Thermal Management and Efficiency Enhancement of Photovoltaic Module Using PCM |Based Finned Heat Sink

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Session 2020-2024

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A thesis is submitted in partial fulfillment of the requirement for the degree of

BACHELOR OF SCIENCE

in

MECHANICAL ENGINEERING

Session 2020-2024

Department of Mechanical Engineering

Faculty of Engineering and Technology

Mirpur University of Science and Technology (MUST), Mirpur

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Certification

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Certified that the contents and form of thesis entitled "Thermal management and efficiency enhancement of photovoltaic module using PCM based finned heat sink" submitted by "Muhammad Atif Razzaq, Huzaifa Khurshid and Syed Muhammad Noman Shah" have been found satisfactory for the requirement of the degree.

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External Examiner: ____________________

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DEDICATION

We dedicate this project to Almighty God our creator, our strong pillar, our source of motivation, wisdom, information, and understanding. He has been the source of our strength throughout this project. We dedicate this project to our Parents who have never failed to give us financial and moral support, for giving all our needs during the time we developed our system and for teaching us that even the largest task can be accomplished if it is done one step at a time. We would like to express gratitude to our institution mentor, Engr. Hafiz Sohaib for his constant guidance and effect of information. As a project supervisor Engr. Hafiz Sohaib was a consistent source for innovating ideas, encouragement and guidance throughout our work.(Laasonen, Pasquarello et al. 1993)

ABSTRACT

Integration of photovoltaic (PV) modules into various applications requires thermal control strategies to reduce degradation-induced temperature and improve the overall process. competence. This work investigates the use of phase change materials (PCMs) in combination with fin electronics to achieve thermal management and performance improvement in photovoltaic modules. The proposed method is used to exploit the latent heat absorption capacity of phase change material to control the temperature change of photovoltaic modules during operation.   This work focuses on the design, construction, and testing of PCM-based finned heat sink system for photovoltaic modules. Temperature tests were conducted in different environments to evaluate the performance of the proposed method in controlling the temperature of PV modules. (Neale, Dingus et al. 2005)

Additionally, the effects of PCM selection, blade geometry, and integrati(Laasonen, Pasquarello et al. 1993)on physical performance were also examined through numerical simulation and sensitivity analysis.   The results obtained from the experiments and experiments demonstrate the ability of the PCM-based electronic generator to reduce the PV module temperature, thereby increasing the power conversion and extending the life of the device. Additionally, economic analysis and comparison with cooling equipment can provide insight into the cost-effectiveness and scalability of the proposed method in real photovoltaic applications.   Overall, this research contributes to the advancement of thermal management technology in photovoltaic systems, providing effective solutions to solve current problems and improving the overall efficiency and reliability of photovoltaic installations.

Keywords: photovoltaic module, thermal management, phase change material (PCM), finned heat sinks and energy conversion efficiency.

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Chapter 1

INTRODUCTION

In the face of increasing energy demand and increasing environmental problems, there is a growing need for sustainability and energy. Among these sources, photovoltaic (PV) technology stands out as a promising method for renewable energy production. However, the performance and reliability of photovoltaic modules are greatly affected by operating temperatures. Temperature will reduce the efficiency of photovoltaic modules, which will reduce power output and shorten their lifespan. Therefore, good thermal management is crucial to ensure the efficiency and longevity of photovoltaic systems. A new approach adopted in recent years is the integration of phase change materials (PCMs) with finned heat sinks to improve the thermal management of photovoltaic modules. PCM has the unique ability to store and release electrical energy during conversion, thereby reducing the temperature of conversion in the PV module. This research paper aims to investigate the feasibility and effectiveness of using PCM-based fins for thermal management and improving photovoltaic module efficiency. This study aims to explain the advantages and limitations of this approach by analyzing the thermal behavior and energy performance of photovoltaic modules equipped with PCM finned heat sinks.

1.1 Solar Panel

Solar panels are used to collect solar energy from the sun and convert it into electricity. The typical solar panel is composed of individual solar cells, each of which is made from layers of silicon, boron and phosphorus. The boron layer provides the positive charge, the phosphorus layer provides the negative charge, and the silicon wafer acts as the semiconductor. When the sun's photons strike the surface of the panel, it knocks out electrons from the silicon "sandwich" and into the electric field generated by the solar cells. This results in a directional current, which is then harnessed into usable power. solar module. The entire process is called the photovoltaic effect, which is why solar panels are also known as photovoltaic panels or PV panels. A typical solar panel contains 60, 72, or 90 individual solar cells

Figure 1-1 Solar Pannel

1.2 Types of Solar Pannel

There are 4 major types of solar panels available on the market today: monocrystalline, polycrystalline, PERC, and thin-film panels

1.2.1 Monocrystalline Solar Panel

Also known as single crystal panels, these consist of a single pure silicon crystal that is cut into multiple wafers. Because they are made of pure silicon, they are easy to recognize by their dark black color. Thanks to the use of pure silicon, monocrystalline modules are also the most space-saving and long-lasting of all three types of solar modules. However, this comes at a cost - producing a monocrystalline cell wastes a lot of silicon, sometimes over 50%. This leads to a high price.

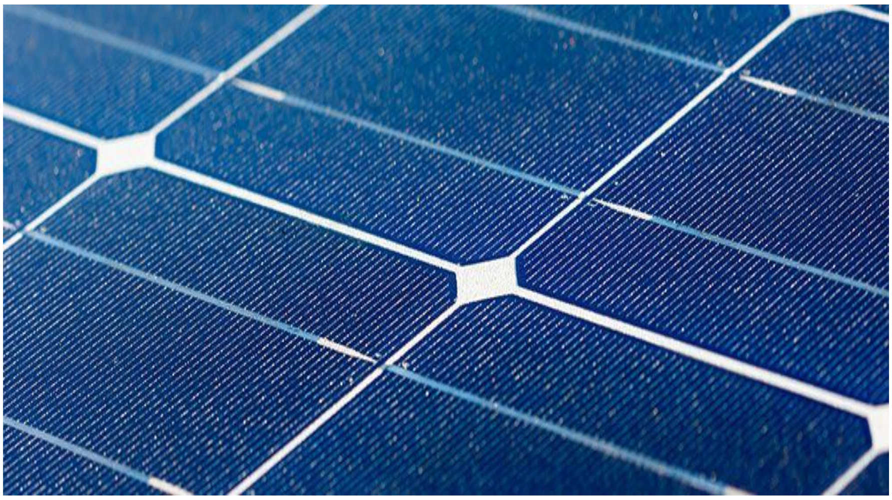


Figure 1-2 Monocrystalline Solar Panel

1.2.2 Polycrystalline solar panels

As the name suggests, these are made of different silicon crystals and not one. The silicon fragments are melted and cast into a square shape. This makes polycrystalline cells significantly cheaper, as there is hardly any waste, and they have the characteristic square shape. However, this also makes them less efficient in terms of energy conversion and space requirements, as the purity and structure of silicon are lower than monocrystalline modules. They also have a lower heat tolerance, meaning they are less efficient in high temperature environments.

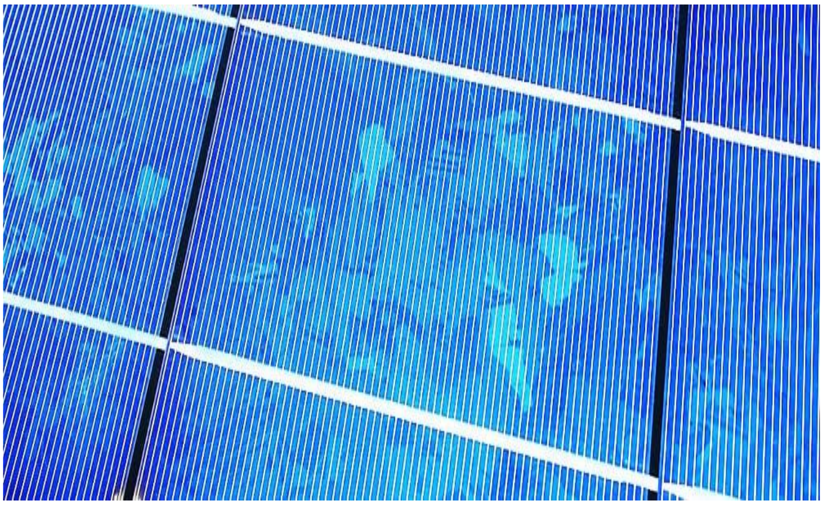


Figure 1-3 Polycrystalline Solar Pannel

1.2.3 Passivated Emitter and Rear Cell (PERC) panels

An advancement above the conventional monocrystalline cell are PERC solar panels. By adding a passivation layer to the cell's back surface, this relatively new method increases efficiency in a number of ways. It increases the quantity of solar energy that is absorbed by reflecting light back into the cell. It inhibits the movement of electrons within the system and lessens their innate desire to recombine. It makes it possible for light to reflect at longer wavelengths. Light wavelengths longer than 1,180 nm are simply able to flow through silicon wafers instead of being absorbed, which causes the metal back sheet of the cell to heat up and lose efficiency. These longer wavelengths are reflected by the passivation layer, which prevents the back sheet from heating up.

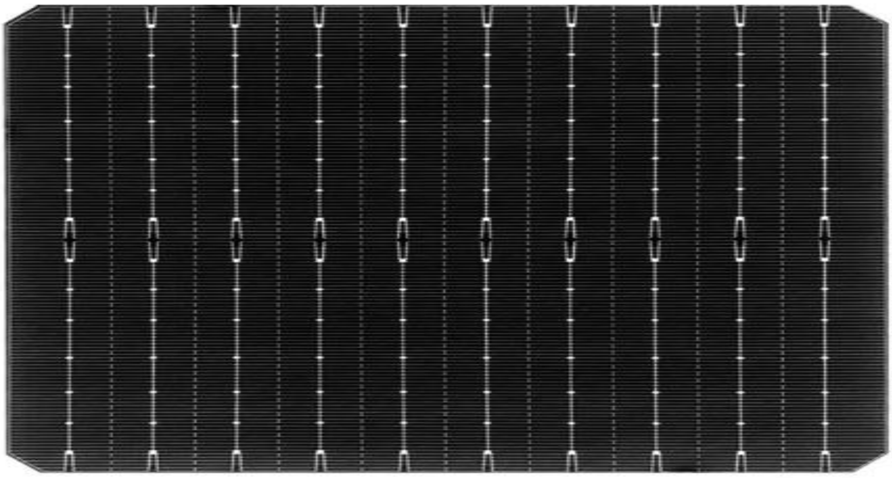


Figure 1-4 Passivated Emitter and Rear Cell

1.2.4 Thin-film solar panels

Thin-film panels are characterized by very fine layers that are thin enough to be flexible. Each panel does not require a frame backing, making them lighter and easier to install. Unlike crystalline silicon panels that come in standardized sizes of 60, 72, and 96-cell counts, thin-film panels can come in different sizes to suit specific needs. However, they are less efficient than typical silicon solar panels.

