Modeling and Simulation of a Hybrid Water Heating System

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PV	Photovoltaic
PVT	Photovoltaic/thermal
$K-\omega$	Turbulence kinetic energy and specific dissipation rate
PBN	Pressure Based Solver

ABSTRACT

The modeling and simulation being performed in this project is keeping in view the budgetary and space constraints of Small and Medium Enterprises in Pakistan while allowing flexible scalability for the solution to be used for commercial as well as for domestic applications. This project will simulate a water pre-heating/heating system that will be based on integrated photovoltaic/thermal (PVT) panels technology which not only generate electrical energy but will also produce thermal energy by covering the same surface area as conventional photovoltaic PV panels. This solution is not only novel its approach but will address multiple issues being faced specifically by SMEs in Pakistan. SMEs have also limited area over which conventional PV panels can be installed, PVT panels on the other hand have hybrid output and produce thermal plus electrical output which will be used to pre-heat the water for the same covered area.

Keywords: PV panels, PVT panels, SME, Chevron type heat exchanger

CHAPTER 1: INTRODUCTION

1.1 Introduction

The ever increasing trend in the population of the country has always been a serious concern. A survey conducted by the United States Census Bureau shows that Pakistan now, is the fifth most populous country in the entire world [1], and with this trend, it is thought to be a serious concern as it is considered to be among the top ten countries which are seriously threatened by the enormous climactic changes [2]. Given these conditions, it was reported that approximately 61.5% of its energy was majorly being produced via fossil fuel utilization for the year 2021, while on the other hand, the production of electricity through renewable energy sources amounted to only around 5.36% [3]. Moreover, load shedding in Pakistan has always been a problem of serious concern, reporting to reach around 13.2 h/day in some areas over the past decade [4]. Additionally, Pakistan is expected to enhance its industrial growth, hence increasing energy requirements [5]. For a smooth happening of events, it is essential for the country like Pakistan to address the supply demand gap, as it is directly related to hinder its economic growth. Under all these circumstances, in authors' opinion, Pakistan should magnify the renewable energy share in the energy resources to overcome the energy poverty [6].

With recent developments, it's becoming evident that the world is transitioning from fossil fuels to renewable energy for multiple reasons such as environmental impact, depletion of resources, cost-effectiveness, and energy security. Environmental issues are now considered to be a major driver, as fossil fuels are a major contributor to the drastic climate change through various carbon emissions. In this regard, various renewable sources of energy, like solar power, wind power and hydroelectric power, produce almost little to no greenhouse gasses and are much safer for the environment [7]. Fossil fuels are also finite resources that will eventually run out; contrary to which, renewable energy is virtually limitless and can provide us reliable energy for generations. Also, it has been observed that the cost of renewable sources of energy technologies is decreasing in recent years, and eventually making them a much more competitive option in market with fossil fuels in terms of cost, long-term maintenance and other such benefits. Lastly, it has been observed that investing in renewable sources can increase a country's energy security for long term and reduce its reliance on foreign sources of energy [5], [7]. All in all, it is evident that the shift towards renewable energy is driven by environmental, economic and geopolitical factors – ultimately providing a pathway that offers a much more sustainable future.

In terms of renewable energy sources, Pakistan is considered to be a very blessed country, as highlighted by Rasheed et al. [7]. Particularly when we talk about solar energy, it has been reported that Pakistan receives a mean value of 5.3 kWh/m^2/day of global insolation [8]. Solar energy is considered to have several benefits, including being abundant, sustainable, and clean [9], [10]. With the fact of having this much importance, the import bill on the photovoltaic (PV) panels rose to about 3.5 billion USDs during the present year [11].

For most of the panels installed, one of the major factors related to the PV panels is that their efficiency shows a decrease with an increase in temperature. Most solar panels come out to be about 20% efficient only. This means that the rest 80% of the sunlight is being trapped within the cells, causing them to heat up. [12]. That being said, it shall also be kept in mind that the lifespan of these panels also deteriorates with a rise in temperature. With these considerations, solar panels need to be kept cold so that their effectiveness and lifespan can be enhanced. This is mainly because of the fact that solar cells become less efficient as the temperature rises and they warm up, with the panel efficiency decreasing by at least 0.3% for every degree over 25°C. [13]. This is specifically important for countries with hotter ambient temperatures, such as Pakistan, which can be categorized as being having a considerably hotter climactic conditions particularly in summers, in accordance with the Köppen–Geiger climactic classification [14].

Solar panels can be cooled in a number of ways. Air cooling, which includes moving air over the solar panels to remove heat, is one of the most popular techniques. You can accomplish this by installing. Installing fans or vents in the panels will do this [20]. Water cooling is an additional technique that includes moving water through the panels to dissipate heat [23]. While this cooling technique is more efficient than air cooling, it may be expensive and maintenance-intensive. Phase change materials and thermoelectric devices are two examples of innovative cooling technologies that some researchers are investigating [27]. Phase change materials may collect and release heat as they change phase, whereas thermoelectric devices can generate power from the difference in temperature between the solar panel and surrounding air [28].

Thus, to increase the factor of performance of already installed PV panels and establish a minimum optimum range of operating temperature of the photovoltaic cells [15], [16], cooling needs to be implemented. Methods to cool down the PV panels and enhance their overall efficiency can be sought from several review papers [16 - 21]. Among these methods, water cooling has been elaborated as superior to air cooling methods [22], and forced water circulation underneath the PV panels can be considered useful for reusing of water after cooling purposes [23]. In addition to this, the warm water collected may also be used to fulfill the basic domestic hot water needs as well [24], [25].

All in all, it is very evident that solar panel cooling is a crucial and major consideration for enhancing the efficiency and durability of solar panels. Multiple key factors will determine the type of cooling technique that shall be used. The method of cooling chosen will be adopted by thinking upon a number of elements, including maintenance needs, the climate where the solar panels will be installed, and the cost for the system. For this an extensive literature review has been carried out.

Keeping in view the above key points, to maximize the enhanced outcomes from PV panels and have maximum utilities for a developing country such as Pakistan, plain water-cooled systems are the most suitable. Although there can be several other modifications to these systems, such as the incorporation of phase change materials with water cooling [26], [27], or the addition of thermoelectric generators [28]. But these are mostly not readily available, and these are much more costly to manufacture locally in authors' experience. Similar reasoning can be considered for the utilization of nano particle additives in water given the facts, in parallel with the above-mentioned methods [29], [30]. For all these systems, a brief literature review considering such techniques has been discussed further in the next chapter.

1.2 Problem Statement

The existing methods of cooling for solar panels, which includes air cooling, clay pot evaporative cooling, water cooling with geothermal systems, nano-plated heat pipe plates, and thermoelectric cooling, suffer from various limitations [16 - 21]. Air cooling is inefficient due to the low coefficient of air and high-power consumption. Clay pot evaporative cooling is not feasible on a large scale. Water cooling systems with geothermal systems are also not suitable for large-scale implementation. Nano-plated heat pipe plates offer efficiency but are expensive. Thermoelectric cooling is also costly. Moreover, the U-tube type heat exchanger fails to effectively maintain optimal panel efficiency. The temperature of the PV cells located between the U-tubes does not decrease adequately, resulting in reduced overall efficiency of the solar panels. Therefore, there is a pressing need to develop a smart, efficient, and cost-effective device or system that can efficiently cool solar panels when the panel temperature surpasses a predefined threshold. This solution should overcome the existing limitations and deliver enhanced cooling capabilities to prevent performance degradation of the solar panels. The ideal smart cooling system should be efficient, inexpensive, and intelligent, ensuring that the solar panels operate at their peak efficiency.

1.3 Objectives

Environment damaging fossil fuels, natural gas and wood are being actively used in the local industry for water heating applications. In this project, existing PV Solar Panels would be theoretically converted to PVT Panels for enhancing their performance by keeping the PV Panel at an optimum temperature and by also simultaneously using the extracted heat energy being absorbed by the panel as useful energy for water heating applications. Altering the existing PV panels with V-type channels akin to the ones used in flat plate heat exchangers, to the best of researched knowledge has not been evaluated. Particularly, not in the case of retrofitting.

