Thermal Management of Solar PV Module by Hollow Circular Fins Integrated with Phase Change Material

By

Muhammad Shoaib

Reg # 00000275603

Session 2018-2020

Supervised by

Dr. Naveed Ahmad

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

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THESIS ACCEPTANCE CERTIFICATE

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Signature: ____________________________

Supervisor Dr. Naveed Ahmad

Date: ________________________________

Signature: ____________________________

HOD-TEE Dr. Majid Ali

Date: _________________________

Signature: ____________________________

Principal Prof. Dr. ADEEL WAQAS

Date: _________________________

Certificate

This is to certify that work in this thesis has been carried out by **Mr. Muhammad Shoaib** and completed under my supervision in, US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Supervisor:

____

Dr. Naveed Ahmad
USPCAS-E
NUST, Islamabad

GEC member 1:

____

Prof. Dr. Adeel Waqas
USPCAS-E
NUST, Islamabad

GEC member 2:

____

Dr. Nadia Shahzad
USPCAS-E
NUST, Islamabad

GEC member 3:

____

Dr. Mariam Mahmood
USPCAS-E
NUST, Islamabad

HOD- Thermal Energy Engineering:

____

Dr. Majid Ali
USPCAS-E
NUST, Islamabad

____

Principal/ Dean: Prof. Dr. Adeel Waqas
USPCAS-E
NUST, Islamabad

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Abstract

Solar PV panels are designed to generate electrical voltage when exposed to sunlight. As sunlight incident on the active area of the PV panel the temperature of the PV cell surface increases. The rising surface temperature of the PV cell leads to the reduction of output voltage which further results in the reduction of the output power of the PV module. In this study, a new type of heat sink composed of pin fins filled with phase change material (PCM) is used to optimize the thermal and electrical performance of the PV module by reducing its temperature. The proposed thermal management model is investigated both experimentally and by using numerical simulations. The thermal and electrical performances of the modified PV module were compared with the unmodified PV module using experimental data. Fins absorb heat from the rear surface of the PV panel through a conduction heat transfer and increase the heat transfer area. The PCM absorbs the heat from the PV module in the form of latent heat transfer by changing its phase. The experimental results showed a decrease of 5.18℃ in the temperature of the PV module. Resulting in increased output voltage by 0.53-Volts and the efficiency of PV-PCM was increased by 2.9%. Moreover, a detailed parametric sensitivity analysis is performed using the validated numerical model to study the effect of wind speed and angle of attack on the modified PV module integrated with PCM. The numerical results showed an increase of 0.4 m/s in wind speed decreases the temperature of the tedlar wall to 0.4196℃ and the temperature of the solar cell also reduces by the rise in the angle of attack of air from 30^{o}-90^{o}. Overall, the application of the PV-PCM solar module is effective in optimizing the output of the PV module.

Keywords: *PV, Passive cooling, Fins, Heat transfer, Phase change material*

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1. Muhammad S, Naveed A et al, “Thermal Management of Solar PV Module by Hollow Circular Fins Integrated with Phase Change Material (Journal of Energy Storage 2022). (Under Review)

Abbreviations

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
Ƞ	Efficiency
V_{oc}	Open Circuit Voltage
I_{sc}	Closed Circuit Current
Ref	Reference

Chapter 1: Introduction

1.1 Current energy scenario of Pakistan

Pakistan currently energy mix is composed of 64% fossils, 27% hydropower, 9% other renewable and nuclear energy power [1] . Renewable energy growth in Pakistan is very slow and currently is accounts for 4% of energy mix. On April 2019, PM Imran announced that Pakistan will be able to produce its 30% energy from renewable like wind, solar and biomass till 2030. In Pakistan, the energy consumption in domestic sector is 47% while other sectors like industries and transportation consumes 29.05% and 31.6% respectively. Pakistan is facing energy crisis due to economic challenges, the electricity price is high due to imbalance between demand and supply[2]. The energy consumption by one person in a year is indicated by one capita which is equal to 235KW per hours in Pakistan [2]. In Pakistan, there is a huge shortfall of electricity such as 6-8 hours in rural areas while 10-12 hours in urban areas. Currently Pakistan is in need for some new renewable energy sources like wind, solar and hydel etc.

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 [3]. 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][4]. To import fuel Pakistan spends its foreign exchange up to 60% [5]. 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 indicate 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 a renewable form of energy that is both clean and ecologically beneficial. In the nation, solar energy is readily accessible. Solar photovoltaic (PV) module research demonstrates that when the temperature of the PV module increases, the electrical conversion efficiency of the PV module drops [6]. Solar cells convert the solar radiation that strikes the solar photovoltaic module from the sun into electrical power, while some unconverted radiations raise the temperature of the solar photovoltaic module [7]. There are two distinct approaches for lowering the temperature of a solar photovoltaic module in order to boost its electrical conversion efficiency: active and passive methods. In this study, a passive cooling approach is applied to lower the temperature of the photovoltaic module.

1.3 Pakistan's solar power potency

The rising cost of fuel and the dangers associated with the combustion of fossil fuels such as coal and gasoline in thermal power plants have resulted in the emergence of greener energy sources such as solar energy. Solar energy is cheapest source of energy which leads to a lot of attention and research in photovoltic cells. . In Pakistan, the average solar power potential is 1600,000MW while the sunshine duration is 3000 per year, which is equal to generating 30 million tons of oil equivalent (MTOE) [4][2]. Pakistan got 6th rank in the world of receiving most sun radiations and sunshine duration[8]. Pakistan receives an average sun global insolation of 5-7 KWh/(m2 /day) [9], which is much more than the worldwide average solar global insolation. In Pakistan, from Feb to Oct the solar radiation are promising and are more than 200 W/m^2. Solar radiation varies across Pakistan throughout the year, for example, from March to October in Baluchistan, February to October in Sindh, April to September in Khyber Pakhtunkhwa and Gilgit Baltistan, and March to October in Punjab. In every area of 100m^2 of southern Punjab, Baluchistan, and Sindh has a solar power potential of 45MW to 80 MW per month.The solar power generation in the southern part of the country is ideal with direct solar normal irradiance of 5 kwh/m^2 [8], as shown in figure 1-1.

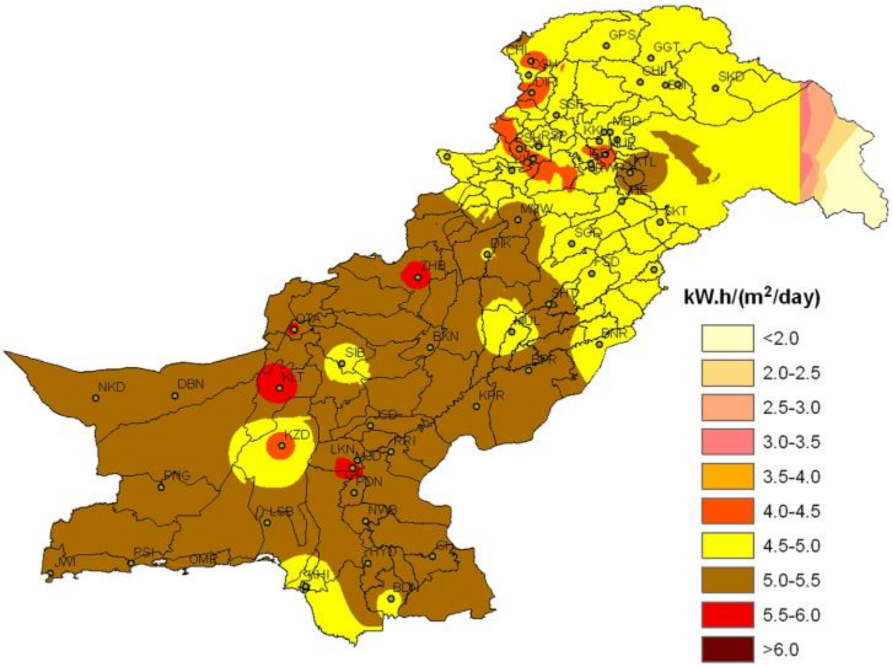

Figure 1-1 Pakistan solar potential map[8]

There are two methodes to convert the solar energy into useful useful power source.

- Photovoltaic conversion
- Solar Thermal conversion

In photovoltaics conversion, negative and positive holes are created in a PV cell at the moleclar level which produces electrical current [10]. For this phenomenon, the energy of photons of the sun radiations should be absorbed in the material of the cell. To absorb the photons energy, semiconductor is the best material due to their energy bands such as valence electron band and energy band. The valence energy band has electrons 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 band gap is the diffrence of energy between the electrons of two enegy bands. Photon energy ($E = h\upsilon$, h refers to Plank's constant and υ refers to Photon's frequency) is greater than the bandgap energy when falls on the PV module and is absorbed in the cell. When photons hits the solar cell it excites the electrons in the cell and move them to the conduction band from valece band. As an outcome, the valence band develops the pairs of positive holes. Using an external circuit, the electrons and holes in the conduction band and valence band are now separated, resulting in a potential difference between P-type and N-type semiconductors [10].

1.4 Novelty of the research

Due to a drop in solar PV module efficiency caused by a rise in operation temperature, current PV modules are unable to deliver nominal electrical output. Many active and passive cooling solutions for PV modules have been explored in the literature. Fins of various geometries are advantageous in boosting the efficiency and performance of PV modules by enhancing heat transmission [11]. The originality of this inquiry is to raise the efficiency of solar photovoltaic modules by boosting their electrical output. As a result, a passive cooling strategy was employed in this work to reduce the surface temperature of the monocrystalline solar photovoltaic module by attaching circular pin fins integrated with phase change material (PCM) to the rear side. The round aluminum pin fins were chosen due to their light weight, good thermal conductivity, resistance to corrosion, cheap cost, and market availability. The total bulk of the photovoltaic module with pin fins is a significant limitation that has an effect on the PV module's installation, mobility, and transportation costs. The staggered configuration of pin fins provides greater airflow channel which eventually increase the cooling effect.

