature, improving its performance by trying to increase the differential temperature between the two sides of TEG has drawn extensive research efforts, such as by lowering and raising the temperature at the cold side and hot side, respectively. For temperature reduction, water and air cooling are the only conventional methods used to cool the TEG. Meanwhile, using an external heat source is the conventional strategy for raising the hot end temperature. However, the additional energy needed for conventional cooling or heating methods causes electric loss as well as lowers the efficiency of TEG (Wang, et al., 2023). Thus, promoting the recently created energy-saving and ecologically beneficial TEG requires the search for a passive cooling technique that is independent to the consumption of energy.

Passive radiative cooling (PRC) runs continuously and requires no input. Also, due to its key advantages of being affordable, highly practical as well as pollution-free, PRC has gained a lot of interest (Wang, et al., 2023). In the process of radiative cooling, thermal radiation is emitted from a surface to lower its temperature. This phenomenon occurs when thermal energy is released into the surroundings, where an object cools down by emitting infrared radiation (Boretti, 2023), as shown in Figure 2.5. Dissipating heat radiation from the radiative cooling surface to the extremely cold outer space at approximately 3K through the long-wave infrared transmission window of atmosphere which has wavelengths of approximate 8 μm to 13 μm, as well as lowering the temperature of objects below the surrounding air temperature results in a passive cooling effect (Shi, et al., 2023).

The PRC technique has been successfully used in a number of applications, including solar-cell heat dissipation, personal thermal management as well as building cooling (Wang, et al., 2023). With that, temperature reduction of the cold side of a TEG is a more recent application of PRC. It is possible to significantly increase the differential temperature between the cold side as well as the hot side. Eventually, generation of power can be increased by featuring thermoelectric generator with radiative cooling effect (Shi, et al., 2023).

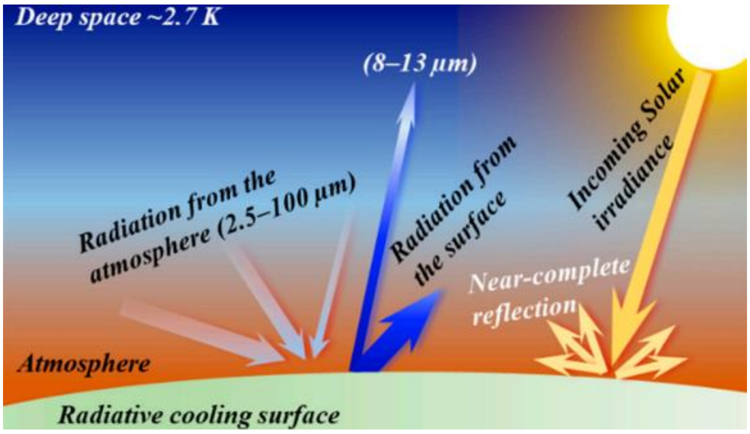

Figure 2.5: Radiative cooling surface that faces the sky and its radiative heat exchanges with the atmosphere (Aili, Yin and Yang, 2021)

2.4 RADIATIVE COOLING MATERIALS AND STRUCTURES

Materials with specialized characteristics such as the capability to reflect as well as emit light in various wavelengths are frequently applied to facilitate radiative cooling. Radiative cooling materials must be designed in a precise manner in order to lower the temperature of the surface even in the presence of direct sunlight (Yu, Chan and Chen, 2021). Majority of these materials are created with specialized optical properties that allow for strong emissivity in the atmospheric window while reflecting or transmitting sunlight in the visible as well as near-infrared ranges. Radiative cooling materials can attain temperatures that are lower than their surroundings by efficiently reflecting heat away as well as lowering the amount of solar energy absorbed (Boretti, 2023).

For example, silicon dioxide (SiO_2) is a unique and popular material that has been extensively studied and used for radiative cooling. It is one of the best materials for attaining sub-ambient radiative cooling during the day due to its being physically transparent to solar radiation and having an extinction coefficient of zero over the full solar radiation band. Apart from that, the unique impact of the phonon-polariton resonances is present near the wavelengths of 10 μm and 20 μm, where SiO_2 exhibits two high peaks in its extinction coefficient (Zhao, et al., 2019). However, different radiative cooling materials exhibit varying cooling characteristics due to the differences in infrared emissivity (Liu, et al., 2020). The effectiveness of power generation using various radiative cooling materials must therefore be investigated.

2.4.1 Radiative coating

Selective radiative coatings are frequently designed to possess high thermal IR emissivity as well as a low absorbability of solar radiation. Radiative coating can be used with wide variety of substrates such as polymers and metals. Selective radiative coatings are usually composed of multilayer structures with each having unique optical characteristics. Besides that, the outermost layer is made to reflect a substantial amount of sunlight since it is made to absorb light from the Sun with little efficiency. With that, it aids in reducing the solar energy absorption of the coating as well as the underlying material. In addition, the layers that come after the solar-reflective layer are designed to exhibit strong emissivity in the mid-IR band. These layers are made to radiate heat effectively, which encourages cooling. With that, the coating may emit heat efficiently to the cooler surroundings due to its high mid-IR emissivity. Moreover, selective radiative coatings are frequently made of materials that can survive extreme heat as well as climatic conditions without degrading. As a result, radiative coatings tend to be more stable and durable over the long term, maintaining the radiative cooling performance over time (Boretti, 2023).

2.4.2 Thin film

Thin film which is created of material like silicon dioxide (SiO_2) can be utilized to improve radiative cooling. By applying the thin film on a substrate, it can alter the emissivity as well as thermal characteristics of the surface. The thickness of a thin film is often measured in micrometers or nanometers. They can be used on a variety of surfaces such as curved and irregularly shaped. Without significantly changing the characteristics of the underlying material, thin films can be deposited onto a variety of substrates, including glass, metal as well as polymer. Also, due to its lightweight, effective heat transfer, affordable fabrication as well as compatibility with current systems, thin films are frequently employed in radiative cooling applications. For effective radiative heat transmission, thin films offer a direct route. The film can absorb and emit thermal radiation quickly due to its thinness. With that, heat is efficiently transferred from the surface to the film, followed by the film effectively emits the heat into the surrounding. Eventually, the surface is cooled effectively. In addition, physical vapor deposition, chemical vapor deposition as well as spin coating are several deposition techniques that can be used to create thin films. These techniques provide exact control over the thickness of the film and make it possible to produce large quantities of film at low cost (Boretti, 2023).

For example, to design a passive thermoelectric system that features the concept of radiative cooling effect, Wang, et al. (2023) used an affordable and scalable thin film that was created by combining liquid acrylic resin with SiO_2 microparticles. This is shown where the plate is covered with a radiative cooling thin film that is constructed of a hybrid SiO_2-acrylic resin with a thickness of 70 μm and is facing towards the sky. As a result, they found that this material demonstrated a significant radiative cooling impact with an average emissivity of 0.93.

2.4.3 Metamaterial

Radiative cooling metamaterials are now feasible due to the advancement and maturity of nanofabrication technology. Metamaterials are synthetic materials that have greater bounds than naturally occurring materials because they have undergone substantial design as well as optimisation. The patterned surface that sits on top of the metamaterial as shown in Figure 2.6 plays a role of adjusting the surface's spectral emissivity to the atmospheric window (Yu, Chan and Chen, 2021). In the atmospheric window, metamaterials can be made to have a high thermal emissivity. Metamaterials have great promise for improving radiative cooling effectiveness, where they can be designed to have improved light-trapping capabilities. Metamaterial structures can effectively capture thermal radiation by being customized in terms of size, shape as well as arrangement. With that, it enhances the material's capacity to dissipate heat, which aids in effective cooling. In addition, metamaterials can be adjusted to maximize the performance of radiative cooling based on shifting ambient circumstances or cooling needs by adding materials with customizable characteristics or using external stimuli (Boretti, 2023).

Figure 2.6: Metamaterial

2.4.4 Multilayer structure

The multilayer structure has been used for radiative cooling for a very long time. Multilayer film, also known as a 1D photonic crystal, is a common photonic radiator that is made up of alternating layers of material with various dielectric constants (Zhao, et al., 2019), and a reflective metal as the lowest layer, as demonstrated in Figure 2.7. Due to its great reflectivity in the sun spectrum, silver is mostly chosen as the reflective metal. This reflective metal is to reflect sunlight, which lowers the amount of heat absorbed. The layers above the reflective metal are primarily intended to increase the emissivity in the atmospheric window (Yu, Chan and Chen, 2021).

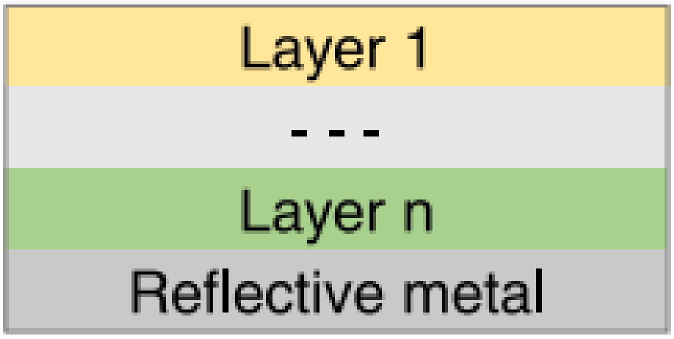

Figure 2.7: Multilayer structure

2.4.5 Randomly distributed particle structure

The randomly distributed particle structure is a promising method for cost-effective and extensive radiative cooling. Similar to the multilayer structure as well as metamaterial, there is a reflective metal at the bottom that offers high solar reflectivity, as shown in Figure 2.8. Meanwhile, the top layer of randomly arranged particles primarily plays a role of adjusting infrared emissivity to the atmospheric window. The microsphere particles embedded in this layer are made of an inorganic substance such as Al_2O_3, BaSO4, $CaCO_3$, SiO2 and TiO_2. As the foundation of this layer, a polymer is frequently used, while other materials such as wood are employed as well (Yu, Chan and Chen, 2021).

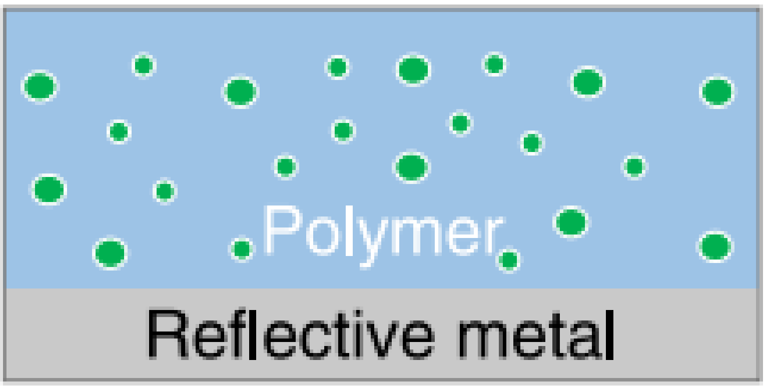

Figure 2.8: Randomly distributed particle structure

2.4.6 Porous structure

In numerous investigations, radiative cooling materials have been created with a reflective metal at the bottom that reflects light. However, the use of a reflective metal at the bottom layer limits the use of radiative cooling materials for paints as well as increases production difficulty and cost. According to recent research, replacing the reflective metal layer with light-scattering air gaps in a polymer as shown in Figure 2.9, might boost optical performance to cutting-edge levels while lowering the cost of material. This method can be applied as a coating or painting, expanding the spectrum of situations in which radiative cooling technology can be used (Yu, Chan and Chen, 2021).

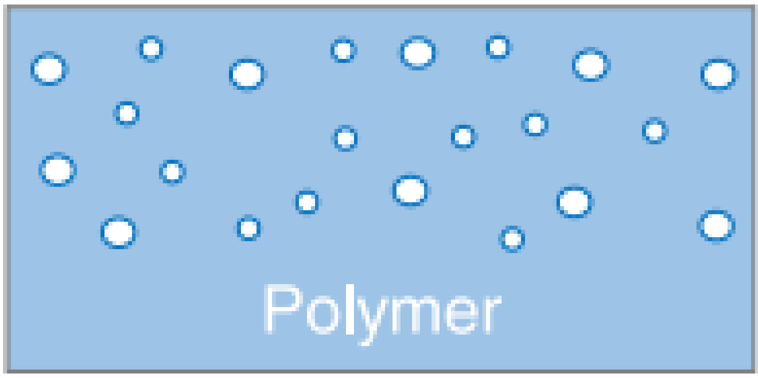

Figure 2.9: Porous structure

2.5 DEVELOPMENT OF RADIATIVE COOLING THERMOELECTRIC GENERATOR

Radiative cooling-driven thermoelectric power generation (RC-TEG) has been presented most recently because of the integration and advancement of thermoelectric and radiative sky-cooling technologies (Ji and Lv, 2023). In 2019, Raman, Li and Fan (2019) proposed a low-cost, readily available RC-TEG as shown in Figure 2.10 to capture the cold of space with the use of radiative cooling. The thermoelectric module's cold side is attached to a sky-facing surface that radiates heat into space and has its warm side heated by the surrounding air, allowing energy to be produced at night. As a result, a power generation of 25 mW/m^2 is produced which is sufficient to passively power an LED, creating light from darkness. Besides that, Xia, et al. (2019) introduced a thermoelectric generator with two pairs of n-p thermoelectric legs to generate electric energy continuously around the clock via the temperature difference brought on by passive cooling through the atmospheric window. In a single day, they found that the average voltage produced is 1.78 mV, and the average temperature differential created is 4.4 K.

Consequently, Zhao, Pei and Raman (2020) optimized the shape as well as the operating condition such as the maximum power point and maximum efficiency point of RC-TEG by creating a combined electrical as well as thermal model. As a result, the ideal operating condition produces more electricity than was initially anticipated. In addition, Ishii, Dao and Nagao (2020) mounted a wavelength-selective-emitter (SE) which was produced from a glass substrate as well as an aluminium thin sheet on a TEG as shown in Figure 2.11. They demonstrated that SE which is installed on a TE module can radiatively cool and continue to provide voltage throughout the day without going below zero. Also, based on thermally insulating as well as optically selective polyethylene aerogel (PEA), a RC-TEG was created by Liu, et al. (2021) as shown in Figure 2.12 and was optimized using the mathematical model to examine the influences on the performance of thermoelectric generator. They found that the developed RC-TEG had a substantially higher performance in generating power as demonstrated in Figure 2.13 due to the poor heat conductivity of PEA.

In a more recent study, Shi, et al. (2023) developed a thermoelectric generator device with the combination of radiative cooling paint for a constant generation of power throughout the day, as shown in Figure 2.14. In their study, they demonstrated that a power of 241.46 Wh/m^2 to 423.86 Wh/m^2 can be generated annually based on the radiative cooling module to the TEG module with an ideal area ratio of 11. In the same year, Wang, et al. (2023) presented a TEG with the integration of passive radiative cooling as well as greenhouse effects as shown in Figure 2.15. Based on a 24-hour experimental study conducted, they found that the proposed TEG can passively generate a constant power of 90.74 mW/m^2 throughout the day. However, the power generated is low when compared to a typical solar photovoltaic system, whose output throughout the day is on the scale of hundreds of W/m^2. Therefore, there is still a ton of possibility for performance enhancement such as by improving the TEG modules, radiative cooling structure, as well as the greenhouse cavity.