Figure 1-5 Thin Film Solar Panel

1.3 Problem Statement

Loss of performance in solar panels due to temperature and high sunlight is a major concern. To achieve thermal efficiency, these losses must be minimized. In particular, traditional thermal management techniques such as cooling techniques have been used to reduce the thermal stress of PV modules. However, these methods often require high cost, complexity and energy consumption; this limits their effectiveness, especially in remote or off-grid installations. In recent years, phase change materials (PCMs) have become popular solutions for thermal management of photovoltaic systems. PCM has the advantage of storing and releasing electrical energy during conversion, thus controlling the temperature change in the photovoltaic structure. Additionally, the use of heating fins further increases thermal performance by increasing heat transfer to the system.

1.4 Aims and Objectives

The main objective of this study is following

1. Enhancement of PV module efficiency using passive cooling.
2. Concept of heat sink based on fins and phase change material (PCM) at the back surface of PV module
3. Assessment of PV module performance with and without heat sink
4. Identification of suitable heat sink geometry
5. The designed geometry will allow maximum thermal efficiency of the solar receiver in the dish-micro gas turbine

Chapter 2

LITERATURE REVIEW

2.1 Review of solar thermal technologies

Since last few decades, with the increase on of global population, and the technology growth in the developing world, the electricity demand has been increased continuously [1] and there is no sign to slowdown. According to the IEA report 2017, the energy demand has been increased by 2.1% in 2017, which is more than twice to the previous years. The electricity generation during this year was increased by 3.1%, which is faster than all other energy demands. Although, the energy consumption is high in the large cities, there are significant consumers in the rural areas which have limited access to the electric grid [2]. More than 1.5 billion people, mostly in Sub-Saharan Africa and South Asia regions, still have no access to electricity. The need is to focus on the renewable energy alternative for the small and medium scale energy production.

Among all other renewable energy resources, solar energy is most promising energy source which is abundantly available on the earth crust. About 1.75×10^{14} kW of the sun power has been intercepted continuously on the earth crust, some of which reflected by clouds. Considering the 60% transmittance by clouds, about 1.05 1.75×10^{14} kW power continuously available on the earth surface [3]. If only 0.1% of this energy can be converted to the electricity, it will be the 3.5 times the total energy generating capacity by using all other resources [4]. The need is the more efficient devices for the solar energy to electricity conversion.

2.2 Experimental investigation of performance of PV

One of the widespread technologies of solar energy utilization is the Photovoltaic system (PV) which convert solar radiations directly into electricity (reference). PV technology is the most promising renewable energy technology widely use worldwide. Since last few years, decrease of solar cell prices with considerable increase in their efficiency result in the successful growth of PV technology. About 1,600 large scale installations (> 4MW) of PV systems worldwide has a combined capacity of 22,500 MW_e. Some large-scale power plants have been installed in recent years. In last years, a 1000 MW PV power plant has been installed in Bahawalpur, Pakistan. In first stage, it is adding 100 MW in national grid. Over a short period, the PV technology has grown with comparatively highest growth rate. For example, in ten years (2004-

2014), the total installed capacity of the PV technology has been increased about 70 times, from 2.6 GW (in 2004) to 177 GW (in 2014).

Among the several advantages displayed by the PV modules, there are some problems associated with them which reduce their usage in large extent. Efforts are made to reduce these issues to have an efficient system for power generation. PV systems undergo following major problems,

- The most important is the low efficiency of solar cells. This results in the large PV area for the required power which consequently increases plant cost [5][6].

- Secondly, the unstable electricity generations due to the intermittent solar energy supply. As the efficiency of the PV system strongly depends on the solar radiations and because of the natural fluctuations in the solar flux, the output electric power fluctuates. The electricity stability is big challenge for PV systems. Moreover, peak efficiency of the PV system can be obtained only for 2-3 hours of peak DNI.

- The dust deposition on the PV systems is an important factor and has a strong impact on its performance. The layer of the dust formed on the PV module surface, reduces the transmittance of solar radiations to its glazing surface [7]. In some desert areas, the dust could cause up to 70% decrease of PV efficiency. To avoid this, an appropriate cleaning mechanism required which consequently increase the system cost [8].

- Another relevant issue is the performance degradation of the PV modules with time to ‘sunlight exposure [9]. This problem has been faced in the Quaid-e-Azam solar power plant in Pakistan, with significant decrease of power with time [10]. Research is focused on some advance solar cell materials to overcome this issue.

Figure 2-1 Arial view of 1000 MW Quaid-e-Azam PV solar power plant, Pakistan [10]

The decrease of PV module efficiency with the increase of PV module temperature is an important concern for the PV modules particularly at high solar irradiance. PV modules absorb about 75-80% of solar irradiance into electricity. The remaining part causes the increase of PV module temperature [11]. The reason is the conversion of specific spectrum of light into electricity and other into heat [12]. The increase of PV module temperature results in the considerable decrease of the output voltage of the PV module and resultant decrease of PV module efficiency. Bashir et al. [5] analyzed the PV module performance in the environmental condition of Taxila, Pakistan. It was found that the efficiency of monocrystalline and polycrystalline PV modules was decreased by 8.9% and 5.3% with the increase of PV module back surface temperature of 22 °C to 33 °C respectively. In a similar study, Ali et al. [13] measured the PV module efficiency during the peak summer at Taxila, Pakistan and found that it is much lower than the module efficiency at same sight at peak winter. The average PV module efficiency of monocrystalline and polycrystalline modules was 19.8% and18.7% lower than the module efficiency of the same site at peak winter months. Pandey et al. [14] performed the energy and exergy analysis of the polycrystalline PV modules in India. It was found that maximum energy efficiency was in December and minimum in July. This was due to the higher PV module temperature in July compare to December. Figure 2.2 shows the variation of the I-V curve of the PV cell/module with the cell/module temperature. The voltage of the PV module sharply decreases with the increase of module temperature.

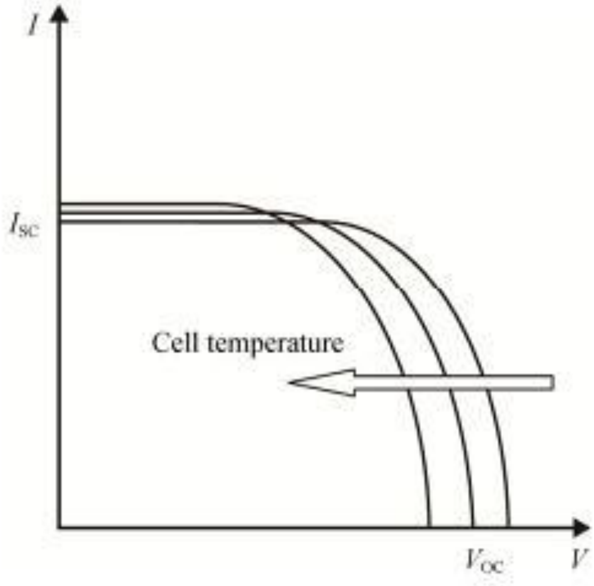
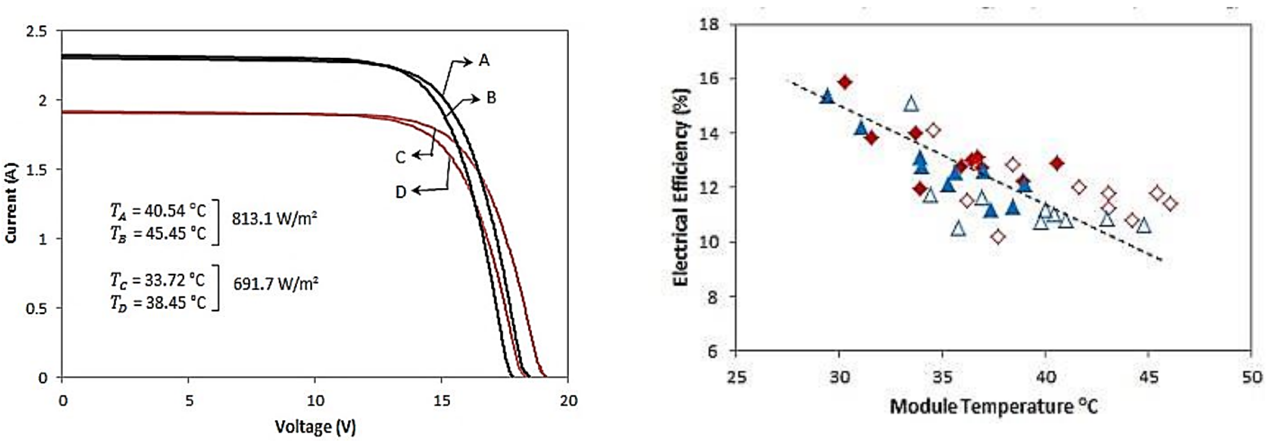


Fig. 2.2- The variation of PV module characteristics with the change of PV module temperature [3]

2.3 Calculating Polycrystalline PV Module Temperature

The Efficiency of PV module considerably decrease with the increase of PV module surface temperature. Every 1 °C surface temperature rise of the PV module causes a reduction in efficiency of 0.4-0.5% [15]. Particular, for the regions of high solar flux, the cell temperature reaches up to 80 °C and considerable decrease in efficiency taes place. For such regions, effective cooling mechanism is required to maintain the efficiency of PV modules. Bashir et al. [16] performed experimental study of crystalline PV modules and showed that the PV module temperature increased from 34 to 46 °C with the increase of solar irradiance from 300 W/m^2 to 900 W/m^2. This increase of module temperature results in decrease of PV module temperature of about 3-5%. The effect of PV characteristic curve with the variation of module temperature from this study is shown in Fig. 2.3 (a). Similarly, the decrease of PV module efficiency with the increase of module temperature is shown in Fig. 2.3 (b)



(a) (b)

Fig. 2.3- The effect of PV characteristic curve with the variation of module temperature (a), The variation of PV module efficiency with temperature [16]

Some other researchers [17][18] described about the considerable decrease of the PV module efficiency with the increase of its temperature.

2.4 A Review on recent development of cooling technologies for PV

To have an efficient PV system, it is necessary to control the rise of PV module temperature. Different cooling mechanisms are used for this purpose including water cooling, air cooling, jet impingement, extended fins, phase change materials etc. In the previous literature, these methods have been described in term of temperature reduction and efficiency enhancement. Fig. 2.4 described the cooling methods generally used for the PV cell/module

Fig. 2.4- The most common cooling methods used for PV cell/module cooling [19]

In this study [20], there are a lot of techniques were used like fluid medium cooling, optimizing structural configuration cooling and phase change material cooling. Water based cooling will give better cooling efficiency for PV modules, structural configuration boosts the increase in disturbance or heat transfer and PCM's can have increased thermal conductivity and results in improving cooling efficiency. Ahmed et.al [21] did an experiment on Enhancement of the performance of Photovoltaic/Trombe wall system using the porous medium. It was confirmed that porous medium lowers down the temperature of PV cells. By this technique, the thermal and electrical efficiencies increase by the factor of 20% and 0.5%respectively. Elberki et.al [22] performed an experiment on passive cooling technique of PV module using lapping fins. It was found that the reduction in temperature from 64.3^{o}C to 39.73^{o}C. The electrical efficiency is increased by 11.2%. Ibtisam A. Hasan [23] did a test on enhancement of performance of PV panel by using rectangular fins as Heat Sink. It was observed that there is a drop of temperature about 5.7^{o}C and an average increase in module output power about 15.3%. In another study, Selimefendigil et.al [24] did an experimental analysis and dynamic modeling of a PV module with porous fins. The surface temperature of the non-fins panel is 49^{o}C, the surface temperature of the fins surface is 48.51^{o}C. Kim et.al [25] did a study on the cooling performance of fins and metal mesh attached on a PV module using meshes made up of iron and aluminum. Iron and aluminum mesh reduced the PV module temperature by approximately 4.35^{o}C and 6.56^{o}C respectively. Aluminum mesh caused a greater improvement in the PV electrical efficiency (0.11% vs. 1.44%). Vittorini et.al [26] did an experiment on fin-cooled photovoltaic module modeling--Performances mapping and electric efficiency assessment under real operating conditions, it was found that electric efficiency is enhanced by the factor of 0.9% and there is a drop of 2.6^{o}C in temperature. Pandey et.al [27] worked on global advancement of cooling technologies for PV systems using PV cooling technology i.e. passive and active cooling. It was noted that, in passive cooling system temperature in the range of 6–20^{o} C with an improvement in electrical efficiency up to 15.5% maximum and in active cooling system, a reduction in PV module temperature as high as 30^{o} C with an improvement in electrical efficiency up to 22% maximum.