1.5 Research questions

- How to design a heat sink which extracts residual heat from the PV module?
- What impact does PCM play in transferring heat from a PV module though fins?

1.6 Objectives

The primary goal of this study is to use circular pin fins combined with PCM mounted to the backside of the PV panel to reduce the temperature of a traditional PV module. Specifically, the following objectives will be focused on:

- Reduce the operating temperature of standard PV modules to boost their electrical output.
- To discover an appropriate and efficient solution to encapsulate the PCM in order to help improve heat transmission from the PV module.

1.7 Scope of this study

The goal of this research is to increase the electrical efficiency of a standard solar PV module in both residential and commercial settings.

1.8 Limitations of this study

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

- The experiments are performed on prototype
- This study is limited to the islamabad region only.
- A major issue in tranporation of these PV-PCM solar modules. The extended fins can damage the PV module during transporation
- The efficiency of PV-PCM solar module will be effected by cyclic reversability of PCM.

1.9 Organization of the thesis

Chapter: Introduction

Current energy scenario of Pakistan, problem statement, Pakistan's solar power potency, novelty of the research, research questions, objectives, scope of this study and limitations of this study.

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.

Chapter 3: Research methodology

The approach of study, block diagram of research methodology

Chapter 4: Experimental setup

Design, Modeling and fabrication Prototype and Experimental setup.

Chapter 5: Numerical Modeling

Initial and boundary conditions, Meshing, Model validation.

Chapter 6: Results and discussion

Experimental and numerical results.

Chapter 7: Conclusion, and Future work

Summary

The energy issue and the solar energy potential of south Asia, notably Pakistan, are briefly explored in this chapter. The energy mix sources with their related problems in Pakistan are addressed but due to the high potential for solar energy, solar energy has been focused. Photovoltaic are essential for turning solar energy into electricity. The goal of this research is to increase the PV module's electrical output efficiency by lowering its surface temperature.

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Chapter 2: Literature Review

2.1 Types of commercial photovoltaic (PV) modules

The purpose of the PV module is to produce electric power from solar thermal energy. PV modules are classified on the basis of module's material. Silicon and germanium are fundamental elements used in the manufacturing of PV module cells due to their semiconductor qualities[12]. PV modules are made up of these cells while assembling of numerous PV module forms a photovoltaic array. PV modules are classified on the basis of their manufacturing and application [12].

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

2.1.1 Monocrystalline silicon PV module

The term 'monocrystalline' refers to a single-crystalline solar photovoltaic module. These modules can be recognized by the black color of solar cells. The cells cut into a single silicon which is being used in the manufacturing of monocrystalline solar PV module and is almost 90% pure. When silicon molecules are perfectly aligned then it indicated the pure form of silicon. More pure material enhances the efficiency of converting sunlight to electrical energy. The most effective monocrystalline PV modules in the current market are operating at 22.8% [13].

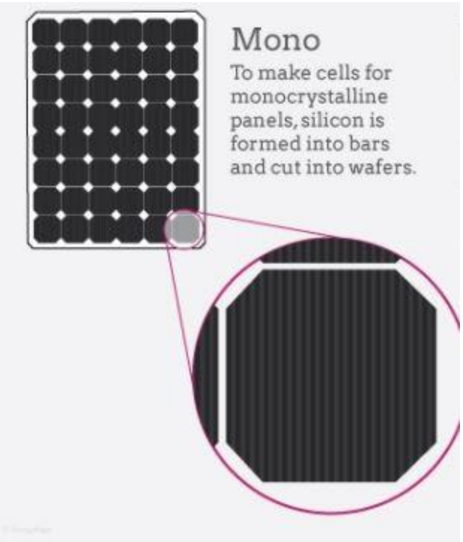

Figure 2-1 Monocrystalline PV module[14]

2.1.2 Polycrystalline silicon PV module

Polycrystalline modules are made of many pieces or fragments of silicon that is why it is called polycrystalline or multi-crystalline PV module. Polycrystalline is blue due the light reflecting from silicon fragments. Due to forced moment of electrons, the polycrystalline module has lower efficiency as compared with monocrystalline module thus the electrical output is less than the monocrystalline PV module of the equal description[14].

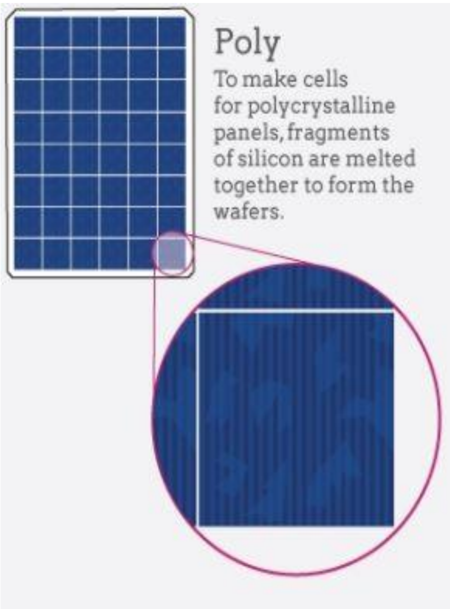

Figure 2-2 Polycrystalline PV module [14]

2.1.3 Thin-film PV module

The PV modules preferred for space projects are thin-film because of their lower weight and potable [15]. Thin-film PV modules are constructed from variety of semiconductor materials which are placed on each other creating a thin film [16]. The highest efficiency record in the world of thin-film module is 22.6% [17]. Thin-film modules are not expensive but still are not common for residential purpose because of their high space necessity for installations.

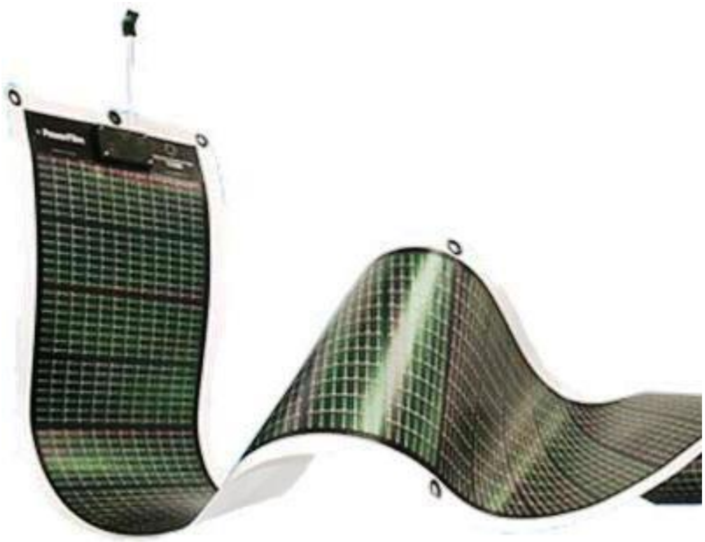

Figure 2-3 Thin-film PV module [18]

2.2 Significance of cooling in the PV system

The solar PV module transforms just a tiny fraction of incoming solar energy into electricity, while the bulk of it is used to heat the solar module [11]. Furthermore, raising the temperature of a solar PV module lowers the open-circuit voltage simultaneously enhancing the short-circuit current [11]. In addition to the standard module temperature of 25 °C, a 1.0 °C rise in PV module temperature affects outage voltage efficiency by 0.08–0.1% [6]. As a result, it is critical to cool solar PV modules in order to optimize their electrical efficiency. Additionally, life span of PV module decreases due to thermal stress caused by heating [19].

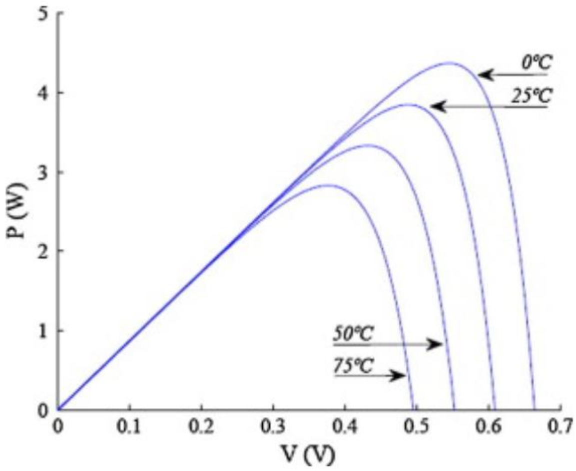

Figure 2-4 Significance of cooling [20]

2.3 Types of the cooling method in PV technology

To maintain the surface of a PV module closer to the specified working conditions, a variety of cooling methods are used. The methods of cooling are:

- Active cooling technique
- Passive cooling technique

2.3.1 Active cooling technique

The most prevalent cooling approach is active cooling, in which heat transfer fluids, such as liquid or air, are spread across PV modules to eliminate extra heat created by the PV modules. The heat transfer fluid, air or water, is circulated around the PV module using blowers or pumps [21]. Energy is consumed during circulation of heat transfer fluid. This energy is called parasitic energy [22]. 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 fundamental methods of active cooling. It is predicated on heat exchange through forced convection. A blower or fan is used to drive air over the surface of the PV module in air-based cooling. The extra heat from the PV module's surface is then absorbed by air, which may then be utilized for various heating applications [23].

Figure 2-5 Advanced air-based cooling technique [23]

2.3.1.2 Coolant spray technique

The coolant spray technique involves spraying water or another kind of coolant over the surface of the photovoltaic module. During peak hours, the cooling effect is caused by water evaporating from the surface of the photovoltaic module. This technology is very successful in cooling and self-cleaning the photovoltaic module, which results in an increase in the module's electrical output. Limitation of process is the coolant requirement which increases the capital and operational cost of the PV module.

(a) *(b)*

Figure 2-6 Water spray cooling method [24]

2.3.1.3 Backside water cooling technique

In this system, there is a continuous flow of water though pipes at the backside of PV module which removes residual heat from PV panel. Pipes can be arranged into different geometries depending upon the shape of PV module. According to [25], backside cooling water technique can increase the efficiency of Solar module up to 9% with the fall in temperature of 20%.

