Thermal and Electrical Management of Conventional Solar PV module Using Rectangular Aluminum Tubes Filled with Phase Change Material

By

Sheher Yar Khan

Reg # 00000273814

Session 2018-20

Supervised by

Dr. Adeel Waqas

A Thesis Submitted to U.S.-Pakistan Center for Advanced Studies in Energy partial fulfillment of the requirements for the degree of MASTER of SCIENCE in THERMAL ENERGY ENGINEERING

U.S. – Pakistan Center for Advanced Studies in Energy (USPCAS-E)

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Mr. SHEHER YAR KHAN, (Registration No. 00000273814), of Center for Advanced Studies in Energy, has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is within similarities indices limit and accepted as partial fulfillment for the award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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ABSTRACT

Some of the recent challenges encountered in the research and development of the solar photovoltaic industry include a decrease in electrical output efficiency of conventional solar Photovoltaic (PV) module due to the rise in its surface temperature. The main objective of this research work is to enhance and improve the electrical output efficiency of common Silicon-based solar PV module by lowering the operating temperature of the PV module, this was accomplished by attaching hollow rectangular aluminum tubes filled with PCM to the rear surface of the solar PV panel. The proposed geometrical configuration of tubes helped to increase the PV module heat transfer rate to the surrounding air by increasing the effective heat transfer area. In this experimental study, a comparative analysis has been presented for PV modules with PCM and without PCM. Moreover, the results of this experimental study suggest the dependence of the seasonal operating conditions of the PV module upon the selection of PCM for the PV-PCM cooling system. The results getting from experiments demonstrated that the attached tubes reduced the average temperature of the PV module up to 11.24 %. The cooling effect produced due to PCM improved the open-circuit voltage up to 14.1 % and electrical output efficiency up to 5.05 % of the previous efficiency i.e. efficiency without PCM. Furthermore, the results are thoroughly compared with other published studies which revealed that the proposed configuration is cost-effective and structurally sound.

Key Words: Photovoltaic Module, Rectangular Aluminum tubes, PV cooling, PV passive cooling

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NOMENCLATURE

PCM	*Phase Change Material*
PV	*Photo Voltaic*
STC	*Standard Testing Condition*
$\dot{Q}_{conv}$	*Convection Heat Transfer*
H	*Convection Coefficient*
A_s	*Heat Transfer Surface Area*
$T_{no\ fin}$	*Temperature without fins*
T_{fin}	*Temperature with fin*
Ta	*Average Temperature*
T_s	*Surface Temperature*
N	*Number of fins*
P_{max}	*Maximum Power*
Avg	*Average*
I	*Initial*
ε	*Effectiveness of fins*
GHI	*Global Horizontal Irradiance*
β	*Temperature Coefficient*
η	*Efficiency*
V_{oc}	*Open Circuit Voltage*
I_{sc}	*Closed Circuit Current*
Ref	*Reference*

Chapter 1

INTRODUCTION

1.1 Current Energy Scenario of the Glob particularly Pakistan

Recently, 84% of the total energy mix of the world comes from high carbon sources like crude oil, furnace oil, LNG, natural gas, and coal. The remaining 16 % of the global energy mix is composed of low carbon sources which include hydropower, wind energy, geothermal, energy from biomass, and nuclear energy[1]. In Pakistan, the energy mix is composed of 87% thermal, 11% Hydropower, and 1.7% Nuclear energy. In 2013, the overall power supply was 64.5 million tons of oil equivalent (MTOE). The main power sources were Oil (20.96 MTOE), Gas (31.1 MTOE), LPG (0.3 MTOE), Coal (3.8 MTOE), Hydropower (7.1 MTOE), Nuclear electricity (1 MTOE), and the power imported from a different state of shares was (0.08 MTOE) [2][3]. To import fuel Pakistan spends its foreign exchange up to 60% [4]. In Pakistan, the domestic sector consumes 47% of the total consumption, transportation, and industrial sectors consume 31.6% and 29.05%, respectively [2]. Pakistan is facing severe economic challenges that give birth to energy crises in the form of electricity's price and imbalance between energy demand and supply. Energy utilization per capita is one of the tools which indicates the power used by one individual per year. The energy utilization per capita in Pakistan is 235 kW per hour [2]. Recently, Pakistan encounters a serious shortfall of electricity which is about 6-8 hours in urban areas and 8-10 hours in rural areas [2]. In Pakistan, the necessity of the time is to develop alternative sources like wind energy, biomass, and solar energy to decrease the duration of load shading.

1.2 Problem Statement

Solar energy is one of the clean and green energy sources and it is broadly spread and abundantly available everywhere in the country [4]. The knowledge of solar PV modules reveals that an increase in surface temperature has an adverse effect in the form of a reduction in the electrical conversion efficiency of conventional solar PV panels [5]. The radiations coming from the sun are converted into electrical power by a solar cell and some amount of the radiations remains unconverted which increases the surface temperature of the panel [6]. So to counter this effect there are several methods of lowering the surface temperature of the solar PV module by increasing the rate of heat transfer [7] from the PV module. In this research work, the method of passive cooling has been used to reduce the surface temperature of the solar PV module.

1.3 Pakistan's solar power potency

The increasing price of fuel and hazardous emissions of thermal power plants leads to the development of alternative sources like solar power which is one of the cheapest sources of renewable energy and leads to the enormous amount of research and development of photovoltaic cells. In Pakistan, the average potential of solar power is 1600,000MW with sunshine hours of 3000 per year, which could lead to generating 30 million tons of oil equivalent (MTOE) [3][2]. Pakistan ranks 6^{th} in the world of most receiving sun radiations and sunshine hours [8]. In Pakistan, the mean annual solar insolation is about 4.45 to 5.83kWh/m^2 which is much higher than words mean annual solar insolation [3]. [8] indicates In Pakistan, the intensity of solar radiations is promising from February to October i.e. more than 200 W/m^2. It is observed that the intensity of solar radiations varies annually throughout the country i.e. from March to October in Baluchistan, from February to October in Sindh, from April to September in Khyber Pakhtunkhwa and Gilgit Baltistan and from March to October in Punjab. In an area of every 100m^2 of southern Punjab, Baluchistan, and Sindh the solar power potential is about 45MW to 80 MW per month. Figure 1.1 shows that the southern part of the country is ideal for solar power generation with direct solar normal irradiance of 5 kwh/m^2 [8].

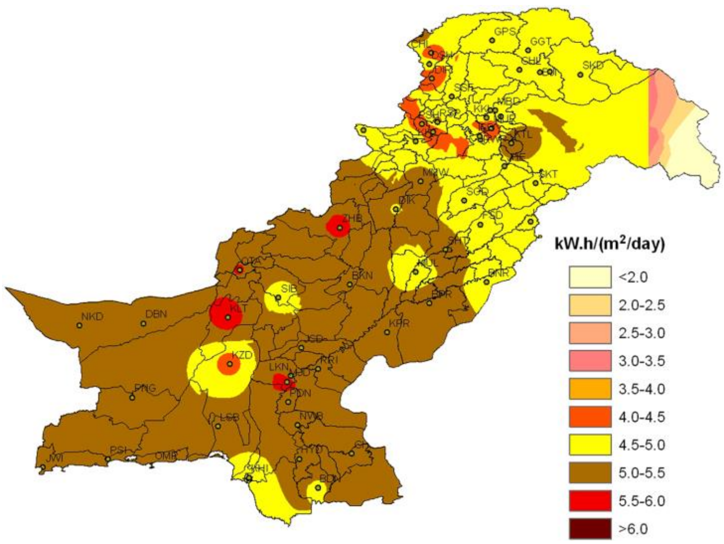

Figure 1-1: Pakistan solar potential map

Now to convert solar energy into a useful power source, there are two types of conversion.

- Photovoltaic conversion
- Solar Thermal conversion

In photovoltaics conversion, electrical current is produced at the molecular level by creating negative and positive pairs of holes in a PV cell [9]. For this to happen, the material of the cell should have the ability to absorb the energy of the photons of the sun radiations. The semiconductor is the best material to absorb photons energy due to its two energy bands, one is the valence electron band and the other is the conduction band. The electrons of the valence energy band are of low energy level and occupied full band while the conduction band contains electrons of high energy level and partially occupied its band. The energy difference between the electrons of the two energy bands is known as the energy bandgap. Photon energy ($E = h\upsilon$, h refers to Plank's constant and υ refers to Photon's frequency) greater than the bandgap energy when hits the cell of the PV and absorbed in the cell. The photons excite the electrons in the cell. As a result, the electrons cross the band gap i.e. from the valence band to the conduction band, and create pairs of positive holes in the valence band. Now the electrons in the conduction band and holes in the valence band are separated using an external circuit which leads to producing potential difference using P-type and N-type semiconductor [9].

1.4 Novelty of the research

Due to the rise in operating PV cell temperature, current conventional PV modules are not able to convert solar energy into the nominal electrical output. Several active, and passive techniques of cooling discussed in the literature to enhance heat transfer from PV modules using different fins geometries always seem beneficial in improving the overall performance and efficiency of the PV module. However, some important factors like increasing cost and structural stability related to the modification of the PV module using finned architecture need to be optimized and justifiable[19,20]. The novelty of the current research work is to enhance the electrical output efficiency without increasing the cost, and overall bulk of the modified PV module. Therefore, the technique used in this study is to lower the surface temperature using hollow rectangular tubes of aluminum filled with phase change material (PCM) assembled at the rear surface of the monocrystalline solar PV module. Rectangular aluminum tubes are selected because of the aluminum's lightweight, high thermal conductivity, resistance to corrosion, low cost, and availability in the market. The overall bulk of the PV module with heat sink is an important parameter that can influence the installation, mobility, and shipment cost of the PV module [21,22]. The rectangular channel between fins also provides an airflow channel which can ultimately increase the cooling effect[23].

1.5 Research Questions

- How to design a heat sink which extracts residual heat from the PV module?
- How it will affect the overall bulk and structure of the PV module?
- Is it feasible economically?

1.6 Objectives

The overall main objective of this research work is to reduce the temperature of the conventional PV module by using the PCM integrated at the backside of the PV panel. Specifically, the following objectives will be focused on:

- To enhance the electrical output of the conventional PV modules by lowering down its operating temperature.
- To find an appropriate and effective way to encapsulate the PCM that can assist in enhancing the heat transfer from the PV module
- Economic analysis of the PV cooling system

1.7 Scope of this study

The Scope of this study is to enhance the electrical efficiency of a conventional solar PV module on a domestic and commercial level.