2.5 Improving Performance of a PV Pane by Pin Fins

Another study of Sedaghat et.al [28] told that improving performance of a Photovoltaic Panel by pin fins. It was found that the power output increases by 1.24-4.16& and surface temperature of the PV panel to decrease by 2.3^{o}C. Karthikeyan et.al [29] worked on analysis and performance improvements of photovoltaic system by using fins for heat reduction by CFD. They found that the efficiency of a monocrystalline PV panel decreases around 0.3% for every degree rise in temperature after 30^{o}C. Temperature reduced by 4^{o}C. Kim et.al [30] analyzed numerical analysis on the thermal characteristics of photovoltaic module with ambient temperature variation. It was a comparison between a PV module with and without fins. The temperature of PV module to attach fins to the backside of PV module was lesser than without fins because heat was emitted at the fins. Range of temperature was increased from -25 to 50^{o}C. Kim et.al [31] performed study on the cooling effect of attached fins on PV using CFD simulations. It was found that increase in electrical efficiency as 14.39% and temperature reduction were calculated by approximately 15.13^{o}C by using fins. Du et.al [32] analyzed that thermal management system for photovoltaic passive cooling by heat sink or heat spreader. It was found that efficiency of crystalline silicon cells drops at a rate of around 0.45%/C. Natural ventilated systems have temperature in the range of 50-70^{o}C and forced ventilated systems were found to achieve a lower temperature range of 20-30^{o}C. Elminshawy et.al [33] analyzed performance of PV panel coupled with geothermal air-cooling system subjected to hot climatic using pre-cooled ambient air over back panel surface was experimentally investigated for local conditions of Port Said, Egypt. It was possible to decrease the PV module temperature from an average 55 °C (without cooling) to 42 °C with the help of geothermal pre-cooled air flow over the back surface of a PV module at an optimum rate of 0.0288 m3 /s. At this optimum flow rate, due to the decrease in PV module temperature, an average improvement in the PV module output power and electrical efficiency of about 18.90% and 22.98% respectively was achieved.

Bayrak et.al [34] worked on Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection. It was observed that the highest energy and exergy efficiencies values of the finned panels (A5) were calculated as 11.55%, and 10.91%, respectively. In another study, Idoko et.al [35] performed on enhancing PV modules efficiencies and power output using multi-concept cooling technique. It came out with these results an increase in efficiency above 3%, an output power increase of 20.96 W and an increase in output power of 20.96 watts. Hasan et.al [36] worked on enhancing the performance of PV panel by using fins as heat sink. It showed that by using fins, there is a drop of temperature about 5.7^{o}C and increase in output power of about 15.3%. Chandrasekar et.al [37] did an experiment on Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling. It analyzed that the PV module temperature got reduced by 12 % while the electrical yield is increased by 14 %. Borkar et.al [38] did an experimental investigation of PV panel with fin cooling under natural convection. It was found that due to this technique of cooling of the PV panel dropped significantly & the power output was improved by 5.5% under natural convection. Bayrak et.al [39] performed Experimental study for the application of different cooling techniques in photovoltaic (PV) panels. It was observed that PV with fin system produced the highest power generation of 47.88 W while PV with PCM and TEM produced the lowest power generation of 44.26 W.

In present study, the cooling of PV module has been numerically investigated using extended fins at the back surface of the PV modules (Passive Cooling). The detailed thermal analysis has been performed using commercial code of ANSYS R3. The parametric analysis has been performed considering the different factors of the fin structure including fin height, fin diameter and fin spacing. Moreover, effect of air flow on the PV panels with attached extended fins is also investigated. The result of this study presents the optimum extended finned passive cooling structure for the PV system.

Chapter 3

Experimental Setup

The passive mechanism that is used in the cooling of PVs are normally done by attaching a heat sink at the rear side of the PV panel. In the case of this experiment, the PV module and heat sink is cooled by fins and PCM. This mechanism of cooling PVs comes with a number of advantages such as the non-use of water which would have come as an extra cost and also the mechanism is relatively simple to construct.

3.1 Material Selection

3.1.1 Selection of PV module

In the case study, electrical category is the most important criterion, followed by mechanical features. Under the electrical category, PTC power rating is the most important objective of the experts, followed by the STC power per unit of area. This means that the PTC power rating is the most important factor in selecting solar panels. Under the mechanic characteristics, material type is the highest concern. Material manufacturing process has the biggest priority among the environmental criteria. Under the customer satisfaction category, reliability is the criterion with the highest priority.

After considering electrical, mechanical, financial, environmental and customer satisfaction performance of each panel we can conclude that Monocrystalline Solar Pannel is the most suitable one that can be used in our research. Although the results/ may be case specific, the proposed model can be tailored and applied to other cases in different locations or countries as a reference when selecting the most appropriate solar panels

Figure 3-1 PV Module and its properties

3.1.2 PCM Selection

Conventional way to select PCMs for solar air conditioning applications is mostly based on the design engineers' experience or material availability. Recent studies in PCM ranking neither had no successful attempt to address the system goals explicitly, nor did they account for the subjective choices of designers Select a Phase Change Material (PCM) with suitable melting temperature in the range of (40^{O}-60^{O}) and latent heat capacity to effectively absorb and release thermal energy within the desired temperature range of the photovoltaic module. The use of paraffins as PCMs for enhancing PV module performance through passive cooling.

A comprehensive literature survey was performed for the selection of Phase Change Material (PCM). The paraffins are fund suitable in this temperature range. Following PCMs are among the shortlisted for usage in this experiment.

Material	Melting point (C^O)	Latent heat of fusion (KJ/Kg)
n – Heneicosane	41	215
n – Docosane	44	249
n – Tricosane	47	234
n – Tetracosane	51	255
n – Pentacosane	54	238
Paraffin Wax	32	251
n – Hexacosane	56	257
n – Heptacosane	59	236

3-1 Different PCM properties at melting point range(40-60)

The selected PCM, Paraffin, has a melting point of 32°C and is appropriate for thermal energy storage in building materials due to its high latent heat capacity and stability. Paraffin was selected due to its moderate melting point, which correlates well with the operating temperature range of the intended application. Additionally, its cost-effectiveness and availability make it a practical choice. This PCM will be incorporated into the building envelope to enhance thermal regulation. By absorbing surplus heat during the day and releasing it at night, it is expected to reduce the need for active cooling.

Figure 3-2 Paraffin wax

3.1.3 Finned Heat Sink

Steel finned heat sinks are passive heat exchangers used in industrial applications, heavy machinery, and severe conditions. Despite being less thermally conductive than materials like aluminum or copper, steel is selected due to its durability, strength, and corrosion resistance. These fins increase surface area for effective heat dissipation, making them valuable in environments where mechanical strength and stability are crucial.

3.1.4 Thermocouple

A thermocouple is a temperature-sensing device that operates based on the feedback effect, where two dissimilar metals are joined at one end to form a junction. When this junction (called the "hot junction") is exposed to a temperature different from the other extremities of the metals (the "cold junction" or "reference junction"), it generates a voltage proportional to the temperature difference. This small voltage can be measured and converted into a temperature reading, making thermocouples widely used in industrial applications for their ability to measure a broad range of temperatures rapidly and durably.

3.1.5 Voltage and Current Sensors

A multimeter is a multifunctional instrument used to measure electrical parameters such as voltage, current, and resistance. Among its numerous types, the Digital Multimeter (DMM) is widely used due to its precision and ease of use. Unlike analog multimeters, which use a needle and scale to display measurements, a DMM provides digital readouts on an LCD screen, offering clear and accurate readings. DMMs come with configurations for measuring DC and AC voltage, DC and AC current, resistance, and sometimes additional functions like capacitance, diode testing, and continuity checking. Their digital display reduces the risk of misreading compared to analog meters, making them invaluable instruments for both professional electricians and electronics enthusiasts.

To measure current and voltage with a multimeter, follow these steps:

- Set the multimeter to the appropriate voltage setting (AC or DC) for household electronics.
- Connect the sensors to the appropriate ports for voltage and current measurement.
- Touch the black probe to the ground or negative point of the circuit and the red probe to the positive point.
- Read the voltage value on the display.
- For current measurements, set the multimeter to the appropriate current setting (AC or DC) and connect the probes in series with the circuit.
- Break the circuit and insert the multimeter between the two terminals.
- Measure the current value on the display.
- Before using a multimeter, commence with the highest setting to avoid damaging it. Power off the circuit before connecting the multimeter and avoid connecting it directly to a power source.

3.2 Experimental Apparatus Setup Requirement

It sounds like you're conducting an experiment to study the thermal management and efficiency of photovoltaic (PV) modules using various cooling techniques. Here's a concise breakdown of what you're exploring

3.2.1 Solar Panel Without PCM or Fins (Control):

This panel functions as the control in your experiment. It will help you comprehend the baseline performance of the PV module without any thermal management enhancements.

Figure 3-3 Reference Plate

3.2.2 Solar Panel with Fins:

Fins are typically added to enhance thermal dissipation. By attaching fins to the solar panel, you can increase the surface area, allowing for better cooling, which could potentially contribute to better efficiency by reducing the temperature of the PV cells.

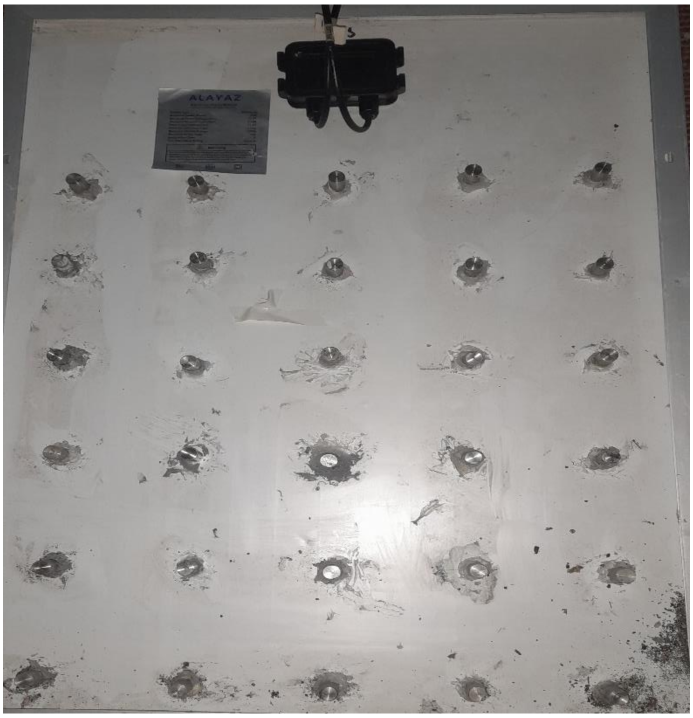


Figure 3-4 PV Module with finns

3.2.3 Solar Panel with PCM and Fins:

PCM (Phase Change Material) is used to absorb excess heat by transforming its phase (from solid to liquid, for example). Combined with fins, this setup should theoretically offer the best thermal management, maintaining lower temperatures and thus increasing the efficiency of the solar panel.