Our project aim is to:

- Research on the chevron type geometric configuration of channel.
- Carry out the simulation studies on the heat exchanger plate chevrons.
- Validate with experimentation setup and compare the results.

1.4 Scope

The existing PV panels with V-type channels or chevron channels akin to the ones used in flat plate type of heat exchangers, has not been really evaluated. Particularly, not in the case of retrofitting. The project aims to deliver an efficient, cost-effective, scalable, and intelligent solar panel cooling system that maintains optimal panel performance and maximizes the benefits of solar energy. The proposed method not only addresses the issue of global warming but also focuses on the accuracy, functionality, scalability, throughput, and effectiveness of the system by developing a bespoke real-time simulation platform which can bring economic benefit to a company.

1.5 Relevance to National Needs

- Modeling and simulation for improving efficiency of already installed solar systems in Pakistan.
- In depth study to implement green and clean energy alternatives in Pakistan.

1.6 Thesis's Organization

This study is divided among 6 Chapters. A brief description for each chapter is described in paragraphs below:

The current chapter i.e., Introduction elaborates the background and motivation of this research. This chapter also describes the main objectives of the study.

Chapter 2 constitutes of literature review.

Chapter 3 deals with the methodology adopted.

Chapter 4 discusses the results.

Chapter 5 discusses the conclusions that are drawn based upon the results and discussion in the previous chapters.

Chapter 6 discusses the Recommendations and Future Works that are not incorporated in the current study. Study's references are listed in numbering order followed by appendices in the last section of the thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Cooling Techniques

Many methods have been proposed to alleviate this issue of solar panels overheating, ranging from passive cooling to active cooling. Figure 2.1 the shows main features of a general flat plate PVT collector. This literature review seeks to discuss and assess recent research in the subject of solar panel cooling.

2.1.1 Passive Cooling Approaches

Passive cooling techniques such as reflecting coatings, thermally conductive materials, and radiative cooling have been researched in recent years. A study conducted by Hossain [21] indicated that reflecting coatings can bring down the temperature of the solar panels by up to the figure of 10 °C.

2.1.2 Clay Pot Evaporative Cooling

M. Kesavan [35] shows that clay pot evaporative cooling water that employs thin film of water to cool the panel can decrease reflection loss and temperature, therefore boosting the electrical efficiency of the combined system as observed. The overall temperature of the panel can be controlled by water cooling, and the water that is collected can be heated. In the investigation, a pot water which cooled PV/T panel obtained an overall efficiency of 62%, which is greater than the water cooled PV/T and simple PV panels. The pot water cooling method keeps the overall temperature of the panel 5-8°C cooler than the surrounding air through the basic evaporative impact of cooling water in a clay pot. In comparison to the other two of the panels, the pot water cooled PV/T panel performed better in terms of the electrical efficiency, which was the main output, the thermal efficiency, and then overall efficiency, power output, and the sensible heat recovery. Unfortunately, because of the unavoidable water losses in this process, it cannot be used on a large scale.

2.1.3 Nano-Plated Heat Pipe Plate

Nam Cao Hoai Le [36] discovered that nano-plated heat pipe plate lowers the actual temperature variation within the solar panel from 1.0 to 2.5°C and reduces the overall rise in temperature of the panel by 47-50%, leading to the recovery of the efficiency loss of about 50% and an extended lifetime of the used solar cells. Analyzing the variation in the values of thermal resistance and comparing the temperatures at various sections of given heat pipe plate can be used to find out the heat pipe plate's effective mode of working. This current heat pipe plate can deliver an overall cooling flux of about 380 W/m2, which is adequate for the majority of real-world scenarios. However, some additional techniques of cooling at condenser section are needed to further improve the heat removal ability to 600 W/m2, enabling solar cells to be cooled down in values ranging close to ambient temperature. Also, coating life of the plate is only a few years and this process is pricey.

2.1.4 Active Cooling Techniques

The techniques of active cooling, such as water cooling, air cooling, and the thermoelectric cooling have also been researched [23], [24]. A study found that the water cooling can majorly reduce the temperature of the solar panels by up to the value of 25°C, resulting in a 3.5% improvement in power output. Similar to this, air cooling has been proven to be a successful cooling technique; showing that using air cooling increased power output by 5.5%.

2.1.5 Thermoelectric Cooling

Thermoelectric cooling has also been researched as a potential cooling solution for solar panels. A study by Feng [20] revealed that thermoelectric cooling may reduce the overall temperature of solar cells by up to the value of 17°C, resulting in a 3.6% improvement in power output. However, thermoelectric cooling has higher costs and energy consumption than other cooling methods.

2.1.6 Forced Convection

Abdelgalil Eltayesh [37] utilized forced convection to cool PV panels. A total of two different methodologies of cooling were carried out: one was the use of PV panels aided with forced air-cooling by installing the lower duct and thus supplying air for it through the blower, and PV panels with forced type of air-cooling using some small fans which are arrayed out in a symmetrical manner on backside of the PV panels. The temperatures which came out through the CFD simulations are compared to the results obtained from the experimentation. The results were observed to be in a good comparison. The results obtained elaborated that cooling the panel with small fans on the backside may enhance the overall performance and a 2.1% of maximum total increase in PV panel efficiency with almost 7.9% saving of energy can be achieved. On the other hand, the use of blower cooling technique attains a maximum of 1.34% total increase in PV panel efficiency with around 4.2% saving of energy. This isn't as efficient as the previous methods and has greater power consumption.

2.1.7 Phase Change Material

The usage of a phase change material (PCM) based cooling tower with nano-fluids to enhance the electrical efficiency of a solar panel was studied Abdollahi, [39]. The results observed showed that the flow rate and concentration of the nano-fluid had a substantial impact on the temperature reduction of solar panel, with the largest temperature decrease achieved at the flow rate of 18.91 mL/s and a nano-fluid concentration of 0.1 wt.%. A maximum of the electrical power and overall efficiency of the solar panel were achieved at the maximum value of flow rate along with the concentration of nano-fluid.

2.1.8 Geothermal Pre-Cooled Air Flow

K. Morad [40] employed method of geothermal pre-cooled air flow across the back side of a PV module at an ideal rate of about 0.0288 m3/s. Because of the reduction in PV module temperature at ideal flow rate, improvements in output power of PV module and electrical efficiency of around 18.90% and 22.98%, respectively, were made on an average scale. According to the economic analysis performed, this suggested cooling system reduces summertime CO2 emissions by roughly 13896 g, which helps to improve the relative leveled cost of energy by almost 12%. Geothermal cooling through water system has the maximum attainable electricity generation increase of 11.6%.. Overall, geothermal cooling is not a feasible solution as it is costly, requires a lot of space, and isn't that efficient comparatively.

2.1.9 Thermal Collectors

Maciej Sułowicz [41] suggests an innovative thermal collector model for photovoltaic-thermal systems. The thermal response of the designed cooling box flow and photovoltaic module are coupled to attain the electrical and thermal conversion efficiencies of this water-based PV/T system. Different inlet mass flow rates and temperatures are simulated. Investigated are the layers of the photovoltaic module's average temperature distribution. The results show that the PV module obtains an electrical conversion efficiency of about 17.79% with a thermal efficiency of 76.13% at a mass flow rate of 0.014 kg/s and an inlet flow temperature of 15 °C. This design shows better results in comparison to the other techniques. The research presented in the paper emphasizes the value of PV/T systems and their enormous significance to spread awareness of solar energy while simultaneously harvesting both the thermal and the electrical energy. These panels are however, not available locally and as it's an integrated solution, the existing panels cannot be utilized.

2.1.10 Different Tubing and Heat Exchanger Systems

Considering such systems, Shalaby et al. [32] performed the experimental evaluation of the half circular shaped tubes under the panel. From their investigations, an increase of 13.8% in efficiency of the collector. Furthermore, Majeed et al. [33] conducted the experimental evaluation of a spiral shaped cooling shaped and underground cooling water. From their evaluations, an increase in electrical efficiency of around 127.3% was observed. Similarly, Hassan et al. [34] conducted experimental investigation of a PVT panel with copper tubes at the bottom. They reported the highest reduction of around 6°C from the considered parameters. Adhya et al. performed experimental investigation of aluminium pipe thermal collector placed horizontally at the backside of panel. They used distilled water for cooling and indoor sun simulator of 3000 W/m2 irradiance. They found a temperature decrease of 33.1% and increase of about 18 % power output by this cooling arrangement [42].