1.8 Limitations of this study

This current work covers various issues regarding the PV-PCM colling system but there are always some limitations related to any research work. These limitations are:

- The experiments are performed on a domestic level
- How the PV-PCM model will perform in different localities
- The life cycle of PCM and its lower thermal conductivity

1.9 Organization of the thesis

- Chapter: Introduction

  Current energy scenario of Pakistan, Problem identification, Solar energy potential in Pakistan, Advantages of solar PV power generation, Justification of research, and Objectives.
- Chapter 2: A literature review

  Types of PV cell, Types of the cooling model, PV cooling techniques, Cooling materials, Water cooling techniques, Selection criteria, Weather data, Solar radiations data, Solar angles impact, Airmass
- Chapter 3: Methodology

  The approach of study, Block diagram of research methodology
- Chapter 4, Design, Modeling and fabrication Prototype and Experimental setup
- Chapter 5, Results, and discussion

  Formulation of major parameters, Graphical results with and without PCM

- Chapter 6, Conclusion, and Future work

Summary

This chapter briefly addressed the energy crises and the potential of solar energy in South Asia and particularly in Pakistan. Numerous energy sources with their associated problems in Pakistan are discussed but due to the country's solar power potency, solar energy has been focused. The best way to utilize solar energy is photovoltaic which converts solar energy into electrical power. The purpose of this research work is to enhance the electrical output efficiency of the PV module by lowering its surface temperature.

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Chapter 2

LITERATURE REVIEW

2.1 Types of Photovoltaic (PV) modules

The main function of the PV module is to convert solar thermal energy into electrical power. There are different types of PV modules mainly classified based on the module's material. The basic elements which are used in the manufacturing of PV module cells are silicon and germanium because of their semiconductor characteristics[10]. The PV module is composed of these cells and the installation of several PV modules forms a photovoltaic array. The PV modules are divided into three well-known types based on their methods of manufacturing and application [10].

- Monocrystalline silicon PV module
- Polycrystalline silicon PV module
- Thin-film PV module

2.1.1 Monocrystalline silicon PV module

A monocrystalline PV module is also known as a 'single-crystalline module'. The color of a monocrystalline PV module is black. The silicon used in the manufacturing of monocrystalline PV modules is about 90 % pure. The pure form of silicon means that the arrangement of silicon molecules is perfectly aligned. The efficiency to convert solar energy to electrical power is more when the material is pure. The most efficient monocrystalline PV modules in the current market have an efficiency of 22.8 % [11].

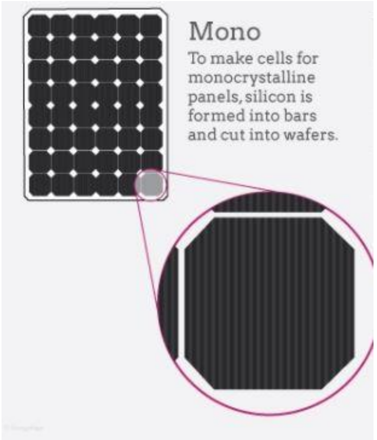


Figure 2-1 Monocrystalline PV module [12]

2.1.2 Polycrystalline silicon PV module

The polycrystalline module is composed of silicon flakes or fragments that is why it is called polycrystalline or multi-crystalline PV module. Polycrystalline is blue due to the silicon fragments' blue spectral. Due to the constrained motion of the free electron, the polycrystalline PV module is generally less efficient than the monocrystalline module therefore the electrical power output is lower than the monocrystalline PV module of the same specification [13].

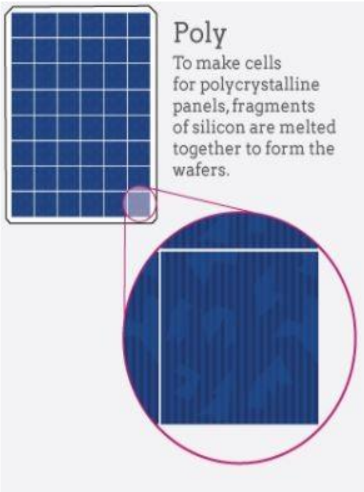


Figure 2-2: Polycrystalline PV module [12]

2.1.3 Thin-film PV module

Space photovoltaics prioritize thin-filmed PV modules among the PV modules because of their lightweight [14]. The photovoltaics of space refers to provide electrical power to a satellite in space by converting solar energy[15]. Thin-film PV modules are composed of layers of different semiconductor materials placed on one another forming a thin film [16]. The maximum efficiency of a thin-film PV module is 22.6 % which is a world record[17]. Moreover, a thin-film module is vastly used in many applications because it is flexible, light in weight, easy to install [17]. A thin-film PV module is not common for residential purposes because it requires a lot of space for its installation.

2.2 Significance of cooling in the PV system

Solar PV module converts a small part of the solar irradiance into the electrical output while most of the fraction of incident solar irradiations contributes to the heating of the solar PV module [18]. The rise of PV module temperature reduces the open-circuit voltage significantly while increases the short circuit current of no importance [18]. In [5] it was noticed that a 1.0 ℃ increase in the PV module temperature, over the nominal module operating temperature of 25 ℃, decreases the electrical output efficiency by 0.08–0.1 %. Therefore, cooling of the PV module is essential to improve its electrical output efficiency. Moreover, the heating causes thermal stress over the surface of the PV module which shortens the life span of the PV module [19].

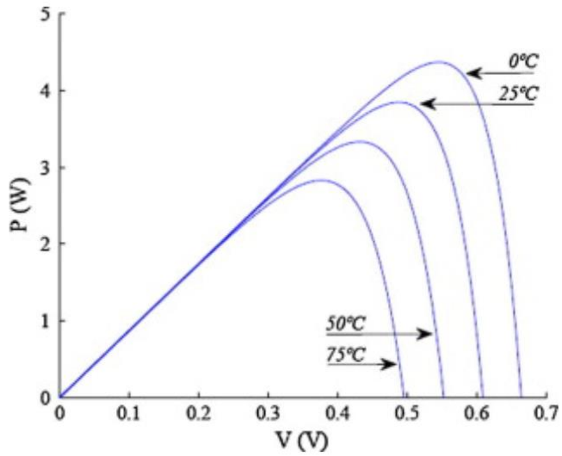


Figure 2-3: Significance of cooling

2.3 Types of the cooling method in PV technology

There are several PV cooling techniques used to keep the surface temperature of the PV modules close to the designed operating conditions. The cooling technique may be:

- Active cooling technique
- Passive cooling technique

2.3.1 Active cooling technique

Active cooling systems are the most common cooling method in which heat transfer fluid i.e. liquid or air is circulated through the PV surface to extract the excess heat generated by the PV modules. Heat transfer fluid is circulated using pumps or blowers depending on the nature of the heat transfer fluid [7]. The circulation of the heat transfer fluid needs energy for its circulation. This energy, in most of the scenarios, is provided from the cooled PV modules generally called parasitic energy [20]. Active cooling is further subdivided into:

- Air-based cooling
- Spraying coolant technique
- Backside water pipe cooling technique

2.3.1.1 Air-based cooling

Air-based cooling is one of the most basic types of active cooling. In air-based cooling, there is forced convection of heat transfer. A blower or fan is used to force the air over the surface of the PV module. The air that passes over the surface of the PV module gets heated by collecting residual heat from the PV module surface which can be used for other heating purposes[21]. Figure 2.3 shows the air-based cooling system.

Figure 2-4: Advanced air-based cooling technique [21]

2.3.1.2 Coolant spray technique

This cooling technique includes the spray of water or other coolants over the PV module and creates a cooling effect due to the evaporation of spraying coolant during the peak hours of the day. Experiments in [22] reveal that the electrical power output of the PV module boosted to 7% with a 5.9 % rise in electrical output efficiency. This technique also helps in the self-cleaning of the PV module which additionally contributes to the rise in power output of the PV module. The downside of this method is the requirement of a coolant or water recovery setup which rise the capital and operational cost of the PV system.

(a) (b)

Figure 2-5: Water spray cooling method [22]

2.3.1.3 Backside water cooling technique

It is a continuous process in which a piping system is attached to the rear surface of the PV module, water is pumped into the system, and carry the residual heat from the PV module. The piping system can be of different arrangements depending on the size and shape of the PV module. Water enters through the inlet of the pipe flowing of the piping system and carry residual heat from the back surface of the PV module and then discharges from the outlet. inside the piping system and removes heat from the panel. Using the backside water cooling technique [23] increases the efficiency of the PV module up to 9% with a 20 % drop in temperature.

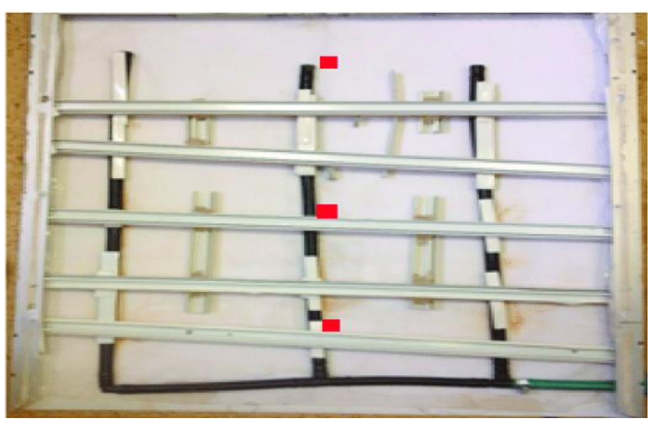


Figure 2-6: Backside water cooling system[24]

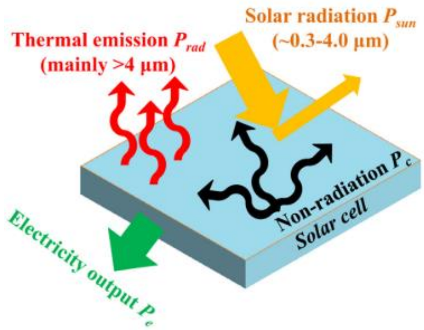
2.3.2 Passive cooling method

Contrary to active cooling, passive cooling techniques do not need parasitic energy because passive cooling solely depends on natural convection. Therefore, the use of pumps or blowers can be eliminated by using passive techniques for the cooling of the PV modules. Also, the maintenance cost of a passively cooled PV module is either zero or very low compared to the active cooling systems [7]. The passive cooling technique is further subdivided into:

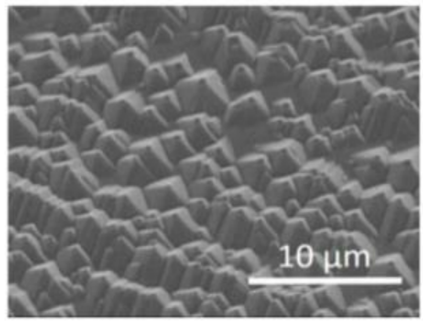
- Radiative cooling
- Fins attached to the backside of the PV module
- Using Phase Change Material (PCM)

2.3.2.1 Radiative cooling

There is a new passive technique in which the sky is used as a heat sink leading the temperature of a surface lower than its surrounding's temperature named night sky cooling or radiative cooling [25]. The work was conducted by a researcher [26] on the frontal glass of a crystalline silicon cell and replaced it with a glass coated with polydimethylsiloxane (PDMS) film. The fabricated model was compared with the same cell having conventional frontal glass via simulation. The results revealed that in an ideal case the overall temperature of the solar cell is decreased by just 1.75 ℃. In the actual case, there is no improvement in cooling. Another theoretical study [27] was performed on the same model with some modifications in the microstructure of the polydimethylsiloxane (PDMS) layer. The PMDS was coated in the form of pyramid structure ranges 8-13 µm which increase the emissivity near to unity. The calculated result revealed that the new microstructure can reduce the temperature of the solar cell up to 10℃ . Compare to the conventional techniques of cooling there are some shortcomings in radiative colling like there is a lot of potential of dew formation in night and early morning on the surface of PV module in radiative cooling which is the main cause soiling of PV module [28]. The metamaterials used in radiative cooling are generally very unstable kinetically and required a lot of care during their application [28]. Theoretically, there is a lot of potentials to enhance the electrical output efficiency but on a practical basis, the effect is negligible.