Figure 3-5 PV module with both fins and PCM

Our study will likely entail comparing the temperatures, power output, and efficiency of these three setups under similar environmental conditions. The results should yield insights into how effective these thermal management techniques are in improving the performance of solar panels.

3.2.4 PV module Schematic diagram with both fins & PCM

A PV module is a system consisting of a PV module, fins, phase change material (PCM), supporting structure, thermal insulation layer, and ventilation paths. The PV module is the primary component, converting sunlight into electrical energy. Fins enhance the surface area for heat dissipation, transferring heat away from the cells more effectively. PCM absorbs excess heat generated by the PV cells by altering its phase, storing thermal energy and maintaining a stable temperature. The fins and PCM are typically affixed to a supporting structure, which ensures proper alignment and contact between the PV module, PCM, and fins. A thermal insulation layer may be placed around the PCM to retain heat and facilitate thermal management. The design often incorporates paths or channels to enable air to flow over and between the fins, facilitating convective cooling.

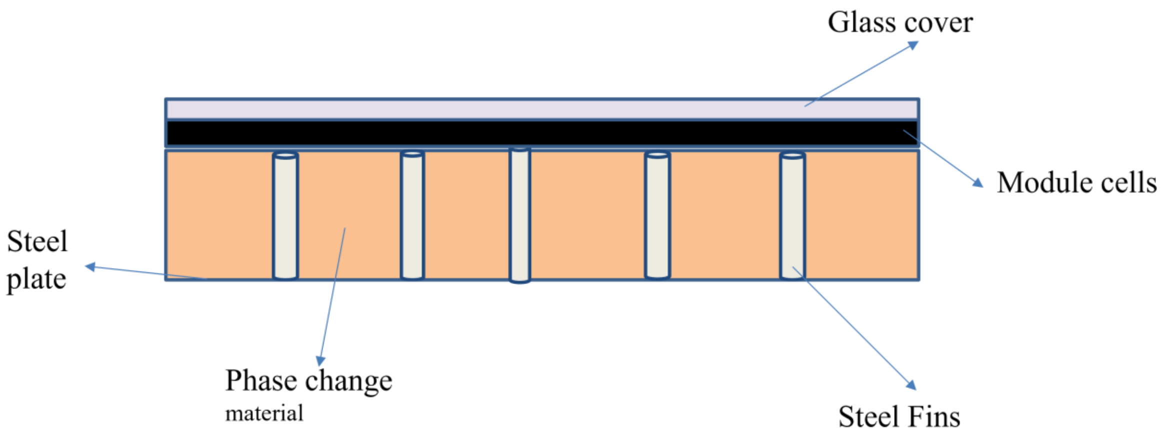


Figure 3-6 PV Module with Fins and PCM

Figure 3-7 Experimental setup front view

Figure 3-8 Back view of experimental setup

3.3 Experimental procedure

3.3.1 Mount the PV Modules

To mount the PV (photovoltaic) module for testing, follow these steps:

Mount the solar panel on a sturdy stand to ensure stability and correct alignment. Make sure the stand is securely fixed to the earth or another stable surface. Adjust the stand so that the solar panel is oriented towards the sun at the optimal angle for maximal sunlight exposure. Double-check all connections and fastenings to prevent any movement or displacement during use.

3.3.2 Install PCM-Based heat sink

The installation of a solar power module requires a steel-finned heat sink, paraffin wax PCM with a suitable melting point, thermal adhesive or conductive paste, sealing material, and hardware. The procedure involves cleaning the rear surface, attaching the heat sink, filling the paraffin wax, sealing the heat sink, inspecting for breaches or air pockets, and testing the module under normal operating conditions. The process involves cleaning the rear surface, applying thermal adhesive or conductive paste, melting the paraffin wax in a controlled environment, sealing the heat sink, and conducting final inspection to ensure the security of the seals.

Chapter 4

Results and Discussion

For our study, "Thermal Management and Efficiency Enhancement of Photovoltaic Module using PCM-based Finned Heat Sink," these are the anticipated outcomes.

4.1 Temperature Regulation with PCM-Based Finned Heat Sink

The use of a Phase Change Material (PCM) and a finned heat sink can increase the efficiency of photovoltaic modules. PCM's consistent heat absorption and release can mitigate temperature fluctuations, while fins increase heat dissipation surface area, enhancing thermal management. This approach is promising for those working on or researching photovoltaic module initiatives.

The photovoltaic (PV) module's electrical performance should be enhanced by the use of a phase change material (PCM)-based finned heat sink. Lower operating temperatures are expected to boost the PV module's power output. It is anticipated that the PV module will have a greater efficiency than a normal module that does not include PCM-based cooling.

4.2 Temperature Behavior

It is anticipated that the finned heat sink with PCM base would efficiently control the PV module's temperature. When solar radiation is at its highest, the heat sink will collect surplus heat and release it when it is at its lowest. It is anticipated that the working temperature of the PV module would be much lower, improving efficiency.

4.3 Durability and Longevity

It is anticipated that the PV module's lifetime and durability would be improved by the usage of PCM-based cooling. Lower temperatures might lead to less thermal stress and eventual breakdown of the module. It is anticipated that the PCM material will hold up over the course of the module's life.

Overall, the anticipated outcomes show that PCM-based finned heat sink integration may improve PV module performance, dependability, and longevity, supporting efficient and sustainable solar energy systems.

Power Output and Efficiency

The lower operating temperatures observed in the PV panels with fins and PCM also translated into enhanced power output. The study discovered that the PV system utilizing both fins and PCM achieved a 2% higher power saving compared to the system with only fins. In the specific case of Mirpur, Pakistan—a region characterized by hot and stable climatic conditions—the efficacy of the combined fins and PCM system was even more pronounced. The PV panel with fins and PCM in this environment attained a 6-7°C higher temperature drop and resulted in 3% more power savings compared to the panel with only fins.

Comparison of Systems

Interestingly, when comparing the PV panel with only fins to the one with both fins and PCM, it was observed that the PV panel with only fins achieved a slightly higher temperature decrease and power savings in certain conditions. Specifically, the fins-only configuration resulted in a 6-7°C temperature drop, which was higher than the temperature drop attained with the combined fins and PCM system under some circumstances. Additionally, the fins-only system achieved up to 3% more power savings compared to the combined system, suggesting that in certain climatic conditions, the addition of PCM may not always be necessary for achieving optimal results.

Overall Performance

Overall, both the fins-only and the combined fins and PCM systems demonstrated the ability to accomplish higher PV temperature drops and increased efficiency, with improvements ranging from 2-3%. However, the combined system's performance is more consistent and notably advantageous in extreme hot climates, where maintaining lower temperatures is crucial for the longevity and efficiency of PV systems.

4.4 Calculation

The calculation entails determining the thermal performance of the photovoltaic (PV) module integrated with a phase change material (PCM) based finned heat sink. This includes analyzing the heat transfer rate, temperature distribution, and efficiency improvement by applying energy balance equations and Efficiency formula. The results from these calculations are used to evaluate the efficacy of the PCM and fins in enhancing the module's cooling and overall efficiency.

4.4.1 Power of PV Module

The power of a photovoltaic (PV) module can be calculated using the formula

$$P = V \times I$$

where V is the voltage, and I is the current. These parameters are typically acquired from the PV module's specifications. The power output is crucial for assessing the performance and efficiency of the PV module with and without thermal management enhancements.

4.4.2 Efficiency of PV Module

The efficacy of a photovoltaic (PV) module can be calculated using the formula

$$\eta = \frac{P}{A \times E}$$

where P is the electrical power output of the module, A is the area of the PV module, and E is the solar irradiance (usually in watts per square meter). This formula expresses how effectively the PV module converts incident solar energy into electrical energy. Higher efficiency indicates greater performance in converting sunlight into usable electricity.

4.4.3 Day One Observation and Calculation

On the first day, the PV module was exposed to sunlight, and the voltage (V), current (I), and temperature (T) were recorded at regular intervals from 12;30pm to 6:30 pm. The voltage and current measurements are essential for determining the power output of the module, which is calculated using the formula

Temperature readings are equally essential, as the performance of a PV module is highly sensitive to temperature variations. Typically, as the temperature of the module increases, its efficacy decreases. To accurately monitor this, temperature sensors were placed on the surface of the module and at various points within the system to capture the thermal behavior throughout the day.

By continuously monitoring these parameters, the data collected can be used to analyze the performance tendencies of the PV module over time. This analysis helps in understanding the impact of temperature on the module's efficiency and aids in optimizing the system for improved performance

4.4.4 Reference Plate Observation and Calculation Day 1

Sr No	Time	Tamb (℃)	T1 (℃)	Solar Irradiance (W/M²)	V (Volt)	I (A)	Power (Watt)	Efficiency (%)
1	12:30 PM 1:00PM	36	60	1200	24.4	2.83	69.052	17.98229167
2	1:00 PM 1:30PM	36	58	1190	23.3	2.85	66.405	17.43828782
3	1:30PM 2:00PM	37	57	1130	23	2.69	61.87	17.11006637
4	2:00PM 2:30PM	38	54	1080	23.1	2.51	57.981	16.77690972
5	2:30PM 3;00PM	36	53	1050	23.2	2.32	53.824	16.01904762
6	3:00PM 3:30PM	32	48	1010	23	2.05	47.15	14.5884901
7	3:30PM 4:00PM	39	52	995	23.1	1.7	39.27	12.33354271
8	4:00PM 4:30PM	38	46	800	22.9	1.3	29.77	11.62890625
9	4:30PM 5:00PM	36	43	720	22.8	0.98	22.344	9.697916667
10	5:00PM 5:30PM	35	35	680	22.5	0.56	12.6	5.790441176
11	5:30PM 6:00PM	33	37	470	21.5	0.26	5.59	3.716755319
12	6:00PM 6:30PM	32	35	330	19.4	0.08	1.552	1.46969697