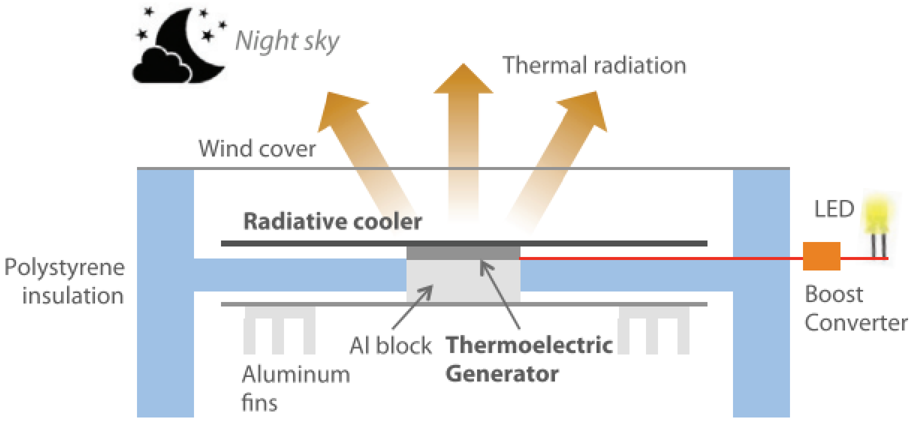

Figure 2.10: Low-cost radiative cooling thermoelectric generator (Raman, Li and Fan, 2019)

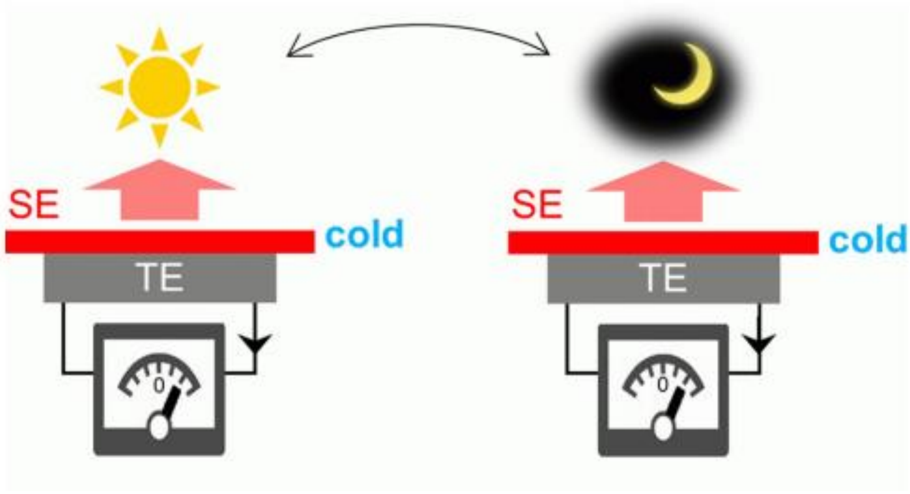

Figure 2.11: Thermoelectric generator with a wavelength-selective-emitter on top (Ishii, Dao and Nagao, 2020)

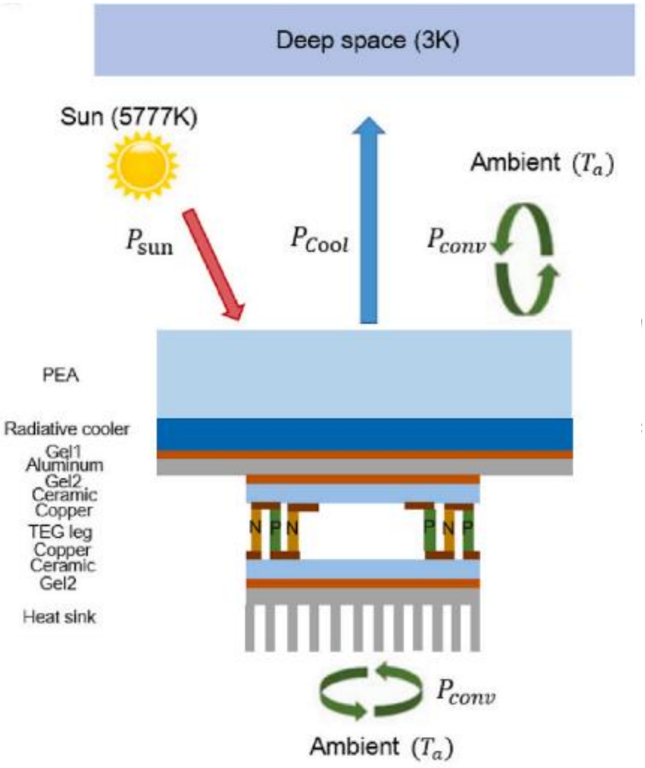

Figure 2.12: Radiative cooling thermoelectric generator with PEA (Liu, et al., 2021)

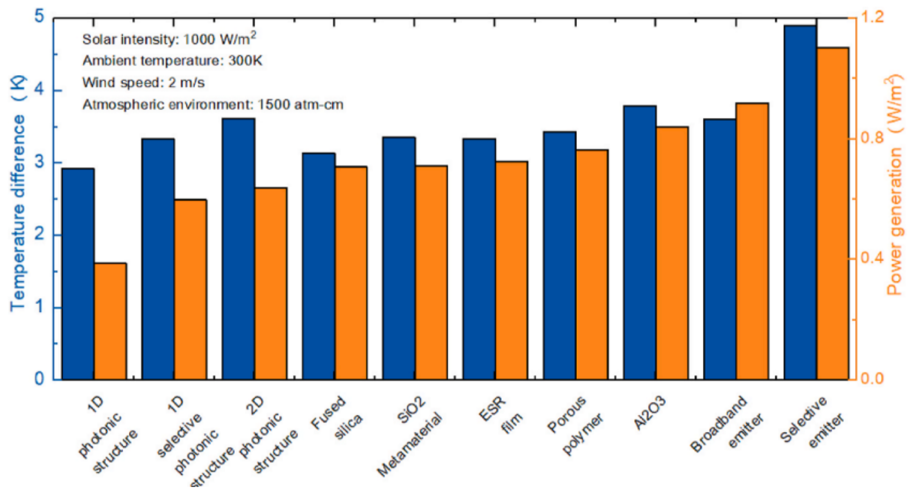

Figure 2.13: Temperature difference and maximum power generation of radiative cooling thermoelectric generator with PEA (Liu, et al., 2021)

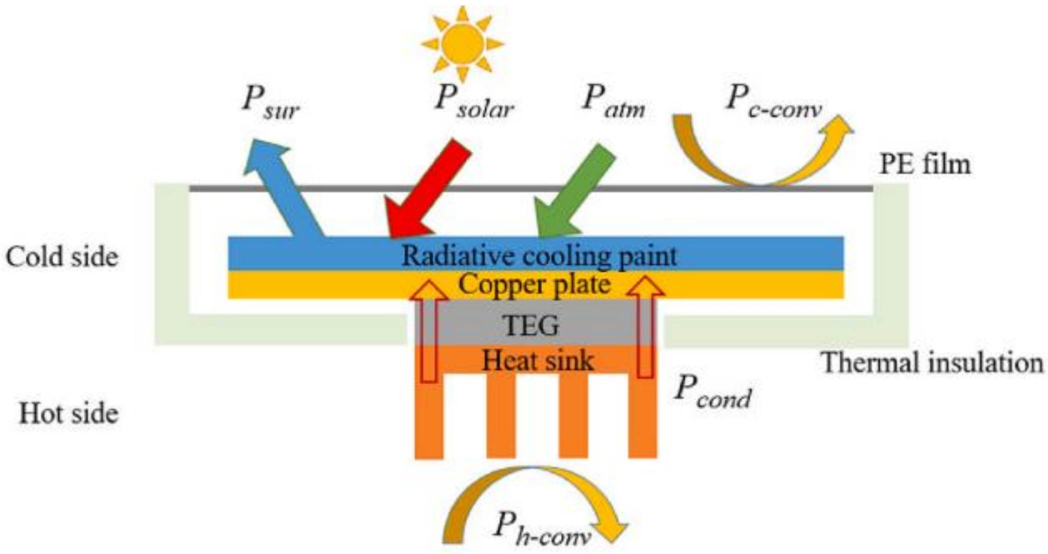

Figure 2.14: Sketch of TEG module with the combination of radiative cooling paint (Shi, et al., 2023)

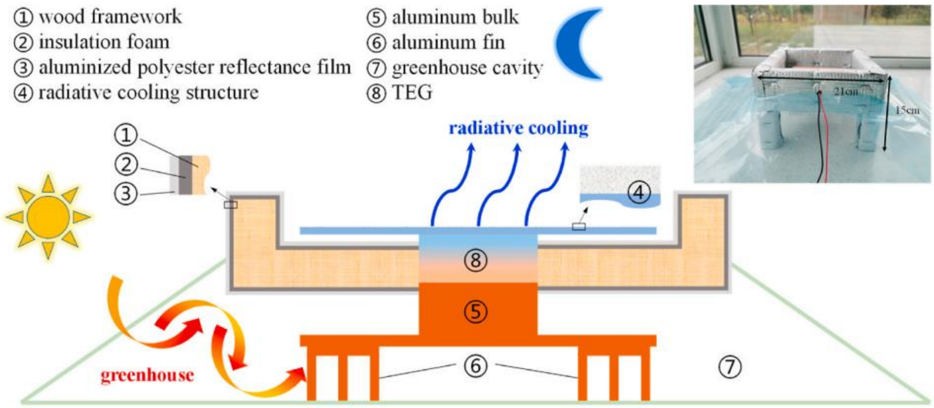

Figure 2.15: Thermoelectric generator prototype that features the concept of passive radiative cooling and greenhouse effects (Wang, et al., 2023)

2.6 SUMMARY

In summary, this chapter provides an exploration of thermoelectric generators (TEGs) as well as radiative cooling. To address energy challenges and to achieve a sustainable as well as enhanced power generation, the development of integrating radiative cooling with thermoelectric generator is also reviewed in this chapter and is summarized in Table 2.1 shown below.

Table 2.1: Summary on the development of radiative cooling thermoelectric generator

Author	Findings
Raman, Li and Fan (2019)	Proposed a low-cost RC-TEG and reported that a power generation of 25 mW/m^2 is generated
Xia, et al. (2019)	Reported that with the use of radiative cooling, their proposed thermoelectric generator can generate an average voltage of 1.78 mV in a single day with a 4.4 K difference in temperature
Zhao, Pei and Raman (2020)	Reported that the RC-TEG generate larger power output than anticipated when using a combined thermal and electrical model, as well as with optimal operating conditions
Ishii, Dao and Nagao (2020)	Reported that the TEG module can radiatively cool and continue to provide voltage throughout the day without going below zero by installing a wavelength-selective-emitter on a TEG module
Liu, et al. (2021)	Reported that the developed RC-TEG had a substantially higher performance in generating power due to the poor heat conductivity of PEA
(Shi, et al., 2023)	Reported that TEG modules with the combination of radiative cooling paint can generate a power of 241.46 Wh/m^2 to 423.86 Wh/m^2 annually based on the radiative cooling module to the TEG module with an ideal area ratio of 11
Wang, et al. (2023)	Reported that the TEG can generate a constant power output of 90.74 mW/m^2 throughout the day by featuring the concept of passive radiative cooling and greenhouse effects in the proposed prototype

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In this proposed project, the flow of the project is designed via the Taguchi method. To investigate how various factors impact the mean as well as the variance of a process performance metric that measures how efficiently the process is working, the Taguchi method is established for designing experiments (Fraley, et al., 2023). The Taguchi method is a problem-solving approach that can assist in boosting productivity as well as process performance. Also, it is a statistical technique used to enhance and maintain low output variance. Additionally, as it is always important to support the objectives in the event of a poor outcome, the Taguchi method is widely utilised in developing a backup plan. In this proposed project, the problem will first be defined to set a focus point and to narrow down the parameters that will then be analysed in the later stage. To gain more information and knowledge about the scope of the topic, studies, as well as research, are conducted.

With this information and knowledge, a comprehensive review of the literature related to the RC-TEG, energy conversion efficiency as well as the effect of radiative cooler coatings will then be developed. Before proceeding to the experimental study, the variables will first be identified to investigate the performance of RC-TEG in power generation. Next, a simple prototype model will be developed and validated by comparing the results obtained from the developed model with the data collected from the literature and other relevant sources. If the model is workable and the results produced are reasonable, it will then proceed with the investigation of energy conversion efficiency with the use of radiative cooler coating, otherwise, troubleshooting will be carried out to solve the issue. If the problem still exists after troubleshooting, further studies and research are then required to solve the issue.

After the experimental results are collected, a comparative experimental study on the power generation performance of RC-TEG under the present and absence of radiative cooler coating, as well as with different radiative cooler coatings will be conducted and is then followed by an evaluation of the result. If the target result is achieved, a conclusion will then be drawn based on the results obtained from the simulation model as well as make recommendations for future research. However, if the target value is just partially achieved or does not meet the required performance standards, then design optimization, as well as further research, is required, respectively. The detailed flow chart of the proposed project using the Taguchi method is demonstrated in Figure 3.1.

3.2 IDENTIFYING VARIABLES

This study aims to investigate the impact of different radiative cooler coatings on the energy conversion efficiency of TEG modules for power generation. The design and geometry of the RC-TEG prototype will remain constant throughout the experiment. By varying the radiative cooler coating, we aim to understand its impact on the efficiency of energy conversion of TEG modules.

Independent variable	: Type of radiative cooler coating used for RC-TEG
Dependent variable	: Energy conversion efficiency of TEG modules
Constant variable	: Design and geometry of the RC-TEG prototype

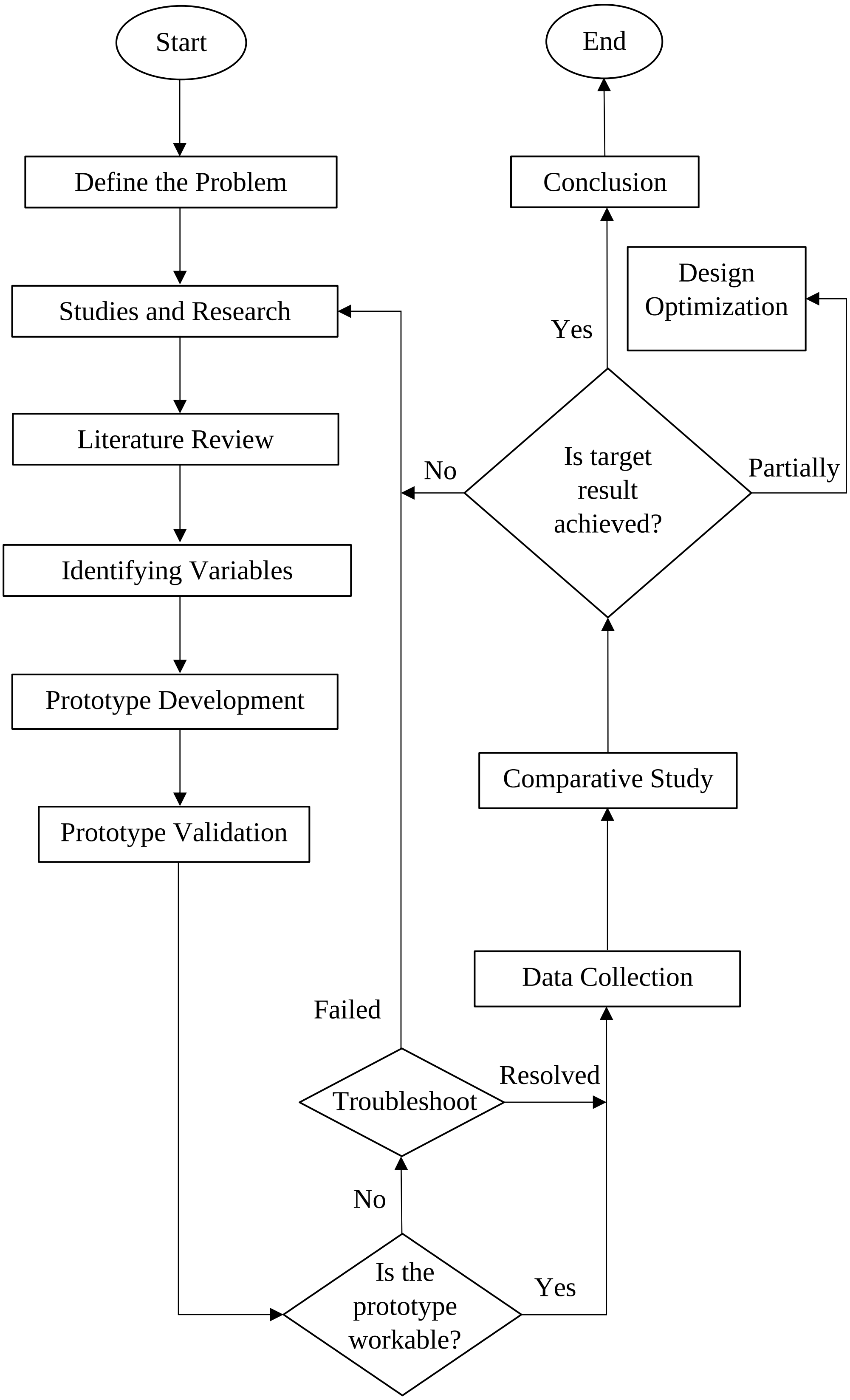

Figure 3.1: Project flow chart

3.3 WORK SCHEDULE

The successful implementation of RC-TEG as a sustainable and efficient power generation solution requires overcoming the low energy conversion efficiency challenge. With the use of a Gantt chart as shown in Table A-1 and Table A-2, the following work schedule outlines the tasks and timeline that will be undertaken to address this issue and improve the performance of RC-TEG. The tasks include designing a prototype for RC-TEG, analyzing energy conversion efficiency, and comparing the power generation performance with different radiative cooler coatings. By accomplishing these tasks, this research aims to contribute valuable insights towards the development of more efficient as well as reliable RC-TEGs, thereby promoting their widespread adoption in the pursuit of sustainable energy solutions.