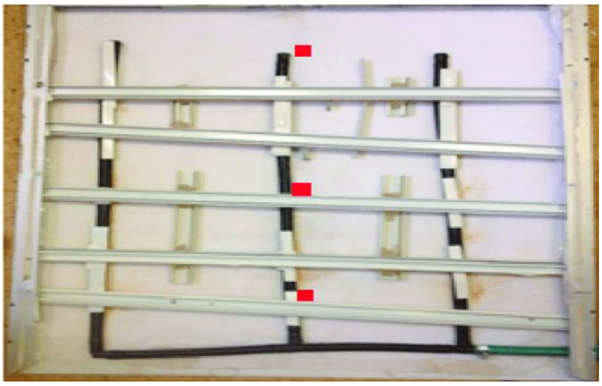

Figure 2-7 Backside water cooling system[26]

2.3.2 Passive cooling method

Passive cooling technologies, as opposed to active cooling, do not need any parasitic energy since heat is extracted by natural convection. Additionally, it has either very low or zero the maintenance cost related to active cooling [21]. The passive cooling technique is further subdivided into:

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

2.3.2.1 Fins attached to the backside of the PV module

Various passive cooling technologies reported in the literature may remove heat from the PV module. Attaching extended surfaces like fins to the solar module is one of the most frequent methods for eliminating heat. To optimize the electrical output, a comparative examination of L profiles fins of random and parallel arrangement mounted to the rear of PV module [27]. The random arrangement proved more efficient, with a 4.6 percent drop in cell temperature and a 2% gain in electrical efficiency. A recycled material with fins was used to enhance PV module performance in another study, resulting in a 22.7 percent decrease in solar PV module temperature and an 11.6 percent gain in electrical output [27] In an analytical model, aluminum fins with diameters of 2cm, 4cm, and 6cm were placed on the back of a PV module, resulting in a 4.16 percent increase in electrical output [28]. Another study used rectangular ribs with variable cross-sections to remove heat from PV panel temperatures, resulting in a 5.7°C reduction in solar PV module temperature and a 15.3 percent increase in output power [29]. Another experimental study was performed in which aluminum and copper fins were used to extract heat which resulted in the 12.03% increase in efficiency for aluminum fins and 12.029%

copper fin of PV module [30]. In a numerical simulation, fins were used as a heat sink at the backside of a PV module. The temperature was lowered to 8.62°C, and the efficiency was raised from 13.24% to 15.13% [31].

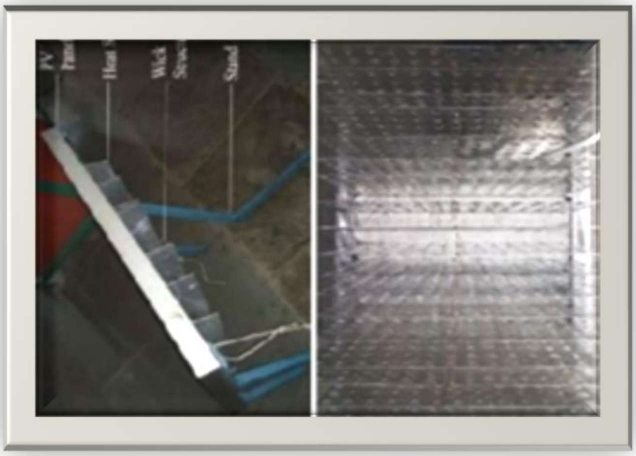

Figure 2-8 Different fins arrangements [27][30]

2.3.2.2 Using phase change material (PCM)

Heat sinks may also be heat storage units, such as phase change materials (PCM). During the day, this heat storage device may be connected to the solar module to harvest leftover heat. PCM with a low melting point absorb both sensible and latent heat from the cooling surface, which is favorable. A 20-mm-thick PCM slab with a 32°C melting point was placed to the back of a solar module in an indoor experiment, functioning as a heat sink and decreasing the module's surface temperature by 10°C [32]. Furthermore, when PCM TR24 was filled in copper tubes attached to the rear of a PV module, the fins collected residual heat and released it to the environment, increasing the electrical conversion efficiency by 3% [33]. According to another study, an experiment was performed to both hot and cold climate in which PCM with melting of 29℃ was used for passive cooling of PV module. PCM was shown to be more effective in hot climates than in cold climates [34].

For the use of PCM for any system, two important factors should be considered

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

PCM selection for passive cooling is a primary requirement. The melting point of PCM should be in the range of working temperature. PCM is more effective if the melting point of PCM and hottest day temperature difference is 10℃ PCM must be able to absorb as much heat as feasible, which necessitates a high specific heat capacity and a high latent heat of fusion. For charging and discharging of PCM, it should have uniform and high thermal conductivity. PCM should be cost effective, chemically stable and most important inflammable [35].

Summary

PV module types such as monocrystalline PV modules, polycrystalline PV modules, and thin film PV modules are briefly reviewed in this chapter. This section discusses the advantages of cooling PV modules to increase output power. PV modules can be cooled in one of two ways. Passive cooling does not require any external force such as the installation of a heat exchanger, but active cooling requires some external force such as a fan and water.

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Chapter 3: Research Methodology

In this chapter, the fundamental methods for conducting numerical simulation and the experimental process are briefly explained. The experimental study is divided into three parts, theoretical study for passive cooling of PV-PCM, designing and assembling of respective system. The theoretical study entails the literature evaluation bases on already published research regarding cooling of conventional PV modules especially PCM based passive cooling. The geometry, size, and structure of the heat exchanger connected to the rear surface of the solar PV module are all part of the prototype construction. The experimental investigation is exclusively based on real-time data collected using all of the necessary equipment and systems for obtaining thermal characteristics such as global horizontal irradiance, ambient temperature, and air velocity. PCM selection for the system to absorb residual heat depends on its availability in the market, cost and effectiveness. The results of the experiment are accumulated within the shape of datasheet after which these trends are converted to the graphical form for evaluation. Then numerical simulation approach is performed to study the heat transfer through fins from PV module. The numerical model is validated for detailed comparison to study the different analysis on PV module. Final conclusion has been made by achieving all the milestones.

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.

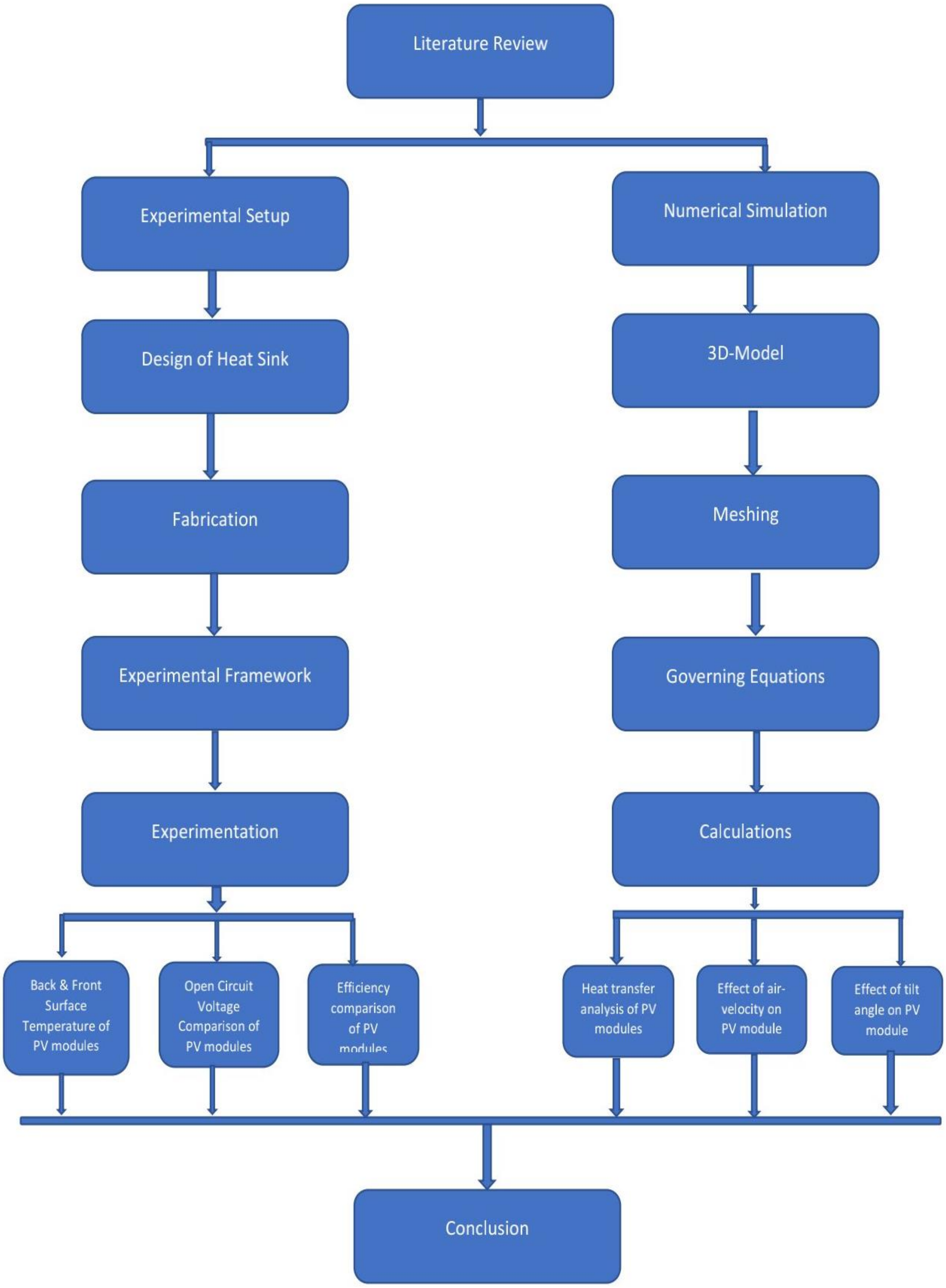

Figure 3-1 Overall research methodology

3.1.1 Literature review

The various cooling techniques used for photovoltaic modules, including active and passive cooling, were examined through a review of the literature. These strategies were investigated separately in order to gain better insights of the heat transfer process and its relationship to photovoltaic modules. From the literature review, a passive cooling method of circular fins integrated with PCM is used in this research work.