4-1 Day 1 observation and calculation

4.4.5 Power and Efficiency graph of Reference Plate

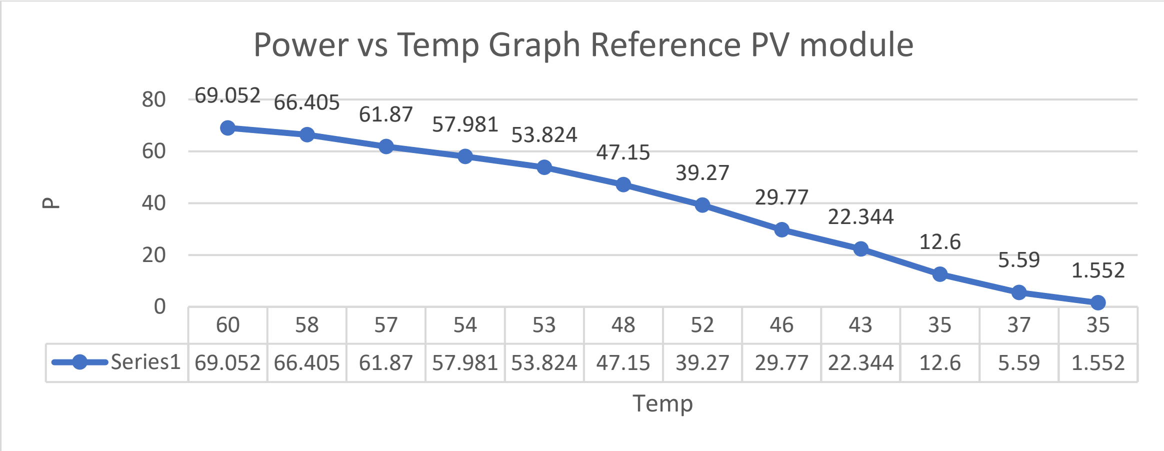


Figure 4-1 Power and Temperature Graph Day 1

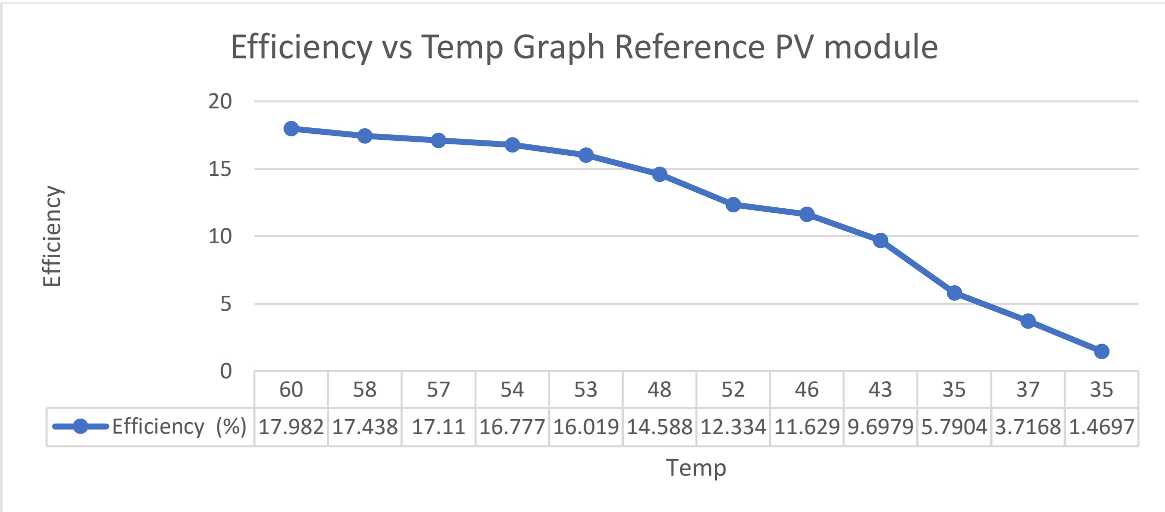


Figure 4-2 Efficiency vs Temperature Graph Day 1

4.5 Fins Based PV Module Observation and Calculation Day 1

Sr No	Time	Tamb (℃)	T2 (℃)	Solar irradiance (W/M^2)	V (Volt)	I (A)	Power (Watt)	Efficiency (%)
1	12:30 PM 1:00PM	36	50	1200	24.4	3.08	75.152	19.57083333
2	1:00 PM 1:30PM	36	52	1190	23.8	3.13	74.494	19.5625
3	1:30PM 2:00PM	37	53	1130	23.5	2.91	68.385	18.91178097
4	2:00PM 2:30PM	38	52	1080	23.5	2.67	62.745	18.15538194
5	2:30PM 3;00PM	36	53	1050	23.6	2.42	57.112	16.99761905
6	3:00PM 3:30PM	32	51	1010	23.5	2.12	49.82	15.41460396
7	3:30PM 4:00PM	39	52	995	23.4	1.75	40.95	12.8611809
8	4:00PM 4:30PM	38	48	800	23.5	1.35	31.725	12.39257813
9	4:30PM 5:00PM	36	41	720	23.3	0.99	23.067	10.01171875
10	5:00PM 5:30PM	35	36	680	23.2	0.58	13.456	6.183823529
11	5:30PM 6:00PM̊	33	38	470	22.4	0.27	6.048	4.021276596
12	6:00PM 6:30PM	32	35	330	21	0.08	1.68	1.590909091

4-2 Data of PV module with fins attached

4.5.1 Power and Efficiency graph of Fins Plate Day 1

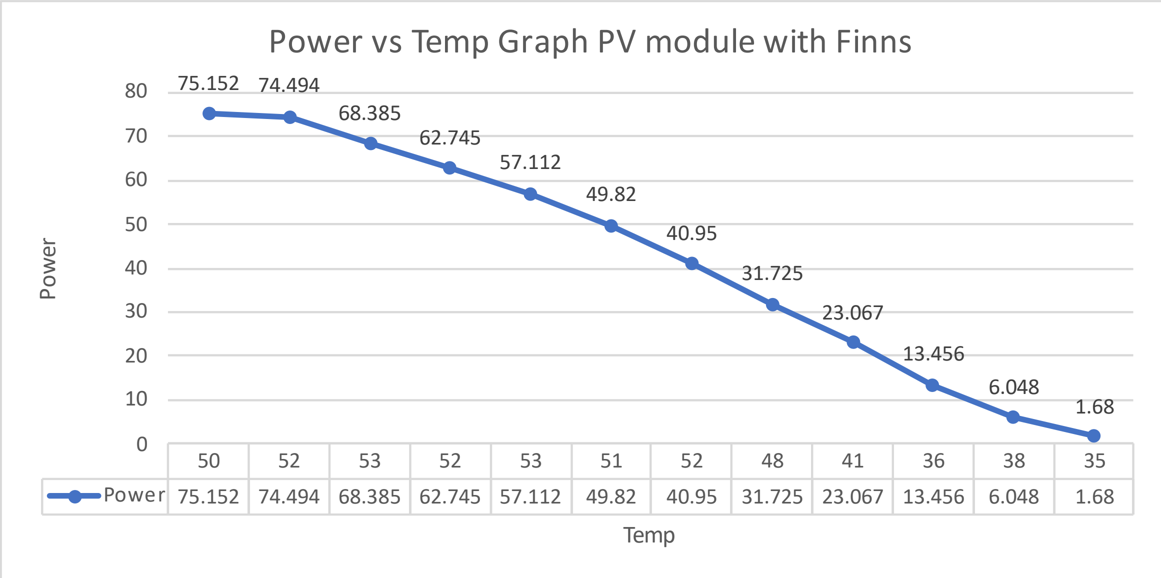


Figure 4-3 Power vs Temperature Graph Day 1

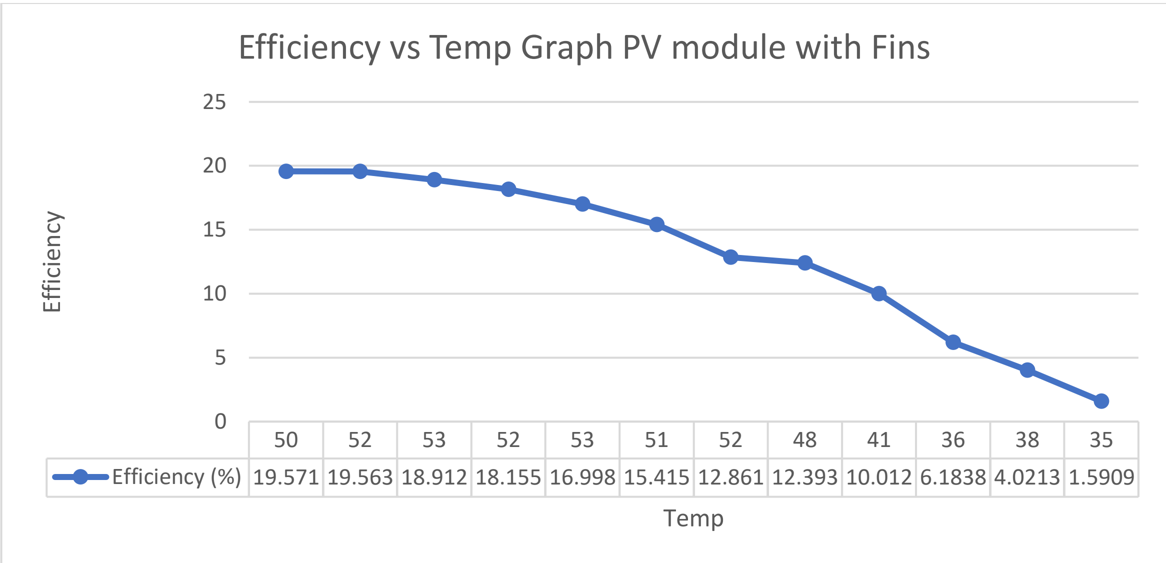


Figure 4-4 Efficiency vs Temperature Graph Day 1

4.6 Fins and PCM Plate Observation and Calculation Day 1

Sr No	Time	T_{amb} (℃)	T3 (inner) (℃)	T4 (out) (℃)	Solar irradiance (W/M^2)	V (Volt)	I (A)	Power (Watt)	Efficiency (%)
1	12:30 PM 1:00PM	36	44	45	1200	22.8	3.1	70.68	18.40625
2	1:00 PM 1:30PM	36	46	38	1190	22.6	3.1	70.06	18.39810924
3	1:30PM 2:00PM	37	43	38	1130	22.3	2.89	64.447	17.8227323
4	2:00PM 2:30PM	38	45	35	1080	22.4	2.63	58.912	17.0462963
5	2:30PM 3:00PM	36	48	38	1050	22.4	2.35	52.64	15.66666667
6	3:00PM 3:30PM	32	44	36	1010	22.3	2.04	45.492	14.07549505
7	3:30PM 4:00PM	39	47	42	995	22.4	1.64	36.736	11.53768844
8	4:00PM 4:30PM	38	45	39	800	22.2	1.24	27.528	10.753125
9	4:30PM 5:00PM	36	44	36	720	22.4	0.89	19.936	8.652777778
10	5:00PM 5:30PM	35	40	34	680	21.8	0.52	11.336	5.209558824
11	5:30PM 6:00PM	33	44	36	470	21.1	0.23	4.853	3.226728723
12	6:00PM 6:30PM	32	43	35	330	19.4	0.07	1.358	1.285984848