Task 1: Literature review development (Week 1-6)

Conduct a comprehensive literature review on radiative cooling thermoelectric generators (RC-TEG) and energy conversion efficiency. Information on different radiative cooler coatings used in RC-TEG is gathered as well.

Task 2: Prototype model design and development (Week 7-12)

Design and develop a RC-TEG prototype that will be used for power generation. The testing process is then conducted to verify the model's workability and make necessary adjustments.

Task 3: Experimental setup and data collection (Week 13-16)

Investigate the energy conversion efficiency of RC-TEG prototype by conducting the experiment. Collect the data for analysis and verification. Further experiments using different radiative cooler coatings are conducted as well.

Task 4: Comparative study (Week 17-19)

Conduct a comparative experimental study on the power generation performance of TEG modules with and without radiative cooler coating as well as with different radiative cooler coatings. The data obtained are then recorded.

Task 5: Data analysis (Week 20-22)

Analyze the data collected from the experimental study to draw conclusions and make recommendations for the application of RC-TEG in power generation.

Task 6: Documentation and presentation (Week 23-24)

Review, compile, and finalize the findings of the study into a final report as well as presentation slides. Also, practice the presentation to ensure effective communication of the project's objectives, methods, results as well as conclusions.

3.4 MATERIAL LIST

Table 3.1: List of Material

No.	Description	Applications	Quantity
1	Thermoelectric module	To be used for power generation	6 units
2	Aluminium heat sink	To offer good thermal contact with the surrounding air	6 units
3	Wood	To make the body and supporting structure of the prototype	2 units
4	Polystyrene foam	Cover the surrounding of RC-TEG prototype to reduce heat loss and make sure that the performance of TEG modules is measured more precisely	3 units
5	Low-density polyethylene film	Act as an infrared-transparent wind cover to cover the top opening of the enclosure, and act as a greenhouse film at the hot side of TEG modules	1 unit
6	Thermocouple	To sense the temperature at hot and cold sides of the TEG modules	6 units
7	SANWA CD800a Digital Multimeter	To measure voltage and current generated by TEG modules	1 unit
8	UT320D Thermometer	To read the temperature at the heat sink and at the surface of TEG modules	1 unit
9	Thermal paste	To reduce contact resistance	3 units
10	Radiative cooling paint	Act as a radiative cooler coating	1 unit

11	SiO_2 microparticles	Micro-nano structures that mix with liquid acrylic resin to form a radiative cooler coating
12	Liquid acrylic resin	A solvent that mixes with SiO_2 microparticles to form a radiative cooler coating

3.5 DETAILS OF PROTOTYPE DESIGN

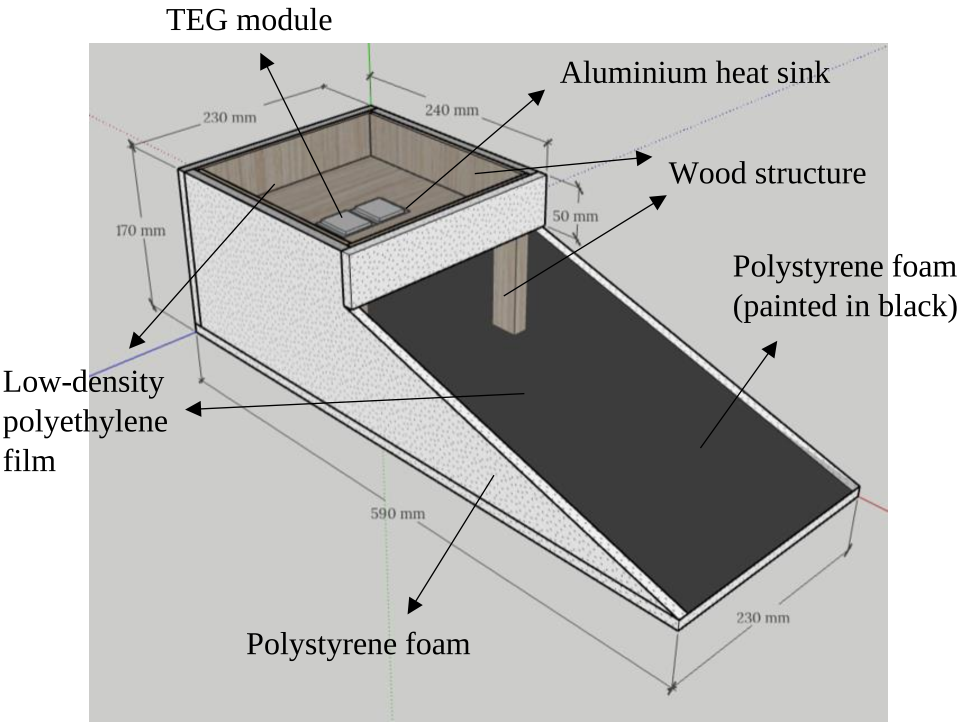

Figure 3.2: The design of RC-TEG prototype encompasses its overall structure and dimension

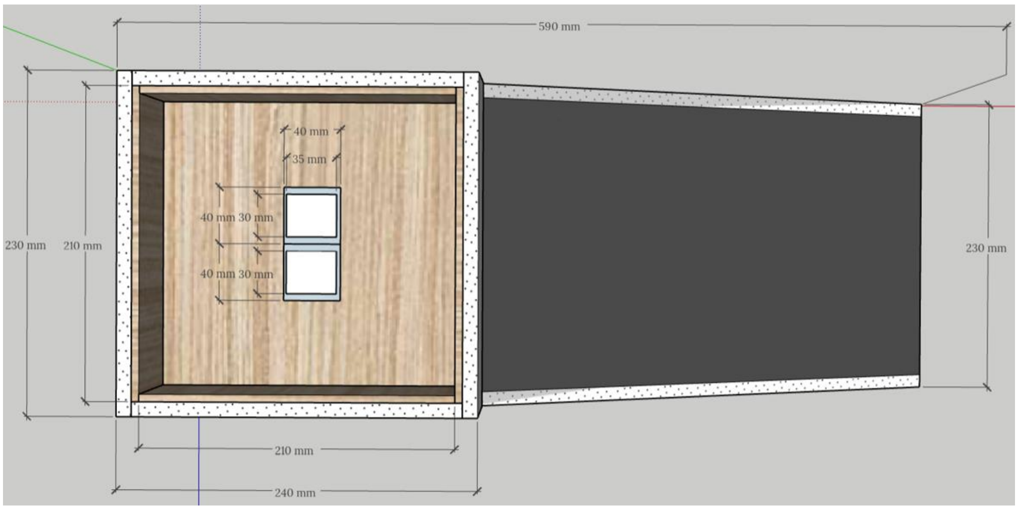

Figure 3.3: Top view of RC-TEG prototype design

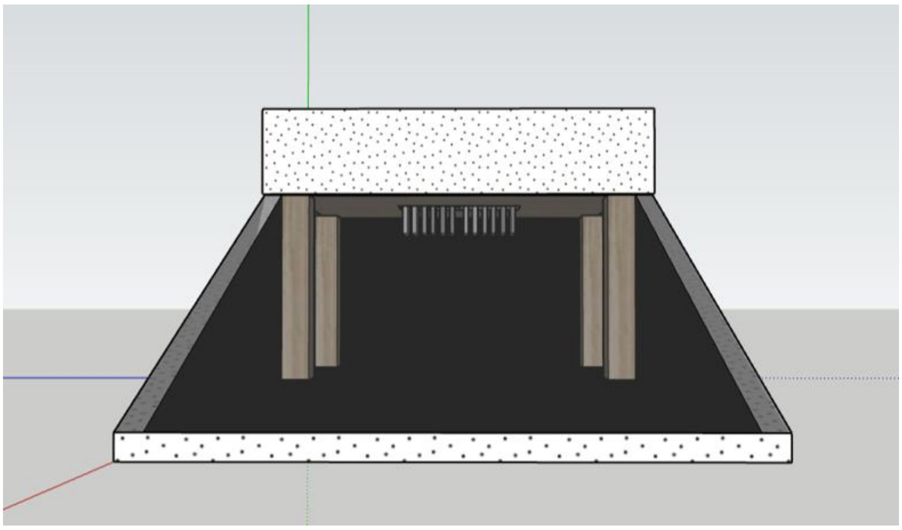

Figure 3.4: Front view of RC-TEG prototype design

Firstly, according to Solar Energy Research Institute (SERI), National University of Malaysia, the optimum orientation and tilt angle of solar collector in Kuala Lumpur is facing south with an inclined angle of 15° (Fadaeenejad, et al., 2015). Hence, unlike most cube or rectangular designs with flat upward-facing solar collector seen in previous studies, the proposed RC-TEG prototype features a trapezoidal shape with a 15° tilt in the solar collector. With that, it enables the collector to absorb the greatest amount of solar radiation possible throughout the day during peak hours. Besides that, in order to trap the heat inside the enclosure, low-density polyethylene film is used to minimize convection by isolating the air inside from the surrounding air outside, creating a greenhouse effect within the enclosure. With that, it transmits visible light but blocks infrared solar radiation from escaping, which eventually amplifies the heat-trapping effect, making it possible to reach similar temperatures on cold and windy days as on hot days. Moreover, the surface inside of the enclosure is painted with black or colour with low reflectivity. This helps to absorb a larger portion of the solar spectrum, including visible, infrared as well as ultraviolet light. This absorbed energy is then transformed into heat, making the enclosure warmer.

3.6 EXPERIMENT SETUP

To study and analyse the performance of the TEG modules, a simple RC-TEG prototype with a dimension of 590 mm × 230 mm × 170 mm (l × w × h) is first designed and fabricated as shown in Figure 3.5. The supporting structure of the prototype is made of wood board and is covered in insulation foam with a thickness of 10 mm. The cold side of the TEG modules is facing up the sky, meanwhile, the hot side of the TEG modules is attached to an Aluminum heat sink. The Aluminum heat sink is installed inside the greenhouse cavity. The temperature of the hot side rises throughout a typical day as a result of the greenhouse cavity absorbing the solar radiation. As a result, the temperature at the hot side of TEG modules is higher than its cold side that faces the sky. Throughout the night, the cold side of the greenhouse cavity chilled down below ambient, while the hot side stays close to the ambient temperature. This allowed a difference in temperature between the two sides of the TEG modules and eventually led to the continuous generation of effective output power for 24 hours daily. In this study, the experiment will be conducted at outdoor as shown in Figure 3.7, with the orientation of the prototype facing South. To investigate the efficiency of energy conversion and the performance of TEG modules, the experimental study is conducted under 4 different conditions, as shown in Figure 3.8, Figure 3.9, Figure 3.10 and Figure 3.11.