Figure 2.1 shows main features of a flat plate PVT collector [43].

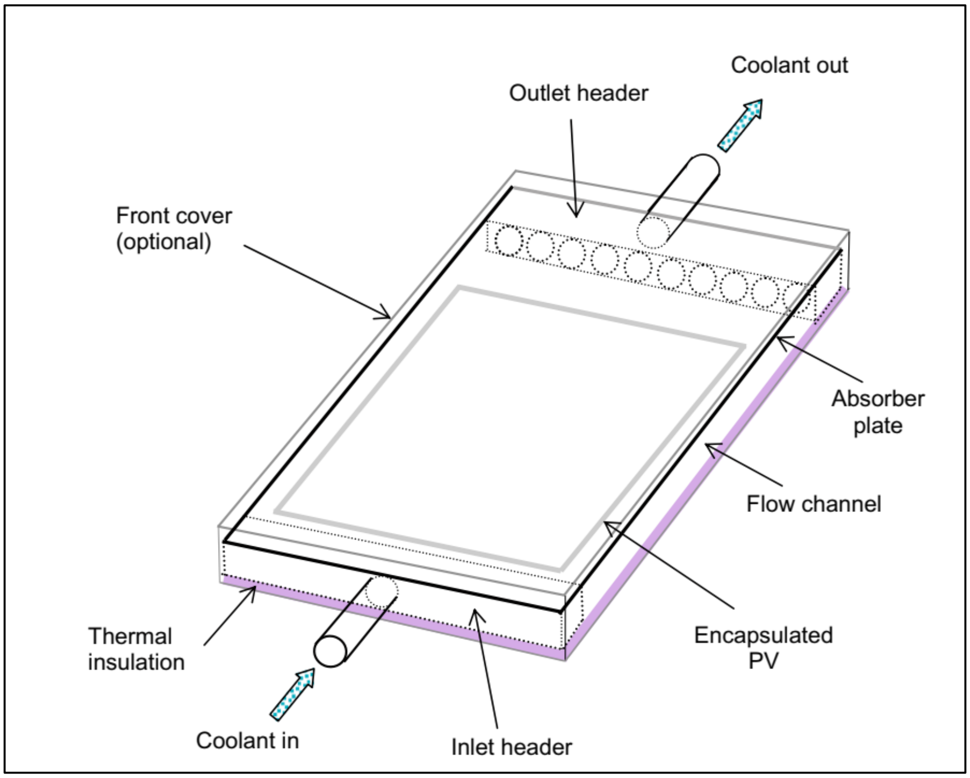

Figure 2.1 Features of a PVT collector

2.2 Summary of Literature Review

A summary table was developed that shows the brief overview of different authors discussing various cooling techniques of a PV panel.

Table 2.1 Summary of literature review

Authors	Year	Features	Findings
Hossain et al. [21]	2020	Passive cooling approaches:reflecting coatings	Reflecting coatings: Panel temperature reduced by up to 10 °C
M. Kesavan et al. [35]	2016	Clay pot evaporative cooling water approach	Pot water cooling method keeps temp. of panel 5-8°C cooler than surrounding air through evaporative impact. (But unavoidable water losses)
Nam Cao Hoai Le et al. [36]	2016	Nano-plated heat pipe plate	Lowers the variation of temperature within the panel to 1.0-2.5°C and reduces the rise of temperature of the panel by 47-50%. (But less coating life and expensive)
Amin et al. [23] [24]	2020	Active cooling techniques: water cooling, air cooling	Water cooling: temperature reduction of panels by up to 25°C, resulting in 3.5% improvement in power output. Air cooling increased power output by 5.5%.
Abdollahi et al. [39]	2020	PCM based cooling tower with Nano-fluids	Temperature decrease achieved at flow rate of about 18.91 mL/s. (Very expensive and delicate)

Feng et al. [20]	2020	Thermoelectric cooling	Cooling may reduce temperature of solar cells by up to 17°C, giving a 3.6% improvement in the power output. (But higher cost and energy Consumption)
Abdelgalil Eltayesh et al. [37]	2023	Forced convection: Using lower duct blower and symmetrically arranged small fans at back	Small backside fans: attain max. total increase of 2.1% in the efficiency with 7.9% energy saving. Blower cooling method obtains a max. increase of about 1.34% in PV panel efficiency with around 4.2% saving of energy. (Isn't efficient in comparison)
K. Morad et al., Jafari et al. [40]	2020	Geothermal method using pre-cooled flow of air across the back side of a PV	Maximum attainable electricity generation increases 11.6% & reduces summertime CO_2 emissions. (But costly, require huge spaces and less efficient comparatively)
Maciej Sułowicz et al. [41]	2022	Thermal collector for (PV/T) systems	Electrical conversion efficiency: 17.79%, thermal efficiency: 76.13%. (not available locally & it's an integrated solution, so existing panels cannot be utilized)

2.3 Research Gap

- Altering the existing PV panels with V-type channels akin to the ones used in flat plate heat exchangers, to the best of researched knowledge has not been evaluated.
- Particularly, not in the case of retrofitting.

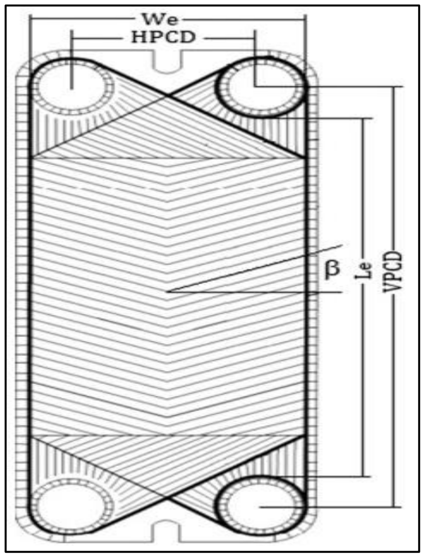

Figure 2.2 Geometry of chevron type plate heat exchanger

2.3.1 Filling the Research

The project aims to deliver an efficient, cost-effective, scalable, and intelligent solar panel cooling system that maintains optimal panel performance and maximizes the benefits of solar energy. The proposed method not only addresses the issue of global warming but also focuses on the accuracy, functionality, scalability, throughput, and effectiveness of the system by developing a bespoke real-time simulation platform which can bring economic benefit to a company.

CHAPTER 3: METHODOLOGY

3.1 Process Followed

Now that the research part is done, the study is headed towards narrowing down the approaches. Flat Plate heat exchanger with V-shaped pattern installed behind the plate of solar panel is the main configuration we will be working upon.

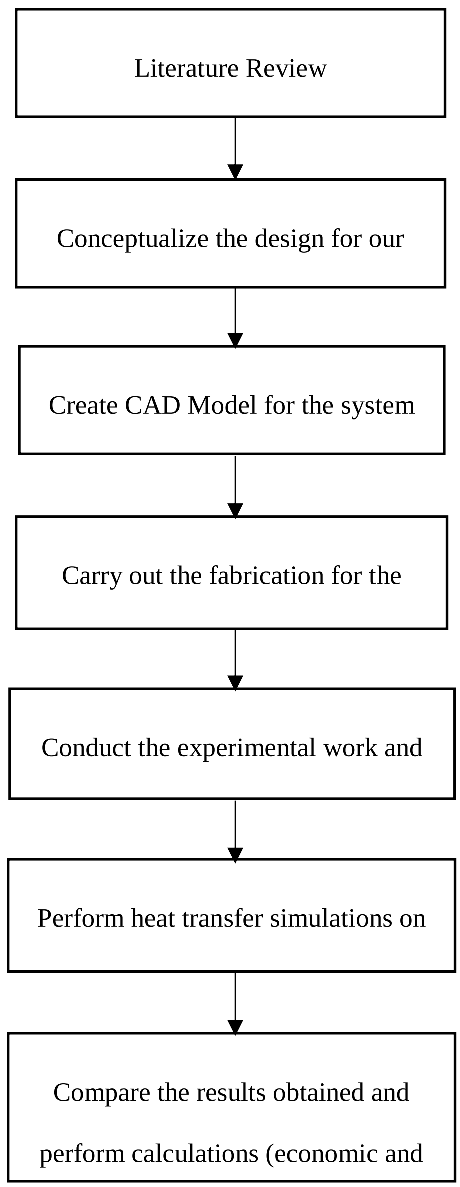

Figure 3.1 Methodology of the study

3.2 Plate Type Heat Exchanger

The plate type heat exchangers are a type of heat exchanger that use a series of thin, corrugated plates to transfer heat. Normally, there are two fluids i.e. Hot and Cold fluid. But this study is considered to design a novel parallel plate heat exchanger in which heat is transported by only one fluid and it works on the principal of Conduction and Convection. This parallel plate heat exchanger works in a way that heat is first transported through conduction to the fluid which is continuously moving on the other side. That heat is then transferred to the working fluid and can be used for other purposes such as swimming pool water, geyser water etc.