(a)



(b)

Figure 2-7: Radiative cooling process and radiative surface [25]

2.3.2.2 Fins attached to the backside of the PV module

The most common way to increase heat transfer from any surface is by attaching extended surfaces known as fins to it. There are several passive PV cooling techniques using fins have been reported in the literature. A comparative study was performed between parallel and random configurations of (L profile) fins coupled to the rear side of the PV panel to enhance the performance of PV. It was seen that the random configuration was more efficient decreases 4.6% of the cell temperature with a 2 % rise in electrical conversion efficiency [29]. Another study was conducted using repurposed material integrated with fins which resulted in a 22.7 % reduction in the temperature of the solar PV module with an 11.6 % rise in power output [30]. An analytical model was formulated in which pin fins made of aluminum with 2 cm, 4 cm, and 6 cm diameter were joined to the rear surface of the PV panel, the modified configuration increased the output power of the PV module by 1.24 % to 4.16 % [31]. In another study rectangular variable cross-section fins (ribs) were used as a heat sink for the PV panel which resulted in a 5.7 ℃ drop in average solar PV module temperature and a 15.3 % rise in power output [32]. An iterative mathematical approach of a fin-cooled PV model was performed explicitly to assess the boost in the efficiency of the PV cell under different operating conditions. A 2.6 % rise in efficiency was noted with a 3 ℃ drop in temperature of the PV [33]. In another experimental study, aluminum copper fins were used as a heat sink and it was observed that the efficiency of the PV module increased from 12.03 % to 12.29 % for aluminum fins and 12.52 % in the case of copper fins [34].

An indoor experimental study was conducted in which a solar simulator was used to study the performance of solar PV before and after the attachment of meshes as fins made of iron and aluminum that reduced the operating temperature PV cells by 6.56 ℃ and 4.53 ℃, respectively [35]. Another indoor experimental work was performed with economic justifiability in which aluminum sheets as a fin were used to increase the heat transfer area of the rear surface of the PV module. The study concluded a 7.4℃ reduction in the working temperature of the PV module that resulted in a 2.72 % rise in efficiency [36]. A CFD simulation study was conducted for a fin assembled to the rear surface of the PV module. The simulation results showed an 8.62 ℃ reduction in the PV module's working temperature after the attachment of fins that enhanced the efficiency from 13.24 % to 15.13 % [37].

Figure 2-8: Different Fins arrangements [30][34][38]

2.3.2.3 Using phase change material (PCM)

Heat sink can be of heat storage entity like phase change material (PCM) attached to the backside of the PV panel which can absorb residual heat during sunshine hours of the day. The lower melting point of phase change material enables the system to absorb sensible as well as latent heat of the cooling surface. The first indoor experiment was performed on PV-PCM in which a PCM slab having a melting point of 32 ℃ and thickness of 20mm was attached to the backside of the PV panel as a heat sink and concluded 10 ℃ drops in PV panel surface temperature [39]. Another study was conducted in which circular copper tubes filled with phase change material RT24 attached to the backside of the PV panel, the tubes produce fin effect and store residual heat and discharge it to the ambient which results in a 3% rise in electrical conversion efficiency[40]. In another study in which PCM having a melting point of 29 ℃ was used for hot and cold climates and concluded that passive cooling of a solar PV panel using PCM is more effective in a hot climate as compared in cold climate[41]. A comparative study was performed between two PV panels with and without fins under natural convection and concluded a 4.2% reduction in the temperature PV panel surface [42]. Using phase change material for cooling system two important factors should be under consideration

- Selection of phase change material (PCM)
- Integration of phase change material with the PV module

Selection of PCM for the cooling system is a primary prerequisite, engineers need to understand the merits of the operating conditions. Firstly, the melting point of the PCM should be in the range of the operating temperature. A study suggests that maximum advantage can be achieved if the temperature difference between the melting point of the PCM and the average temperature of the hottest day is 10 ℃ [5]. Secondly, high latent heat of fusion and large specific heat capacity of PCM is required. Thirdly, the PCM should have a uniform and high thermal conductivity to conduct and discharge more heat. Lastly, the density of material should be on the lower side considering the reduction in volume. Moreover, the PCM should be inflammable, chemically stable, and cost-effective [43].

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Chapter 3

RESEARCH METHODOLOGY

This chapter refers to the overall procedure and methodology to conduct the experimental study. This research work is divided into three sections; theoretical study of the PV-PCM cooling system of the proposed design, design & fabrication of heat exchanger, experimental study of the respective system. The theoretical study involves the literature review based on already published studies regarding cooling of conventional PV modules particularly PCM based passive cooling. The prototype construction mainly the geometry, size, and shape of the heat sink attached to the PV module has been analyzed using CAD. The experimental study is purely based on real-time data for two weeks using all devices and equipment required for the collection of thermal parameters like ambient temperature, Global Horizontal Irradiance, and wind speed. The selection of PCM incorporated into the heat is purely based on the availability of the PCM in the market, cost, and the operating conditions of the PV module. The results and trends are collected in the form of a datasheet and then converted to the graphical form for comparison and discussion. Finally, a conclusion has been made by achieving the required objectives as discussed in the earlier section.

3.1 Methodology of the study

To achieve the objectives of this research work, the methodology in the form of a process chart in figure 3.1 is adopted.

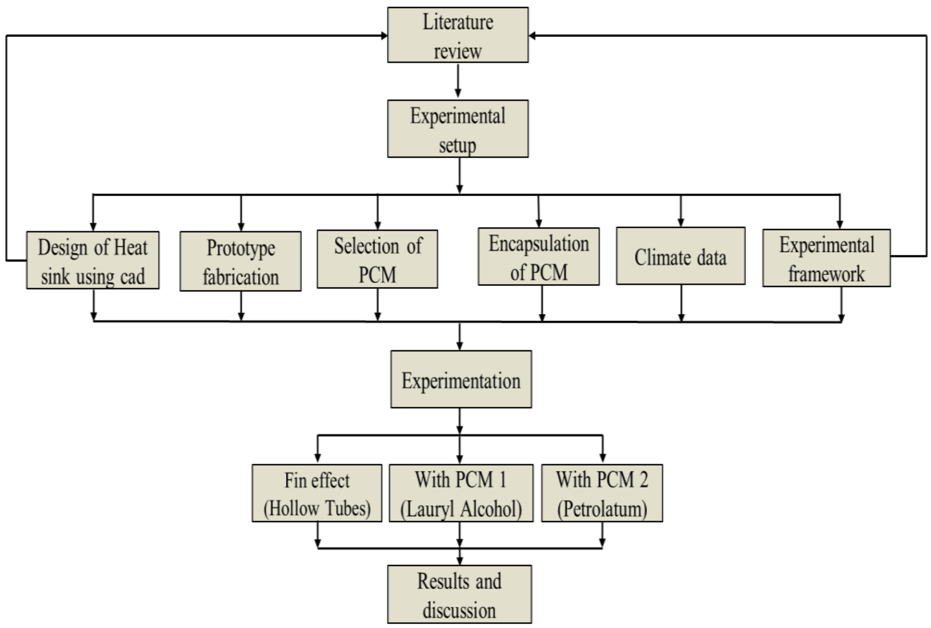

Figure 3-1: Overall Research methodology

3.1.1 Literature review

The literature review was conducted to understand various techniques of cooling mainly active and passive cooling. Each technique was separately studied with their types like active cooling of PV module using blowers, fans, and pumps and passive cooling like attachment of heat sink using fins or PCM. Moreover, a novel method of passive cooling known as radiative cooling is also discussed in the literature. In the next section of the literature review, the passive cooling using phase change material with relative numerical equations are discussed in is briefly explained and selected this method for the current research work.

3.1.2 Prototype fabrication

A prototype was fabricated by modification of a monocrystalline PV module using rectangular hollow tubes. The prototype fabrication was performed in three steps:

- Design of heat sink in CAD model
- Modification of the PV module according to the proposed model in cad

- Selection and encapsulation of PCM

The model of the heat sink was designed in the solid works 2016 version a. The square rectangular geometry and dimensions of the tubes were proposed to fit the assembly onto the rear surface of the PV module. Three samples were proposed for the design of a heat sink having a common base surface with different spacing between the tubes. One of the three samples was selected based on the literature review as shown in figure 3.1. The prototype based on the proposed sample was constructed in a machine shop of USPCASE NUST discussed in the next chapter. After the modification of the PV module lauryl alcohol was selected as PCM due to its availability in the market. The PCM was encapsulated in the rectangular tubes in molten form by using a thermal heat gun detailed discussed in the next chapter. Later on, the Lauryl alcohol does not meet the objective of this research work therefore it is replaced by another PCM named Petrolatum or soft paraffin.

3.1.3 Experimental setup and climate data

The experimental setup was constructed on top of the roof of the US-Pakistan center of advanced studies in energy (USPCASE), NUST, Islamabad (33.642364°N, 72.984290°E) for three weeks. The climate data including ambient temperature, wind speed, and global horizontal irradiance of the experimental site is obtained from the meteorological station installed at the experimental site.

3.1.4 Experimentation

A series of the experiment were performed with different arrangements. Firstly, an experiment was conducted in November 2019 in which the PV module having hollow rectangular tubes without PCM on its rear surface was compared with an unmodified PV module. In the second phase, the rectangular tubes are filled with PCM i.e. Lauryl Alcohol, and compared with the unmodified PV module. At last, lauryl alcohol was replaced by soft paraffin known as Petrolatum and concluded results. The PCMs used in this research work is purely based on working conditions and availability in the markets and laboratories. The results of these experiments are discussed in the next chapter.

Summary

In this chapter, the methodology that defines how to carry out the work is properly discussed. The selection of cooling material and frame metal is depending on the local availability of material and its thermo-physical properties. Design and fabrication of setup take place according to the detailed study of the literature review and the experimentation was conducted at the rooftop of USPCAS-E NUST.