3.1.2 Prototype fabrication

In this section, the monocrystalline PV module is modified by assembling circular fins. This fabrication was done by following steps:

- Design of heat exchanger for PV module
- Selection of fin material
- Fabrication of proposed design on PV module
- Selection of PCM and encapsulation

The proposed designed of circular fins geometry and dimensions were assembled at the back of solar module. Fins were welding together on a rectangular plat with staggered arrangement. As seen in figure 4-1, three rectangular plates with proposed fins were constructed on the rear surface of the solar module. The proposed heat exchanger was designed in the workshop of USPCASE NUST discussed in the next chapter. From the literature review and market survey, Petrolatum or soft paraffin was chosen as PCM. The PCM was melted with thermal gun and then encapsulated into the circular fins.

3.1.3 Experimental setup and climate data

The experiment was undertaken on the roof of the US-Pakistan Center for Advanced Studies in Energy (USPCASE), located at NUST in Islamabad (33.642364°N, 72.984290°E). The experimental site's meteorological station provided the weather data for the days of the experiment.

3.1.4 Experimentation

The experiment was conducted on different sunny days of November 2020. In this experiment, the modified PV module with circular fins integrated with PCM was compared with unmodified PV module of same specifications. The PCM used in this study was selected on the experimental condition, its obtainability, cost and effectiveness. Results are briefly discussed in the next chapter.

3.1.5 Numerical Model

The numerical model of modified module with circular fins integrated with PCM and unmodified PV module was constructed in Ansys-Fluent. The effect of air flow on solar modules was studied by different outdoor experimental condition such as temperature, Global horizon irradiance (GHI), Wind speed etc. It is critical to acquire accurate numerical simulation meshing results. Meshing depends upon the grid size which was chosen from literature review. The results deducted from the numerical simulation are discussed in next chapter.

Summary

The experimental and numerical methodologies utilized to perform the investigation are discussed in this chapter. After a comprehensive analysis of the literature, the heat sink was created. Fin materials and PCM are chosen based on marketability, as well as thermochemical and physical properties. This experiment was carried out at NUST's USPCASE. The numerical model is created, and the findings are verified using outside testing conditions.

Chapter 4: Experimental Setup

4.1 Modification of the conventional PV module

The experimental study is conducted using 10-watt monocrystalline solar PV modules. The electrical characteristics and dimensions of PV modules are listed in table 4-1. To compare the thermal performance of solar modules, the following comparisons were made:

- Modified PV module with circular fins incorporated with phase change material (PCM).
- Unmodified PV module

Aluminum was used for the round fins because of its excellent heat conductivity, availability, and inexpensive cost [36]. The properties of aluminum fins are listed in table 4-1. On a rectangular aluminum sheet, these fins were welded together. Three sheets were assembled at the back surface of PV module. The diameter of each fin is 1.27 cm and the spacing between fins is 7.3 cm. The length of each fin is 5.08 cm. For better efficiency of fins, staggered arrangement is preferred over in line arrangement because air does not get a straight route[37].

Figure 4-1 Circular fins attached on the back of the PV module

To inject PCM into the fins, fins were drilled with a drill bit of 0.508 cm to depth of 3.81 cm. Hollow fins are less efficient but they are cost effective. At room temperature 27℃, PCM named Petrolatum or soft paraffin was in solid-state. The properties of Petrolatum (PCM) are mention in table 4-2. To pour the PCM into the fins for effective heat transfer, PCM was melted to liquid-state in a glass beaker with the help of heat gun as shown in figure 4-2. Each fin contains 0.005gm of PCM.

Figure 4-2 Drilling of fins and encapsulation with PCM

PCM was not entirely poured into the fins; 10% of the capacity was left to allow for thermal expansion during the melting process. On the back surface of the PV module, fastens were used to attach the aluminum circular fin geometry with staggered arrangement.

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 Watt
Maximum voltage (V_{max})	18 Volt
Open-circuit voltage (V_{oc})	21.24 Volt
Electrical efficiency at STC	15.3 %
Dimensions	(279.4×333×12.7) mm^3
Weight	1.1 Kg
Properties of aluminum circular fins	
Number of fins	20

Length	5.08 cm
Outer diameter	1.27 cm
Inner diameter	0.508cm
Spacing between fins	7.3 cm
Density (ρ)	3.2×10^4 (kg/m^3)
Thermal conductivity (K)	205 (W.m^{-1}. K^{-1})

Table 4-2 Properties of petrolatum

Properties of ($C_{15}H_{15}N$) Petrolatum	
Commercial name	Petrolatum/Soft Paraffin
Melting point (℃)	37
Thermal conductivity (W/m.K)	0.11
Specific heat capacity (kJ/kg K)	0.117
Density(kJ/m^3)	900

4.2 Experimental framework

The experimental framework is made up of the following components:

- Monocrystalline PV modules, one modified and other unmodified
- 12 K-type thermocouples with a tolerance of ±0.5℃
- 12-Channel data logger
- Digital multimeter (DMM)
- Pyrometer, and Anemometer installed at USPCASE NUST weather station

Table 4-3 Specifications of instruments

Sr. No	**Equipment Name**	**Measuring Range**	**Error & Accuracy**
1	K-type Thermocouple	(-40 to 260) ℃	± 0.5 ℃

2	Anemometer	(0 to 25) m/s	5% Accuracy
3	Pyranometer	(0 to 2000) W/m^2	±10 W/m^2
4	Multimeter (Dc Voltage)	400 mV to 1000 V	±(0.5% + 5)
	Multimeter (Current)	40.00 uA to 10 A	±(0.8% + 3)

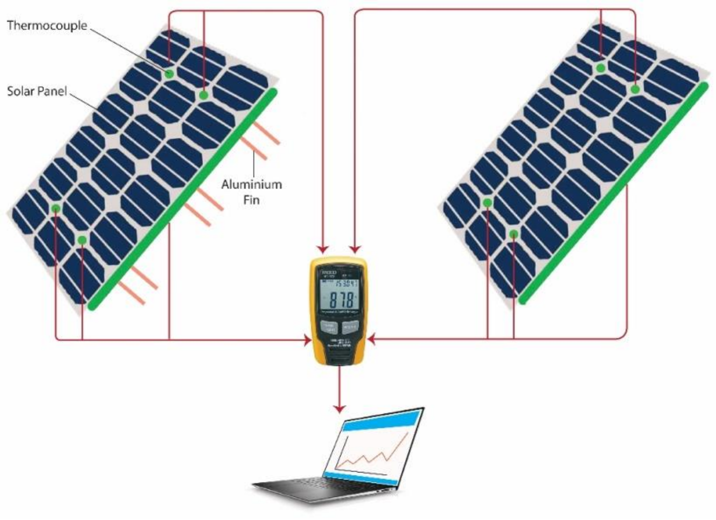

Figure 4-3 Schematic configuration of experimental configuration

The PV modules were mounted on an aluminum frame with a 45^o tilt angle to the ground, facing south-east. The measuring range and error percentage of equipment are mentioned in table 4-3. To detect the surface temperature of each PV modules, twelve k-type thermocouples were fitted. Figure 4-4 shows how these thermocouples were attached on both the front and back sides of PV modules. Four thermocouples were attached on the front of each PV module while 2 were attached on the rear side. A 12-channel data logger was used to record the temperature of each thermocouple by a time interval of every 10 mins. Data was recorded on different sunny days of November.

To precise the readings of the experiment, few safety measures were taken such as:

- Adhesive tape was used to secure the thermocouples on the rear and front sides of the PV module.
- Before beginning the experiment, all of the equipment (data logger and DMM) was reset.

- For protection and accuracy, data logger was placed in the shade
- PV modules were placed under the no shading area and with proper air circulation during the interval of the experiment

Figure 4-4 Experimental setup

4.3 Numerical equations of important parameters

Sun radiations falls on the solar PV module, only 15-20% are converted into electricity while remaining are being converted into heat[38]. A passive cooling system is planned for the rear of the PV module to improve its efficiency. Therefore, heat is transferred to the fins by convection heat transfer. The heat transfer from fins is computed by fin's effectiveness. It is represented in equation (1)

$$\varepsilon = \frac{\dot{Q}_{fin}}{\dot{Q}_{nofin}} = \frac{nh_{unfin}A_{unfin}(T_{s,unfin}-T_{env})+nh_{fin}\eta_{fin}A_{fin}(T_{s,fin}-T_{env})}{h_{nofin}A_{nofin}(T_{s,nofin}-T_{env})} \quad (1)$$

$$\varepsilon = \frac{n(A_{unfin}+\eta_{fin}A_{fin})}{A_{no\,fin}} \quad (2)$$

The above equations show that if the value of ε < 1 then fins will have negative effect i-e fins will act as insulation. If the value is ε is unity e.g. ε = 1, then fins will have no contribution in the heat transfer such as$\dot{Q}_{fin} = \dot{Q}_{nofin}$. When ε > 1, then fins are operational and increase the rate heat transfer. For the current study, the value of e is greater than 1 i-e e = 1.32. This value can be calculated by putting the values in equation (2) such as $A_{unfin} = 1.26610e-4\ m^2, A_{fin} = 1.215e-3\ m^2, A_{nofin} = 0.092204m^2, n = 20, n = 0.86426$. The results show that

$$\varepsilon = \frac{\dot{Q}_{fin}}{\dot{Q}_{nofin}} = 1.32 \quad (3)$$

Equation (3) shows, the rate of heat transfer from PV module due to fins is 1.82 times greater from the PV module without fins. Fins are effective and increased the rate of heat transfer up to 32%.