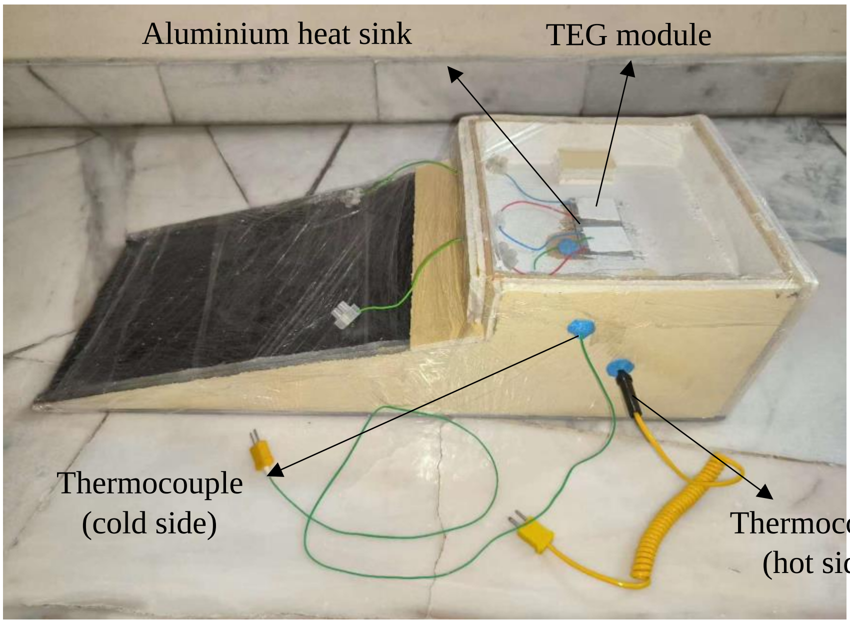

Figure 3.5: RC-TEG prototype

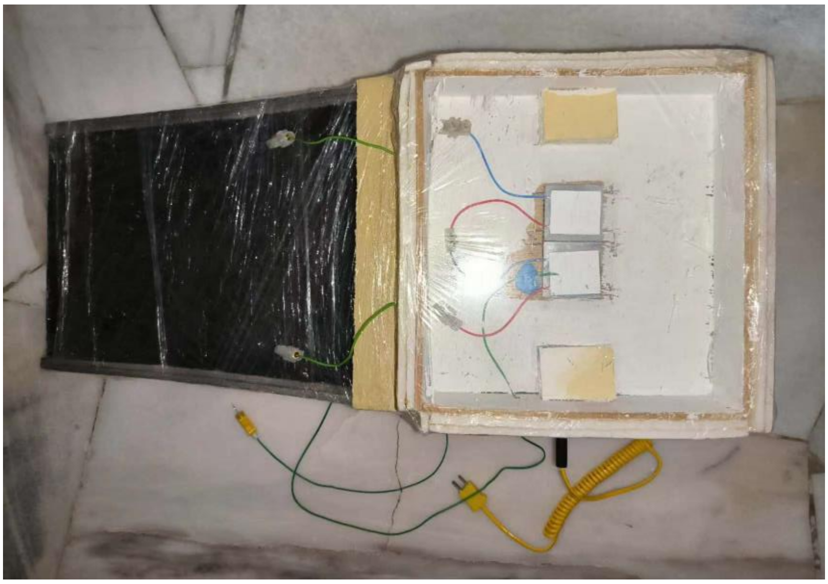

Figure 3.6: Top view of RC-TEG prototype

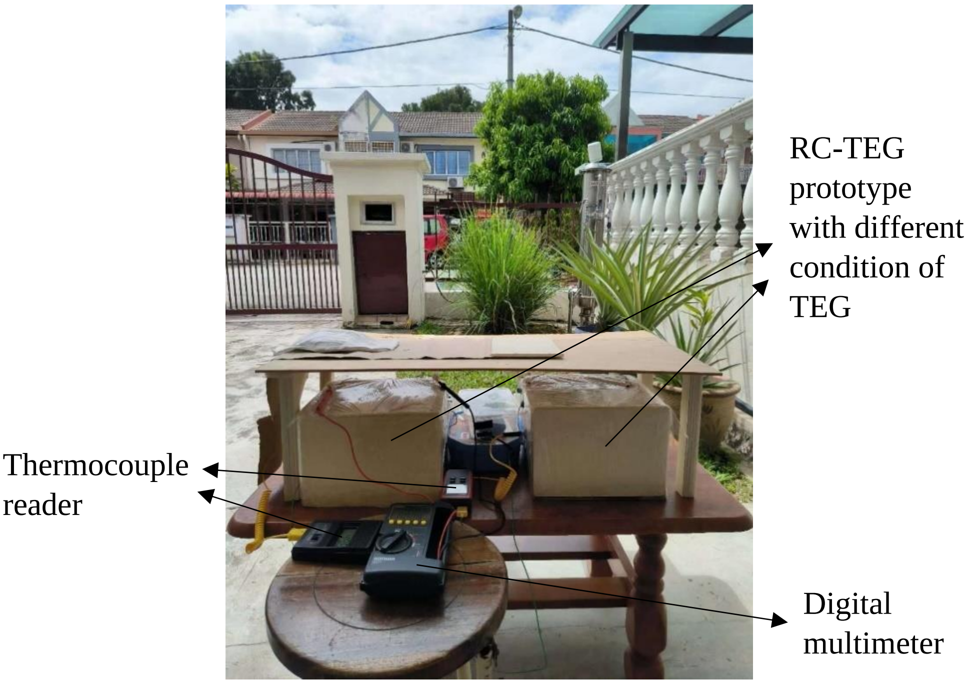

Figure 3.7: Experiment setup of RC-TEG

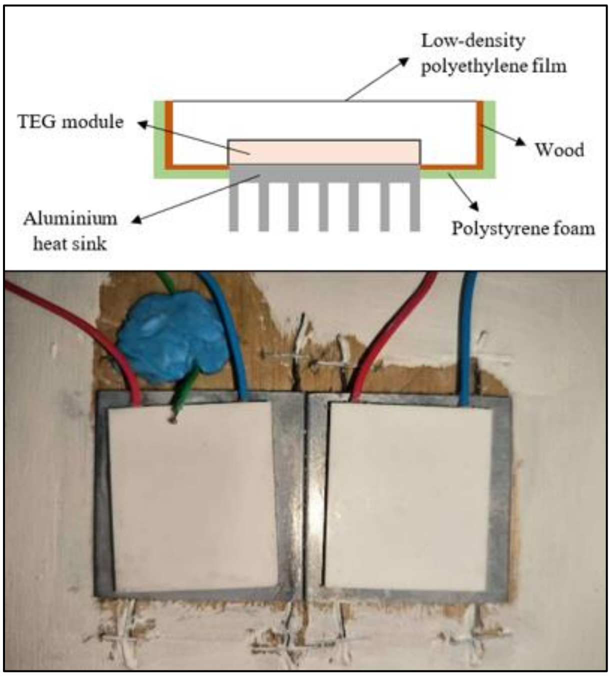

Figure 3.8: TEG modules in the absence of radiative cooler coating

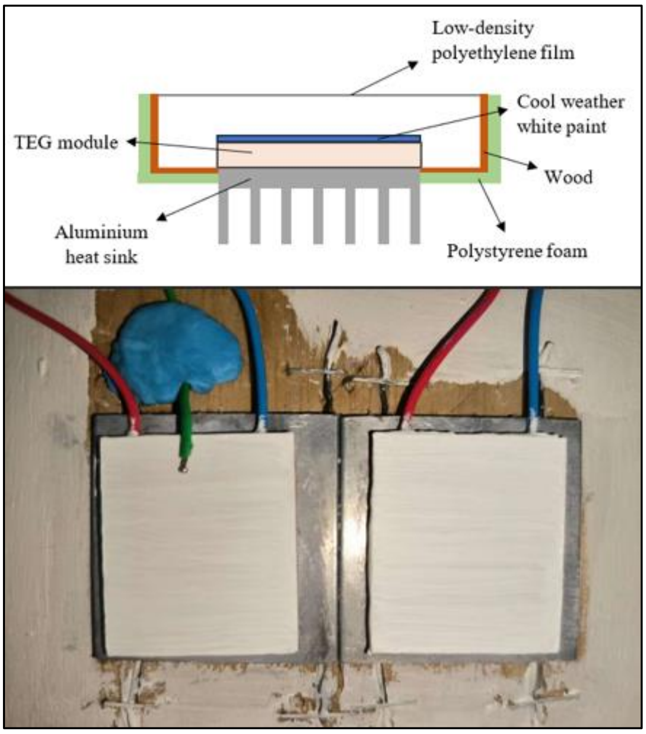

Figure 3.9: TEG modules with cool weather white paint as radiative cooler coating

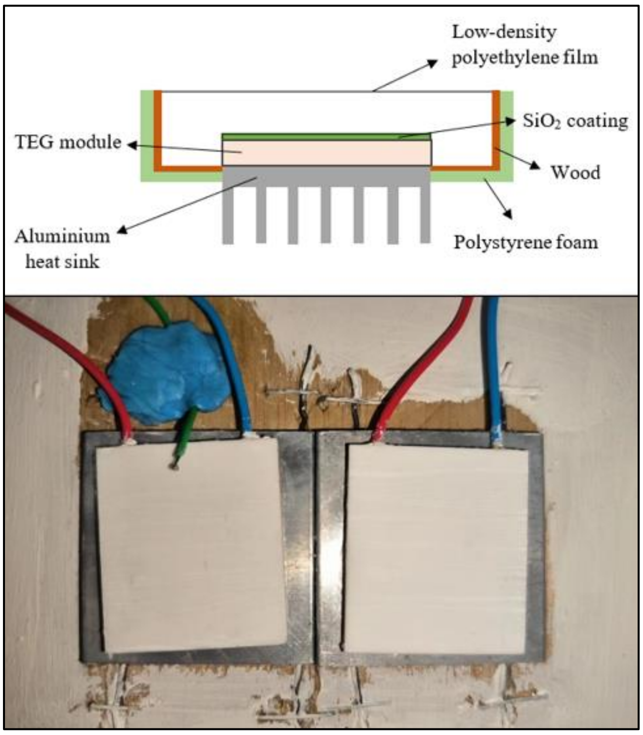

Figure 3.10: TEG modules with SiO_2 coating as radiative cooler coating

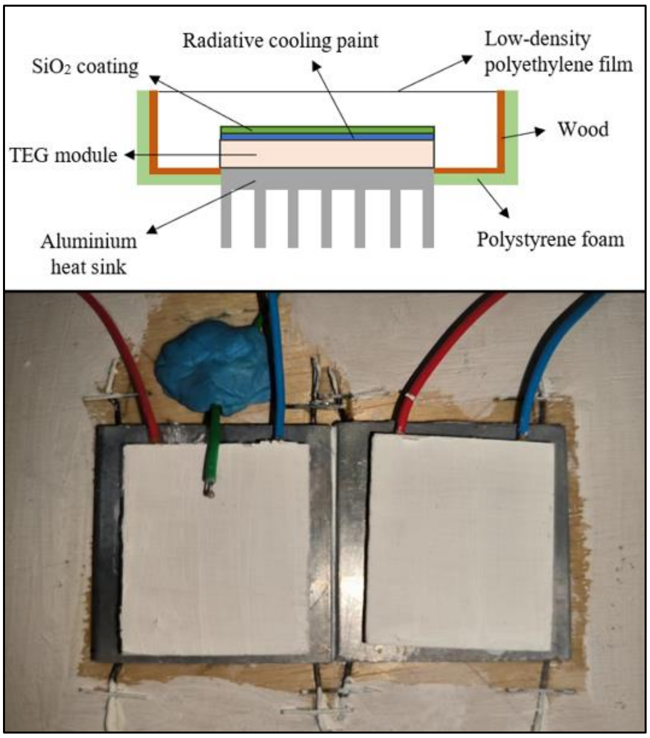

Figure 3.11: TEG modules with cool weather white paint + SiO_2 coating as radiative cooler coating

3.6.1 Preparation of Silicon Dioxide Coating

Numerous micro-nano structures have been developed for use in radiative cooling applications. Apart from radiative cooling paint that is readily available, a low-cost thin film consisting of liquid acrylic resin mixed with silicon dioxide, SiO_2 microparticles will also be used as a radiative cooler coating to investigate the performance of the TEG modules in this study. To create the SiO_2 radiative cooler coating, liquid acrylic resin is to be mixed with SiO_2 particles to create a slurry with a SiO_2 volume fraction of 6% (Wang, et al., 2023).

With that, a 40 g of liquid acrylic resin as well as 2.55 g of silicon dioxide powder is first obtained with the use of weight balance as shown in Figure 3.12 and Figure 3.13. The 40 g of liquid acrylic resin and 2.55 g of silicon dioxide powder is then mixed in a beaker and is stirred uniformly for 1 hour at a speed of around 200 rpm with the use of magnetic stirrer as shown in Figure 3.14. Once a smooth and spreadable silicon dioxide coating is formed, it is bladed on to the surface of TEG modules with a thickness of 150 µm using a bar coating machine as shown in Figure 3.15, which allows for fine thickness control. After the coating is done, it is left to dry completely.

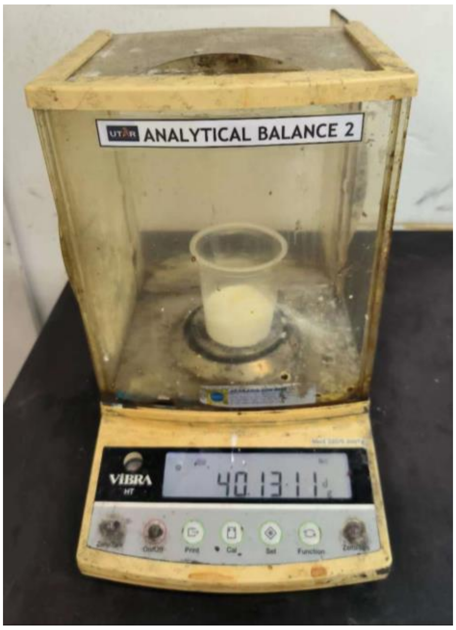

Figure 3.12: Obtaining 40 g of liquid acrylic resin with the use of weight balance

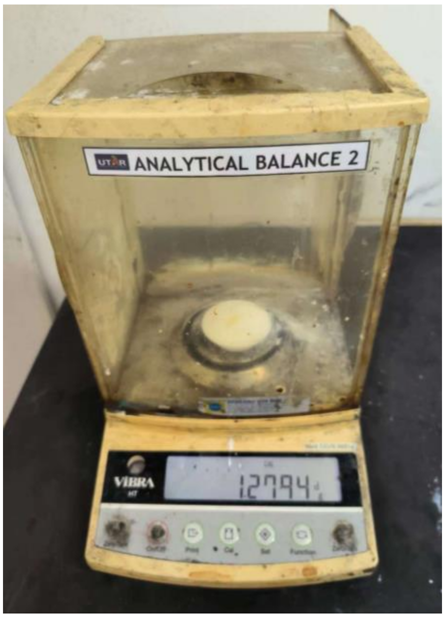

Figure 3.13: Obtaining 2.55 g of silicon dioxide powder with the use of weight balance

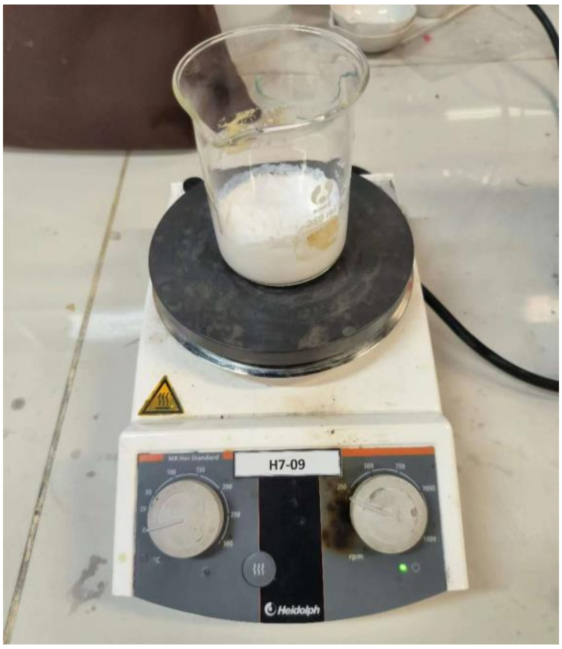

Figure 3.14: Mixing the liquid acrylic resin and silicon dioxide powder with the use of magnetic stirrer

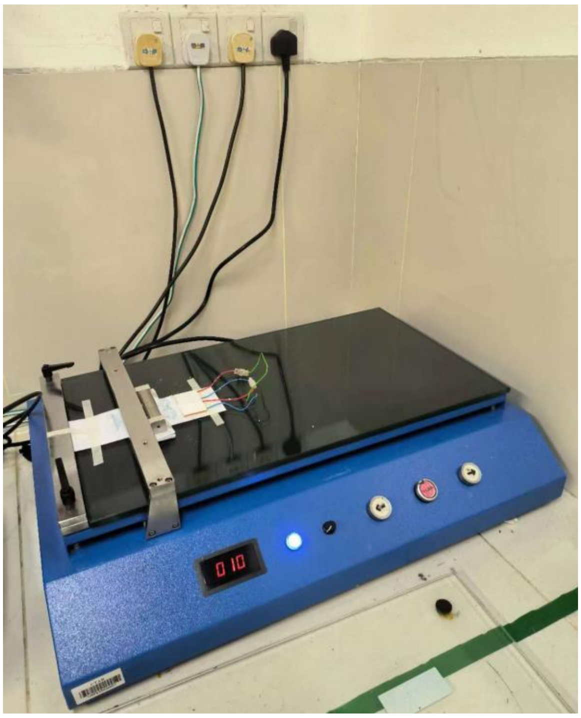

Figure 3.15: Applying the silicon dioxide coating on the surface of TEG with the use of bar coating machine

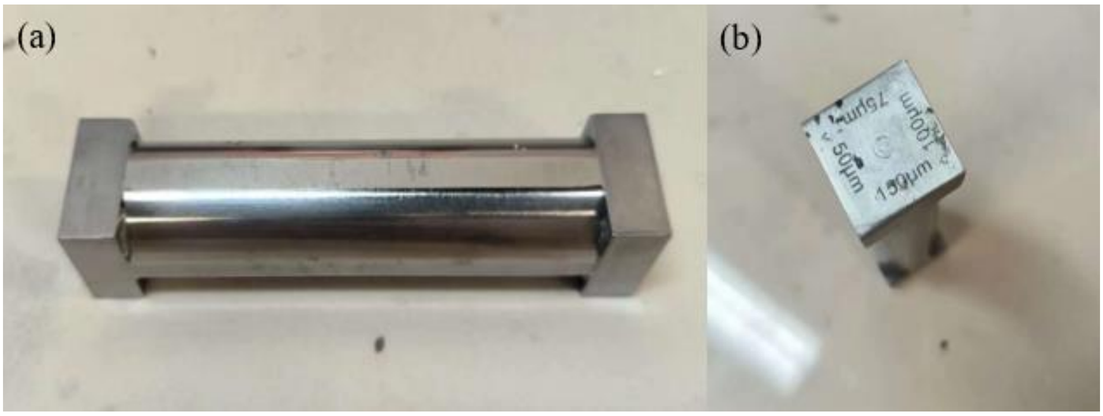

Figure 3.16: (a) Film applicator (b) Different options of thickness

3.6.2 Data Collection

The experimental study involves comprehensive monitoring of critical parameters such as the temperature differentials between the hot and cold sides of the TEG modules, as well as the voltage output generated by the TEG modules. The data collection process is conducted with measurements taken at regular intervals of 1 hour, starting at 12:00 noon and continuing for a duration of 24 hours. To read the temperature measured by the thermocouples that are positioned at both the hot and the cold sides, thermocouple readers were utilized. Besides that, the voltage generated by the TEG modules is measured with the use of a digital multimeter. This approach to data collection aims to provide a comprehensive understanding as well as facilitating in-depth analysis and insights into the performance characteristics of the TEG modules over a period of 24 hours.

3.7 CALCULATION OF ENERGY EFFICIENCY OF TEG MODULES

In order to determine the efficiency of energy conversion of the TEG modules, the figure of merit, ZT must first be determined. The ZT of a material is strongly linked to the efficiency of the thermoelectric device. This can be calculated by applying the following equation.

$$\mathrm{ZT} = \frac{\mathrm{S}^2\sigma}{\mathrm{k}} \times \mathrm{T}$$

where S represents the Seebeck coefficient, σ represents the electrical conductivity in S/m, k represents the thermal conductivity in W/mK and T represents the mean temperature in K. Once the value of ZT is determined, the following formula is used to calculate the energy conversion efficiency of TEG modules.

$$\eta = \left(\frac{\mathrm{T_H} - \mathrm{T_C}}{\mathrm{T_H}}\right)\left(\frac{\sqrt{1+\mathrm{ZT}} - 1}{\sqrt{1+\mathrm{ZT}} + \frac{\mathrm{T_C}}{\mathrm{T_H}}}\right)$$

where T_H represents the temperature of hot side of TEG in K and T_C represents the temperature of cold side of TEG in K (Duran, et al., 2022).

3.8 SUMMARY

In this chapter, the work schedule is detailed using a Gantt chart, outlining tasks such as designing the RC-TEG prototype, analyzing energy conversion efficiency as well as comparing the power generation performance with different conditions of TEG modules. Four different conditions of TEG modules will be studied to understand its effect on energy conversion efficiency which are with the absence of radiative cooler coating, with cool weather white paint, with silicon dioxide coating as well as with both cool weather white paint and silicon dioxide coating. The prototype design includes considerations such as a trapezoidal shape with a 15° tilt in the solar collector to maximize solar radiation absorption, and the use of low-density polyethylene film to trap heat inside the enclosure. After the fabrication of the RC-TEG prototype, a 24-hour experimental study will be conducted outdoor. Data collection will be carried out at hourly intervals, allowing for thorough analysis and evaluation of performance. Furthermore, the formula that will be applied to determine the energy conversion efficiency is also presented in this chapter, which is essential for evaluating the performance of the TEG modules.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the experimental results of the proposed radiative cooling thermoelectric generator prototype will be covered. In this project, the primary objective of conducting this experiment is to study and analyze the energy conversion efficiency and the performance of the proposed RC-TEG prototype in generating power. Data such as the temperature of hot side as well as the temperature of cold side are pivotal in determining the feasibility of utilizing the proposed prototype for power generation through leveraging the temperature differential between these sides. To achieve this, a comprehensive series of experimental studies were undertaken to assess the performance of the prototype under varying conditions of TEG modules. This is facilitated by the application of different radiative cooler coatings. The experimental studies will be conducted for 24-hours, and the results obtained are presented as well as discussed further in the following section.