Chapter 4

EXPERIMENTAL SETUP

4.1 Modification of the Conventional PV module

Monocrystalline solar PV modules of 10-watt capacity are used for the current experimental study. The electrical properties and dimensions of the PV modules are displayed in tabulated form in Table 4.1. To study the thermal behavior of the PV modules comparison has been made between:

- PV module with rectangular hollow tubes integrated with phase change material (PCM).
- PV module without phase change material

The model of the heat sink was designed in the solid works 2016 version as shown in figure 4.1. The square rectangular geometry and dimensions of the tubes were proposed to fit the assembly onto the rear surface of the PV module. Square rectangular tubes of dimension 0.5-in were considered instead of extended rectangular tubes because of the structural issue discussed in [44]. Initially, three samples were proposed for the design of a heat sink having a common base surface with different spacing between the tubes. The spacing between the tubes was 0.5-in, 0, 1-in, and 1.5-in for the proposed four designs, respectively as shown in figure 4.1. The sample with 1-in spacing was selected as the heat transfer from fins is optimum when the unfinned space is more than the width of their respective fin [45].

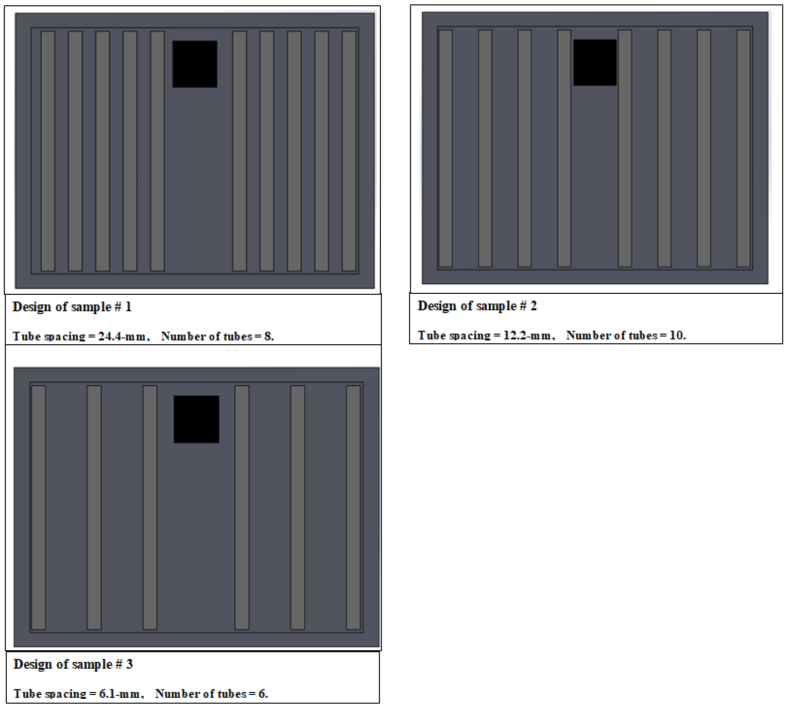

Figure 4-1: Design of different samples in cad model

The prototype for this research work was constructed in a mechanical lab. The Mono-crystalline PV module detailed in table 4.1 was modified and fabricated in several steps. Firstly, a long square rectangular aluminum tube of length 2000-mm having a square annular area of 161.29-mm^2 was cut into eight pieces each having length of 230-mm. The properties of aluminum tubes are present in table 4.1.

Table 4-1: Properties of PV module and Aluminum tubes

Properties of PV module	
Type of PV module	Mono-crystalline
Peak power output (P_{max})	10 Watts
Maximum voltage (V_{max})	18 Volts
Open-circuit voltage (V_{oc})	21.24 Volts
Electrical efficiency at STC	15.3 %
Dimensions	(279.4×333×12.7) mm^3

Weight	1.1 Kg
Properties of Aluminum tube	
Cross-sectional area	161.29 mm^2
Length	230 mm
Wall thickness	1.9 mm
Density (ρ)	3.2×10^4 (kg/m^3)
Thermal conductivity (K)	205 ($W.m^{-1}. K^{-1}$)

Secondly, the tubes were connected in parallel arrangement with each other having spacings of 25.4-mm between them. The tubes were joined with each other by using flat rigid strips. Thirdly, for the first phase of the experiment, a PCM named lauryl alcohol of 190-gm mass in solid-state was put into the beaker and changed into the liquid phase by heating it with a thermal heat gun. The liquid PCM was poured into the tubes with the help of a glass funnel. Each tube was filled with 76 % of the total volume to accommodate the thermal expansion of PCM during melting. For the second phase of the experimentation, the PCM lauryl alcohol was replaced by petrolatum. The properties of lauryl alcohol and petrolatum are mentioned in table 4.2. Lastly, the assembly of the tubes filled with phase change material was incorporated into the rear surface of the PV module with the help of screws and washers. The step by step procedure of modification of PV module is explained in figure 4.2.

Table 4-2 Properties of Lauryl Alcohol and Petrolatum

Properties (Dodecanol) Lauryl alcohol	
Commercial name	Lauryl alcohol
Melting point (℃)	24 ℃
Latent heat (kJ/kg)	215.83
Thermal conductivity (W/m K)	0.18
Specific heat capacity (kJ/kg K)	
Density (kg/m^3)	831
Properties of ($C_{15}H_{15}N$) Petrolatum	

Commercial name	Petrolatum/Soft Paraffin
Melting point (℃)	35 ℃
Latent heat (KJ/kg)	
Thermal conductivity (W/m K)	0.11
Specific heat capacity (kJ/kg K)	0.117
Density (kg/m^3)	900

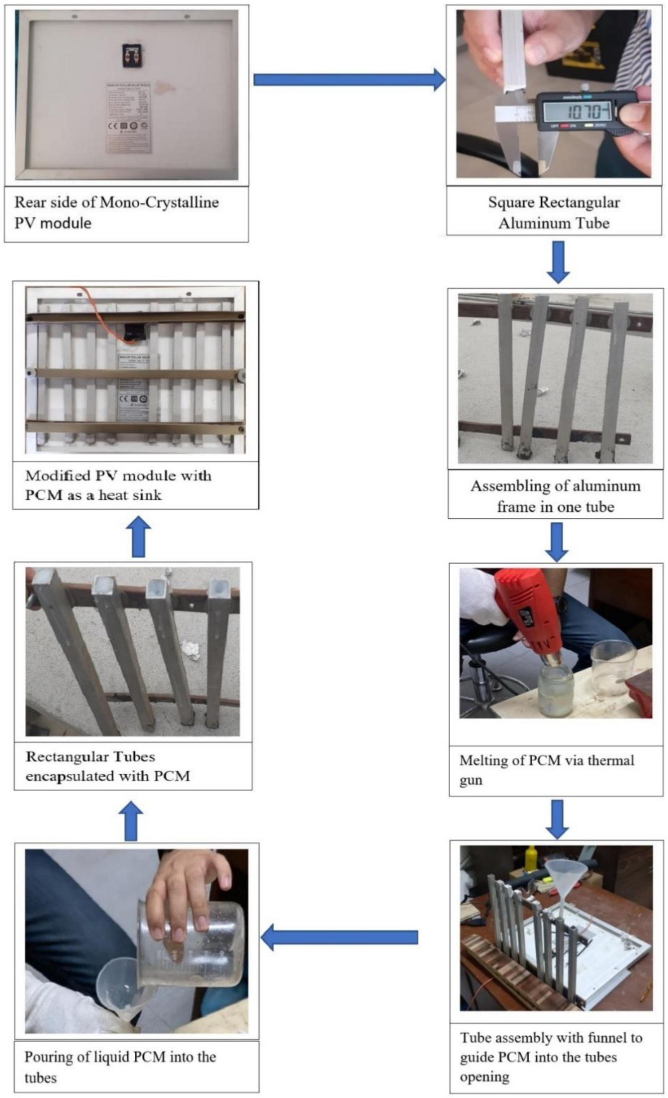

Figure 4-2: Step by step process of prototype fabrication

4.2 Experimental framework

The experimental framework consists of:

- Two Monocrystalline PV modules are detailed in table 4.1.

- Seventeen K-type thermocouples with maximum and minimum deviation of 0.5 ℃
- EXTECH temperature data logger of 12-Channel
- Multimeter of UNI-T was used to measure the electrical parameters
- Pyranometer, and Anemometer of USPCASE NUST weather station

The PV modules were placed on aluminum and wooden stands facing south-east with a 35° inclination to the ground. To measure the surface temperature on both sides of the PV modules, eight thermocouples were attached to both the PV module. Four thermocouples were fixed to the rear side and four to the front side of the modules as shown in Figure 4.3. The same number of thermocouples with the same alignment was fixed to the module with fins. One thermocouple was placed in front of both the modules to measure the ambient temperature. Solar radiations and wind speed were measured every 10 min with the help of a pyranometer and anemometer provided by the weather station installed at the experimental site. Temperature data loggers of twelve ports were used to record and store the temperature data every 5 min. A multimeter was used to compute the open-circuit voltage and short circuit current of both the PV modules after every 10 mins.

Before starting the experiment, some precautionary steps were followed. The thermocouples were properly attached to the rear and front surfaces of the PV modules with adhesive tape. With proper reference assigned each port of the dataloggers to the respective thermocouple. All the data loggers and equipment were reset before starting the experiment. The orientation of the PV modules w.r.t the stands were up to the mark. Data loggers were placed in such a way that they should be in shade rather than in the open sky to avoid exposure to sun radiation. The experiment was performed on the complete sunny day 4th November 2019 from 9:00 to 17:00.

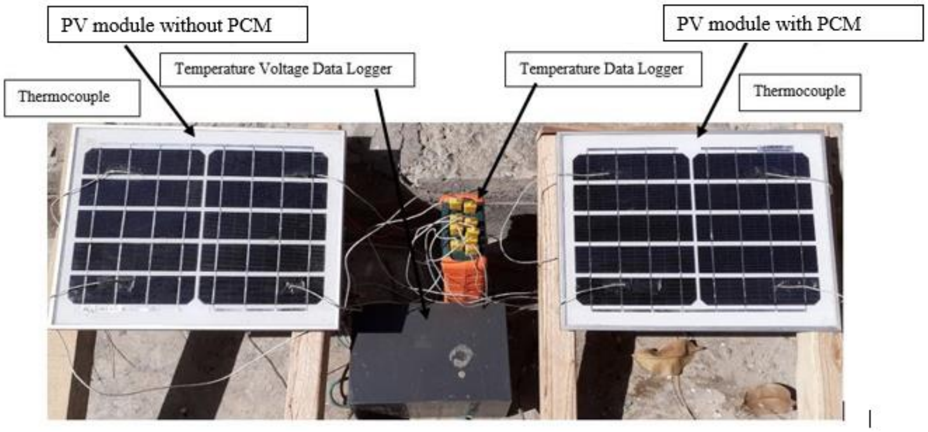

Figure 4-3: Experimental setup

4.3 Climate data of the experimental site

The climate data including ambient temperature, wind speed, and global horizontal irradiance of the experimental site is obtained from the meteorological station installed at the experimental site. The Experimental study was conducted on top of the roof of the US-Pakistan center of advanced studies in energy (USPCASE), NUST, Islamabad (33.642364°N, 72.984290°E) for three weeks. The climate data of the experimental days are averaged for three weeks from 9:00 to 17:00 as shown in Figure 4.4 in which the average ambient temperature recorded 30.62 ℃, with a minimum value of 19 ℃ and the highest value of 35 ℃. Similarly, wind speed fluctuated in a non-uniform manner with a mean value of 2.16 m/s forming variable crests and troughs. The average value of the global horizontal irradiance during the experiments was 668.168 W/m^2 with a maximum value of 787.6 W/m^2.