4-3 Observation & Calculation of PV module with both PCM and Fins are attached

4.6.1 Power and Efficiency graph of Fins Plate

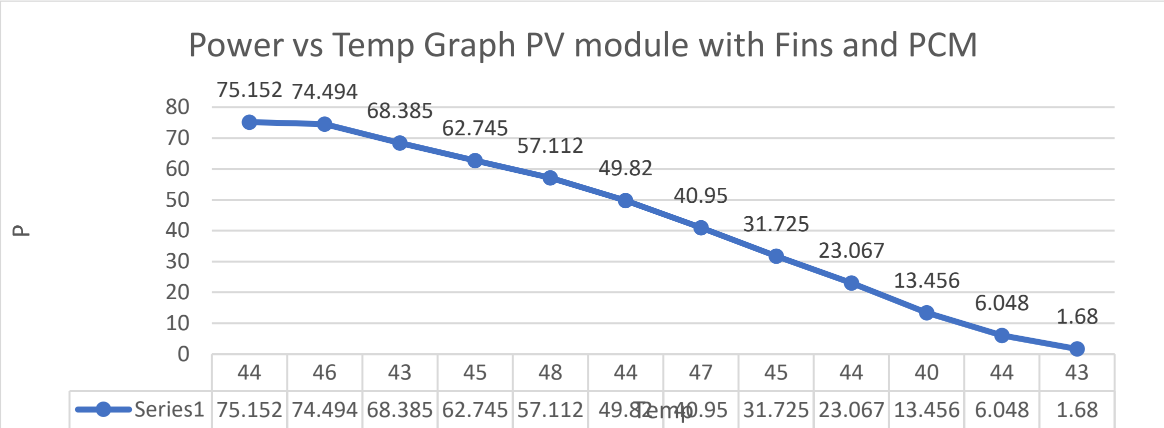


Figure 4-5 Power vs Temperature Graph of PV module with both Fins and PCM are attach

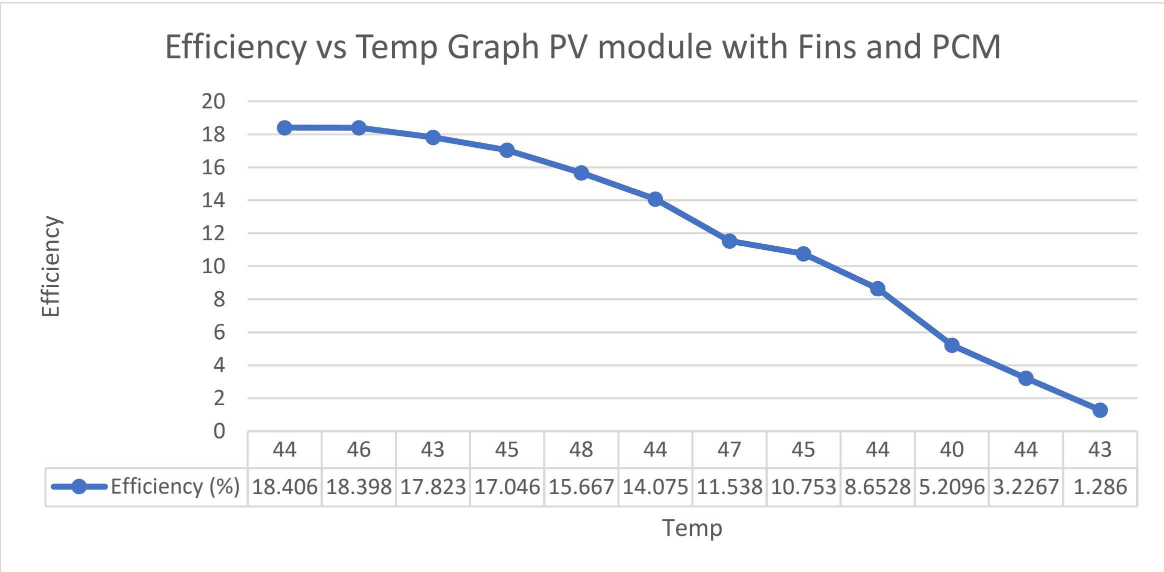
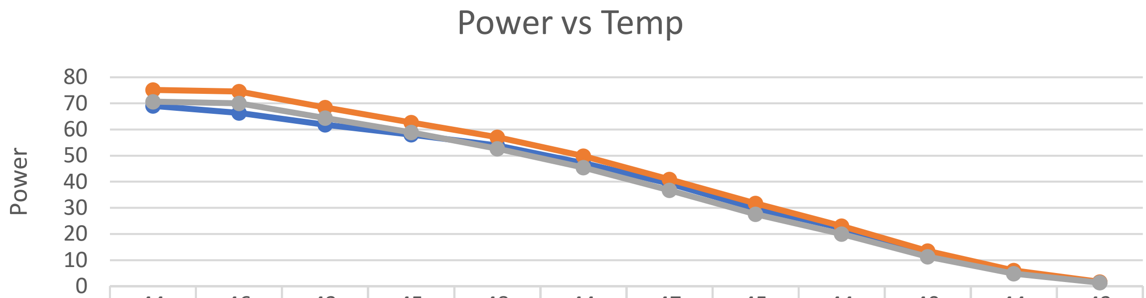


Figure 4-6 Efficiency vs Temperature Graph of PV module Efficiency with both Fins & PCM attach

4.7 Power Comparison of All Plate Day 1



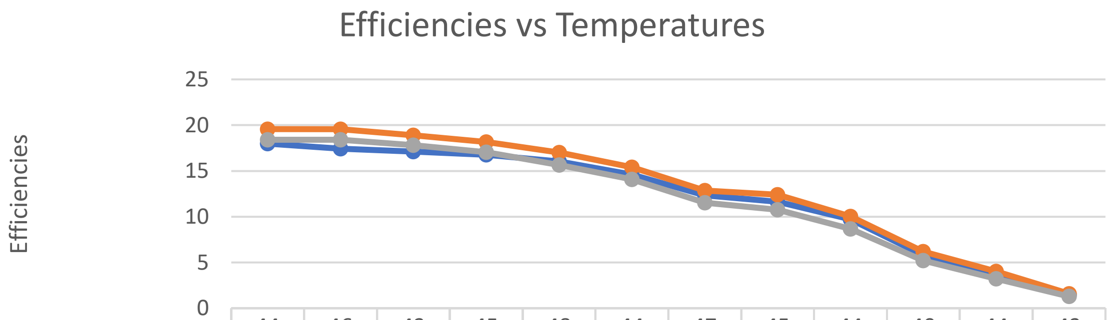
	44 50 60	46 52 58	43 53 57	45 52 54	48 53 53	44 51 48	47 53 52	45 48 46	44 41 43	40 36 35	44 38 37	43 35 35
P1	69.052	66.405	61.87	57.981	53.824	47.15	39.27	29.77	22.344	12.6	5.59	1.552
P2	75.152	74.494	68.385	62.745	57.112	49.82	40.95	31.725	23.067	13.456	6.048	1.68
P3	70.68	70.06	64.447	58.912	52.64	45.492	36.736	27.528	19.936	11.336	4.853	1.358

Temperatures

P1 P2 P3

Figure 4-7 Power comparison of all Plate Day 1

4.8 Efficiencies Comparison of All Plate Day 1



	44 50 60	46 52 58	43 53 57	45 52 54	48 53 53	44 51 48	47 52 52	45 48 46	44 41 43	40 36 35	44 38 37	43 35 35
PV module(1)η	17.982	17.438	17.11	16.777	16.019	14.588	12.334	11.629	9.6979	5.7904	3.7168	1.4697
PV module(2)η	19.571	19.563	18.912	18.155	16.998	15.415	12.861	12.393	10.012	6.1838	4.0213	1.5909
PV module(3)η	18.406	18.398	17.823	17.046	15.667	14.075	11.538	10.753	8.6528	5.2096	3.2267	1.286

Temeratures

PV module(1)η PV module(2)η PV module(3)η

..

Figure 4-8 Efficiencies Comparison of All Plate Day

4.9 Day Two Observation and Calculation

On the second day, the PV module was exposed to sunlight, and the voltage (V), current (I), and temperature (T) were recorded at regular intervals from 11:00AM to 6:00PM. The voltage and current measurements are essential for determining the power output of the module, which is calculated using the formula

Temperature readings are equally essential, as the performance of a PV module is highly sensitive to temperature variations. Typically, as the temperature of the module increases, its efficacy decreases. To accurately monitor this, temperature sensors were placed on the surface of the module and at various points within the system to capture the thermal behavior throughout the day.

By continuously monitoring these parameters, the data collected can be used to analyze the performance tendencies of the PV module over time. This analysis helps in understanding the impact of temperature on the module's efficiency and aids in optimizing the system for improved performance.

4.9.1 Reference Plate Observation and Calculation

Sr. No	Time	T(amb) (℃)	Solar Irradiance (W/M^2)	V (Volt)	I (A)	T1 (℃)	Power (Watt)	Efficiency (%)
1	11:00PM	36	1130	23.2	2.6	49	60.32	16.68141593
2	11:00PM 12:00PM	34	1200	22.8	2.91	40	66.348	17.278125
3	12:00PM 1:00PM	36	1190	22.2	0.95	51	21.09	5.538340336
4	1:00PM 2:00PM	38	1080	21.9	2.42	54	52.998	15.33506944
5	2:00PM 3:00PM	42	1010	23	2.26	51	51.98	16.08292079
6	3:00PM 4:00PM	34	800	22.9	1.52	44	34.808	13.596875
7	4:00PM 5:00PM	33	680	22.6	0.72	40	16.272	7.477941176
8	5:00PM 6:00PM	32	350	22	0.2	37	4.4	3.928571429