4.2 EXPERIMENTAL RESULT

4.2.1 Condition of TEG Modules in The Absence of Radiative Cooler Coating

The performance evaluation of the proposed radiative cooling thermoelectric generator prototype without any radiative cooler coating being applied on the surface of TEG modules was first studied. This experimental study took place from 12:00 on January 31st 2024 till 12:00 on February 1st 2024. The weather is partly sunny during the daytime. The temperature throughout this period of experimental study ranged from a high of 34 ℃ to a low of 24 ℃, as shown in Figure 4.1.

The temperature distributions of the hot and cold side of the TEG, alongside the distribution of temperature differential are depicted in Figure 4.2 and Figure 4.3, respectively. Notably, the most significant temperature differential of 5.7 °C was recorded at 13:00 with a hot side temperature of 56.1 ℃ and a cold side temperature of 50.4 ℃. This substantial temperature difference observed at this period indicates significant heat absorption by the hot side due to the greenhouse effect, resulting in generation of power. With that, a maximum voltage of 0.023 V and a maximum power output of 0.04370 mW is generated at this period as illustrated in Figure 4.4 and Figure 4.5, respectively.

Conversely, during the nighttime from 19:00 to 07:00, both ends of the TEG experienced a gradual decrease in temperature, accompanied by fluctuating temperature differentials ranging from 0.4°C to 1.0°C. With that, the measured voltage generated fluctuated between 0.0003 V to 0.0100 V with a power output varying between 0.00001 mW to 0.00900 mW. With the subsequent rise in solar irradiation upon sunrise at 07:27, both end temperatures as well as the generated voltage and power output increased gradually.

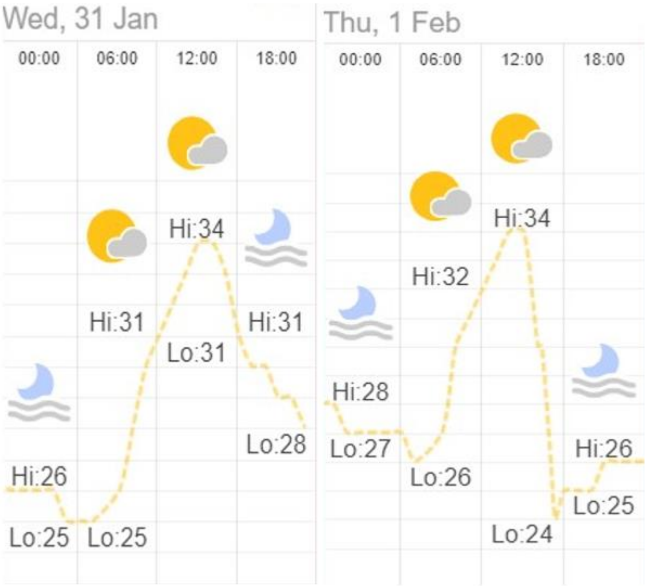

Figure 4.1: Weather condition from 31st Jan to 1st Feb 2024 (timeanddate, 2024)

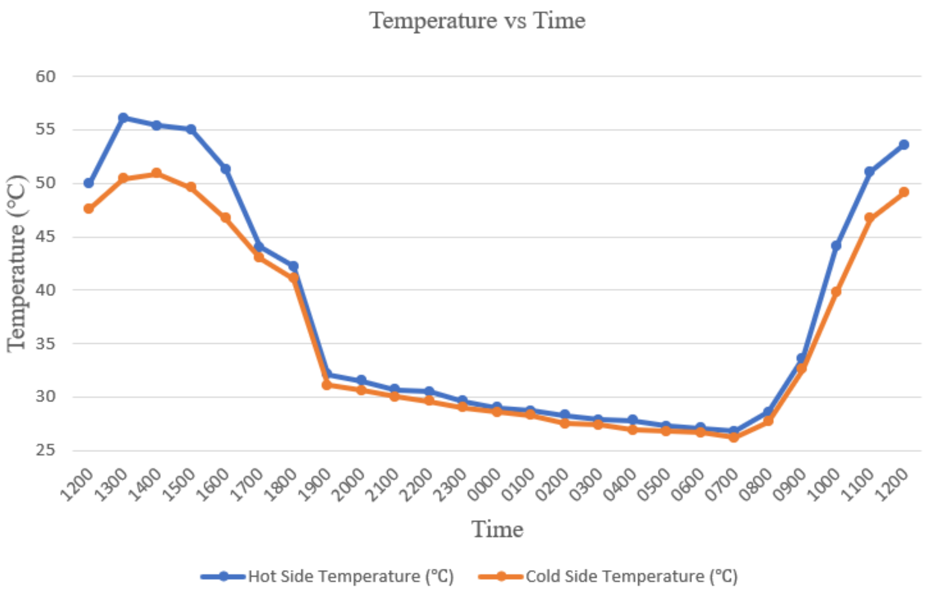

Figure 4.2: Temperature measured of hot and cold sides for 24 hours

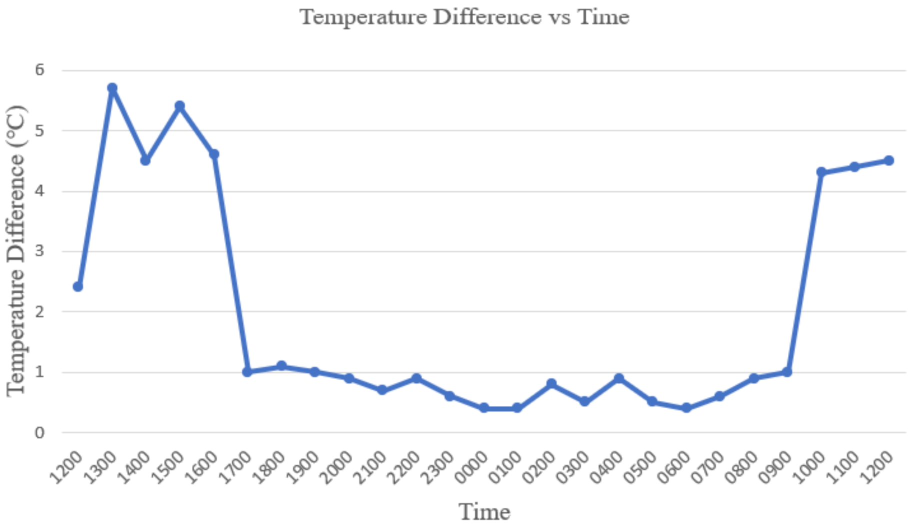

Figure 4.3: Temperature difference obtained for 24 hours

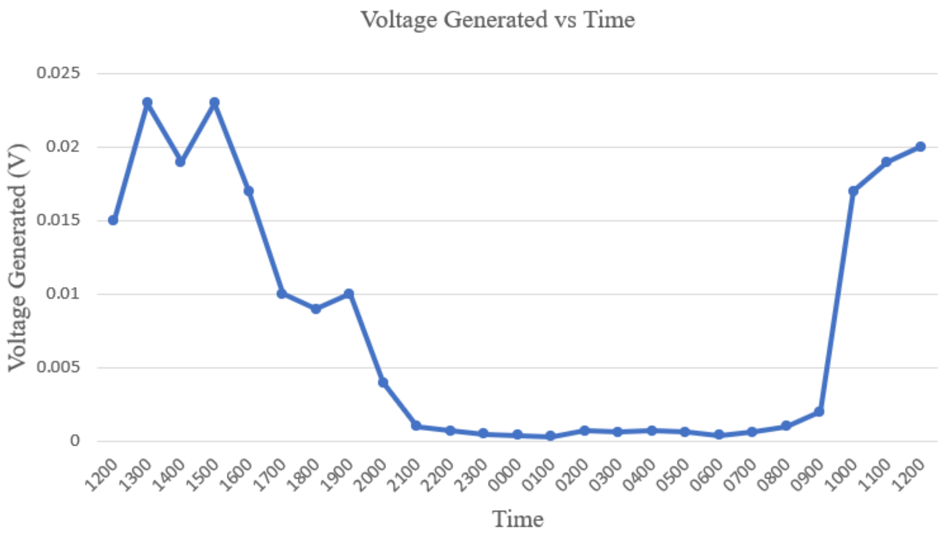

Figure 4.4: Voltage generation of TEG modules for 24 hours

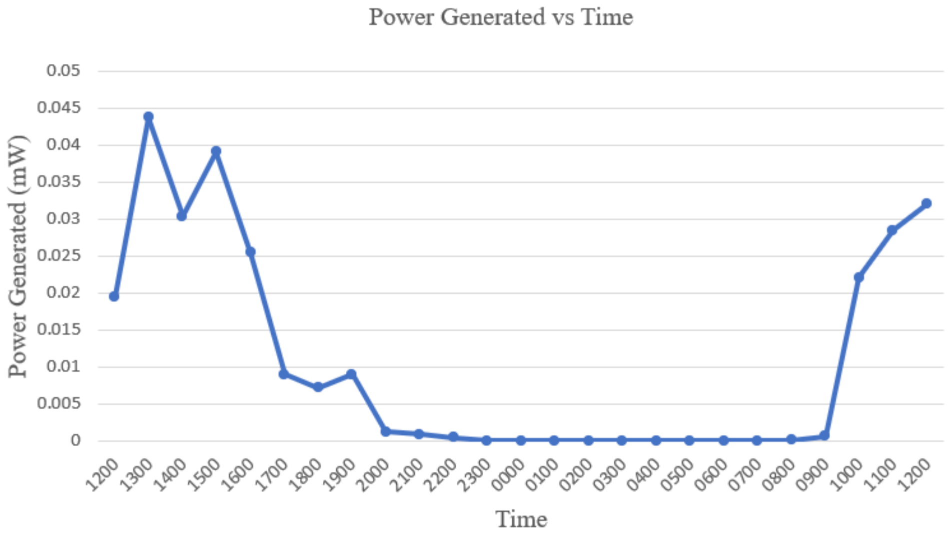

Figure 4.5: Power generation of TEG modules for 24 hours

4.2.2 Condition of TEG Modules with The Use of Cool Weather White Paint

In order to enhance the performance of the TEG modules, the temperature difference has to be increased. Thus, radiative cooler coating is to be applied on the surface of TEG modules. In this experimental study, there are several radiative cooler coatings to be applied and examine the performance of the RC-TEG in generating power. One of the radiative cooler coatings that will be used and studied in this experimental study is the cool weather white paint.

This experimental study is conducted simultaneously with TEG in the absent of radiative cooler coating as discussed previously. Upon applying cool weather white paint to the surface of TEG modules, it was observed that the temperature of the cold side is slightly lower compared to the prototype where there is no radiative cooler coating being applied on the surface of TEG modules. The temperature distributions of the hot and cold sides of the TEG modules, along with the temperature differential distribution are illustrated in Figures 4.6 and Figure 4.7, respectively. It is noted that the temperature difference is the largest at 13:00 which is 8 ℃ with a hot side temperature of 55.5 ℃ and cold side temperature of 47.5 ℃. With that, a maximum voltage of 0.035 V and a maximum power output of 0.10500 mW is generated at this period as shown in Figure 4.8 and Figure 4.9, respectively. This indicates the effectiveness of the cool weather white paint in reducing heat absorption.

Meanwhile, during the night period from 19:00 to 07:00, the temperature at both sides dropped steadily with temperature difference fluctuated between 0.3 ℃ to 1.3 ℃. With that, the measured voltage generated fluctuated between 0.0004 V to 0.0100 V yielding a power output ranging from 0.00001 mW to 0.02850 mW. Due to the significant rise in solar radiation on the next day when the Sun rises, the temperature increased progressively at both sides starting from 08:00, same goes to the measured voltage generated and the power output.