4.4 Climate data of the experimental site

The experiment takes place on the roof of the US-Pakistan Centre for Advanced Studies in Energy (USPCASE), which is part of NUST in Islamabad (33.642363°N, 72.984291°E). The ambient temperature, wind speed, and global solar radiations are among the climatic data collected at the test site. The climate data is collected from 9:00 to 17:00 as shown in figure 4-5, as the experiment was performed during these hours of the day. The average ambient temperature recorded was 27.3 ℃, with a minimum and maximum value of 19.5 ℃ and 32 ℃, respectively. Similarly, the average wind speed during experimental hours was 1.7-m/s. Furthermore, throughout the studies, the global horizontal irradiance averaged 710 W/m^2 with a high of 810 W/m^2.

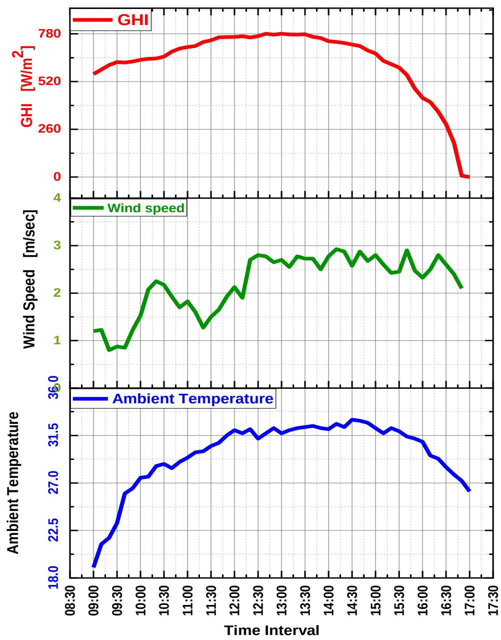

Figure 4-5 Averaged climate data of the two weeks of experimental time

Summary

The design and fabrication of PV modules are briefly discussed. In the first section, fins material and type of PCM, for the desired geometry of heat sink are selected on the basis of their characteristics. Equipment used in the experiment is illustrated in detail. Moreover, the framework of the experiment and climate data of the site is figured in this chapter.

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Chapter 5: Numerical Modeling

5.1 Numerical model

The numerical analysis is utilized to assess the fins' thermal performance mounted to the rear side of the solar photovoltaic panel. To briefly investigate the passive cooling method, a numerical model is created to study the influence of airflow and angle of attack on the solar PV module under average experimental circumstances i-e temperature, GHI, and velocity, etc. The general equations of convection heat transfer from the fluid mechanics were used in this model. The mathematical model is solved using basic continuity, momentum and energy equation of Ansys-fluent. This model uses finite volume method. Table 5-1 lists the material parameters of solar PV modules.

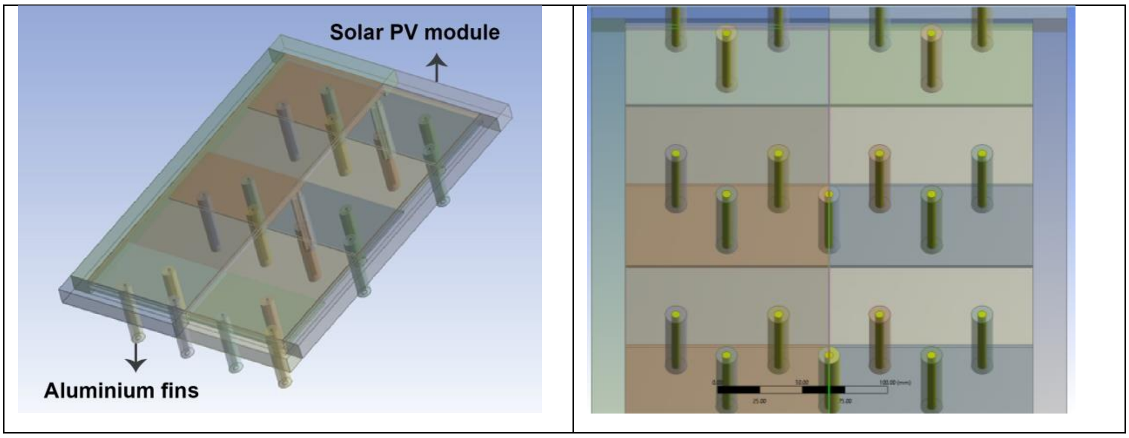

Figure 5-1 3D model Solar Panel with attached fins

Table 5-1 Material properties of solar module [39]

PV Layers	Material	Thermal Conductivity (W/m.K)	Specific Heat Capacity(J/kg.K)	Density(kg/m3)
Top Cover	Tempered Glass	2	500	2450
Encapsulated	EVA	0.311	2090	950
PV Cell	Silicon	130	677	2330
Bottom Cover	Tedlar	0.15	1250	1200

5.2 Mathematical modeling

A 3D-mathematical model is solved by using a basic energy equation. The major part of the solar radiation is absorbed by the PV-PCM system and some part of solar radiation is attributed to radiation and convection heat transfer to the ambient. Firstly, the thermal component of the solar radiation is transferred through the PV module in conduction mode and transferred to the PCM where the accumulation of heat takes place. The stored heat in the PCM is transferred through the cylindrical surface and transferred to the ambient [40].

The conduction heat transfer through the PV module is governed by the equation (4)[40], [41]

$$\rho C_{ps}\frac{\partial T_s}{\partial t} = \nabla(k_s \nabla T_s) \qquad (4)$$

The term ∇Ts in equation (4) refers to the temperature gradients between the solidus layers of the PV module, where Cps and ks indicate specific heat capacity and thermal conductivity of the PV module, respectively.

The phase change problem in the light of the cylindrical geometry of the rods is solved by using the enthalpy porosity method discussed by [41], [42].

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{u} H) - S = \nabla(k \nabla T) \qquad (5)$$

The 3-dimensional form of equation (5) will be

$$\frac{\partial}{\partial t}(\rho H) + \frac{1}{r}\frac{\partial}{\partial r}(\rho r \vec{u} H) + \frac{\partial}{\partial z}(\rho \vec{v} H) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}(\rho \vec{w} H) - S$$
$$= \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k\frac{\partial T}{\partial \varphi}\right) \qquad (6)$$

In equation (6), the term ρ refers to the density, u,v, and w are the velocity vectors along with r and z-direction, respectively. k is the thermal conductivity, H is the total enthalpy, and the term S is the source term or source heat inside.

The total enthalpy ΔH in the heat balance equation involves the sensible and latent enthalpy as shown in equation (7):

$$H = h + \Delta H \tag{7}$$

The sensible enthalpy h in equation (7) can be written as follows:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p \Delta T \tag{8}$$

where href in equation (8) indicates the reference enthalpy at Tref, and Cp refers to the specific heat. The term H for latent enthalpy change is shown below in equation (9):

$$\Delta H = \beta L_h \tag{9}$$

For solid and liquid the latent enthalpy changes from zero to Lh, whereas the term β refers to the liquid fraction indicating the phase transition b/w liquid and solid when the PCM's temperature is Tsolid < T < Tliquid as shown in equation (10)

$$\beta = \begin{cases} 0 & if\ T < T_s\ , \\ \dfrac{T - T_s}{T_1 - T_s} & if\ \ T_s < T < T_l\ , \\ 1 & if\ \ \ T < T_l . \end{cases} \tag{10}$$

The internal heat term S in equation (11) can be written as:

$$S = A_{mush} \frac{(1-\beta)^2}{\beta^3 + \varepsilon} \vec{u}, \tag{11}$$

where A_{mush} in equation (11) indicates the mushy zone constant, its higher value indicates the harder transition of velocity to zero as the solidification of PCM occurs. The small-term ε prevent the source heat from the division of zero. As far as the accuracy of the energy balance is concerned in fluent the residual monitor of energy starts from above the second-order (1e-02) and increase up to the first order in the first few iterations after that it is reduced up to sixth order because the criteria are set up to sixth order of magnitude and typically the convergence up to sixth order (1e-06) is acceptable.

5.3 Initial and boundary conditions

Initially the solar PV module temperature base temperature is 30℃ and its surface temperature is 35℃. The inlet conditions are assumed according to the average experimental conditions i-e V_{air} = 3.7m/s, GHI = 761W/m^2.The majority of heat transfer is anticipated to take place along the PV module's length. The initial and boundary conditions stated below are used to solve the numerical model:

i. At t = 0

$T_i = T_{fins} = T_{pcm}$ = 27℃

ii. Inlet temperature at t > 0

T_{wind} = 31.2℃

iii. $T_{f,sur}$ = 35℃, $T_{b,sur}$ = 30℃

5.4 Mesh independence

To evaluate the accuracy of numerical model, it is essential to validate the independence of grid size [43]. A grid independence test was performed in this study to ensure that the findings produced from numerical simulation are independent of mesh size. Different grid sizes were employed such as G-1= 0.001m, G-2= 0.0011m, G-3= 0.0012. There is great divergence of grid size G-3= 0.0012 as shown in figure 5-3. The grid size G-1= 0.001 shows more improved and precise results. In order to maintain the calculation accuracy, the grid size of 0.001m is selected to perform the numerical simulation.