3.2.1 Applications in Solar Panels

Parallel plate heat exchangers are particularly effective in solar panel applications because they can provide high heat transfer rates in a relatively compact design. They are also easy to maintain and can be easily cleaned to prevent buildup of sediment or other contaminants.

The main reason that plate type heat exchangers should be used is that they provide the maximum amount of heat transfer from solar panel to fluid because the surface of heat exchanger is fully considered to be in contact with the back side of solar panel. There is no air entrapped to lower the heat transfer. Plus, the fluid is always in contact with the plates of exchanger transferring maximum heat.

3.2.2 Flow without Turbulators

A simple plate type heat exchanger may be installed for cooling of the PV plate, but this may not be considered to be a much efficient solution. To understand this, some calculations performed for the cooling of plate are given below:

Assuming the laminar flow without any turbulator or pattern

$$Length\ of\ Exchanger = 26.3\ in = 0.66802m$$

$$Width\ of\ Exchanger = 17.6\ in = 0.4445m$$

$$thickness\ of\ plate = 0.0254\ m$$

$$Surface\ area = 0.66802 * 0.4445 = 0.29693m^2$$

$$Area\ of\ Cross\ Section = 0.4445 * 0.0254 = 0.01129m^2$$

Prandtl Number is calculated as

$$Prandtl\ number = \frac{4A_c}{P} = \frac{4(0.01129)}{0.0254 + 0.4445} = 0.048108$$

Assuming mass flow rate

$$Q = \frac{1000L}{h} = \frac{0.00027m^3}{s}$$

$$Q = v *\ A_c$$

$$v = \frac{0.02459m}{s}$$

Kinematic viscosity of water is 0.6617 x 10^{-6} m^2/s

$$Re = \frac{v * D}{viscousity} = 1964.9 < 10000$$

That is showing that the flow would be laminar.

Now for the Nusselt number

$$Nu = 7.54 + \frac{0.03\left(\frac{D_h}{L}\right) * Re * Pr}{1 + 0.016(\left(\frac{D_h}{L}\right) * Re * Pr)^{2/3}}$$

Putting the values from above we got

$$Nu = 16.0536$$

Using formula

$$Nu = \frac{h * D_h}{k}$$

Now applying the values

$$h = 99.608W/m^2C$$

$$Q = h * A_s * (Del\ T) = \dot{m} * C_p * \Delta T$$

Assuming that the temperature of solar panel plate at the inlet side is 65 Degrees and inlet fluid temperature is 25 Degrees

Now by putting values in the above equation and equating them afterword gives us

$$T_e = 62.52\ Degrees$$

So, considering the above calculation we can see that plate is cooled only 2.5 Degrees.

3.2.3 Role of Turbulators

Turbulators are the devices that may be installed in the plate type of heat exchangers to increase the overall turbulence of the fluid flow and enhance the overall heat transfer. In the plate type heat exchangers, the fluid generally flows through channels between the plates, and the presence of turbulators can disrupt the flow and create vortices, which increases the convective heat transfer coefficient.

The use of turbulators can improve the performance of plate type heat exchangers, specifically in areas where high heat transfer rates are essential. They can also be of vital importance in reducing the fouling of the surfaces of heat exchanger by preventing the accumulation of deposits on the plates. However, the use of turbulators can also cause the increase of pressure drop in the heat exchanger, which may impact the overall efficiency of the system. Hence, it is important to keep in mind the trade-offs and select the appropriate type of turbulator for the specific application.

The 2 major challenges faced while designing a turbulator are:

1. Maximize the turbulence so that heat transfer will be maximum because in a turbulent flow the momentum transfer between the layers of fluid is maximum.
2. Minimize the pressure drop so that very less energy is wasted in pumping of fluid.

Keeping in view the above discussion, the only option is to intimate the turbulator shape on one side of the exchanger such that there would be engravings on the plate and they will be acting like the turbulator providing the desired heat transfer along with the minimum pressure drop. So, a pattern has been designed of Flat Plate heat Exchanger with V shaped patterns grooved, also known as Chevron Type, the CAD model of which is shown ahead in figure 3.1.

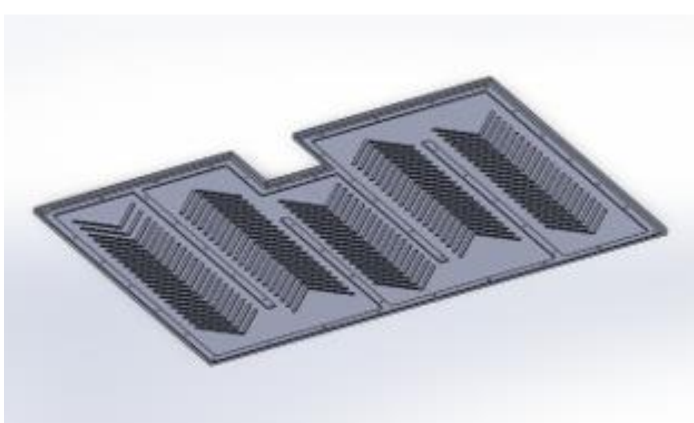

Figure 3.2 CAD model of chevron plate

The pattern shown in the above figure shows arrow like pattern with 2 lined perpendicular to each other as they provide the maximum heat transfer. This pattern also directs the flow of water from inlet to outlet.

3.3 Experimental Setup

The research is carried out with designing a flat plate heat exchanger for the PV solar panel. The setup has been developed to see the major impact of temperature on efficiency of the PV module, and how cooling affects the overall output of power. The experiment is conducted in multiple weather conditions and at various times of the day.

The prime reason for the use of plate type heat exchangers is that they provide the maximum amount of transfer of heat from solar panel to fluid because the surface of heat exchanger is fully in contact with the back side of solar panel. We may consider that there is no air entrapped to lower the heat transfer. Also, the fluid always remains in contact with the plates of exchanger giving us the maximum transfer of heat.

For this, creating an experimental setup for a plate-type heat exchanger includes various steps, such as selecting equipment, configuring the setup, and determining the parameters which are needed to investigate. This setup and procedure will provide a solid foundation for conducting experiments with a plate-type heat exchanger. The specifics are adjusted based on the particular study goals and constraints.

The experimental work is conducted in front of Manufacturing Resource Center in the National University of Science and Technology (NUST), Islamabad, Pakistan. The latitude and longitude of the site are 33.635501^{o} N and 72.989658^{o} E respectively. The elevation from sea level is approximately 540 meters. The data is majorly recorded only on clear atmospheric days when there were no clouds so that the solar radiation remains steady throughout the day. Furthermore, the data is only collected during peak sun hours from 11:00am to 3:00pm. The module is cleaned daily so that the effect of temperature is not impacted by any other factors like dust and sandstorms. In this particular way, a better understanding of the effect of temperature on the PV module is analyzed.

3.3.1 PV Module Setup

The overall experimental setup as shown in figure below, consists of a PV module, a mounting stand, voltage sensor and Hall Effect current sensor. An Arduino Uno is used to monitor the values of sensors. A 40-watt polycrystalline PV module is used whose physical and electrical specifications are given in table. The width and length of the polycrystalline PV module is 0.64 meters and 0.4 meters, respectively. To maximize the incident irradiance, the PV module is mounted to an angle of 32 degrees and the setup is rotated to follow the orbit of the Sun.