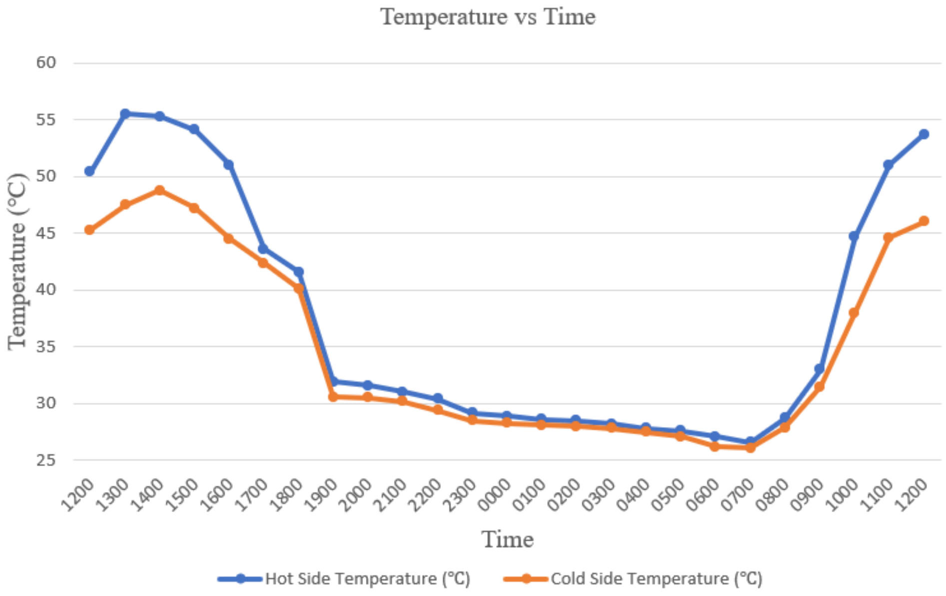

Figure 4.6: Temperature measured of hot and cold sides for 24 hours

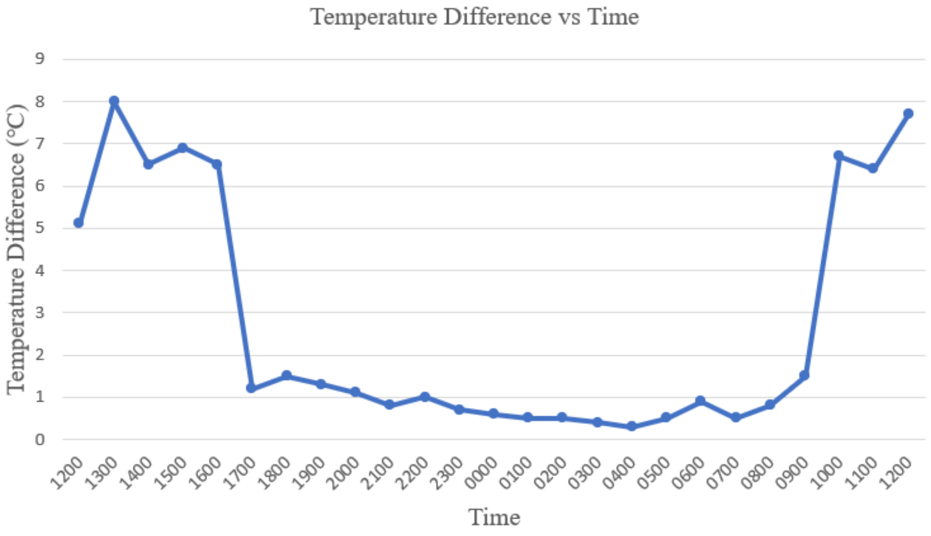

Figure 4.7: Temperature difference obtained for 24 hours

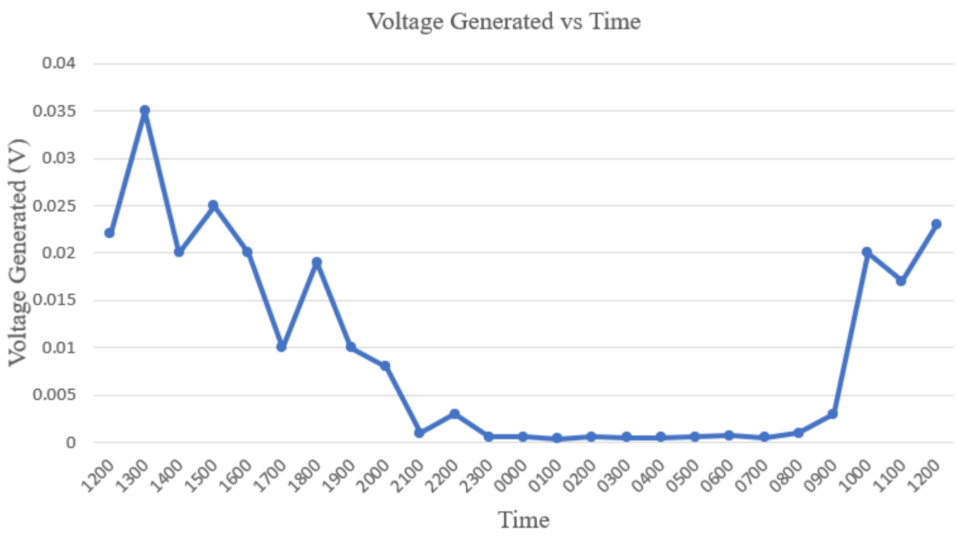

Figure 4.8: Voltage generation of TEG modules for 24 hours

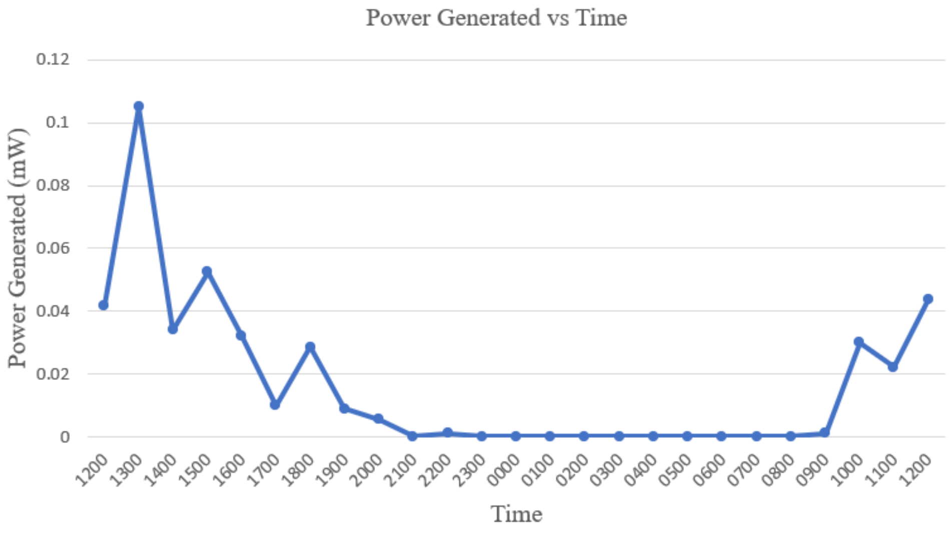

Figure 4.9: Power generation of TEG modules for 24-hours

4.2.3 Condition of TEG Modules with The Use of Silicon Dioxide Coating

Next, the performance of the TEG modules is studied by applying a silicon dioxide coating on the surface of TEG modules. Due to its selective radiation or the Mie resonance effect produced by micro/nanospheres of a particular size, silicon dioxide is the hotspot radiative cooling material (Zhang, et al., 2023). This experimental study took place from 12:00 on February 11th 2024 till 12:00 on February 12th 2024. Similar to the previous experimental study of TEG modules in the absent of radiative cooler coating and TEG modules that coated with cool weather white paint, the weather for this experimental study is also partly sunny during the daytime. Same goes to the temperature, where the temperature throughout this period of experimental study also ranged from a high of 34 ℃ to a low of 24 ℃, as shown in Figure 4.10.

Analysis of temperature profiles for the hot and cold sides of TEG modules, together with the temperature difference distribution is demonstrated in Figure 4.11 and Figure 4.12, respectively. The greatest temperature difference is observed at 14:00 which is 8 ℃, with a hot side temperature of 54.9 ℃ and a cold side temperature of 46.9 ℃. This indicates that silicon dioxide coating is capable of radiating heat from the surface of TEG modules and thereby improving the temperature gradient as well as power generation. With that, a maximum voltage of 0.034 V and a maximum power output of 0.0884 mW is generated at this period as shown in Figure 4.13 and Figure 4.14, respectively.

Meanwhile, a gradual decrease in both end temperatures is observed during the nighttime from 19:00 to 07:00, with the temperature differential fluctuating between 0.7°C and 2.0°C. With that, the generated voltage oscillates between 0.001 V and 0.010 V, yielding a power output ranging from 0.0001 mW to 0.008 mW. With the significant rise in solar irradiation upon sunrise on the following day at 07:27, both end temperatures gradually increase leading to a corresponding rise in the generated voltage as well as power output.

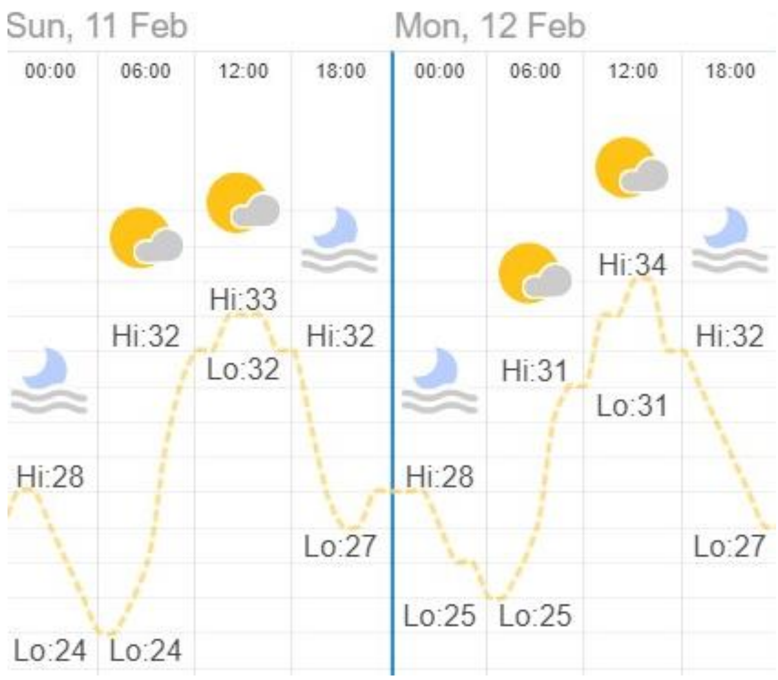

Figure 4.10: Weather condition from 11th Feb to 12th Feb 2024 (timeanddate, 2024)

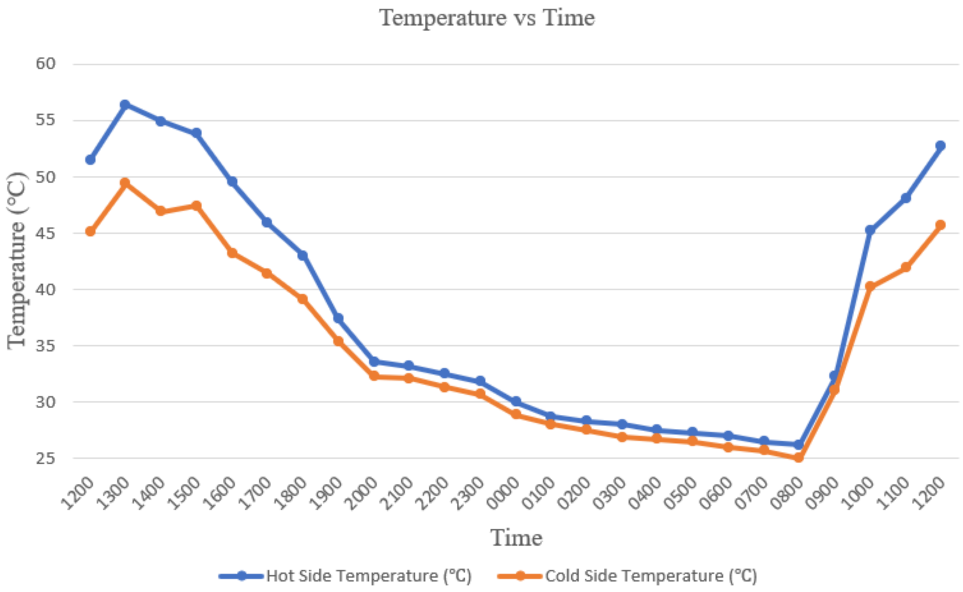

Figure 4.11: Temperature measured of hot and cold sides for 24 hours

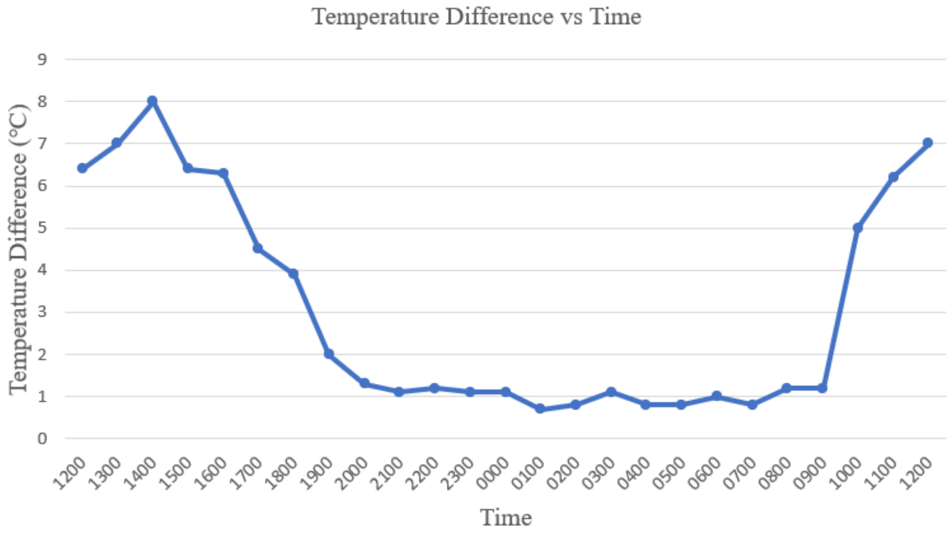

Figure 4.12: Temperature difference obtained for 24 hours

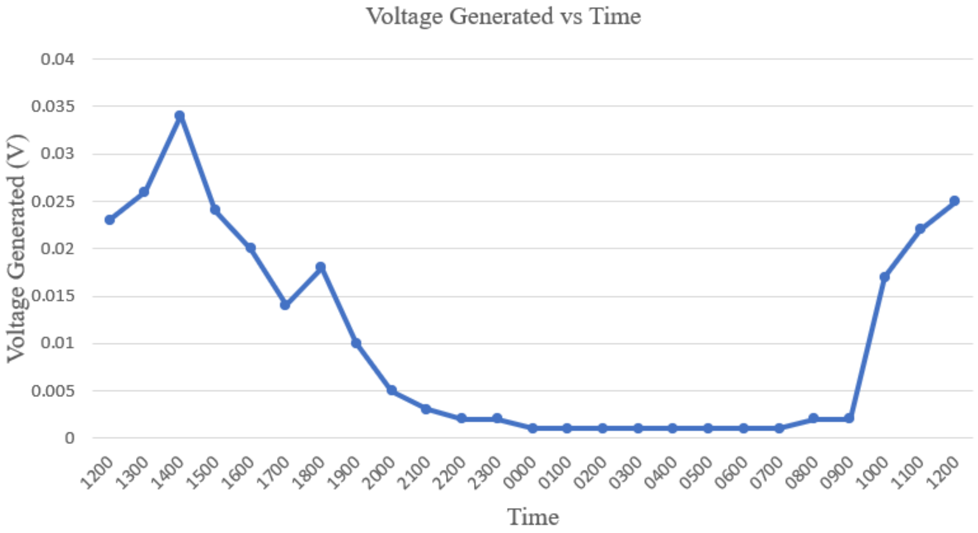

Figure 4.13: Voltage generation of TEG modules for 24 hours

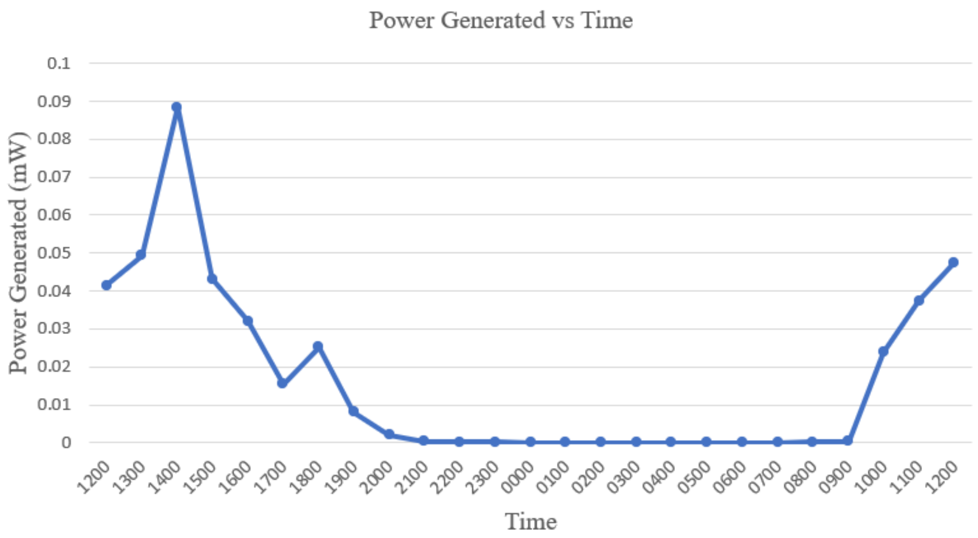

Figure 4.14: Power generation of TEG modules for 24 hours

4.2.4 Condition of TEG Modules with The Use of Cool Weather White Paint and Silicon Dioxide Coating

In addition, the investigation into enhancing the performance of TEG modules extends by applying both cool weather white paint and silicon dioxide coating on the surface of TEG modules. This experimental study is conducted simultaneously with TEG modules that is coated with silicon dioxide coating. Based on the temperature distributions of the hot and cold sides of TEG modules, as well as the corresponding temperature difference which illustrated in the Figure 4.15 and Figure 4.16, it shows that the maximum temperature differential occurs at 14:00, reaching 8.2 ℃. This occurs with a hot side temperature of 54.5 ℃ and a cold side temperature of 46.3 ℃. With that, the TEG modules generate a peak voltage of 0.036 V and a maximum power output of 0.1080 mW at this period, as shown in Figure 4.17 and Figure 4.18, respectively. As a result, by combining both coatings, it further enhances the performance of the TEG modules.

Meanwhile, during the night period from 19:00 to 07:00, the temperature dropped progressively at both sides with temperature difference fluctuated between 0.7 ℃ to 2.5 ℃. With that, the measured voltage generated fluctuated between 0.001 V to 0.011 V with a power output between 0.0001 mW to 0.0099 mW. Due to the significant rise in solar radiation on the next day time when the Sun rises, the temperature increased progressively at both sides starting from 08:00, same goes to the measured voltage generated and the power output.