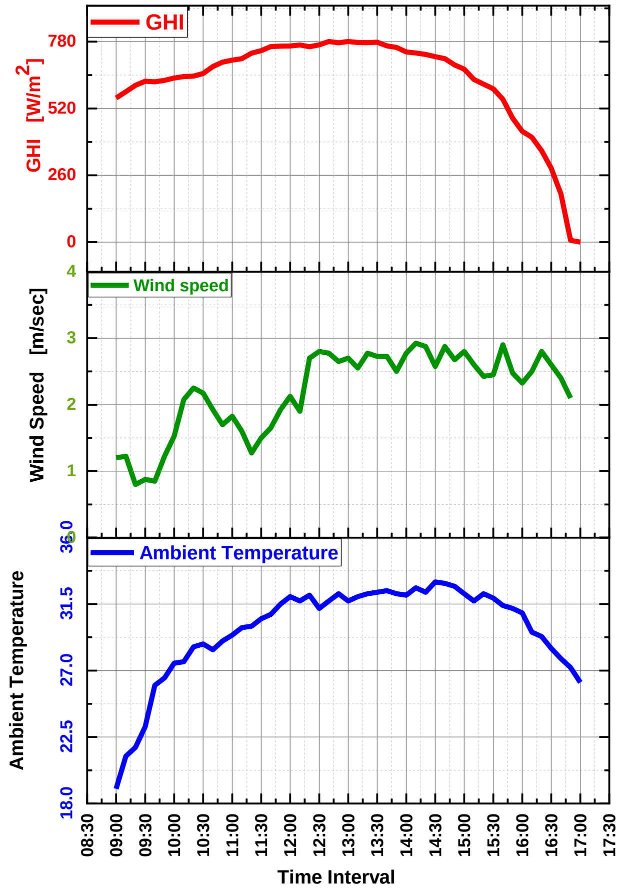

Figure 4-4: Averaged climate data of the two weeks of experimental time

4.4 Experimental details

A series of the experiment were performed with different arrangements.

Firstly, an experiment was conducted on the 23rd of November 2019 in which the PV module having hollow rectangular tubes without PCM on its rear surface was compared with an unmodified PV module. The purpose of this experiment was to verify the fin effect of the extended geometry of the rectangular tube which will also contribute to the cooling effect in later experiments.

Secondly, the rectangular tubes were filled with PCM i.e. Lauryl Alcohol, and compared with the unmodified PV module. The purpose of encapsulating PCM in the tubes is to enhance further the electrical efficiency of the PV module by lowering its cell's temperature. The experiments were performed from the 12^{th} to the 15^{th} of October 2020. The results of these experiments are discussed in the next chapter.

Lastly, lauryl alcohol was replaced by soft paraffin known as Petrolatum and concluded results. Lauryl alcohol was replaced by petrolatum because the results of lauryl alcohol did not meet the objectives of this research study. Thus, petrolatum was used for further experiments performed from 19^{th} to 22^{nd} of October 2020 The results of these experiments are discussed in the next chapter.

Summary

In this chapter design and fabrication of the experimental setup are subsequently discussed. The first section of this chapter refers to the modification and design of the monocrystalline PV module. Also, the advantages and all the details related to the proposed design of the PV cooling system have been discussed. In the second and third sections, the equipment used during the experiments with their characteristics and capacities is briefly illustrated. Moreover, the experimental framework and climate data of the experimental site are figured in this chapter.

Chapter 5

RESULTS AND DISCUSSION

5.1 Numerical equations of important parameters

Since the PCM is encapsulated in extended rectangular tubes and that will contribute to the overall heat transfer from the PV module surface due to their fin effect. So heat transfer due to fin effect is quantified by fin's effectiveness. Mathematically, it is the ratio of the heat transfer from the surface with fins to the heat transfer from the same surface without fins. Equation **(a)** refers to the relation of fin effectiveness.

$$\varepsilon = \frac{\dot{Q}_{fin}}{\dot{Q}_{no\ fin}} = \frac{nhA_{unfin}(T_s - T_a) + nhA_{fin}\eta_{fin}(T_s - T_a)}{hA_{no\ fin}(T_s - T_a)}$$

$$\varepsilon = \frac{n(A_{unfin} + \eta_{fin}A_{fin})}{A_{no\ fin}} \qquad (1)$$

From equation (1), it is evident that if $\varepsilon < 1$ then fins act as insulation, if $\varepsilon=1$ then this indicates no effect of fins i.e. $\dot{Q}_{fin} = \dot{Q}_{no\ fin}$, $\varepsilon > 1$ shows that attachment of fins increases the rate of heat transfer. For current study effectiveness of fins is more than one i.e. **ε** = 1.87, this value of effectiveness is calculated by putting the values of A_{unfin}=5806-mm^2 , A_{fin} = 8709-mm^2, $A_{no\ fin}$ = 74000-mm^2, n = 8, and η_{fin} = 0.83 (From equation 3) in equation 4. The result shows that:

$$\varepsilon = \frac{\dot{Q}_{fin}}{\dot{Q}_{no\ fin}} = 1.87$$

$$\dot{Q}_{fin} = 1.87\dot{Q}_{no\ fin}, \qquad (2)$$

Comment [AN2]: Equation numbering missing for the correlation.

Equation (2) indicates that the heat transfer from the PV module after the installation of fins is 1.87 times to the heat transfer without fins which means that fins increase 87% of heat transfer.

Since the rectangular tubes are encapsulated with PCM which also absorbs the heat energy and raises the temperature of the PCM to the point when the phase transition of the PCM is started Almost 10-20% of the solar irradiance is converted into electrical power output, the remaining 80-90% transformed into convection heat transfer from the PV, radiations heat transfer from the PV, and to the specific heat of the PV (C_{pv}) times the temperature gradient of the PV. The heat sink containing PCM at the rear side of the PV module also absorbs the heat energy and raises the temperature of the PCM to the point when the phase transition of the PCM is started. The energy balance equation of the PV-PCM system is formulated from [46]:

$$Irradiance\ incident\ on\ PV\ (I_r) =$$
$$Electrical\ power\ output\ \left(E_p\right) + Radiations\ emmitted\ by\ PV\ (Q_r) +$$
$$Convection\ heat\ tranfer\ (Q_{conv}) + Heat\ stored\ by\ PCM\ (Q_H) + C_{pv}\frac{dT_{pv}}{dt}$$

(3)

The temperature gradient in equation (3) can be measured by calculating all other parameters present in the equation.

The irradiance incident on the PV module can be found by using equation (4)

$$I_r = \alpha.\emptyset \quad (4)$$

The radiations heat transfer from the PV module can be found by Stefan Boltzmann law which is:

$$Q_r = \varepsilon_p.\sigma\left(T_{pv}^2 + T_{sky}^2\right)\left(T_{pv} + T_{sky}\right) \quad (5)$$

$\mathcal{E}p$ and σ refer to the emissivity of the PV and Stefan Boltzmann constant, respectively whereas T_{sky} indicates the sky temperature and can be calculated by using swim bank equation

$$T_{sky} = 0.037536T_{amb}^{1.5} + 0.32T_{amb} \quad (6)$$

The electrical power output can be determined using equation (7)

$$E_p = \left\{\frac{\emptyset \ln(K_1\emptyset)}{T_{pv}}\right\}.C_{ff} \quad (7)$$

In equation 2, C_{ff} indicates the fill factor of the PV cell.

The convection heat transfer will be different for the front and rear surfaces of the PV module due to the different convection heat transfer coefficients. Also, from the front surface forced convection is involved due to the direct impact of a wind gust. Equation (8) shows the overall convection heat transfer from the PV module.

$$Q_{conv} = \left(h_{natural\,front} + h_{forced\,front} + h_{natural\,back}\right).\left(T_{pv} - T_{amb}\right) \quad (8)$$

Since the characteristics of all the convective heat transfer coefficients are different due to their varying operating conditions. The equations of each convective heat transfer coefficient are listed below:

$$h_{forced\,front} = 2.8 + 3.0v; \quad (8a)$$

The term v in equation (8a) refers to the velocity of the wind.

$$h_{front,natural} = 1.78\left(T_{pv} - T_{amb}\right)^{1/3}, \quad (8b)$$

$$h_{front,total} = \left(h_{forced}^3 + h_{natural}^3\right)^{1/3}, \quad (8c)$$

$$h_{back} = 1.31\left(T_{pv} - T_{amb}\right)^{1/3}. \quad (8d)$$

Electrical output efficiency is one of the major parameters to check the overall performance of the PV module. Also, after the installation of the cooling system to the PV module the electrical output efficiency determines the improvement in power conversion of the PV module using comparative analysis with PV module without a cooling system. Equation (9, 10) shows the relationship of the electrical power output efficiency with the cell temperature of the PV module [47].

$$\eta_{PV} = \eta_{ref}\left[1 - \beta\left(T_{PV} - T_{ref}\right)\right] \quad (9)$$

$$\eta_{PV-fins} = \eta_{ref}\left[1 - \beta\left(T_{PV-fins} - T_{ref}\right)\right] \quad (10)$$

η_{ref} and T_{ref} in equations 9 & 10 show the efficiency and temperature of the PV module's front side while β shows the Temperature Coefficient of the PV module dependent on the material of the PV module. It is found that different manufacturer has different temperature Coefficient. PV modules of mono-crystalline, multi-crystalline, and Cadmium telluride have a temperature coefficient of -0.44 %/℃, - 0.387 %/℃, and - 0.172 %/℃ respectively [48].

5.2 Experimental results

In this section, various parameters of the PV modules with fins and without fins recorded during the experiment are analyzed and discussed. These parameters include front and back surface temperature, open-circuit voltage, short circuit current, and efficiency. First, the four temperatures of PV modules i.e. $(T_{fin})_{back}$, $(T_{fin})_{front}$, and $(T_{no\ fin})_{back}$, $(T_{no\ fin})_{front}$ for the rear and front surfaces are calculated by taking an average of the temperatures measured by their respective thermocouples attached to both sides of the PV module as described in the previous section.

5.2.1 Fin effect of rectangular tubes on PV module without PCM

The addition of tubes will increase the convective heat transfer area according to the newton law of cooling that will enhance the heat transfer rate from the modified PV module. Figure 5.1 refers to the back and front surface temperature difference between the finned and unfinned PV modules i.e., $\Delta T_{back} = (T_{no\ fin})_{back} - (T_{fin})_{back}$ and $\Delta T_{front} = (T_{no\ fin})_{front} - (T_{fin})_{front}$.

In figure 5.1, the highest peak of the curves on the back and front side represent the maximum temperature drop after the installation of fins. The maximum temperature drop on the back and front surfaces are 4.6℃ and 4.8℃, respectively.