4-4 Day 2 Reference Plate Data

4.9.2 Power and Efficiency graph of Reference Plate

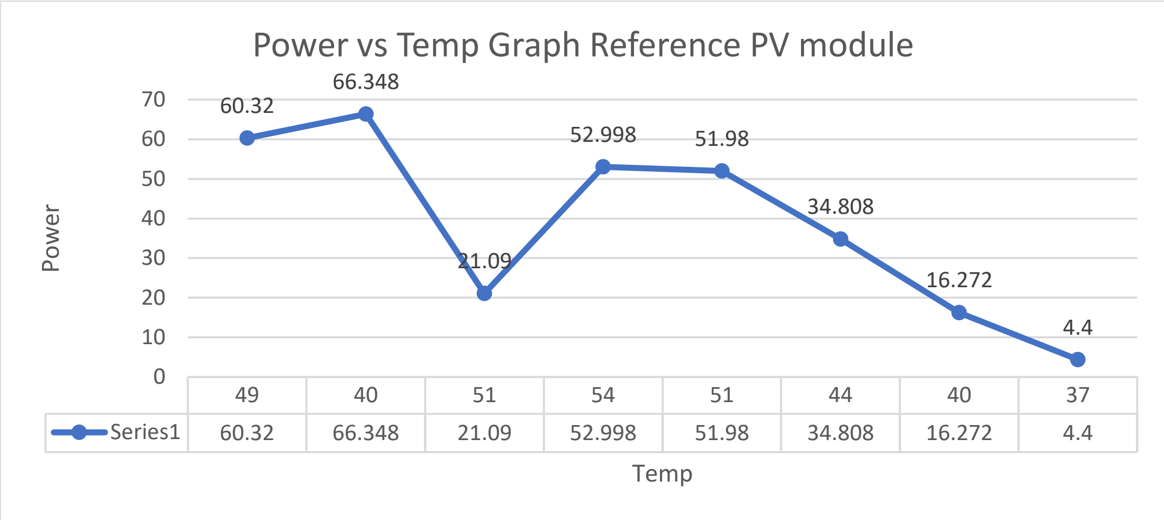


Figure 4-9 Power and Efficiency graph of Reference Plate Day 2

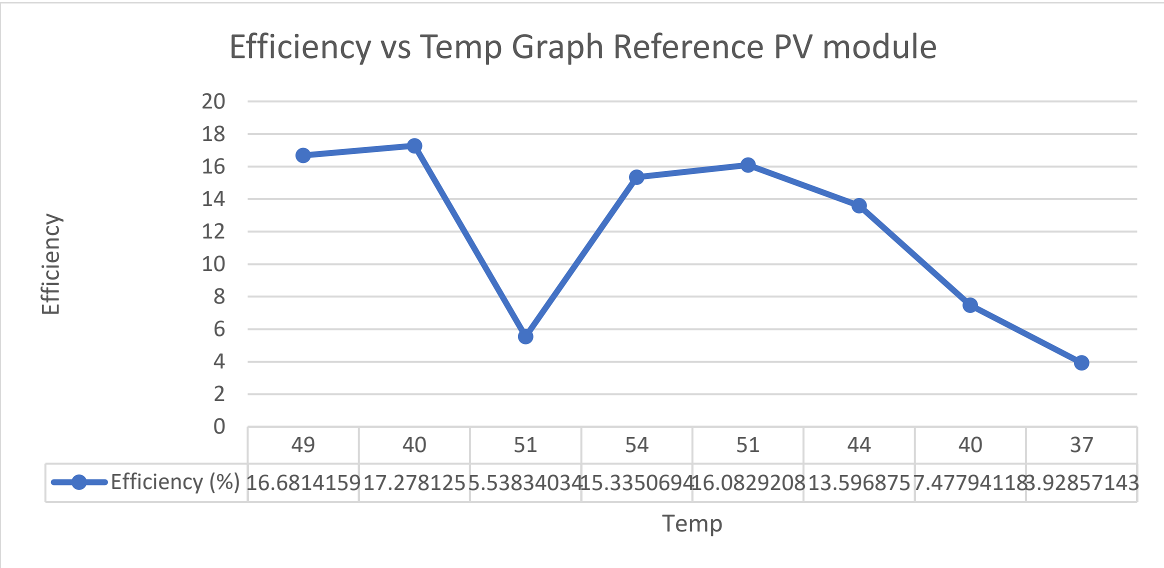


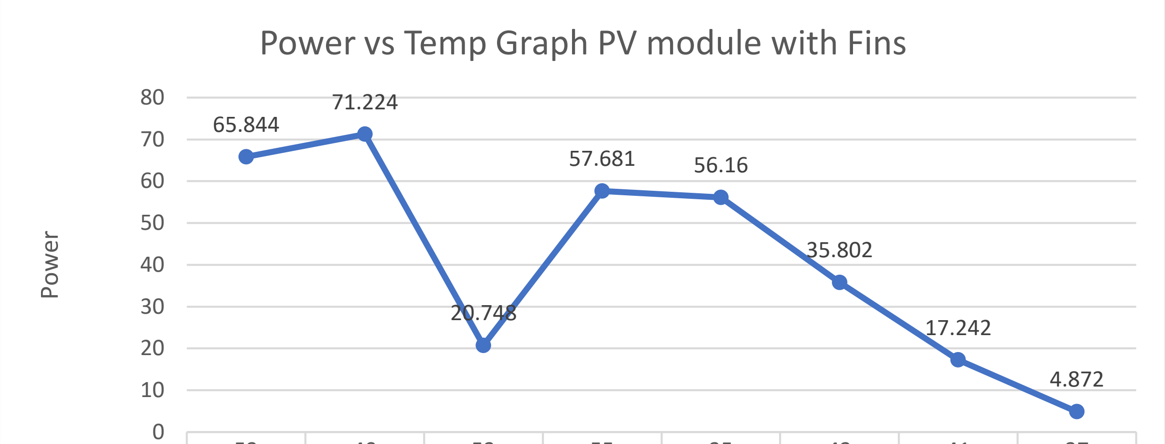
Figure 4-10 Day 2 Temperature and Efficiency Graph of Reference Plate Day

4.9.3 Reference Plate Observation and Calculation Day 2

Sr. No	Time	T(amb) (℃)	T2 (℃)	V (Volt)	I (A)	Solar Irradiance (W/M^2)	Power (Watt)	Efficiency (%)
1	11:00PM	36	52	23.6	2.79	1130	65.844	18.2090708
2	11:00PM 12:00PM	34	40	23.2	3.07	1200	71.224	18.54791667
3	12:00PM 1:00PM	36	53	22.8	0.91	1190	20.748	5.448529412
4	1:00PM 2:00PM	38	55	22.1	2.61	1080	57.681	16.69010417
5	2:00PM 3:00PM	42	35	23.4	2.4	1010	56.16	17.37623762
6	3:00PM 4:00PM	34	42	23.4	1.53	800	35.802	13.98515625
7	4:00PM 5:00PM	33	41	23.3	0.74	680	17.242	7.923713235
8	5:00PM 6:00PM	32	37	23.2	0.21	350	4.872	4.35

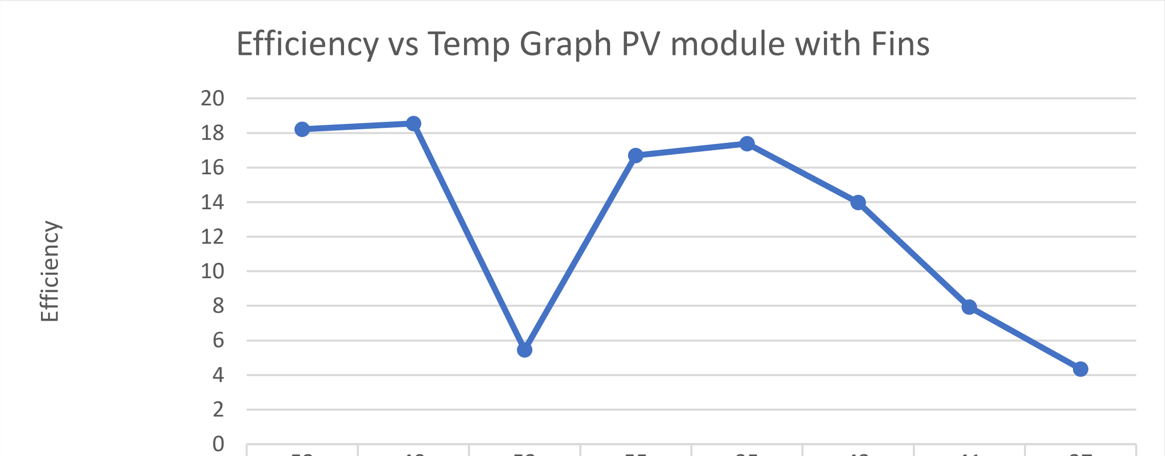
4-5 Data of Reference plate Day 2

4.9.4 Power and Efficiency graph of Fins Plate



	52	40	53	55	35	42	41	37
Series1	65.844	71.224	20.748	57.681	56.16	35.802	17.242	4.872

4-6 Power and Temperature Graph of Reference Plate



	52	40	53	55	35	42	41	37
Efficiency (%)	18.2090708	18.5479167	5.4485294	16.6901042	17.3762376	13.9851563	7.92371324	4.35

Figure 4-11 Efficiency vs Temperature Graph of Plate with only Fins Attach Day 2

4.9.5 Fins and PCM Plate Observation and Calculation

Sr. No	Time	T(amb) (℃)	T3 inn (℃)	T4 (Out) (℃)	V (Volt)	I (A)	Solar Irradiance (W/M^2)	Power (Watt)	Efficiency (%)
1	11:00PM	36	34	39	22.7	2.85	1130	64.695	17.89131637
2	11:00PM 12:00PM	34	32	38	22.3	2.42	1200	53.966	14.05364583
3	12:00PM 1:00PM	36	33	40	21.6	0.89	1190	19.224	5.048319328
4	1:00PM 2:00PM	38	39	45	22.4	2.54	1080	56.896	16.46296296
5	2:00PM 3:00PM	42	38	42	22.6	2.32	1010	52.432	16.22277228
6	3:00PM 4:00PM	34	36	44	22.5	1.45	800	32.625	12.74414063
7	4:00PM 5:00PM	33	36	45	22.2	0.68	680	15.096	6.9375
8	5:00PM 6:00PM	32	35	43	20.8	0.19	350	3.952	3.528571429