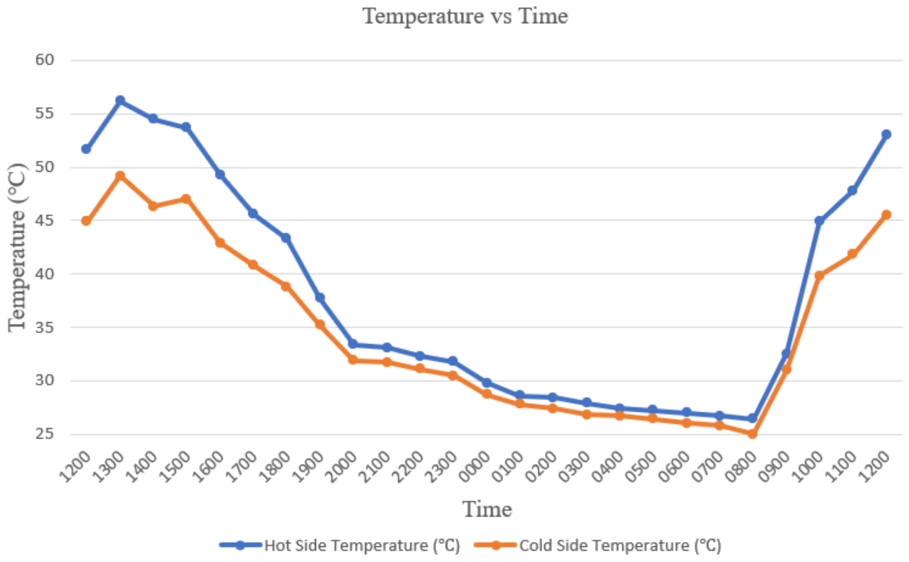

Figure 4.15: Temperature measured of hot and cold sides for 24 hours

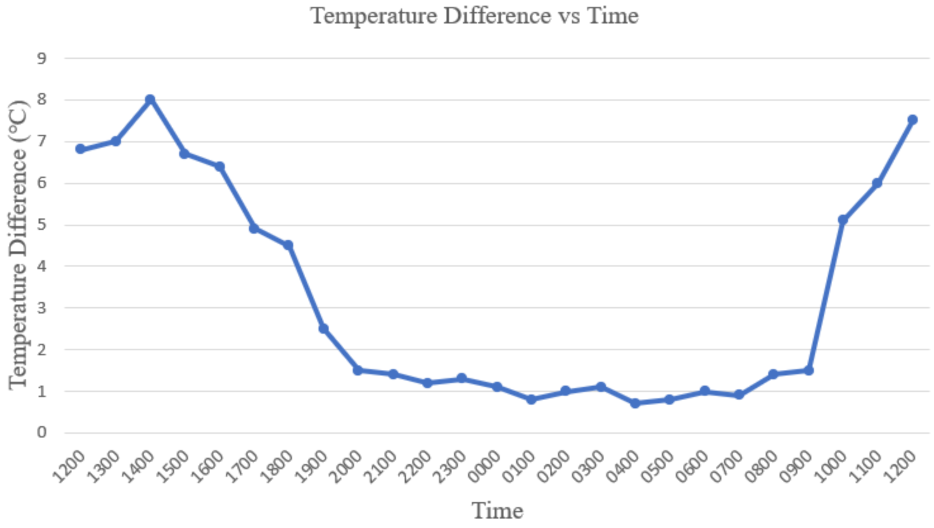

Figure 4.16: Temperature difference obtained for 24 hours

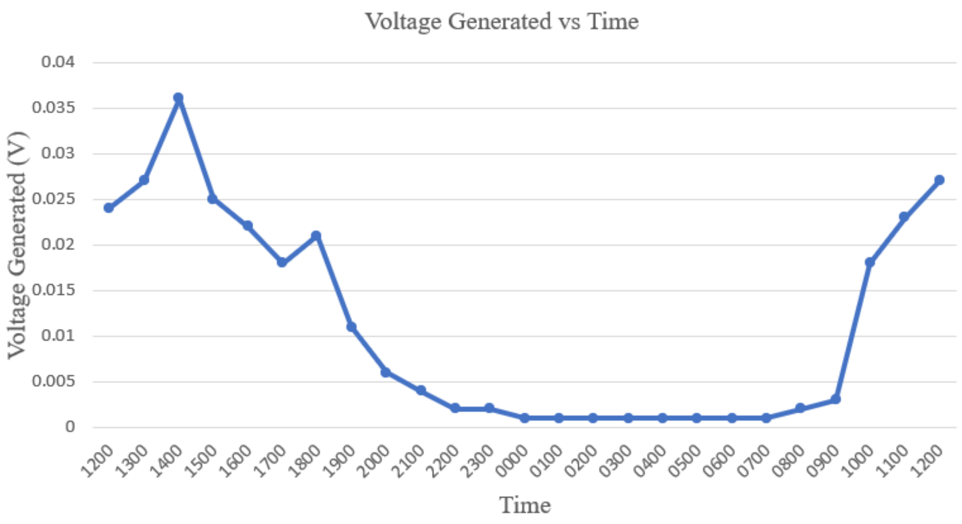

Figure 4.17: Voltage generation of TEG modules for 24 hours

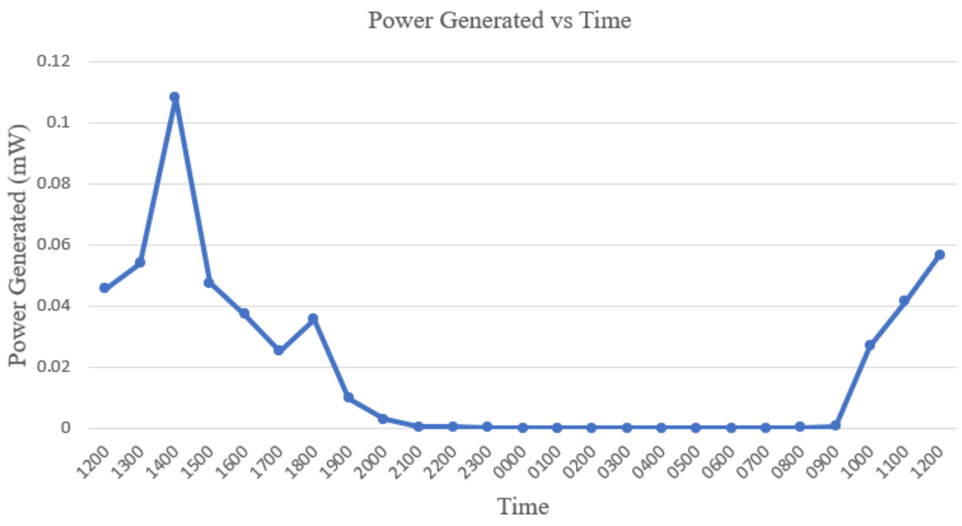

Figure 4.18: Power generation of TEG modules for 24hours

Additionally, for all the four conditions of TEG modules, the temperature difference between the hot and cold sides is observed to be the lowest during nighttime. A low temperature difference during nighttime may be caused by the heat lost from the hot side. This may be due to the enclosure area at the hot side is not well insulated. Also, with lower ambient temperature at nighttime, the dissipation of heat from the hot side may occur more rapidly. This cause both the hot and cold sides to cool down, and thereby minimizing the temperature gradient across the TEG modules. Besides that, the absence of direct solar irradiation during nighttime results in a decrease in external heat source. With no external heat source to maintain the temperature differential between the hot side as well as cold side, both the temperature tends to approach thermal equilibrium, which eventually lead to a reduced temperature difference.

4.2.5 Comparison Among Different Conditions of TEG Modules

The average power output of TEG modules with different conditions are observed and illustrated in a graph as shown in Figure 4.19. Without applying any radiative cooler coating on the TEG modules surface, the TEG modules rely solely on the natural heat exchange between the hot side and cold side. With that, an average power output of 0.0108 mW is obtained, which is relatively the lowest compared to the other conditions.

Besides that, by applying the cool weather white paint on the surface of TEG modules, a portion of the incident solar radiation is reflected, which eventually reduce the cold side temperature as well as enhancing the temperature gradient across the TEG modules. With that, a greater average power output of 0.0167 mW is generated compared to the condition of TEG modules in the absent of radiative cooler coating.

Furthermore, the performance of the TEG modules is enhanced by applying a silicon dioxide coating compared to the uncoated condition. The patterns of the observed temperature difference and power output closely resemble to TEG modules that coated with cool weather white paint, with only slight variations in the values. Hence, by applying a silicon dioxide coating on the surface of TEG modules, an average power output obtained is 0.0166 mW, which is about the same power output as the TEG modules that coated with cool weather white paint.

Lastly, the synergistic effect of both cool weather white paint and silicon dioxide coatings shows a more significant temperature gradient as well as higher power output. The patterns of the observed temperature difference and power output are similar to those with individual coatings but with higher values. Hence, by applying both cool weather white paint and silicon dioxide coating on the surface of TEG, an average power output of 0.0198 mW is obtained, which is the highest among all the conditions of TEG modules.

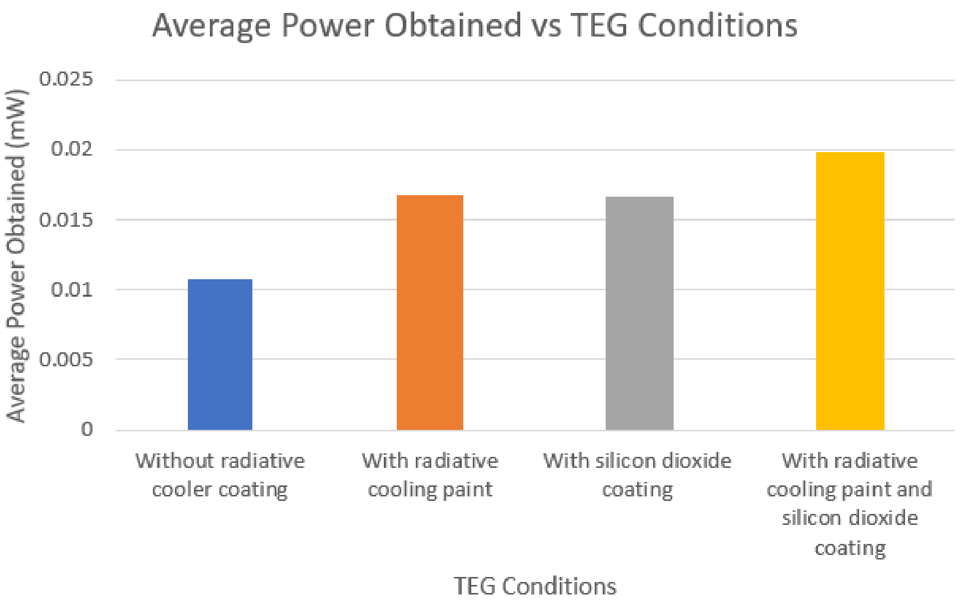

Figure 4.19: Average power obtained under different conditions of TEG modules

4.2.6 Calculation of Energy Conversion Efficiency of TEG Modules

The efficiency of energy conversion of TEG modules under all conditions is calculated at the period where the power output generated is the maximum. Based on the data sheet of TG12-4 from Marlow Industries, Inc, the figure of merit, ZT provided is 0.71. Hence, by substituting the value of ZT in the equation below, the respective maximum energy conversion efficiency of TEG modules for all conditions is obtained as shown in the calculation below. From the calculation below, it shows that condition of TEG modules in the absence of radiative cooler coatings has the lowest energy conversion efficiency which is 0.002327. Meanwhile, the condition of TEG modules with the use of both cool weather white paint and silicon dioxide coating has the greatest energy conversion efficiency which is 0.003375.

- **Condition of TEG modules in the absence of radiative cooler coatings**

Energy conversion efficiency of RC-TEG, η

$$= \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}\right)$$

$$= \left(\frac{329.1 - 323.4}{329.1}\right)\left(\frac{\sqrt{1 + 0.71} - 1}{\sqrt{1 + 0.71} + \frac{323.4}{329.1}}\right)$$

$$= 0.002327$$

- **Condition of TEG modules with the use of cool weather white paint**

Energy conversion efficiency of RC-TEG, η

$$= \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}\right)$$

$$= \left(\frac{328.5 - 320.5}{328.5}\right)\left(\frac{\sqrt{1 + 0.71} - 1}{\sqrt{1 + 0.71} + \frac{320.5}{328.5}}\right)$$

$$= 0.003282$$

- **Condition of TEG modules with the use of silicon dioxide coating**

Energy conversion efficiency of RC-TEG, η

$$= \left(\frac{\mathrm{T_H - T_C}}{\mathrm{T_H}}\right)\left(\frac{\sqrt{1 + \mathrm{ZT}} - 1}{\sqrt{1 + \mathrm{ZT}} + \frac{\mathrm{T_C}}{\mathrm{T_H}}}\right)$$

$$= \left(\frac{327.9 - 319.9}{327.9}\right)\left(\frac{\sqrt{1 + 0.71} - 1}{\sqrt{1 + 0.71} + \frac{319.9}{327.9}}\right)$$

$$= 0.003288$$

- **Condition of TEG modules with the use of cool weather white paint and silicon dioxide coating**

Energy conversion efficiency of RC-TEG, η

$$= \left(\frac{\mathrm{T_H - T_C}}{\mathrm{T_H}}\right)\left(\frac{\sqrt{1 + \mathrm{ZT}} - 1}{\sqrt{1 + \mathrm{ZT}} + \frac{\mathrm{T_C}}{\mathrm{T_H}}}\right)$$

$$= \left(\frac{327.5 - 319.3}{327.5}\right)\left(\frac{\sqrt{1 + 0.71} - 1}{\sqrt{1 + 0.71} + \frac{319.3}{327.5}}\right)$$

$$= 0.003375$$

4.2.7 Power Output and Energy Conversion Efficiency Comparison Between Current Project and Previous Work

According to previous study conducted by Shi, et al. (2023), a passive thermoelectric generator system with the combination of radiative cooling paint was developed to analyse the capability of the TEG module in generating power. Their experimental study was conducted over a 24-hour period at Nanjing Tech University. On the other hand, a passive TEG system that combines the greenhouse effects as well as radiative cooling effect with the use of silicon dioxide coating is designed and investigated by Wang, et al. (2023). Their experimental study was conducted at Yulin, China, and lasted for two 24-hour test cycles, as shown in Figure 4.20. Meanwhile, a passive thermoelectric generator system that features the concept of radiative cooling as well as greenhouse effects is also studied in the current project but in a different design of prototype. In the current project, a 24-hour experimental study of four different conditions of TEG modules is conducted at Puchong, Malaysia.

By making comparison of the power produced by the TEG modules, a maximum power generation of 0.87 mW (0.087 W/m^2) with a radiative cooling module area of 0.01 m^2 and 18.83 mW (1.74 W/m^2) with a radiative cooling module area of 0.0108 m^2 is generated based on the study conducted by Shi, et al. (2023) and Wang, et al. (2023), respectively. In addition, based on the study conducted by Shi, et al. (2023) on the energy conversion efficiency of RC-TEG as shown in Figure 4.21, it showed that the energy conversion efficiency is 0.16 % and 0.45 % at a figure of merit of 0.5 and 2, respectively, with a differential temperature of 5 K.

Meanwhile, the power output obtained in the current project is significantly much lower compared to previous literature works. Among all four conditions of TEG modules investigated in the current project, TEG modules that is coated with both cool weather white paint and silicon dioxide coating generate the greatest power which is 0.1080 mW (0.051 W/m^2) with a radiative cooling module area of 0.0021 m^2, as well as with an energy conversion efficiency of 0.34 % at a figure of merit of 0.71 and a differential temperature of 8.2 K.

The performance of TEG modules in generating power in the current project is worse than the previous study conducted by Shi, et al. (2023) and Wang, et al. (2023) may be due to different TEG used. This is because different TEG modules have different efficiencies based on their design and material. The design of the TEG module such as the number of thermocouples, the thickness and size of the thermoelectric elements as well as the configuration of the TEG modules can all affect the power generation performance of TEG modules. In addition, different materials have different thermoelectric properties such as Seebeck coefficient, electrical conductivity, and thermal conductivity. Some materials may be more efficient at converting temperature differences into electrical power than others. This is demonstrated by the study conducted by Shi, et al. (2023) where the energy conversion efficiency increases with an increase in figure of merit as well as temperature difference. Besides that, the area ratio of TEG modules and radiative cooling module can also influence the performance of TEG modules in generating power. As the area ratio of TEG modules as well as radiative cooling module increases, the differential temperature between the hot and cold sides of the TEG modules increases as well (Shi, et al., 2023).

Apart from that, the poor performance of the TEG modules may also be due to uncertainties in data collection. Every measurement has some degree of uncertainty, which might originate from several sources. Error analysis is the process of assessing the degree of uncertainty related to a measurement result (The University of North Carolina, 2011). In this project, there are several sources of uncertainty such as the uncertainties in temperature measurement. Due to the equipment's practical limits, inaccuracies in experimental measurements are unavoidable (Higazy, 2019). Based on the technical data of the K-type thermocouple of UT320D thermometer as well as the K-type thermocouple with the model of TP-02-D3S200, the temperature accuracy is +/- (0.5 % + 1) and +/- 0.75%, respectively. Additionally, the variations in weather conditions during experimental study can cause fluctuation in the voltage and current generated by the TEG modules, which potentially introducing inaccuracies in power output measurements and impacting the reliability of the results obtained. The cumulative effect of these errors likely contributed to the observed decrease in power generation compared to the previous studies.

Moving forward, efforts should be made to address these sources of error and enhance the robustness of the experimental setup. This could involve implementing more rigorous calibration procedures as well as improving temperature control mechanisms. By minimizing experimental uncertainties, a more accurate assessment of the performance of TEG module can be conducted which eventually lead to better comparisons with existing literature.