The average value of the temperature difference between the PV modules with and without fins for the back and front surface for the whole day is $(\Delta T_{avg})_{back} = 3.54$ ℃ and $(\Delta T_{avg})_{front} = 3.32$ ℃, respectively. These values of average temperature gradient for the whole day are calculated by taking the average of the temperatures from 09:00 to 17:00. Therefore, it can be said that the PV module integrated with the aluminum fins is 3.54^{o}C cooler than the un-finned one.

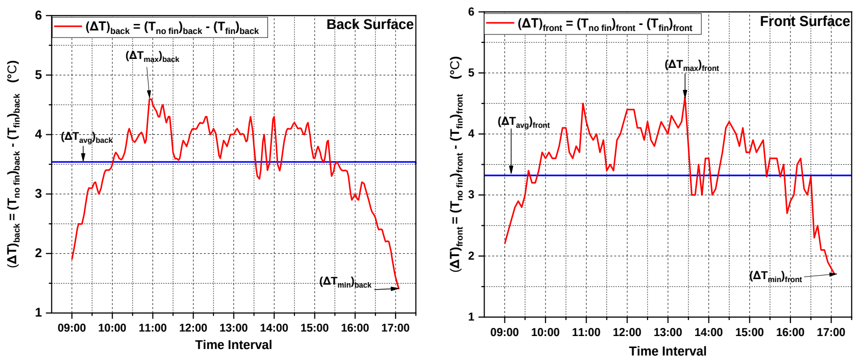

Figure 5-1: The temperature difference between PV module with and without fins

Moreover, it can be observed from Figure 5.1 that at 9:00 and 17:00 the temperature gradient on the back surface is $(\Delta T_{9:00})_{back} = 1.9\,℃$ & $(\Delta T_{17:00})_{back} = 1.4\,℃$, and on the front surface $(\Delta T_{9:00})_{front} = 2.2\,℃$ & $(\Delta T_{17:00})_{front} = 1.7\,℃$ confirming lower fin effect during morning and evening time as compared to noon hours. During the hours when the solar radiation has less intensity to affect the temperature of the module; the temperature gradient between the surface of the PV module and the ambient temperature is on the lower side as shown in figure 5.2. The less temperature gradient slowing down the rate of heat transfer as compared to the noon hours of the day.

Figure 5.2 represents the surface temperatures of the PV module with and without fins i.e. T_{fin} and $T_{no\ fin}$. It can be observed from figure 5.2 that, there is a constant offset between the two curves of hourly surface temperatures for both back and front surfaces. This offset in figure 5.2 indicates the difference between the surface temperature of the finned and un-finned PV module. Overall, the temperature curves of the PV module start decreasing after 13:00hrs due to the decrease in the intensity of the solar irradiance.

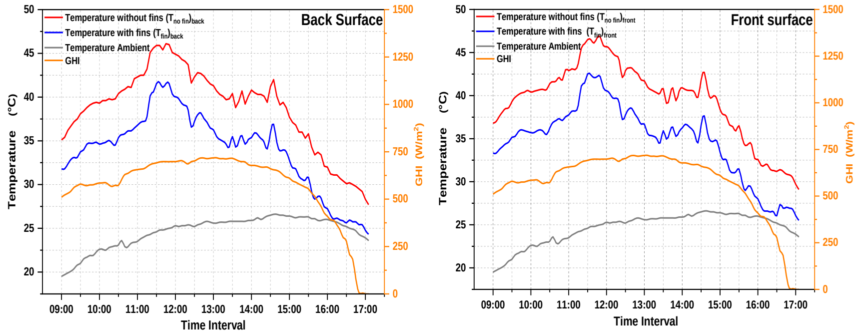

Figure 5-2: Effect of solar radiations on the surface temperature of the PV module

5.2.2 Effect of rectangular tubes filled with PCM (lauryl Alcohol)

The radiations flux coming from the sun falls on the front surface of the modified PV module and raised the temperature of the PV cell. The tubes having PCM attached to the rear surface of the PV module have a lower temperature than the front surface and that creates a temperature gradient between the front surface and tubes having PCM. The temperature gradient causes heat transfer from the front surface through the rear surface and to the tubes. The heat transfer from the front surface heats the PCM encapsulated in tubes and the PCM starts to change its phase and stores that heat through its latent heat capacity. In figure 5.3, it is evident that the temperature difference between the PV module with and without PCM is positive from 9:00 to 11:40 attains a maximum value of 6.4 ℃ and a minimum value of 0.1℃. 11:40 is a critical time for this cooling system because at that time the PCM (lauryl alcohol) is completely melted into a liquid form having a higher temperature than the PV frontal cell. After 11:40 the temperature difference between the PV module with PCM and without PCM becomes negative, it is because the stored heat energy is transferred again to the front surface of the PV module which is a negative effect. At night time the negative temperature difference is acceptable but during the daytime, the cooling system cannot afford this behavior which is contrary to the objective of this research work.

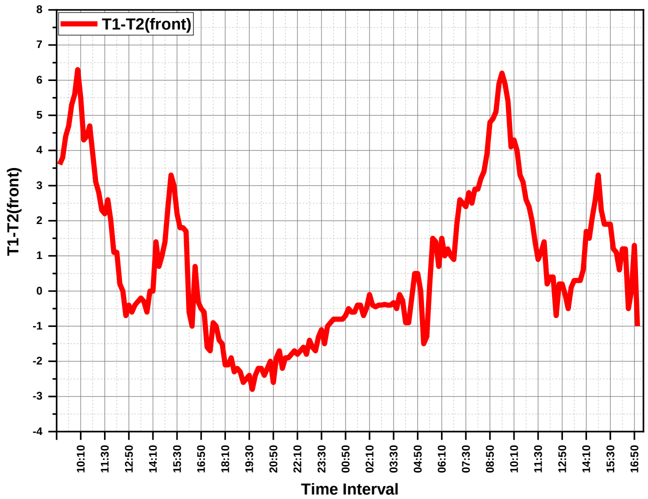

Figure 5-3: The temperature difference between PV module with and without PCM

The PCM (lauryl alcohol) encapsulated in the rectangular tubes having a melting point of 25 ℃ due to which it starts to melt at first go i.e. from 9:00 and converted into the liquid phase at 11:40. The early phase change of the lauryl alcohol creates an effect of sending back the stored heat in PCM to the PV cell embedded on the front surface of the PV module as shown in figure 5.4. Moreover, the overall surface average temperature of the PV module was 45 ℃ at that particular time which is much higher than the melting point of the PCM i.e. lauryl alcohol as shown in figure 5.4.

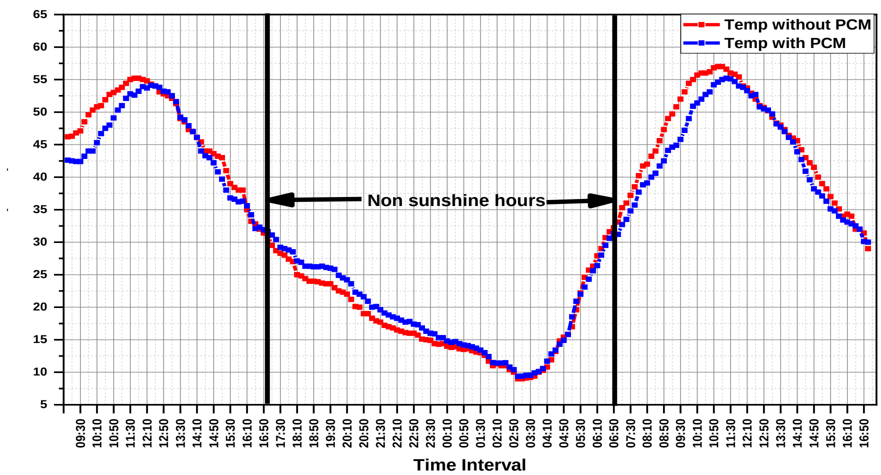

Figure 5-4: Temperature curves of the PV module with and without PCM (Lauryl Alcohol)

5.2.3 Effect of rectangular tubes filled with PCM (Petrolatum)

Now to avoid early melting of PCM, the lauryl alcohol was replaced by petrolatum also known as soft paraffin having a melting point of 35 ℃ with aluminum additives to enhance its thermal conductivity. The properties of petrolatum are tabulated in table 4.2. The idea of introducing petrolatum to the cooling system is because of its melting point which lies between the ambient temperature and the operating temperature of the PV module. Now, due to the delay in the melting point of the PCM because of its higher melting point, the PCM can extract more sensible and latent heat from the front surface of the PV module. Even at 15:00, the phase of the PCM is still in between solid and liquid. After 16:00, the temperature curves of the PV module with and without PCM converges which indicates that the PCM is sending back its stored energy to the front surface of the PV module as shown in figure 5.5.

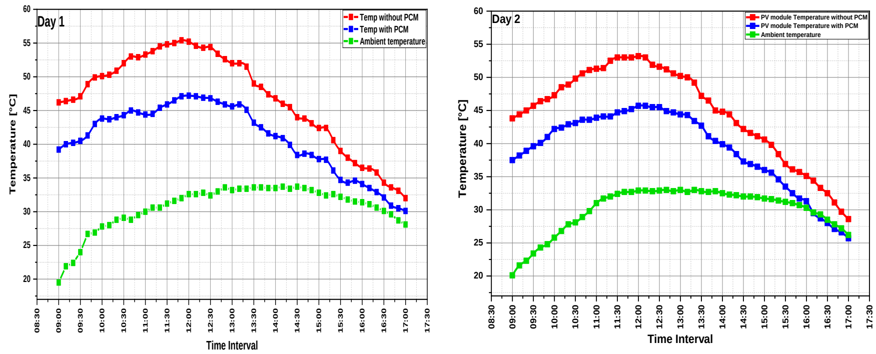

Figure 5-5: Temperature curves of the PV module with and without PCM (Petrolatum)

5.2.4 Comparison between Lauryl alcohol and petrolatum in terms of temperature difference

The average temperature difference between the PV module with and without PCM is more in the case of petrolatum than the lauryl alcohol as shown in figure 5.6. In the case of lauryl alcohol, the negative temperature difference appears during the peak hours of the day i.e. -0.7 ℃ which is contrary to the objective of this research work while in petrolatum there is no negative temperature difference. It is due to the higher melting point of the petrolatum. The maximum temperature difference between the PV module with and without PCM in the case of lauryl alcohol was 4.7 ℃ at 10:40 while in petrolatum the maximum temperature difference was 8.1 ℃ as shown in figure 5.6. Moreover, the percent average drop in the PV module's temperature was 11.24 % while in the case of lauryl alcohol, it was 1.98 %.