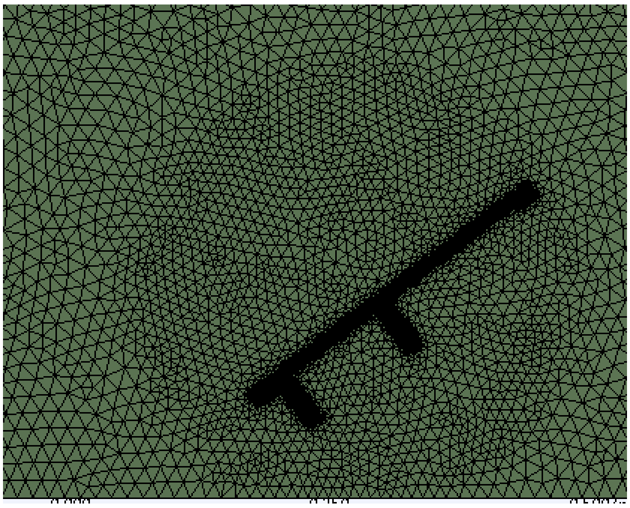

Figure 5-2 Meshing of photovoltaic module with fins

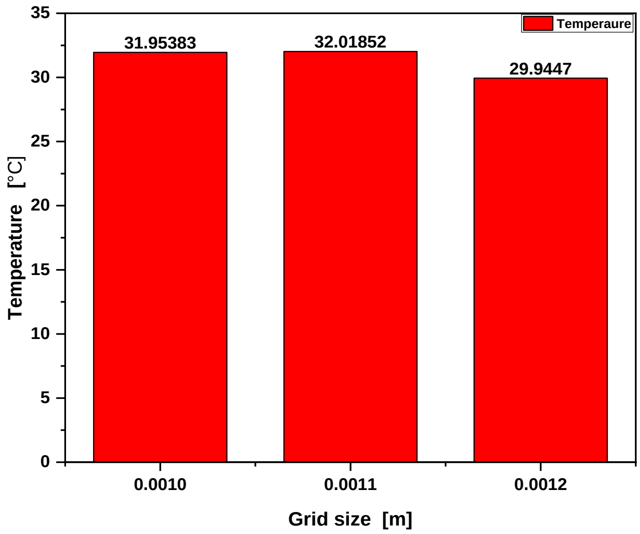

Figure 5-3 Temperature of tedlar wall for different grid sizes

5.5 Model validation

This section validates the numerical model against experimental data. The rear film wall temperature is taken as the Tedlar wall temperature. The temperatures in the numerical simulation are considered as the PV module's average wall temperature. Figure 5-4 depicts the back wall temperature measured both experimentally and numerically for the solar PV module.

At 12:30, the maximum error of 14.6% is recorded with average rear surface temperature of 41.7℃ for simulation and 35.5℃ for experimental results. Additionally, the minimum error is 5.2% with average temperature of 32.5℃ for simulation and 30.8℃ for experimental results. The average percentage error between experimental and numerically evaluated results is 11.7%.

This error difference is due to following factors

- Outdoor experimental conditions were varying continuously in a very short interval of time as compared to numerical simulations
- Small errors in thermocouples were also effecting the results
- Charging discharging time of PCM changes during cyclic reversibility
- Since no thermal paste was employed, there were small gaps between the back surface of the PV module and the rectangular aluminum plate with welded fins.

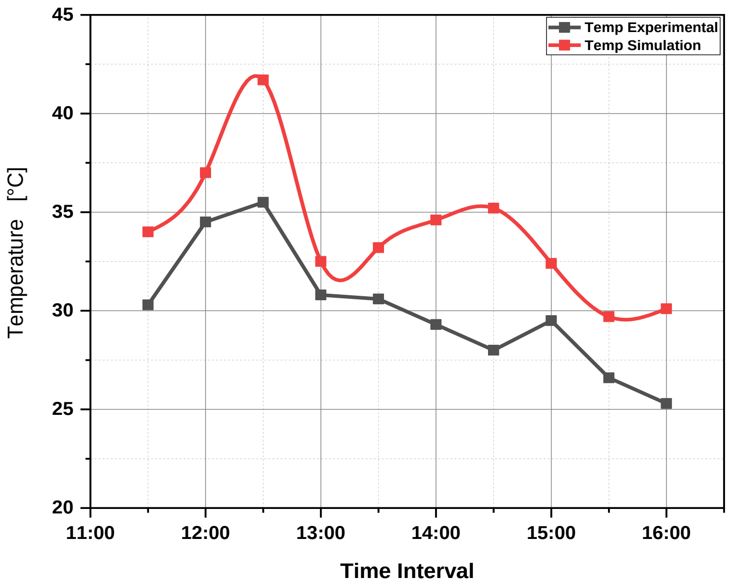

Figure 5-4 Model validation using experimental and numerical data

Summary

The numerical model is constructed for numerical simulations. Additionally, the initial and boundary condition of this numerical model are subsequently discussed. Furthermore, the numerical model is validated which shows the percentage error of 11.7% with experiment results.

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Chapter 6: Results and Discussion

6.1 Experimental results

This section looks at a variety of features of solar modules with and without fins that have been reported. The effect of fins on the front and back surface temperatures of photovoltaic modules, as well as their open-circuit voltage and efficiency, are among these parameters. As previously stated, the temperatures are averages of the temperatures acquired from the thermocouples installed on both sides of the solar module.

6.1.1 Effect of circular fins on PV module with PCM

According to Newton's law of cooling, circular fins increased the convective heat transfer area of the modified PV module. Figure 5-1 refers to the front and back surface temperature of PV modules with fins and without fins i.e., ΔT_{back} = (Tno fin)back − (Tfin)back and ΔT_{front} = (Tnofin)front − (Tfin)front.

The highest point of the curves on the front and back sides of photovoltaic modules (PV modules) reflects the greatest temperature reduction once fins are installed, as shown in Figures 6-1. The average temperature drop of the front surface for the whole day is $(\Delta T_{avg})_{front}$ = 3.02 ℃. The average values for temperature gradient are taken from 11:24 to 16:08

Additionally, the largest temperature differential measured on the backside of a modified photovoltaic module is 6.80°C and the minimum value is 0.10℃ because the PCM within the fins begins melting into liquid form and has a greater temperature than the front side of the PV module, this is a key period for PCM. The average temperature drops at the rear surface of the PV-PCM module is $(\Delta T_{avg})_{back}$ =5.18℃. Therefore, the modified PV module is 5.18℃ cooler the unmodified.

Moreover, the heat exchanger was working perfectly at the beginning but once the PCM reached its latent heat capacity and melted then it has a negative effect as the melted PCM started to transfer its latent heat energy to the PV module. Therefore, the temperature gradient between the modified and unmodified PV modules started declining.

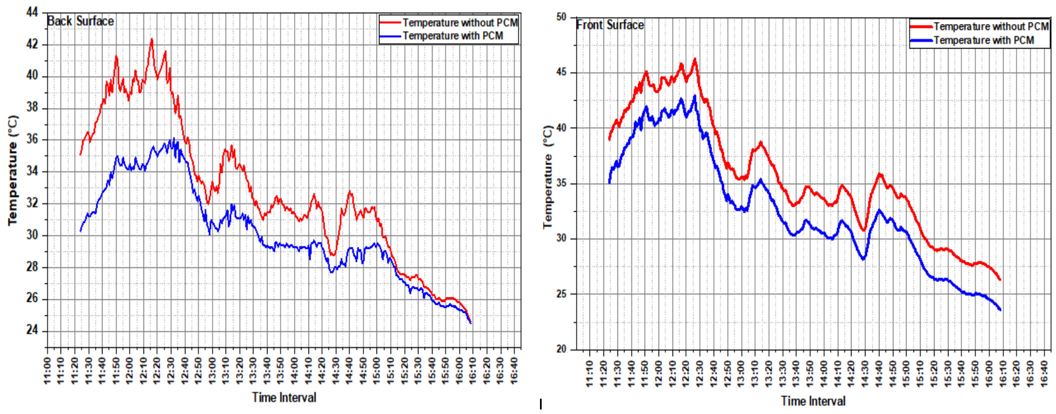


Figure 6-1 The temperature difference between PV module with and without fins

6.1.2 Effect of fin on open-circuit voltage of PV module

From the literature, open circuit voltage is the potential difference of the two terminals of the PV module when they are not connected to any circuit or load. In addition, a 1℃ increase in PV cell temperature results in a 0.4 percent loss in voltage [44]. The open-circuit voltage decreases as the inherent carrier concentration in the conduction band increases [45], from equation (9)

$$V_{oc} = \frac{kt}{q} \ln\left[\frac{(N_a + \Delta n)\Delta n}{n_i^2}\right] \tag{14}$$

Na and Δn in equation 11, indicates the doping concentration and residual concentration carrier while n_i refers to the intrinsic carrier concentration which is equivalent to the number of electrons in the conduction band or holes in the valence band of the intrinsic molecule of the PV module.

In present study, the average output voltage after the installation of PCM circular fins is 18.0V. Furthermore, the average output voltage of the PV module without fins is 16.9V as shown in figure 6-2. The average rise in open-circuit voltage is 1.1v

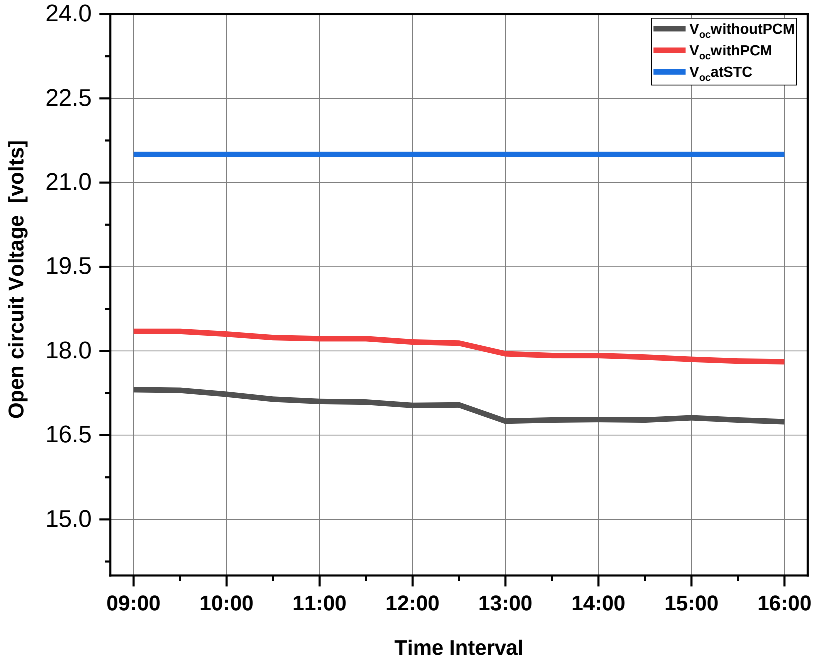


Figure 6-2 Electrical improvement of open-circuit voltage

6.1.3 Effect of fins on electrical output efficiency

Temperature effect on the efficiency of PV module is expressed as

$$\eta_{PV} = \eta_{ref}\left[1 - \beta\left(T_{PV} - T_{ref}\right)\right] \quad (15)$$

$$\eta_{PV-fins} = \eta_{ref}\left[1 - \beta\left(T_{PV-fins} - T_{ref}\right)\right] \quad (16)$$

In the above equation, η_{ref} and T_{ref} shows the nominal out efficiency and operating temperature of PV module at Standard Testing Conditions (STC). β Symbolizes the temperature coefficient of the PV module depends upon the material of PV module. The value of β for the monocrystalline PV module is -0.44 %/℃ [46].