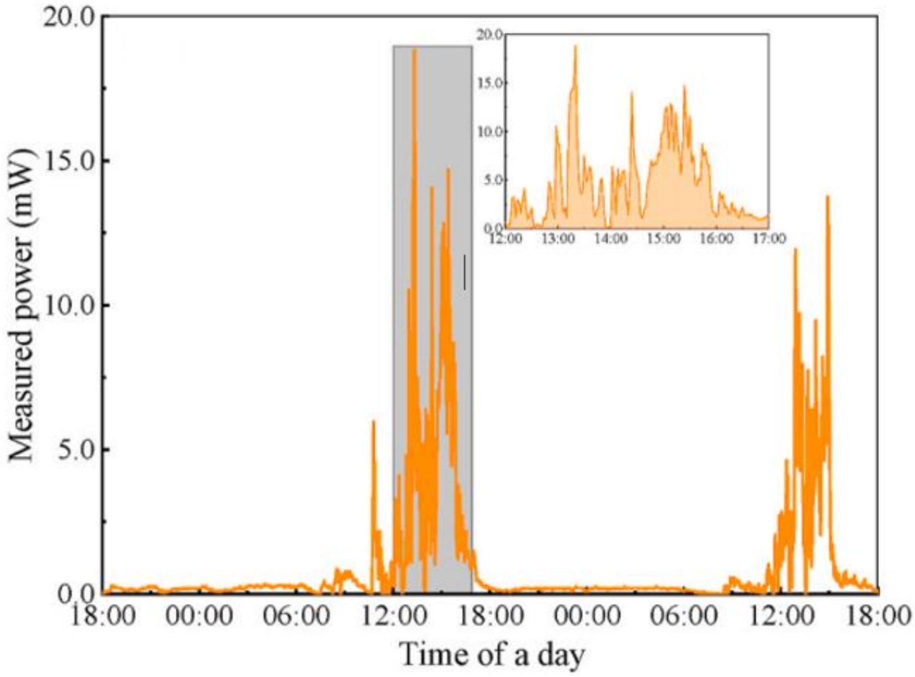

Figure 4.20: Power generation of radiative cooling thermoelectric generator for 48-hours in the study conducted by Wang, et al. (2023)

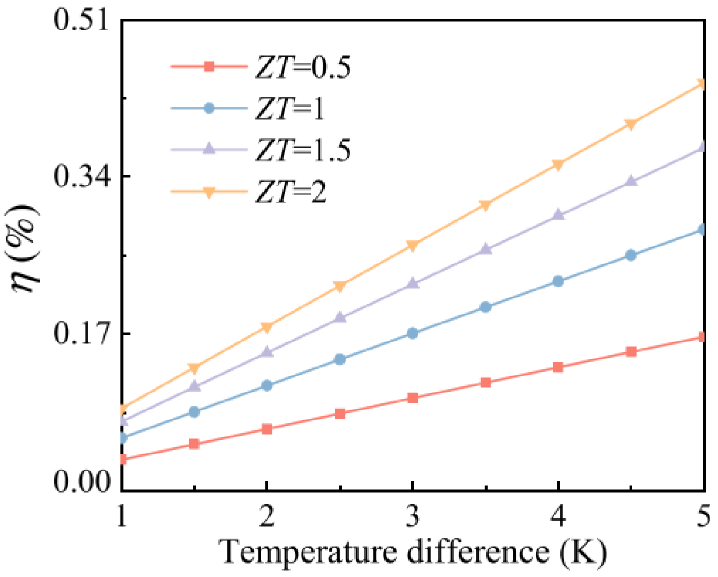

Figure 4.21: Energy conversion efficiency of TEG modules under different figure of merit and temperature difference (Shi, et al., 2023)

4.3 SUMMARY

In this section, the power generation performance of TEG modules under four different conditions is first investigated by conducting experimental study. By performing calculation, the energy conversion efficiency of TEG modules is then analyzed. From the results, it shows that the condition of TEG modules with the use of both cool weather white paint and silicon dioxide coating has a better power generation performance and greater energy conversion efficiency among the other conditions of TEG modules. In addition, the power generation of TEG modules obtained in the current project is compared with the study conducted by Shi, et al. (2023) and Wang, et al. (2023). Based on the comparison, it shows that the TEG modules in the current study generate a significantly lower power. The potential reasons that may lead to the low performance of TEG modules in generating power are then discussed in this chapter.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In conclusion, to investigate the power generation performance of the TEG modules, the experimental study is conducted by fabricating a thermoelectric generator prototype that features the concept of radiative cooling and greenhouse effect. In this study, the experimental results have contributed essential knowledge into the power generation performance as well as energy conversion efficiency under different conditions of TEG modules. These findings highlighted the significant role of radiative cooler coatings in improving the performance of the TEG modules in generating power. In comparison with the TEG modules in the absent of radiative cooler coating, the data collected in this experimental study demonstrated that the application of radiative cooler coatings on the surface of TEG modules at the cold side has positively influenced the performance of the TEG modules in generating power.

In addition, it showed that the condition of TEG modules with the use of both cool weather white paint and silicon dioxide coating has a better performance compared to other conditions of TEG modules. Under this condition, a maximum power output of 0.1080 mW (0.051 W/m^2) is generated with a radiative cooling module area of 0.0021 m^2, as well as with an energy conversion efficiency of 0.34% at a figure of merit of 0.71 and a differential temperature of 8.2 K. Therefore, it shows that the selection and optimization of radiative cooler coating play an important role in the performance of the TEG modules in generating power.

Besides that, in order to maximize the power generation performance and the efficiency of the TEG modules, several improvements can be made such as optimizing the design and material of the RC-TEG prototype, optimizing the selection and application of radiative cooler coatings, performing repeatability on the experimental study as well as conducting continuous comparative experimental studies and simulations. These improvements are further discussed in the following section. Therefore, by incorporating appropriate radiative cooler coatings, it can be a promising approach to further improve the power generation performance of the TEG modules, thereby promoting their widespread adoption in sustainable energy solutions.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Based on the findings of this study, several recommendations can be made for future research and development efforts related to radiative cooling thermoelectric generators. Firstly, future work should focus on optimizing the design of the RC-TEG prototype in order to enhance the power generation performance of the TEG modules. This may involve refining the design of the prototype such as the tilt of the solar collector and exploring alternative materials for better heat trapping and retention inside the enclosure for a longer period.

Besides that, the use of low-density polyethylene film to trap heat within enclosures via the greenhouse effect is effective but is susceptible to degradation over time, which potentially reducing its heat-trapping ability. While replacing low-density polyethylene film with materials like acrylic, glass and polycarbonate sheet, it offers greater durability and resistance to UV radiation. Although acrylic, glass and polycarbonate sheet are more expensive and heavier than low-density polyethylene film, which may require structural adjustments of the prototype, however, these materials provide excellent transparency and long-term performance. Therefore, future work should consider the selection of these materials in creating the greenhouse enclosure to ensure optimal heat trapping effect over a long period of time.

Moreover, future research should focus on optimizing the selection and application of radiative cooler coatings to enhance the power generation performance of the TEG modules. With that, new materials for radiative cooler coating as well as the techniques of applying the coating can be explored and investigated which could lead to even greater improvements in performance.

In addition, the data collection in this experimental study was conducted manually by using thermometer and digital multimeter. Although the experimental study involving four different conditions of TEG modules that conducted in just one 24-hour period each, allowed for sufficient data collection to analyze the impact of the radiative cooler coatings on the performance of RC-TEG. However, performing repeatability on the experimental study could provide valuable insights into the robustness of the findings. Repeatability is essential for validating the consistency of experimental outcomes and establishing the reproducibility of results across multiple tests. Without such validation, there is a risk of drawing premature conclusions or overgeneralizing the findings. Therefore, future research should perform repeatability of the experimental study such as by implementing automated data collection system to further validate the reliability of the data collected.

Finally, it is recommended to continue comparative experimental studies and simulations to further enhance the understanding of the factors influencing the power generation performance of TEG modules, which ultimately contributing to the development of more efficient and sustainable energy solutions. By addressing these recommendations in future work, the potential for radiative cooling thermoelectric generators to become a prominent and sustainable energy generation solution can be further realized.

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APPENDICES

Table A-1: Project flow chart (Part 1)

Tasks	**Project Duration (Week)**											
	Week 1 Sept 19-24 2023	Week 2 Sept 25-Oct 1 2023	Week 3 Oct 2-8 2023	Week 4 Oct 9-15 2023	Week 5 Oct 16-22 2023	Week 6 Oct 23-29 2023	Week 7 Oct 30-Nov 5 2023	Week 8 Nov 6-12 2023	Week 9 Nov 13-19 2023	Week 10 Nov 20-26 2023	Week 11 Nov 27-Dec 3 2023	Week 12 Dec 4-10 2023
Literature review development	🟦	🟦	🟦	🟦	🟦	🟦						
Prototype model design and development							🟦	🟦	🟦	🟦	🟦	🟦

Table A-2: Project flow chart (Part 2)

Tasks	Project Duration (Week)											
	Week 1 Jan 15-21 2024	Week 2 Jan 22-28 2024	Week 3 Jan 29- Feb 4 2024	Week 4 Feb 5-11 2024	Week 5 Feb 12-18 2024	Week 6 Feb 19-25 2024	Week 7 Feb 26- Mar 3 2024	Week 8 Mar 4-10 2024	Week 9 Mar 11-17 2024	Week 10 Mar 18-24 2024	Week 11 Mar 25-31 2024	Week 12 Apr 1-7 2024
Prototype development	🟦	🟦										
Experimental setup and data collection			🟦	🟦	🟦	🟦						
Comparative study							🟦	🟦	🟦	🟦		
Data analysis							🟦	🟦	🟦	🟦		
Documentation and presentation											🟦	🟦

Table A-3: Results obtained without the use of radiative cooler coating

Time	Hot Side Tempe-rature (℃)	Cold Side Temper-ature (℃)	Temperat-ure Difference (℃)	Voltage (V)	Current (mA)	Power (mW) = Voltage × Current
1200	50.0	47.6	2.4	0.0150	1.30	0.01950
1300	56.1	50.4	5.7	0.0230	1.90	0.04370
1400	55.4	50.9	4.5	0.0190	1.60	0.03040
1500	55.0	49.6	5.4	0.0230	1.70	0.03910
1600	51.3	46.7	4.6	0.0170	1.50	0.02550
1700	44.0	43.0	1.0	0.0100	0.90	0.00900
1800	42.2	41.1	1.1	0.0090	0.80	0.00720
1900	32.1	31.1	1.0	0.0100	0.90	0.00900
2000	31.5	30.6	0.9	0.0040	0.30	0.00120
2100	30.7	30.0	0.7	0.0010	0.09	0.00090
2200	30.5	29.6	0.9	0.0007	0.07	0.00049
2300	29.6	29.0	0.6	0.0005	0.04	0.00002
0000	29.0	28.6	0.4	0.0004	0.05	0.00002
0100	28.7	28.3	0.4	0.0003	0.03	0.00001
0200	28.3	27.5	0.8	0.0007	0.06	0.00004
0300	27.9	27.4	0.5	0.0006	0.04	0.00002
0400	27.8	26.9	0.9	0.0007	0.07	0.00005
0500	27.3	26.8	0.5	0.0006	0.05	0.00003
0600	27.1	26.7	0.4	0.0004	0.02	0.00001
0700	26.8	26.2	0.6	0.0006	0.05	0.00003
0800	28.6	27.7	0.9	0.0010	0.09	0.00009
0900	33.6	32.6	1.0	0.0020	0.30	0.00060
1000	44.1	39.8	4.3	0.0170	1.30	0.02210
1100	51.1	46.7	4.4	0.0190	1.50	0.02850
1200	53.6	49.1	4.5	0.0200	1.60	0.03200

Table A-4: Results obtained with the use of cool weather white paint

Time	Hot Side Tempe-rature (°C)	Cold Side Tempe-rature (°C)	Temperat-ure Difference (°C)	Voltage (V)	Current (mA)	Power (mW) = Voltage × Current
1200	50.4	45.3	5.1	0.0220	1.90	0.04180
1300	55.5	47.5	8.0	0.0350	3.00	0.10500
1400	55.3	48.8	6.5	0.0200	1.70	0.03400
1500	54.1	47.2	6.9	0.0250	2.10	0.05250
1600	51.0	44.5	6.5	0.0200	1.60	0.03200
1700	43.6	42.4	1.2	0.0100	1.00	0.01000
1800	41.6	40.1	1.5	0.0190	1.50	0.02850
1900	31.9	30.6	1.3	0.0100	0.90	0.00900
2000	31.6	30.5	1.1	0.0080	0.70	0.00560
2100	31.0	30.2	0.8	0.0010	0.11	0.00011
2200	30.4	29.4	1.0	0.0030	0.40	0.00120
2300	29.2	28.5	0.7	0.0006	0.05	0.00003
0000	28.9	28.3	0.6	0.0006	0.04	0.00002
0100	28.6	28.1	0.5	0.0004	0.03	0.00001
0200	28.5	28.0	0.5	0.0006	0.05	0.00003
0300	28.2	27.8	0.4	0.0005	0.03	0.00002
0400	27.8	27.5	0.3	0.0005	0.05	0.00003
0500	27.6	27.1	0.5	0.0006	0.05	0.00003
0600	27.1	26.2	0.9	0.0007	0.06	0.00004
0700	26.6	26.1	0.5	0.0005	0.05	0.00003
0800	28.7	27.9	0.8	0.0010	0.10	0.00010
0900	33.0	31.5	1.5	0.0030	0.40	0.00120
1000	44.7	38.0	6.7	0.0200	1.50	0.03000
1100	51.0	44.6	6.4	0.0170	1.30	0.02210
1200	53.7	46.0	7.7	0.0230	1.90	0.04370

Table A-5: Results obtained with the use of silicon dioxide coating

Time	Hot Side Tempe-rature (℃)	Cold Side Tempe-rature (℃)	Temperat-ure Difference (℃)	Voltage (V)	Current (mA)	Power (mW) = Voltage × Current
1200	51.5	45.1	6.4	0.023	1.8	0.0414
1300	56.4	49.4	7.0	0.026	1.9	0.0494
1400	54.9	46.9	8.0	0.034	2.6	0.0884
1500	53.8	47.4	6.4	0.024	1.8	0.0432
1600	49.5	43.2	6.3	0.020	1.6	0.0320
1700	45.9	41.4	4.5	0.014	1.1	0.0154
1800	43.0	39.1	3.9	0.018	1.4	0.0252
1900	37.4	35.4	2.0	0.010	0.8	0.0080
2000	33.6	32.3	1.3	0.005	0.4	0.0020
2100	33.2	32.1	1.1	0.003	0.1	0.0003
2200	32.5	31.3	1.2	0.002	0.1	0.0002
2300	31.8	30.7	1.1	0.002	0.1	0.0002
0000	30.0	28.9	1.1	0.001	0.1	0.0001
0100	28.7	28.0	0.7	0.001	0.1	0.0001
0200	28.3	27.5	0.8	0.001	0.1	0.0001
0300	28.0	26.9	1.1	0.001	0.1	0.0001
0400	27.5	26.7	0.8	0.001	0.1	0.0001
0500	27.3	26.5	0.8	0.001	0.1	0.0001
0600	27.0	26.0	1.0	0.001	0.1	0.0001
0700	26.5	25.7	0.8	0.001	0.1	0.0001
0800	26.2	25.0	1.2	0.002	0.1	0.0002
0900	32.3	31.1	1.2	0.002	0.2	0.0004
1000	45.2	40.2	5.0	0.017	1.4	0.0238
1100	48.1	41.9	6.2	0.022	1.7	0.0374
1200	52.7	45.7	7.0	0.025	1.9	0.0475

Table A-6: Results obtained with the use of cool weather white paint and silicon dioxide coating

Time	Hot Side Temperature (℃)	Cold Side Temperature (℃)	Temperature Difference (℃)	Voltage (V)	Current (mA)	Power (mW) = Voltage × Current
1200	51.7	44.9	6.8	0.024	1.9	0.0456
1300	56.2	49.2	7.0	0.027	2.0	0.0540
1400	54.5	46.3	8.2	0.036	3.0	0.1080
1500	53.7	47.0	6.7	0.025	1.9	0.0475
1600	49.3	42.9	6.4	0.022	1.7	0.0374
1700	45.6	40.8	4.9	0.018	1.4	0.0252
1800	43.3	38.8	4.5	0.021	1.7	0.0357
1900	37.7	35.2	2.5	0.011	0.9	0.0099
2000	33.4	31.9	1.5	0.006	0.5	0.0030
2100	33.1	31.7	1.4	0.004	0.1	0.0004
2200	32.3	31.1	1.2	0.002	0.2	0.0004
2300	31.8	30.5	1.3	0.002	0.1	0.0002
0000	29.8	28.7	1.1	0.001	0.1	0.0001
0100	28.6	27.8	0.8	0.001	0.1	0.0001
0200	28.4	27.4	1.0	0.001	0.1	0.0001
0300	27.9	26.8	1.1	0.001	0.1	0.0001
0400	27.4	26.7	0.7	0.001	0.1	0.0001
0500	27.2	26.4	0.8	0.001	0.1	0.0001
0600	27.0	26.0	1.0	0.001	0.1	0.0001
0700	26.7	25.8	0.9	0.001	0.1	0.0001
0800	26.4	25.0	1.4	0.002	0.1	0.0002
0900	32.5	31.0	1.5	0.003	0.2	0.0006
1000	44.9	39.8	5.1	0.018	1.5	0.0270
1100	47.8	41.8	6.0	0.023	1.8	0.0414
1200	53.0	45.5	7.5	0.027	2.1	0.0567