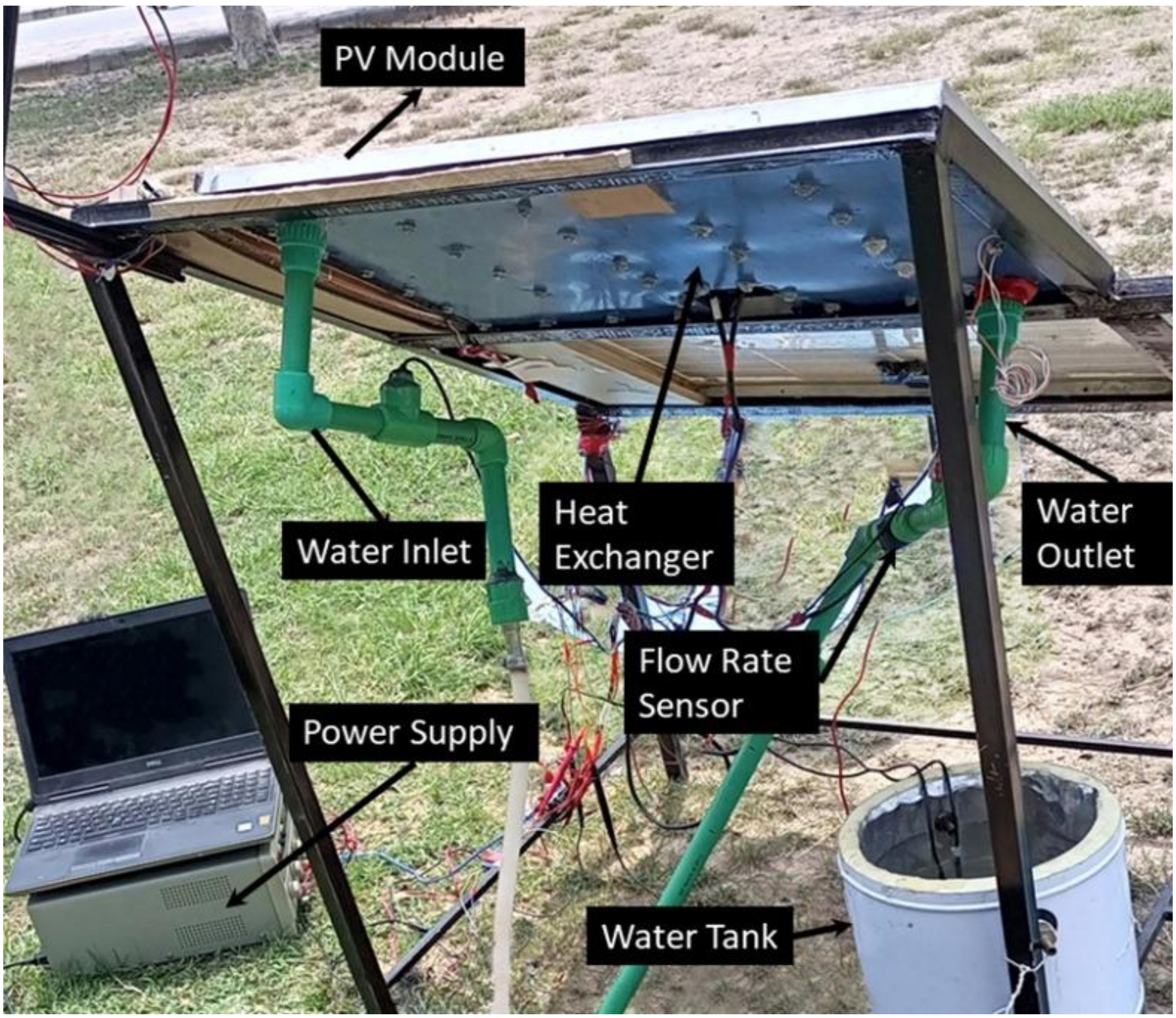

Figure 3.3 Module Setup

The physical and electrical specification of the model system are given in the table.

Table 3.1 Module Specifications.

Model Type	**SH-40W**
Dimensions	40cm * 64cm
Weight	5.5 kg
Maximum Power	40 W
Current at Maximum Power	2.31 A
Voltage at Maximum Power	17.28 V
Open circuit Voltage	21.6 V
Short Circuit Current	2.47 A
Power Tolerance	±3.0%

3.3.2 Cooling Setup

The cooling of solar panels plays a major role in better functioning of the system, providing numerous benefits that enhance system performance, efficiency, and reliability. Efficient heat and energy transfer, improved equipment life, cost effectiveness, compact and space efficient, improved system performance, and enhanced safety are some other benefits that can be achieved by the cooling process. By selecting the right cooling system for our system, it can maximize the advantages the systems has to offer, ensuring optimal performance and sustainability.

With the above discussion in view, in authors' opinion, to maximize the outcomes from PV panels and provide maximum utilities for developing countries such as Pakistan, plain water-cooled systems are the most suitable. Although there are several other modifications to such systems, such as the integration of phase change materials with water cooling, or the application of thermoelectric generators. But these are not readily available, and these are costly to manufacture locally.

A novel cooling system is designed keeping in mind the cost and water usage. The setup consists of a 6-Watt DC water pump which pumps water from a 6 Liter water tank. To prevent heat loss from the water tank, Styrofoam is used to insulate it from the surroundings. Water is carried from the tank through thick PVC pipes to the heat exchanger which is attached to bottom of the PV module. A flow sensor is used to measure the flow rate of water. Temperature sensors are connected to measure the approximate temperature at the water inlet, outlet, storage tank and front surface of the PV module. Additionally, an infrared thermometer is used to validate the results of the temperature sensors. To allow the adjustment of the flow rate a variable power supply is used. The model numbers of the apparatus used are given in table 3.2 below.

Table 3.2 Model Numbers

Apparatus	Model Numbers
Flow Sensor	YF S201
Temperature sensors	DS18B20
Voltage Sensor	10123W150075
Current Sensor	ACS712 5A
Infrared Thermometer	UT-300A+
Variable Power Supply	GPC-3030D

A glazed (with glass cover) PV cooling setup was designed with the top surface of solar cells exposed to solar irradiance with a flat plate type of heat exchanger in the middle and water flowing under it, the said being shown in figure 3.4. A flat plate heat exchanger is designed with only one working fluid, which is water. To increase the overall rate of the heat transfer from the PV module, turbulence is introduced by making multiple V shaped engraved turbulators, with 3.6 mm thickness and 3 mm depth, on the aluminum plate. Separate sections are created on the flat plate to guide the fluid to flow over the entire surface. Figure 3.5 below shows the design of this heat exchanger.