The efficiency of photovoltaic modules in terms of electrical output is estimated using the equation (15, 16). As seen in Figure 6-1, the PV-PCM module has greater efficiency than the PV module without fins. The module's efficiency rises as the ambient temperature drops. The curve of ambient temperature and efficiency of solar module goes in the opposite direction with rising and fall of temperature. Figure 6-3 shows that in the evening, the efficiencies of both PV modules are nearly equal since the PCM are entirely melted, causing the heat to be emitted in a backward manner towards the PV module. The efficiency of the photovoltaic module with fins is increased by 2.9% when compared to the photovoltaic module without fins. The technique is technically capable of recovering leftover heat from the photovoltaic module.

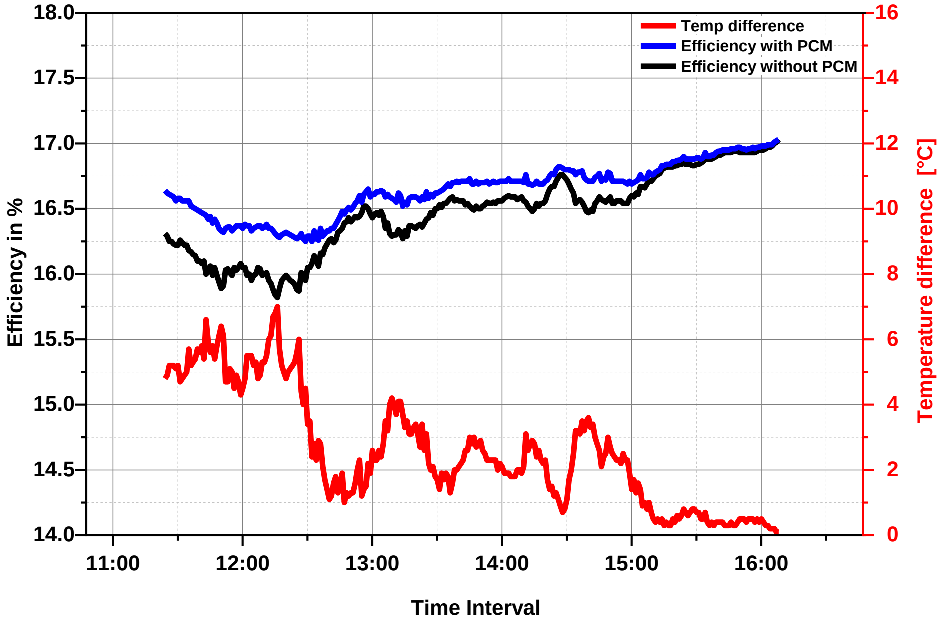


Figure 6-3 Efficiency of PV module with and without fins

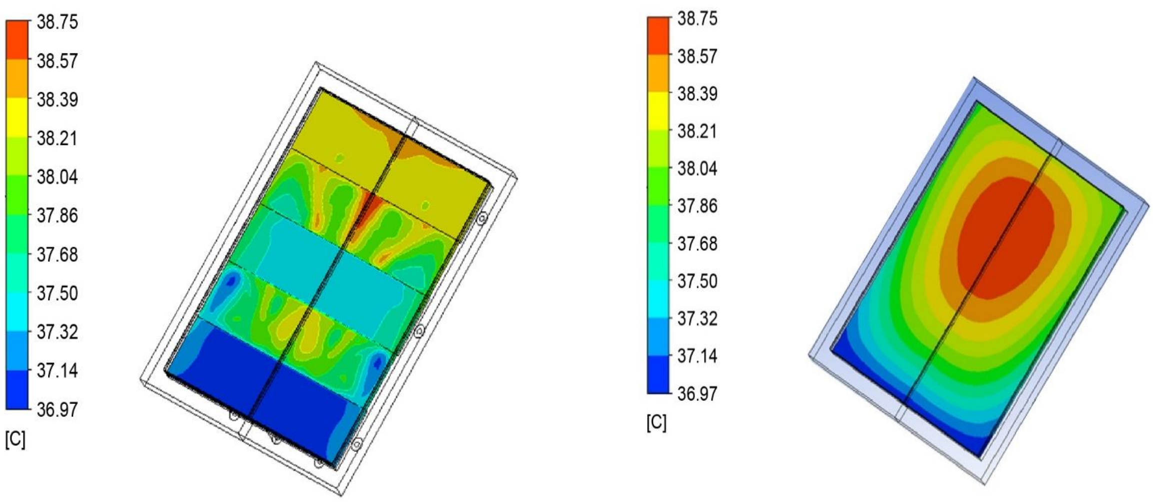
6.2 Numerical results

To better understand the heat transfer mechanism and the impact of air velocity and angle of attack on the temperature of the PV module, a numerical performance study of the PV module is performed.

6.2.1 Temperature distribution of tedlar wall

The tedlar wall and back film temperature are the same as discussed in the earlier section. The numerical results shows the average tedler wall temperature of solar panel without fins is 38.05 ℃ whereas with fins the average temperature is 36.01℃.The temperature drop of modified and unmodified PV module is 2.04℃.

Figure 6-4(a) shows the temperature distribution over the entire surface which indicates the heat is distributed and extracted due to the attached fins while a concentrated heat spot exists in the upper center of the unaltered PV module [47]. Because solar radiation is stronger near the middle of the PV module, the temperature there is higher. When compared to no fin, the average decline in tedler wall temperature of improved PV modules is 2.04°C.



(a) *(b)*

Figure 6-4 Comparison of tedlar wall temperature between fin and unfinned PV module

6.2.2 Temperature profiles of fins

PCM has a melting point of 35°C, which was employed in this experiment. Figure 6-5 depicts the temperature distribution of PCM-filled fins mounted to the rear side of a solar PV module. The fin's temperature is higher than the tedlar wall of solar panel because heat is extracted from the tedlar wall as discussed earlier. As the temperature of fins rises above the melting point of PCM, the PCM inside the fins changes its phase. Fins are arranged in staggered arrangements for maximum sideways air contact. Fins at the top of solar panel have maximum temperature i.e. 41.5.0 ℃ while at the bottom the fins temperature is 38.5 ℃. It is because the dissipated heat is more on the top frontal face of the PV module.

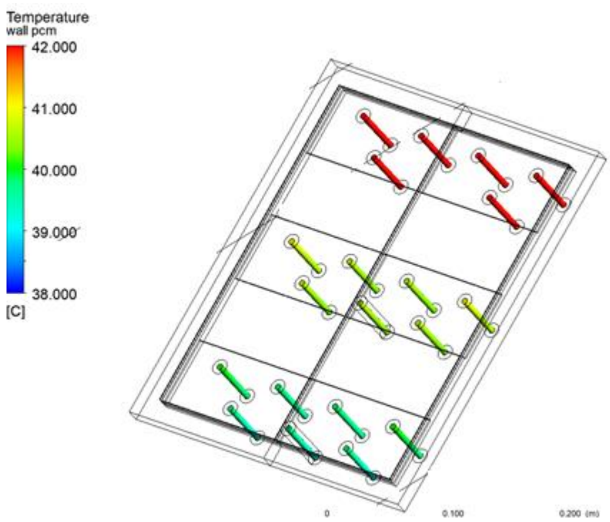


Figure 6-5 Fin`s temperature

6.2.3 Effect of wind speed

Different air velocities were utilized to evaluate the influence of air velocity on PV module temperature while maintaining all other factors constant, such as ambient temperature and GHI. The air is flowing at a 45-degree angle.

Under low air velocity i-e (*v = 3.3 m/s)*, the temperature of solar module is 39.9℃ and at *v = 3.7 m/s*, the temperature of solar module reaches to 39.5℃. By further increasing the velocity i-e (*v = 4.1 m/s)* the forced convection around the module increases resulting in a further fall in the apparent temperature of the photovoltaic module, which is 39.2°C. According to the modelling findings given in figure 6-6, when the air velocity rises, the temperature of the PV module with fins decreases.