4-7 Data of Plate PV module with bot fins & PCM attach Day 2

4.9.6 Power and Efficiency graph of Fins and PCM Plate

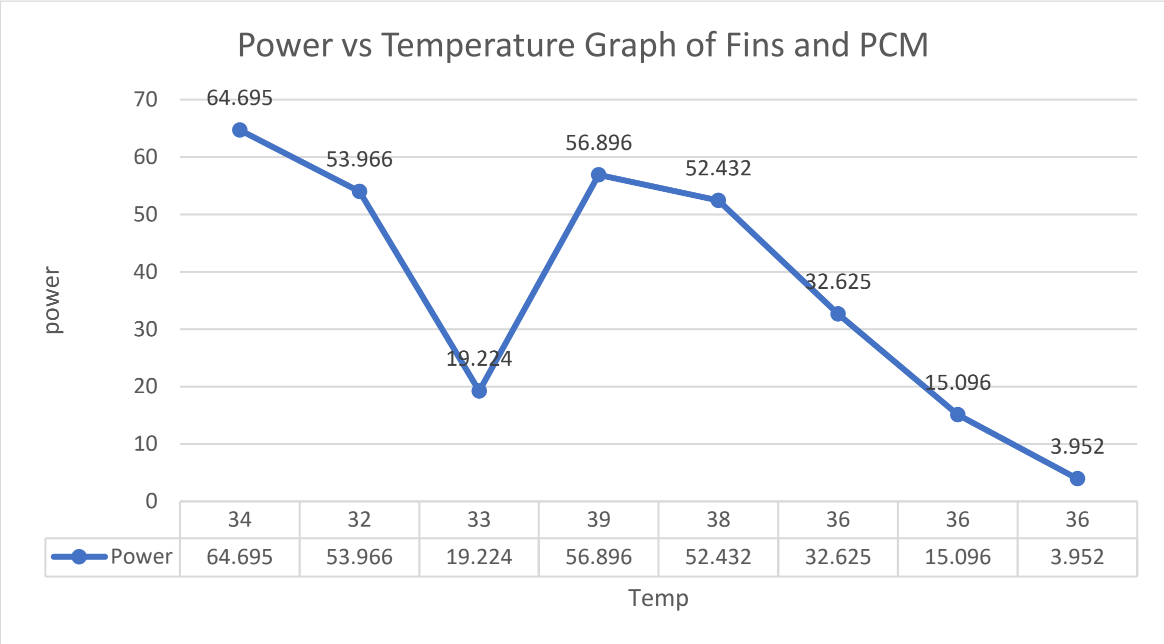


Figure 4-12 Power vs Temperature Graph of Fins and PCM

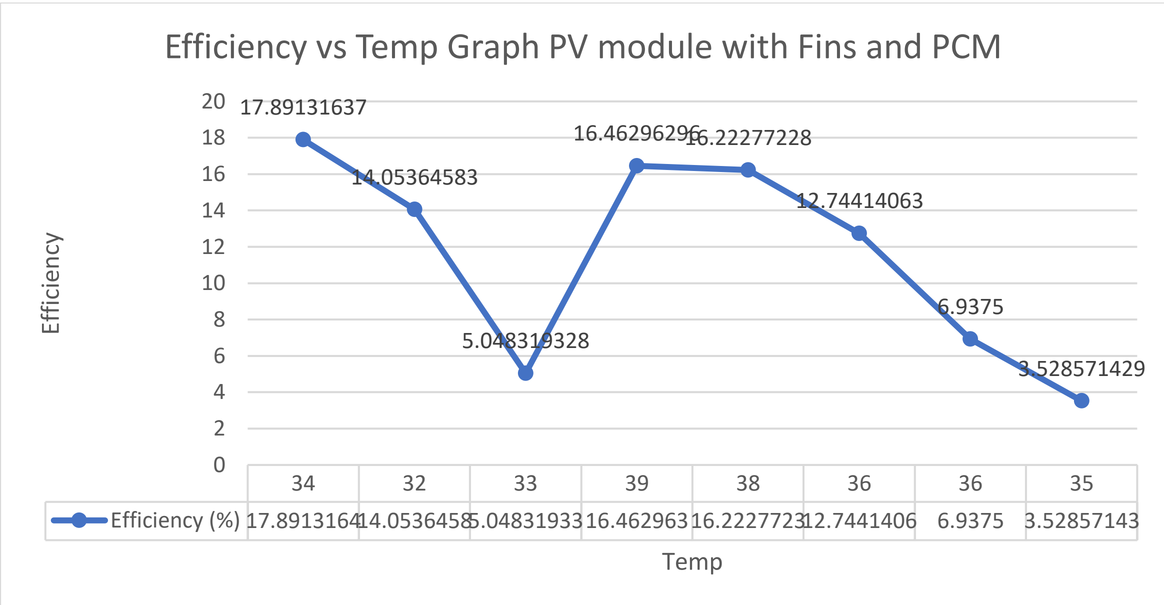


Figure 4-13 Efficiency vs Temperature Graph of PV Module Day 2

4.10 Power Comparisons of all PV Module

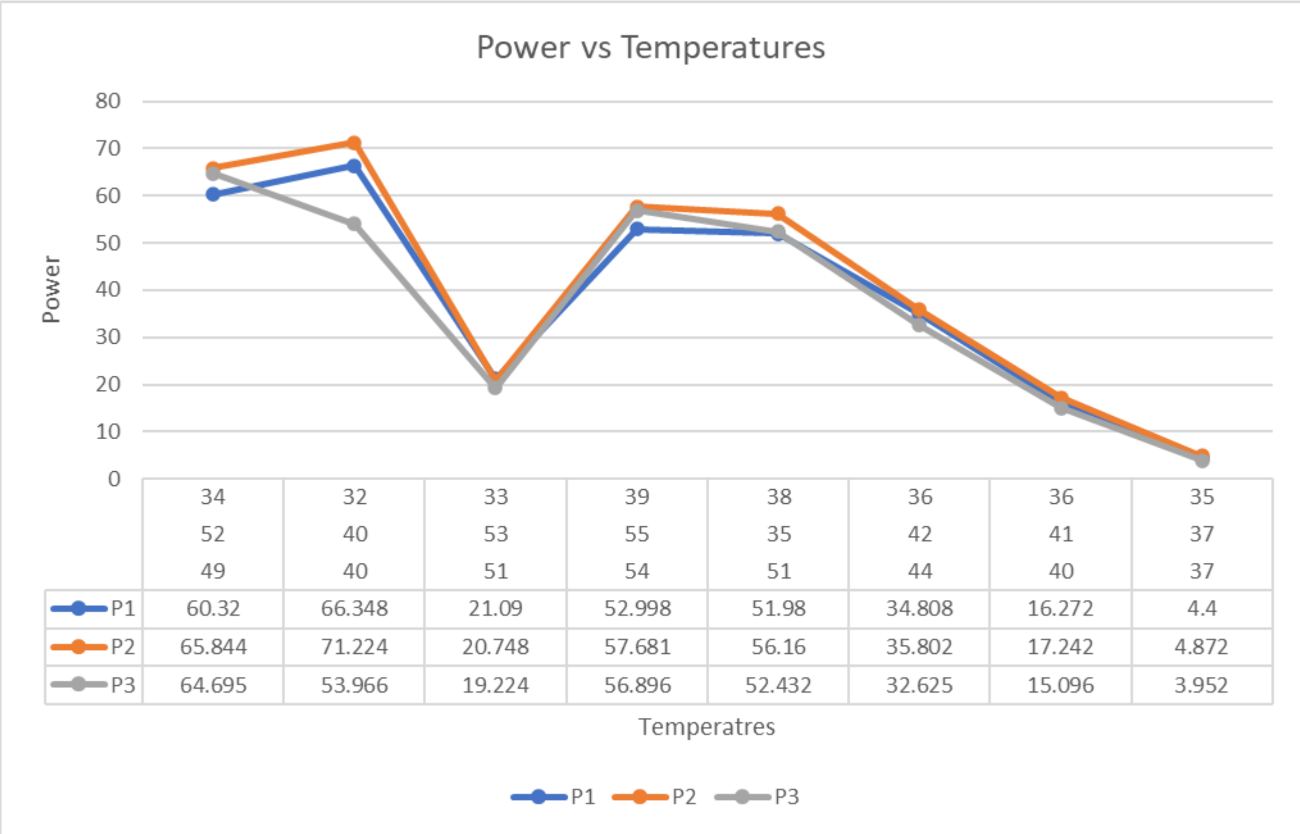


Figure 4-14 Power Comparison of all PV Module Day 2

4.11 Efficiency comparisons all PV module Day 2

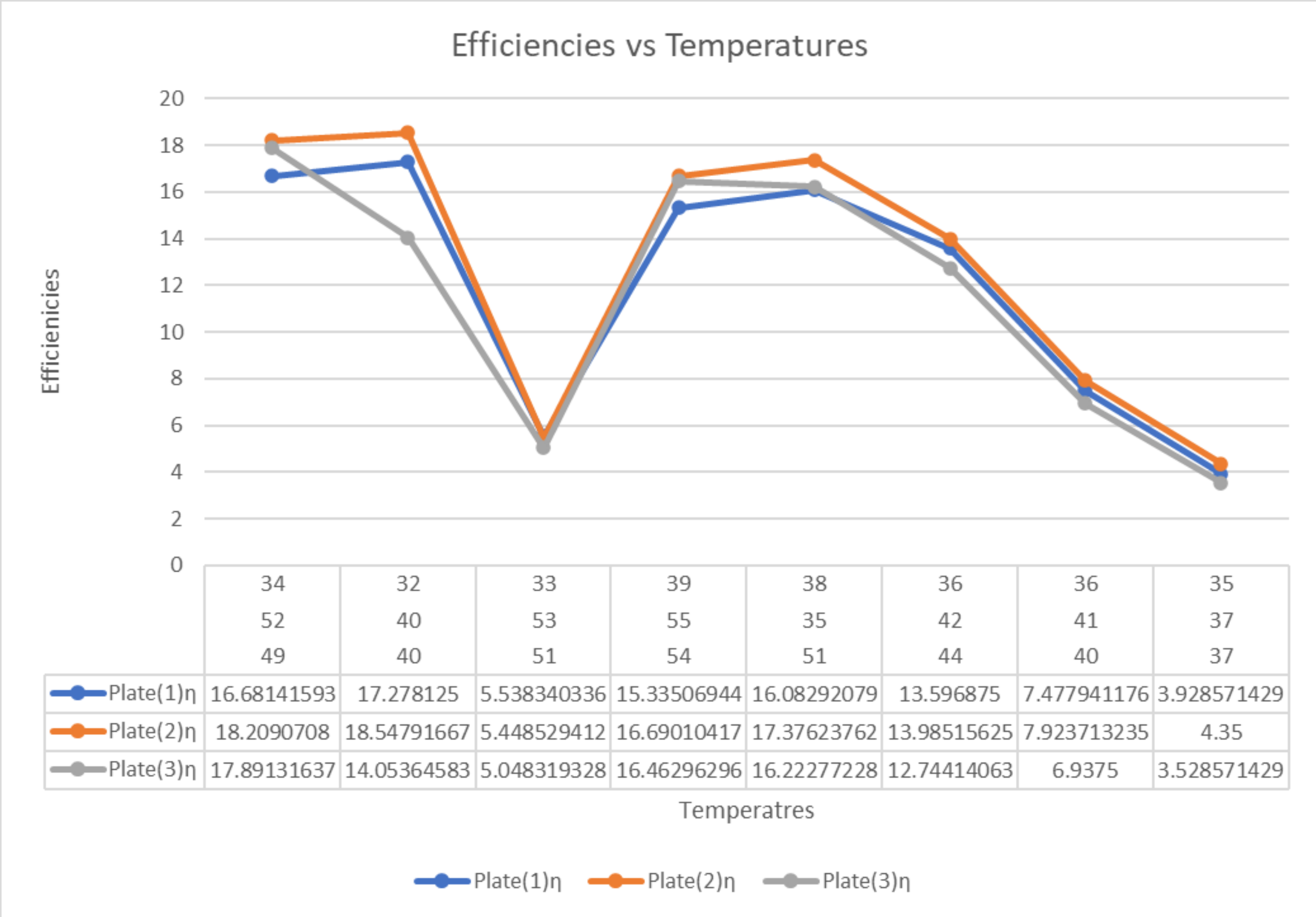


Figure 4-15 Efficiency Comparison All PV Module Day 2

Chapter 5

Conclusion

This paper presents an in-depth experimental evaluation of phase change materials (PCMs) and fins for the thermal management of photovoltaic (PV) devices. The study explored the effects of various configurations, including the use of steel fins with natural ventilation, as well as the combination of fins with PCMs, specifically focusing on the PCM $C_{25}H_{52}$.

The findings of this study underscore the potential of using both fins and PCMs to enhance the thermal regulation of PV panels, thereby enhancing their efficiency and power output. The combination of fins and PCM was found to be notably effective in reducing the temperature rise of PV panels, achieving a 4-5°C higher temperature drop compared to the fins-only configuration. This temperature reduction directly contributed to a 2% increase in power savings.

Moreover, the study highlighted the significant benefits of these systems in humid and stable climatic conditions, such as those found in Mirpur, Pakistan. In such environments, the combined use of fins and PCM led to a 6-7°C higher temperature drop and 3% more power savings, demonstrating the efficacy of this approach in maintaining optimal PV operating temperatures.

However, the study also revealed that in certain conditions, the fins-only system could accomplish slightly higher temperature drops and power savings compared to the combined fins and PCM system. This suggests that the incorporation of PCM may not always be necessary, depending on the specific environmental conditions of the installation site.

In conclusion, the use of fins and PCMs for thermal management in PV systems provides a promising approach to enhancing the efficiency and longevity of solar panels. The combined system is particularly effective in humid climates, where temperature regulation is crucial. However, the design and implementation of such systems should be carefully tailored to the specific climatic conditions of the installation site to obtain optimal results. Future research could explore the use of alternative PCMs with varying thermal properties and investigate the impact of various fin configurations to further optimize the thermal management of PV systems in diverse environmental conditions.

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