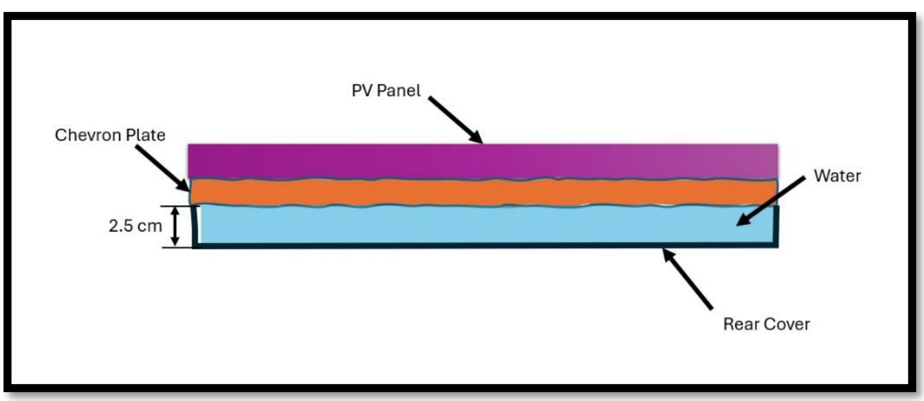

Figure 3.4 Cooling Setup

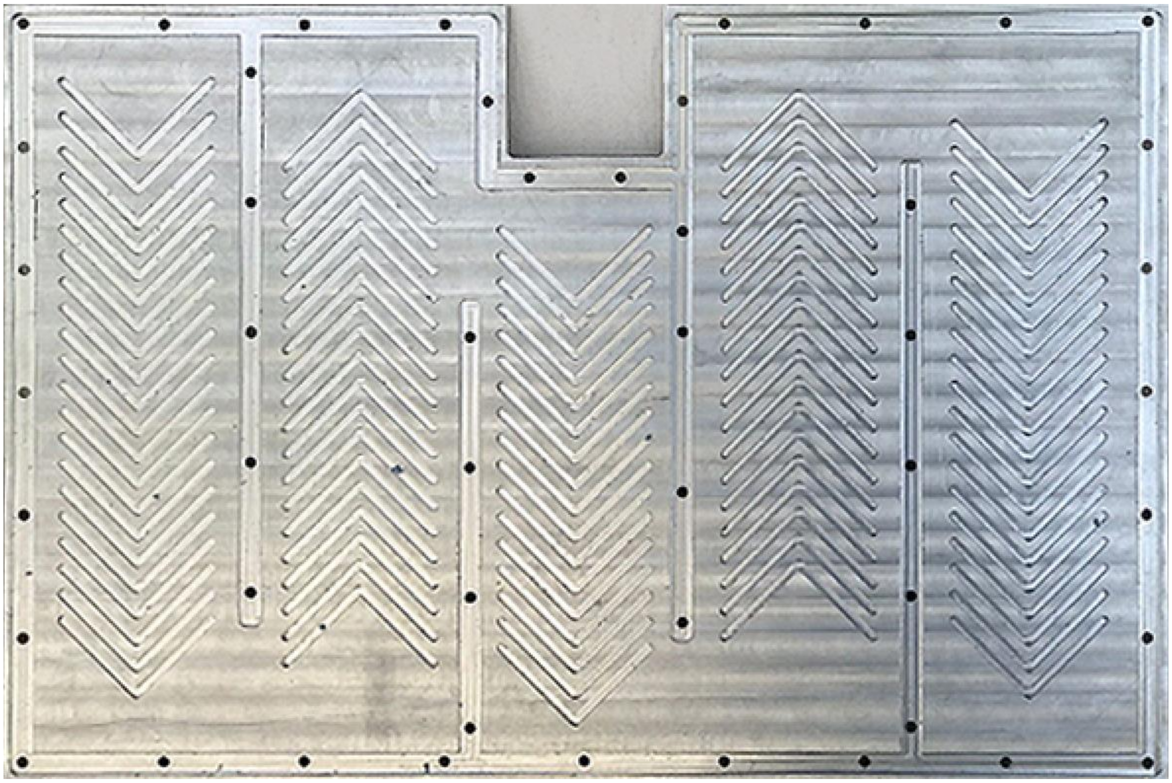

Figure 3.5 Plate Type Heat Exchanger

This setup can be operated both as an open system with water being constantly refilled in the storage tank from an external source or as a closed loop system with water from the outlet of heat exchanger going back into the storage tank and being reused. However, in this case only a closed loop system is operated. The schematic of this system is given in the figure 3.6. Experiments are conducted both with and without cooling system to find the increase in efficiency of the system. Maximum power of the system can be expressed as shown in Eq (1).

$$P_{max} = V_{OC} \times I_{SC} \quad (1)$$

Where V_{OC} is open circuit voltage and I_{SC} is short circuit current which will give the theoretical maximum power. Both the readings with cooling and without cooling are measured on the same solar module. So, it is not necessary to measure the value of the fill factor. The percentage increase in efficiency is given by Eq (2)

$$\% \, increase = \frac{P_{cooled} - P_{not\ cooled}}{P_{not\ cooled}} \times 100 \tag{2}$$

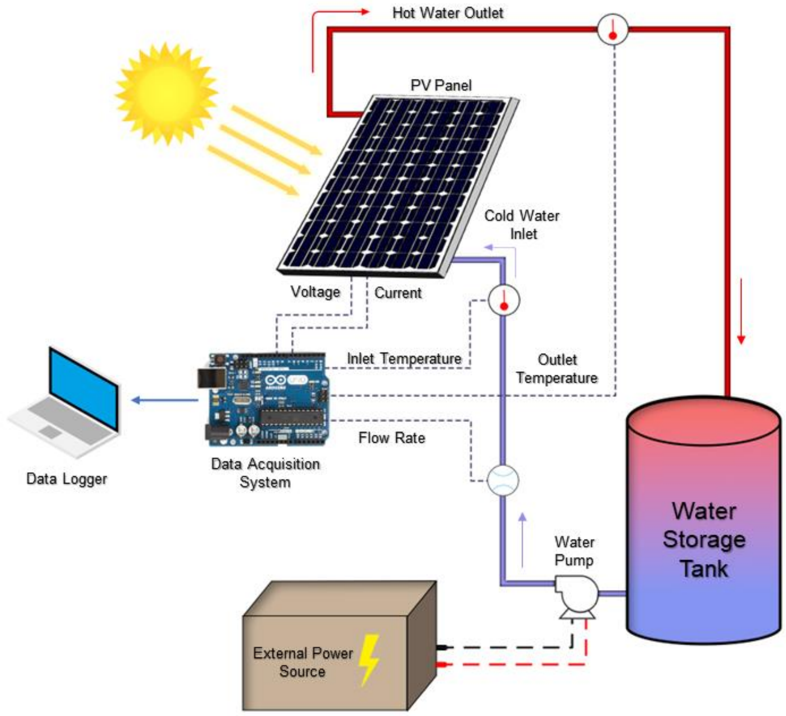

Figure 3.6 Schematic of Closed loop system

3.3.3 Economic Analysis

The overall economic analysis of the cooling system has been performed by comparing the cost of the power produced by the PV module and the cost for installing and running the cooling system. Additional cost as calculated in Eq (3) is the difference between cost of PV module with ($\boldsymbol{C_{PVc}}$) and without ($\boldsymbol{C_{PV}}$) the cooling system. For the cooling system to be feasible, additional cost must be less than the cost recovered by installing the cooling system and their difference must be positive as calculated in Eq. (4). The difference in Cost recovered ($\boldsymbol{C_{Recov}}$) and additional cost ($\boldsymbol{C_{addit}}$) is the profit for installing cooling setup.

$$C_{addit} = C_{PVc} - C_{PV} \tag{3}$$

$$C_{profit} = C_{Recov} - C_{addit} \tag{4}$$

Total cost for PV system without cooling system is $\boldsymbol{C_{PV}}$ while cost of PV module with cooling system ($\boldsymbol{C_{PVc}}$) as calculated in Eq (5) is the sum of initial manufacturing and installment cost ($\boldsymbol{C_{initial}}$), and operational cost ($\boldsymbol{C_{oper}}$) over a period of 25 years. Initial cost is fixed, but it is higher for PV module with cooling system due to additional cost of heat exchanger and cooling setup. While the operational cost given in Eq (6) increases with time.

$$C_{PVc} = C_{initial} + C_{oper} \tag{5}$$

$$C_{oper} = K \times t \tag{6}$$

In Eq (6), ‘K’ is the equivalent one month operational and maintenance cost and ‘t’ is the duration in months. For PV modules with cooling system, the operational and maintenance cost is the cost of running the pump and water filter replacement for heat exchanger.

Cost recovered ($\boldsymbol{C_{Recov}}$) is calculated in Eq (7) using additional energy ($\boldsymbol{E_{addit}}$) produced by installing cooling setup and cost of electricity production per kWh ($\boldsymbol{C_{kWh}}$). Additional energy as shown in Eq (8) is the difference between energy of PV module with the cooling system and the PV module without the cooling system.

$$C_{Recov} = E_{addit} \times C_{kWh} \tag{7}$$

$$E_{addit} = E_{PVc} - E_{PV} \tag{8}$$

3.4 Simulations

3.4.1 Output Required

CFD Simulations are carried out to look for the following outputs for our system:

1. Area weighted average total surface heat transfer coefficient.
2. Area weighted average total surface heat flux.
3. Temperature Contours.
4. Panel Temperature Reduced.