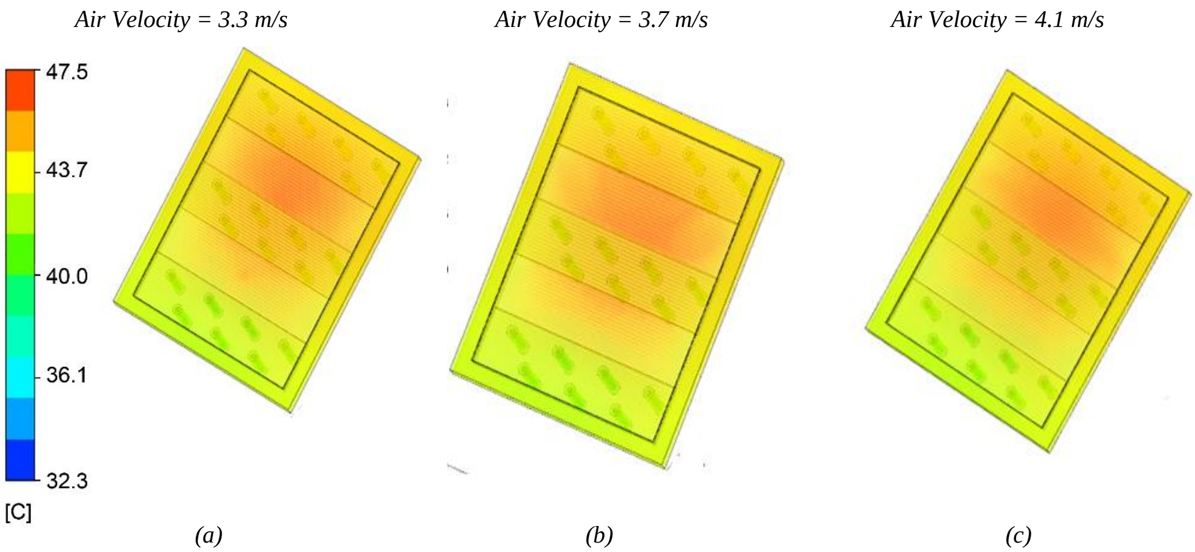


Figure 6-6 Different velocities distribution profiles on solar PV module

6.2.4 Angle of attack

In this section, the angle of inlet air velocity on the PV module is examined by keeping the other parameters constant such as velocity and GHI. The magnitude of air velocity remained constant (3.7m/s). If the air velocity angle is 30^o, then the temperature of PV module is 40.1℃ and when inlet air angle is increased to 60^o, the temperature of PV module is 39.1℃. By further increasing the angle to 90^o, heat transmission from the PV module's surface rises, and the surface temperature drops to 38.3°C as illustrated in figure 6-7. It is determined that altering the angle of incoming air velocity affects the temperature of PV modules.

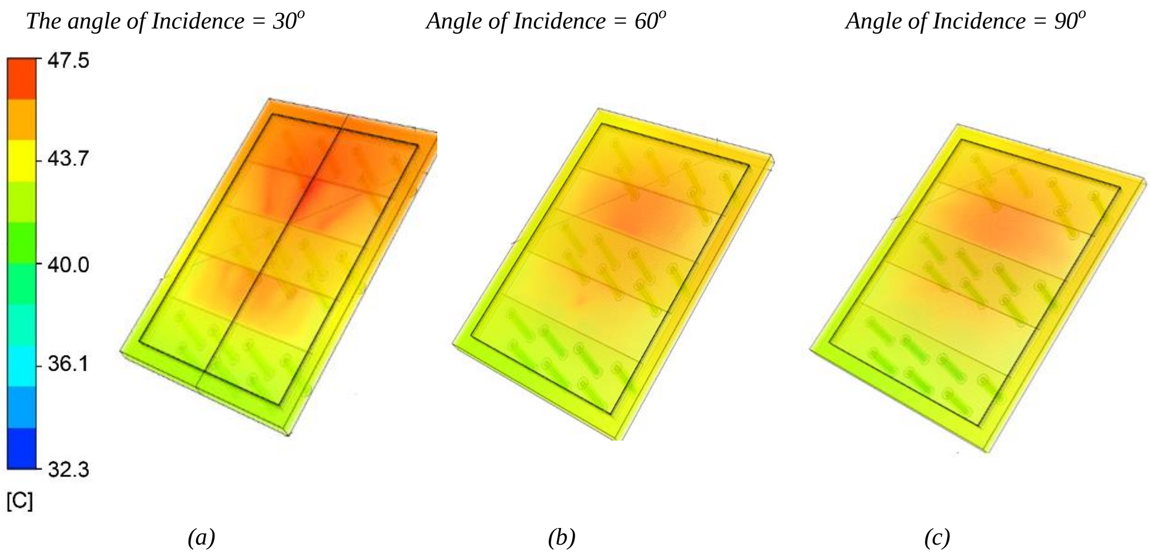


Figure 6-7 Air velocity at different angle of attack (A) 90 (B) 60 (C) 30

6.2.5 Analogy between the already published and current Study

In terms of the various characteristics stated in table 5-1, this section compares several research for a passive cooling approach of the solar PV module. The average drop in temperature of the current study is greater than Ref [31] [48] and [49]discussed in the literature. The average temperature drop of Ref [50] is higher but its efficiency is lower such as 0.8% as compared with present results i-e 2.9%. Ref [50] employed PCM to cool PV modules, has higher efficiency as compared with all other cooling method while all other studies has used aluminum fins for the cooling PV module. The current study is different because it is a combination of both aluminum fins and PCM.

All of the research in Table 6 aim to improve the performance of solar PV modules by lowering their temperature using various heat sinks.

Table 6-1 comparison with already published research and current study

Parameter	**Current study**	**Ref**[31]	**Ref** [48]	**Ref** [51]	**Ref** [49]	**Ref** [50]
Study type	Experimental and numerical	Experimental and numerical	Experimental	Experimental	Experimental	Simulation
Region	Islamabad, Pakistan	Busan, Korea	Madras, India	Vehari, Pakistan	Islamabad, Pakistan	Surakarta, Indonesia
Cooling method	Aluminum circular fins integrated with PCM	Iron and aluminum mesh	PCM	PV-PCM with alumunium fins	Aluminum hollow rectangular fins	Aluminum base plate with perforated fins
GHI(W/m^2)	761	1000	750	950	718	1000
Temperature drop (℃)	5.18	1.53	3.8	12	4.5	13.1
Efficiency (%)	2.9	1.44	4.2	0.8	2.08	0.8

Summary

The experimental and numerical results are subsequently discussed in this chapter. In the first section, experimental results of temperature difference between modified and unmodified PV module, voltages of PV module and their efficiency are graphically debated. In the second, angle of attack of air and influence of air on PV module is numerically studied.

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Chapter 7: Conclusion and Recommendations

7.1 Conclusion

In this work, a passive cooling method is used by attaching fins combined with phase change material. PCM-filled fins installed to the back of a PV module lower the temperature by 5.18°C when compared to an unaltered reference module. During the busiest times of the day, the output voltage of the PV module is 0.53 volts, and heat sinks are found to be useful in extending this value. The results also reveal a 2.9% improvement in efficiency. Pin fins are shown to transmit heat from the solar plate to the surrounding environment in numerical analysis. By increasing the wind speed by 0.4 m/s, the surface temperature of a PV module drops by 0.4196°C, which is the influence of air velocity on heat transfer from the module. PV module heat transmission is affected by the angle of air attack. Maximum heat transmission occurs when air impacts the PV module at 90o, and its value decreases as the angle of attack decreases. There is a lot of potential for improvement in this experimental and computational investigation, including the use of high heat capacity PCM and thin circular fins to promote heat dissipation to the environment and it is a part of future ongoing research.

7.2 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

7.2.1 Different types of fins

Circular fins are employed in this study to dissipate heat from the PV module. Fin geometry may be altered by extending the length and decreasing the diameter of the fins. The outcomes will vary depending on the geometry used.

7.2.2 Performance on a large scale

This is a small-scale prototype for optimizing the productivity of a PV module. An comprehensive investigation will be required to evaluate the performance of PV-PCM systems on a large scale, such as a solar power plant or a commercial size PV module.

7.2.3 Performance on different locations

This study is limited to the Islamabad, Pakistan region only. The temperature of Islamabad is low as comparatively with other cities of Pakistan. Moreover, the operating conditions also influence the performance of the PCM-heat sink lead by the different metrological conditions. This experiment should be performed at different cities of Pakistan.

7.2.4 PV-PCM cooling system analysis on different kinds of PCMs

In this experiment, only one type of PCM was used for of PV module. Every PCM has its own unique characteristics which may affect the results of PV-PCM cooling setup. High heat capacity PCM used be used to further continue this research.

Keywords: *PV, Passive cooling, Fins, Heat transfer, Phase Change Material*

Appendix

Thermal Management of Solar PV Module by Hollow Circular Fins Integrated with Phase Change Material

Muhammad Shoaib[a], Sheher Yar Khan[a], Naveed Ahmad[a], Adeel Waqas[a], Mariam Mahmood[a], Nadia Shehzad[a]

[a]US Pakistan Centre for Advanced Studies in Energy (USPCASE), National University of Science and Technology (NUST), H-12 Sector, Islamabad, Pakistan

Abstract

Solar photovoltaic panels are designed to generate electrical voltage when exposed to sunlight. The temperature of the photovoltaic cell surface rises as a result of sunlight striking the active portion of the panel. The output voltage of the PV cell decreases as the surface temperature of the PV cell rises, resulting in a drop in the PV module's output power. To reduce the operating temperature of the PV module different types of a heat sink having PCM are used in already published studies. This research work also aims to enhance the performance of the heat sink by attaching an alternative and novel kind of heat sink to the rear side of the PV module. The proposed heat sink is composed of an array of drilled cylindrical rods with extended geometry like pin fins filled with phase change material. The proposed thermal management model is investigated both experimentally and by numerical simulations. Using experimental data, the thermal and electrical performances of the modified PV module are compared to the original PV module. Fins absorb heat from the rear surface of the PV panel through a conduction heat transfer and increase the heat transfer area. The PCM absorbs the heat from the PV module in the form of latent heat transfer by shifting its phase. In the trials, the temperature of the PV module is decreased by 5.18℃. The output voltage is raised by 0.53 volts, and the PV-PCM efficiency is increased by 2.9% to the efficiency of the PV module without a heat sink. Moreover, a comprehensive parametric sensitivity analysis is conducted using the validated numerical model to investigate the impact of wind speed and Incidence angle on the PCM-integrated modified PV module. The numerical results show an increase of 0.4 m/s in wind speed decreases the temperature of the Tedlar wall to 0.4196℃ and the temperature of the solar module decreases by increasing the Incidence angle of air from 30^o-90^o. The results indicate that the PCM-integrated modified solar module is successful in optimizing the PV module's output power.

Key words: Solar PV module, PCM, Circular tubes, CFD

Journal: Energy Storage

Current Status: Under Review

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