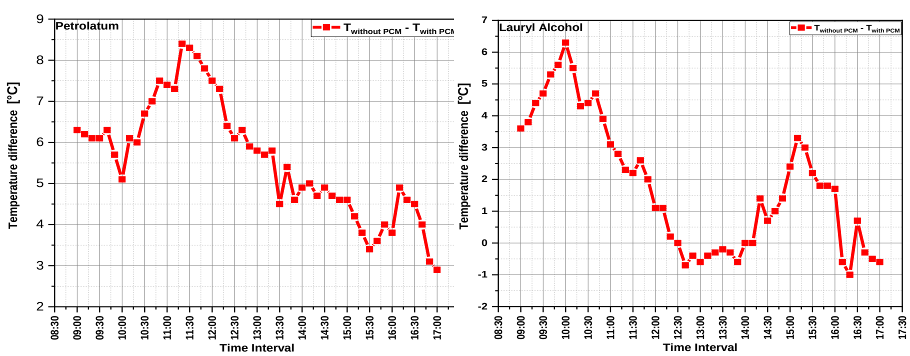

Figure .5-6: Cooling of PV module comparison between Lauryl alcohol and Petrolatum

5.2.5 Effect of PCM on Open Circuit Voltage and Short circuit Current of PV module

Open circuit voltage (V_{oc}) of the PV module is greatly affected by the Cell temperature and drops markedly with the rise of cell temperature while short circuit current increases negligibly. From literature, it is concluded that a 1 ℃ rise of cell temperature (above STC) reduces 0.4 % open-circuit voltage and increases 0.09 %/℃ short circuit current [49]. The open-circuit voltage drops with the rise in the PV module's surface temperature due to the increase in intrinsic carrier concentration in the conduction band as shown in equation (11) [50].

$$V_{oc} = \frac{kt}{q} \ln \left[\frac{(N_a + \Delta n)\Delta n}{n_i^2} \right] \quad (11)$$

Na and *Δn* in equation 11 symbolize the doping concentration and residual concentration carrier while n_i refers to the intrinsic carrier concentration which is equal to the number of electrons in the conduction band or holes in the valence band of the intrinsic molecule of the PV module. The rise of intrinsic carrier concentration with temperature lowers the band gap between the conduction and valence band resulting decrease in the open-circuit voltage [47]. In the current study, it was observed from figure 5.7 that after the installation of PCM tubes the average rise in open-circuit voltage was 1.097 V which amounts 12.56 % increase of the (V_{oc}) before the attachment of PCM tubes, whereas the average drop in short circuit current was 0.002 A. The straight lines in figure 5.7 indicate (V_{oc}) and (I_{sc}) at standard testing conditions i.e. 21.8 V and 0.66 A respectively.

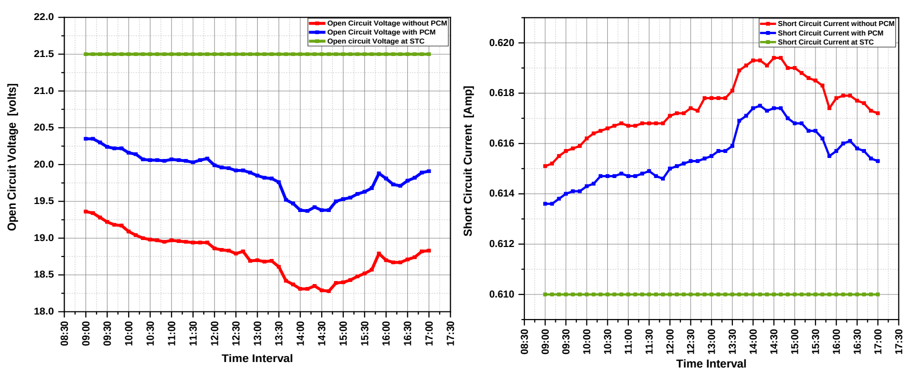

Figure 5-7: Electrical improvement in terms of open-circuit voltage and short circuit current

5.2.6 Effect of PCM on Electrical output efficiency

Equation (9, 10) shows the relationship of the electrical power output efficiency with the cell temperature of the PV module [47].

$$\eta_{PV} = \eta_{ref}\left[1 - \beta\left(T_{PV} - T_{ref}\right)\right] \quad (9)$$

$$\eta_{PV-fins} = \eta_{ref}\left[1 - \beta\left(T_{PV-fins} - T_{ref}\right)\right] \quad (10)$$

η_{ref} and T_{ref} in equations 9 & 10 show the efficiency and temperature of the PV module's front side while β shows the Temperature Coefficient of the PV module dependent on the material of the PV module. It is found that different manufacturer has different temperature Coefficient. PV modules of mono-crystalline, multi-crystalline, and Cadmium telluride have a temperature coefficient of -0.44 %/℃, - 0.387 %/℃, and -0.172 %/℃ respectively [48]. The electrical power output efficiency calculated from equation (12, 13) are plotted in figure 5.8 for the experimental day.

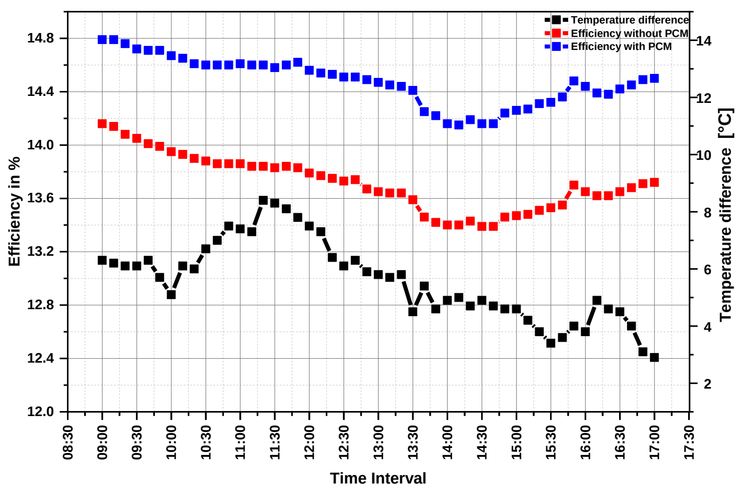

Figure 5-8: Electrical output efficiency comparison between PV module with and without PCM

5.2.6 Effect of rectangular tubes filled with PCM (Petrolatum)

Practically 10-20% of the solar irradiance is converted into electrical power by conventional solar PV module, and the remaining 80-90% are converted into heat which increases the operating temperature of the PV module. The residual heat due to the solar radiations are transfer to the module's back surface by conduction heat transfer and then to the ambient by convection and radiation heat transfer. Also, some part of this heat energy is transferred to the ambient directly from the front surface to the ambient via radiations and convection heat transfer [46] as shown in equation 8.

$$\textit{Irradiance incident on PV } (I_r) = \textit{Electrical power output } (Q_i) + \textit{Heat loss from the front surface of PV } (Q_f) + \textit{Heat loss from the back surface } (Q_b) + \textit{Heat stored by PV } (Q_s)$$

(12)

Now after the attachment of the heat sink containing PCM at the rear side of the PV module absorbs the heat energy and raises the temperature of the PCM to the point when the phase transition of the PCM is started. The energy balance equation of the PV-PCM system is formulated from:

$$\textit{Irradiance incident on PV\&PCM } (I_r) = \textit{Electrical power output } (Q_i) + \textit{Heat loss from the front surface of PV\&PCM } (Q_f) + \textit{Heat loss from the back surface } (Q_b) + \textit{Heat stored by PV\&PCM } (Q_s)$$

(13)

The total radiative power from a solar incident on the PV module can be found by using equation (14) used by [51]

$$Q_i = A_{pv} \times \alpha\tau \times S$$

(14)

The A_{PV} in equation (14) shows the area of the PV module mention in table 4.1 whereas $\alpha\tau$ is the product of the absorptivity and transmissivity of the PV frontal glass.

The heat transfer from the front side of the PV module to the ambient is by convection and radiation heat transfer as shown in equation (15)

$$Q_f = Q_{conv} + Q_{rad} \tag{15}$$

The convection heat transfer is calculated by using the newton law of cooling [44]

$$Q_{conv} = h_{front}(T_{PV} - T_{amb})$$

(16)

The effective convection heat transfer coefficient is a function of combined heat transfer co-efficient influenced by free and forced convection. It can be calculated from equation (17) and 19 previously used by[51].

$$h_{front} = \sqrt[3]{\left(h_{wind}^3 + h_{free}^3\right)}$$

(17)

To find the effective heat transfer coefficient in equation (13), h_{wind} and h_{free} have to be calculated [52] by using equations (14) and (15).

$$h_{wind} = 3.3V_{wind} + 6.5$$

(18)

$$h_{free} = \frac{Nu \times \mathrm{K}}{L}$$

(19)

The *Nu* in equation (19) is a non-dimensional number known as the Nusselt number, it is the ratio of convective to conductive heat transfer of the fluid. The Nusselt number in free convection is dependent on another two non-dimensional numbers known as Prandtl number P_r and Rayleigh number R_a [52]as shown in equation (20).

$$Nu = \left[0.825 + \frac{0.387Ra^{1/6}}{\left[1+(0.429/Pr)^{9/16}\right]^{8/27}}\right]^2$$

(20)

The radiation heat transfer from the PV module can be found by using the Stefan Boltzmann law [46] which is:

$$Q_{rad} = \varepsilon_p . F . \sigma . A_{pv}\left(T_{PV}^4 + T_{sky}^4\right)$$

(21)

In equation (17), $\mathcal{E}p$ and σ refer to the emissivity of the PV and Stefan Boltzmann constant, respectively whereas T_{sky} indicates the sky temperature and can be calculated by using the swim bank equation [46].

$$T_{sky} = 0.037536T_{amb}^{1.5} + 0.32T_{amb}$$

(22)

The convection and radiation heat transfer from the backside is measured in the same manner as in previous equations . The only difference will be in the additional convection heat transfer due to the attachment of rectangular tubes which leads to different Nusselt numbers as shown in equation (23). Moreover, the sky temperature used in radiative heat transfer will be replaced by ground temperature which is equal to the ambient temperature of the experimental site[51].

$$\frac{Nu_D}{(Racos\theta)^{0.25}} = 0.53 + 0.555\left[\left(\frac{t}{Lcos\theta}\right)^{0.25} - \left(\frac{t}{L}\right)^{0.25}\right]$$

(23)

The electrical power output of the PV module was found experimentally as shown in figure 5.9 with the help of voltage (V_{oc}) and current (I_{sc}) using fill factor equation i.e.

$$P = F.F \times (V_{oc} \times I_{sc})$$

(24)

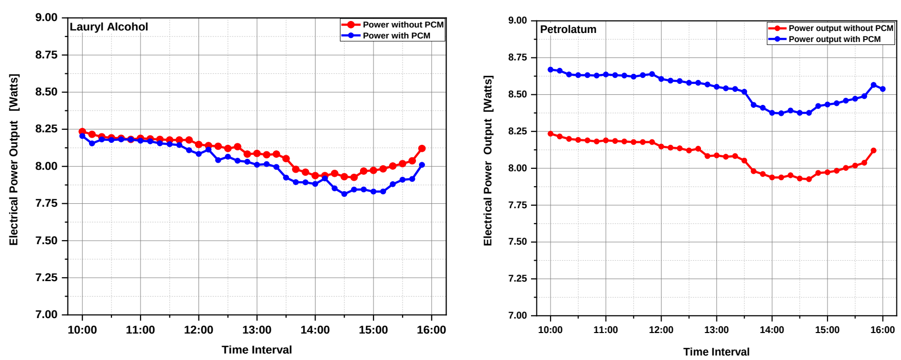

Figure 5-9: Electrical power output of PV and PV-PCM system

The heat storage in the PV and PV-PCM system is calculated by putting all the other parameters in equations 6 and 7. The overall energy balance for PV and PV-PCM systems (Lauryl alcohol and Petrolatum) is calculated and plotted in figure 5.10.

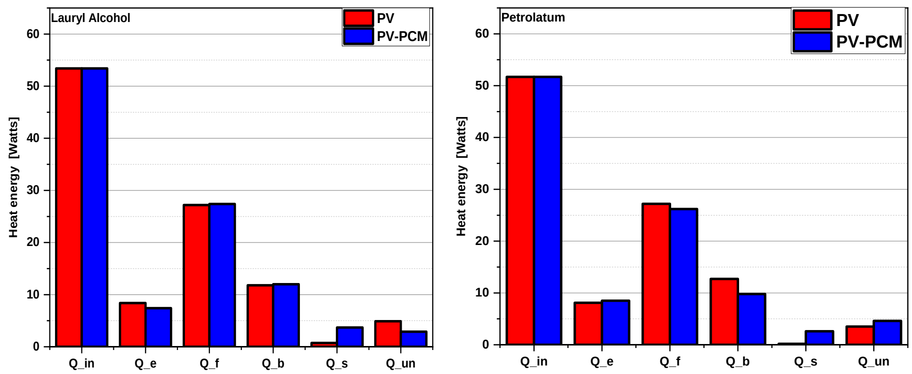

Figure 5-10: Energy balance of PV module with and without PCM

Figure 5.10 shows that the total solar energy incident on the PV module and converted into electrical power and heat energy. Almost 80% of the heat energy is lost to the ambient via convection and radiation heat transfer in both cases i.e. PV and PV-PCM system whereas 8 to 10% is stored in the system. In the case of PV module without PCM the heat storage is lower than the heat storage in the PV-PCM system because the PCM has the latent heat storage capacity as shown in figure 5.10. Also, the heat storage in the case of lauryl alcohol is more than the petrolatum because the lauryl alcohol utilized its latent heat storage capacity due to its lower melting point. The electrical power of the PV-PCM system is lower than PV without PCM because the cell temperature of PV-PCM is higher than the cell's temperature of the PV module without PCM. In the case of petrolatum, the electrical power of the PV-PCM system is higher than the PV because of the temperature drop of the PV cell.

5.2.7 Economic analysis

Exact economic analysis with a payback period of finned PV module may be difficult to perform at this initial stage. However, a brief economic analysis is conducted and compared with other methods of passive cooling of PV module already reported in the literature. The cost of aluminum tubes used in the current study is \$3.55/kg in the local market. The weight of the aluminum tubes attached to the PV module is 0.6 kg, so the cost of the aluminum tubes and PCM in (petrolatum) is used in the prototype is \$ 2.33 and \$ 1.5. The cost of screws and washers used for assembly along with another miscellaneous item is \$ 1.08. So, the total cost of the prototype fabrication for thermal management in this study is \$ 4.1 for the PV area of 0.0929 m^2, \$44.133/m^2 as shown in Figure 5.11.

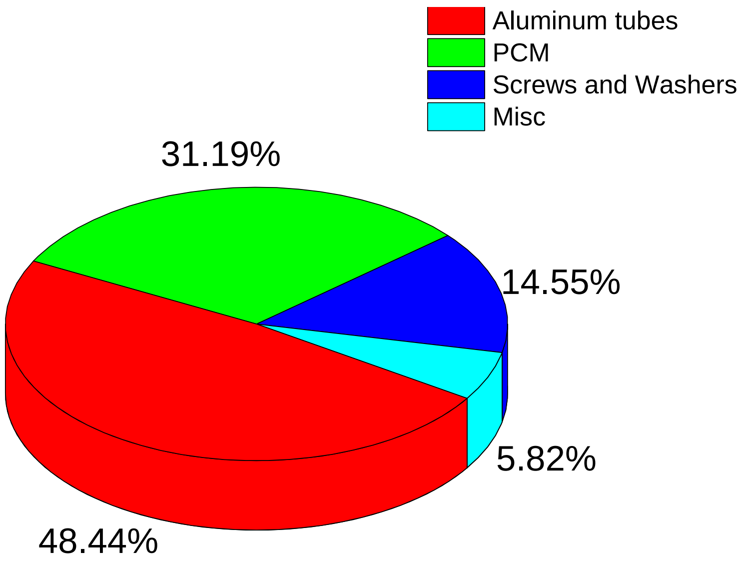

Figure 5-11: Economic analysis chart

5.2.8 Analogy between the Already Published and Current Study

This section refers to the comparison between this study and the already published similar literature in terms of various parameters tabulated in table 5.1. The temperature difference between the two PV modules with and without fins achieved in this study is more than the temperature difference in [6,10,11] studied in the literature. In [12,31] of the literature, the temperature drop in the modified PV module is 1 ℃ to 3 ℃ more than the modified PV module of this study but structurally and economically the method used in the current study is very much sound and less expensive. Table 5.1 refers to the comparison between the current study and previous studies of cooling of solar PV module.

Table 5-1 Analogy between the current study and already published work

Parameters	**Current study**	**Ref** [31]	**Ref**[6]	**Ref**[12]	**Ref** [7]
Type of study	Pure Experimental	Pure Experimental	Experimental	Simulation and Experimental	Indoor simulator
Method of cooling	Passive	Passive	Passive	Passive	Passive
Heat sink type	Rectangular tubes filled with PCM	Circular tubes filled with PCM	Extended L shaped Aluminum Blades	Iron and Aluminum mesh	Repurposed material integrated with fins
Location	Islamabad Pakistan	Hefei China	Croatia	Korea (KIAT)	GJU Jordon Lab at STC
Type of PV module	Monocrystalline	Monocrystalline	Polycrystalline	Polycrystalline	Polycrystalline
Total experimental hours	72 hours	10 hours	10 hours	7 hours	12 hours
Average ambient temperature	24.62 ℃	26 ℃	12 ℃	43 ℃	25 ℃(STC)
Average wind speed	4.2 m/s	3.2 m/s	3 m/s	2 m/s	1.5 Air mass
Average GHI	570 W/m^2	540 W/m^2	740W/m^2	1000 W/m^2	1000 W/m^2
PV module peak surface temperature without heat sink	54.8 ℃	57 ℃	N/A	52.9 ℃	105 ℃
PV module peak surface temperature with heat sink	46.7 ℃	55 ℃	N/A	46.3 ℃	102℃
PV module percent temperature reduction	11.24 %	9.6 %	N/A	6.87 %	22 % (STC)
Improvement in open circuit voltage	14.1 %	N/A	N/A	N/A	N/A
Decrease in short circuit current	0.31 %	N/A	N/A	N/A	N/A
Economic comparison	$44.133/$m^2$	$93/$m^2$	$243/$m^2$	N/A	N/A
Relative increase in efficiency	5.05 %	3 %	2 %	1.44 %	1%

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Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

To increase the electrical conversion efficiency, there are several technologies for cooling solar PV modules. The active cooling techniques require additional accessories and mountings like fan or pumps which also includes operational and maintenance cost while passive cooling techniques are simpler and less expensive. In this article, an experimental study has been conducted using the passive method to cool down the surface of the PV module via attaching an assembly of hollow rectangular aluminum tubes to the rear side which acts as a heat sink.

The overall effectiveness of the PV module with fins calculated in this study is 1.87 which means an 87 % increase in the rate of heat transfer. The average temperature difference between the two PV modules with and without PCM in the case of lauryl alcohol was 0.677 ℃ while in the case of petrolatum it was recorded as 5.12 ℃. 14.1 % rise of open-circuit voltage is observed due to the cooling effect of PCM (petrolatum) which improves PV module's electrical output efficiency up to 2.08 % versus PV module without PCM.

The tubes utilized to the rear surface of the PV module are rectangular instead of circular tubes to avoid structural issues like rigid contact with the PV module's back surface, also the rectangular geometry provides more heat transfer contact area than the circular one. The total cost of the PV module prototype fabrication for thermal management in this study is \$4.1 for the PV area of 0.0929 m^2, \$44.133/m^2.

Comment [AN3]: Give concluding remarks of one sentence in the end highlighting overall significance of your study.

The significance of this research work is that the proposed model enhance the electrical efficiency of the conventional PV module with lower expenses than the other models discussed in the literature. Moreover, it is more likely to operate at large scale.

6.2 Future works

This research work covers various issues regarding the PV-PCM colling system but there are always some shortcomings related to any research work. These shortcomings open various areas of future research work. In this study, there are some important points discussed in the next section on which researchers can perform their research studies

6.2.1 Numerical Analysis

The results and conclusion of this research work are purely based on real-time data by performing experiments. The variations in operating conditions like GHI, ambient temperature, and wind speed greatly influence the performance of the PCM heat sink which is difficult to detect from practical experiments. To counter this dilemma the numerical analysis comes into the picture lead by CFD simulations.

6.2.2 Performance on a large scale

The current study is performed on the performance of conventional monocrystalline PV modules which is premature at this level. To check the performance of PV-PCM systems on large scale like solar park or any other commercial level PV module, an extensive study will require.

6.2.2 PV-PCM cooling system analysis on different kinds of PCMs and metrological variations.

The current experimental studies were performed on two kinds of PCMs and the results show that how the type and characteristics of PCMs affect the results of the PV-PCM cooling system. Moreover, the operating conditions also influence the performance of the PCM-heat sink lead by the different metrological conditions. So, there is a big room for future research studies present in this domain. Researchers should consider the use of different types of PCMs used in the PV-PCM colling system and performs experimental studies simultaneously in different localities and metrological conditions.

Appendix

Journal of Renewable and Sustainable Energy **Article:** scitation.org/journal/rse

Thermal management of solar PV module by using hollow rectangular aluminum fins

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ABSTRACT

Some of the recent challenges encountered in research and development of the solar photovoltaic (PV) industry include the decrease in electrical output efficiency of a conventional solar PV module due to the rise in its surface temperature. The main objective of this research work is to enhance and improve the electrical output efficiency of a common silicon-based solar PV module by lowering the operating temperature of the PV module, which was accomplished by attaching hollow rectangular aluminum tubes as a fin to the rear surface of the solar PV panel. The proposed geometrical configuration of tubes helped to increase the PV module heat transfer rate to the surrounding air by increasing the effective heat transfer area without increasing the overall weight of the PV module. In this experimental study, a comparative analysis has been presented for PV modules with fins and without fins. The results obtained from experiments demonstrated that the attached fins reduced the average temperature of the front and rear surfaces up to 8.97% and 8.41%, respectively. The cooling effect produced due to fins improved the open circuit voltage up to 12.97% and the electrical output efficiency up to 2.08%. Furthermore, the results are thoroughly compared with other published studies, which revealed that the proposed configuration is cost effective and structurally sound.

Kew Words: ***PV, Passive cooling, Fins, Heat transfer***