3.4.2 Mesh Details

For the given geometry of chevron plate, 7.5 million cells with prism layers were formed. Prism layers are structured layers of hexahedral (or prismatic) elements that are typically added next to wall boundaries. They are especially beneficial in resolving boundary layers in turbulent flows, where velocity gradients are steep and require fine mesh resolution to be captured effectively, with figure 3.7 showing the surface mesh. A total of 7 layers with initial cell height of 0.01 mm was given to this system.

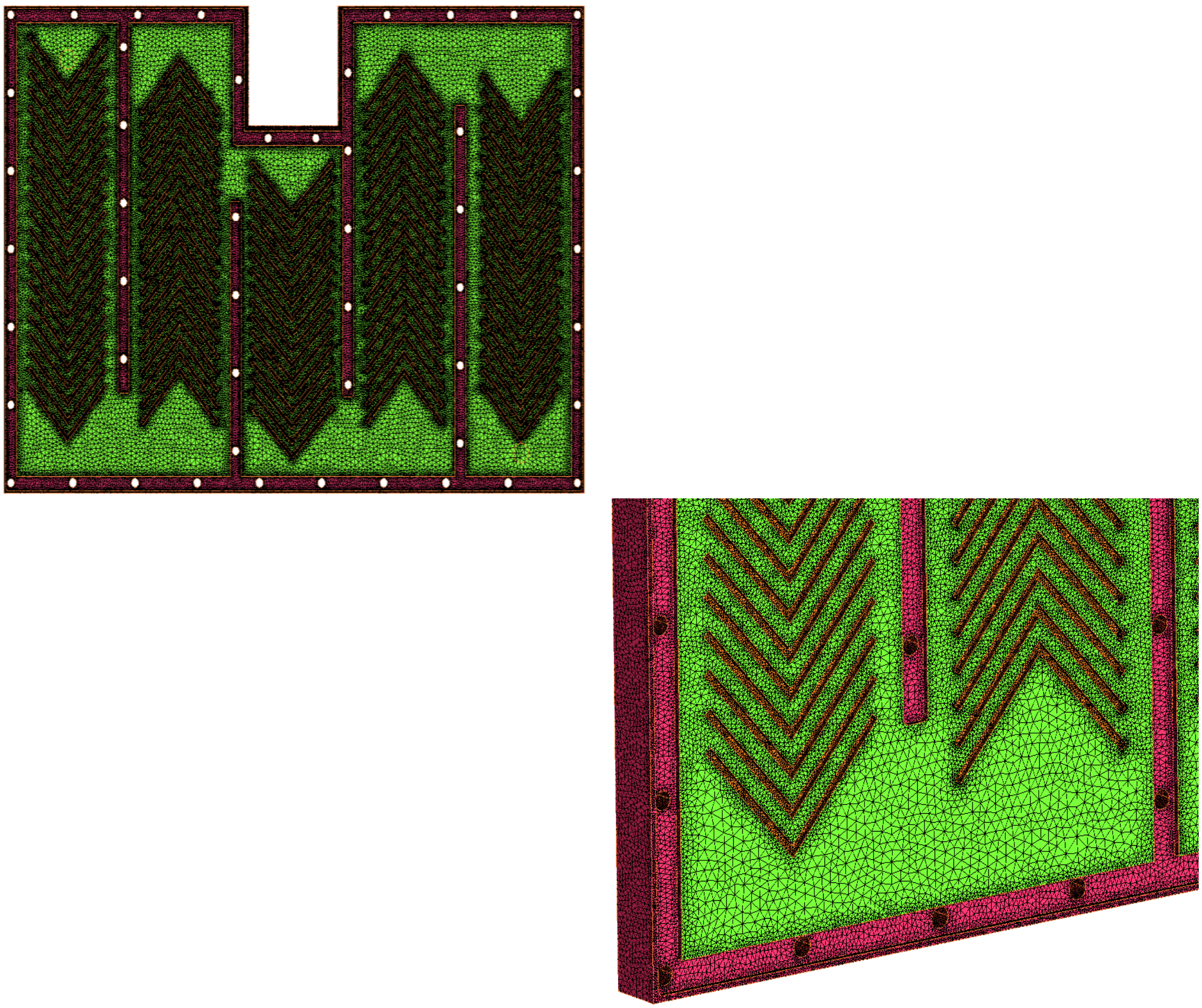

Figure 3.7 Surface Mesh

The cut plane of mesh is shown below in the figure 3.8 while the figure 3.9 shows the volume mesh

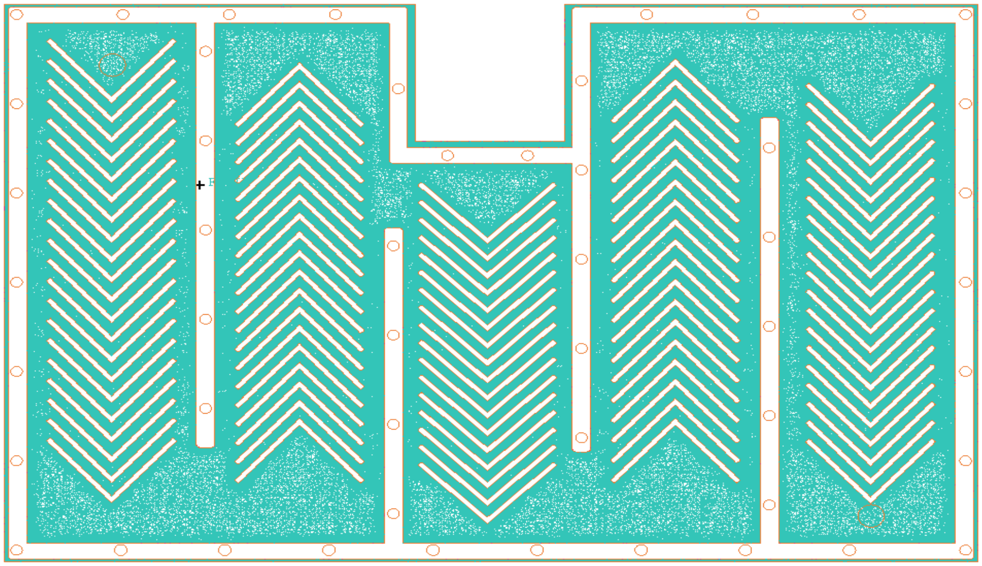

Figure 3.8 Cut Plane of Mesh

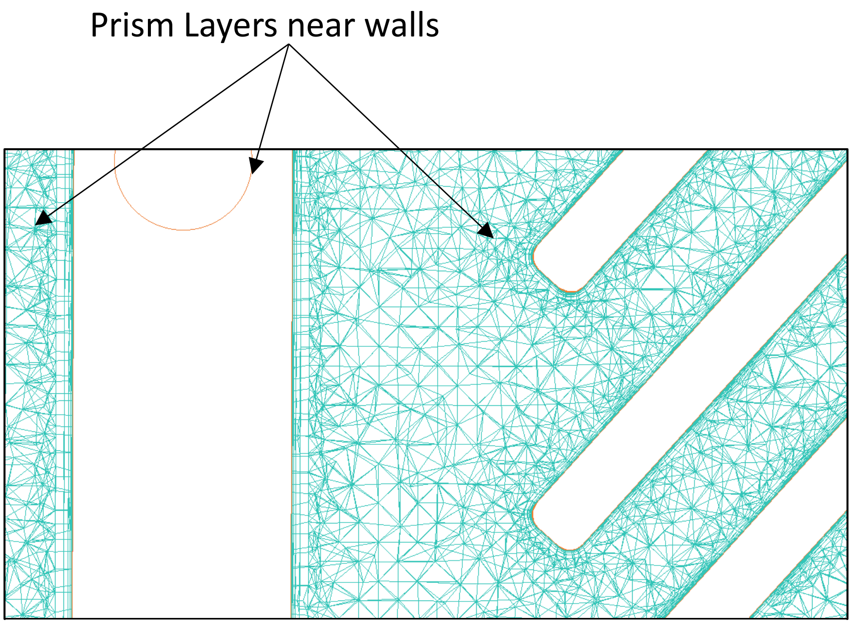

Figure 3.9 Volume Mesh

3.4.3 Boundary Conditions

The boundary conditions initially taken for our system are as follows:

- Water Inlet = Mass flow inlet= 0.138kg/s
- Water Inlet Temp = 20 C^{o} = 293K
- Water Outlet = Mass flow outlet = 0.138kg/s
- Hot Side (panel) Temp = 60 C^{o} = 333K
- Cold Side = Adiabatic walls
- Turbulence Model = SST K-Omega
- Steady State PBNS Fluent

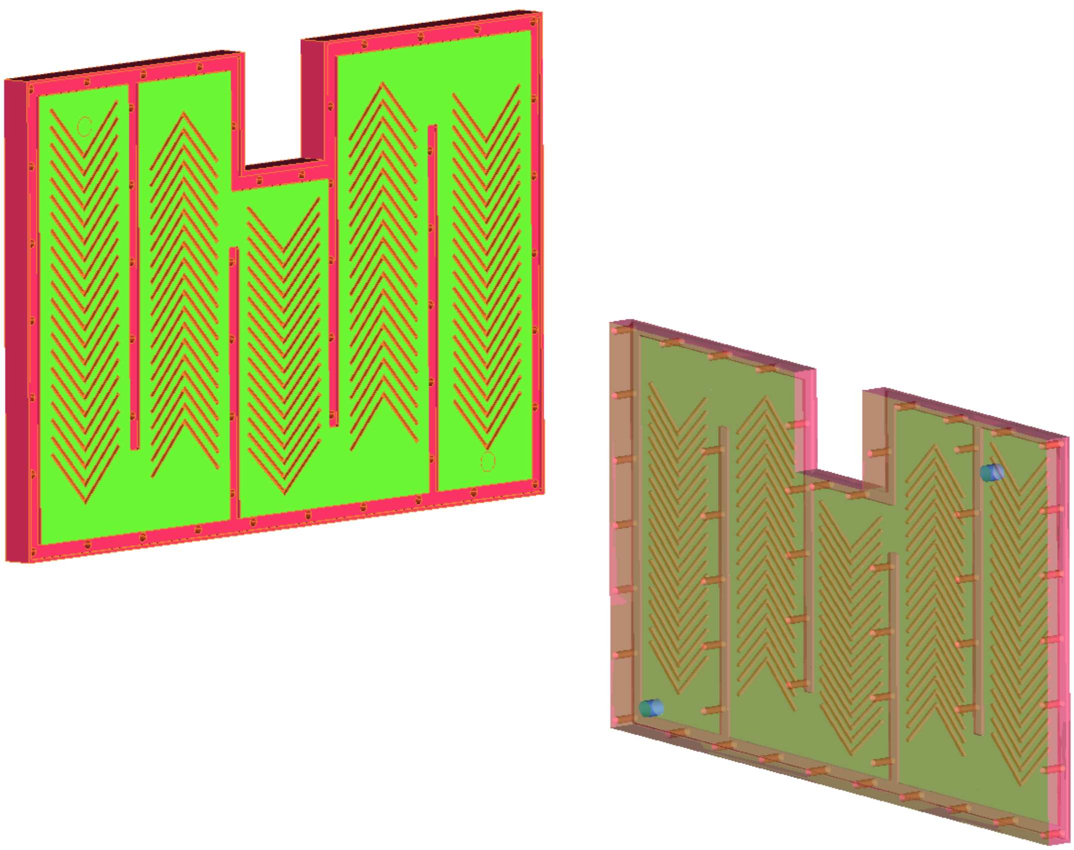

Figure 3.10 Chevron Side of the Panel for CFD

3.4.3.1 SST (Shear Stress Transport) k−ω Model

The Shear Stress Transport (SST) k−ω turbulence model is to simulate the behaviour of turbulent flow. Components of the SST k−ω Model are

- Turbulent Kinetic Energy k,
- Specific Dissipation Rate ω,
- Shear Stress Transport.

Turbulent kinetic energy (k) equation:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k w + \frac{\partial}{\partial x_j}((v+\sigma_k v_t) \frac{\partial k}{\partial x_j}) \tag{9}$$

P_k is the production of turbulent kinetic energy

β^* and σ_k are model constants

Specific dissipation rate (w) equation:

$$\frac{\partial w}{\partial t} + U_j \frac{\partial w}{\partial x_j} = \frac{\Upsilon w}{\partial x_j} P_k - \beta w^2 + \frac{\partial}{\partial x_j}((v+\sigma_w v_t) \frac{\partial w}{\partial x_j}) + 2(1-F_1) \frac{\sigma_{w^2}}{w} \frac{\partial k}{\partial x_j} \frac{\partial w}{\partial x_j} \tag{10}$$

Υ, β, and σ_w are additional model constants

F_1 is a blending function that allows for smooth transition

3.4.3.2Steady state PBNs (Pressure-Based Solver)

This model refers to a method used to solve the Navier-Stokes equations for fluid flow and heat transfer. Commonly used for incompressible and mildly compressible flows

Continuity Equation:

$$\nabla . V = 0 \quad (11)$$

(Ensures mass conservation by adjusting the velocity field)

Momentum Equation:

$$\frac{\partial V}{\partial t} + (V . \nabla)V = -\nabla p + \nabla \cdot (\mu \nabla V) + F \qquad (12)$$

V: Velocity vector

p: Pressure

μ : Dynamic viscosity

F: Body forces (i.e. gravity)

Energy Equation (if applicable):

$$\frac{\partial T}{\partial t} + \nabla \cdot (VT) = \nabla \cdot (k \nabla T) + S \qquad (13)$$

T: Temperature

K: Thermal conductivity

S: Source term (i.e. heat generation)

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Experimental Setup

The results are categorized into the following sections. The first section describes the overall impact of temperature on the PV performance. The second section explains the effectiveness of designed cooling system for PV module. In the third section, the results of economic analysis are shown and discussed to check the overall feasibility of the designed system. Finally, impact of turbulators on the heat transfer rate in a heat exchanger is shown using numerical simulation

4.1.1 Effect of Temperature on PV Performance

This first section describes the effect of temperature on the PV performance.

The power output of the PV module is mainly observed to be inversely proportional to the surface temperature of PV module. The PV module's performance is observed from 11:00am to 3:00pm throughout the experiments. To cater the effect of temperature, only days with similar weather conditions, i.e., high solar irradiance, and minimal coverage of clouds, are considered so that other factors may not affect the validity of the experiments. The parameters which are used to study the effect of temperature on PV performance are surface temperature of PV module, temperature of water inlet, water flow rate, power output and increase in power output by installing cooling system.

The power output of both cooled and uncooled 40-watt PV module is examined across multiple experiments with different ambient temperatures ranging from 34^{o} Celsius to 45^{o} Celsius. Graph ahead shows the effect of temperature on the polycrystalline PV module. It has been observed that the surface temperature of PV module was 45% higher than the ambient temperature because most of the irradiance is converted into heat. The experiments show that the power output of the PV module decreases as the temperature of PV module increases. It was observed in the experiment when temperature of PV module was 46.5o Celsius, average power output was recorded to be 40.23 Watts. But it dropped to 32.26 watts when the temperature reached 62^{o}

Celsius. The experimental results showed an average decrease of 1.3 % in power output per Celsius increase in temperature of polycrystalline PV module.

4.1.2 Cooling System

The cooling of the fabricated PV module (Measuring: 0.4 m (L) × 0.64 m (W), Area = 0.256 m^2) is carried out by flowing cold water through the aluminum flat plate type of heat exchanger attached on the bottom of this PV module. There are V-shaped engraves in the flat plate to maximize heat transfer from hot PV module to cold water. A 6-watt water pump is employed to transfer water at 30 degree Celsius from a 6-Liter water tank to heat exchanger. The energy consumed by the cooling system for 15 minutes is calculated to be 5.4 kJ. On average, the heat transfer rate after 15 minutes is not enough to justify running the system to further decrease the temperature. The flow rate of the water in the heat exchanger is measured by the flow rate sensor is found to be 8.3 LPM or 2.2 GPM while the maximum flow rate observed of the used water pump is 10 LPM or 2.6 GPM. Since water is incompressible, the flow rate is assumed to be constant throughout the heat exchanger. Only 3 Liters of water needs to be available in the storage tank for water to complete one cycle through the heat exchanger. The observed results of the cooling system have been shown to be true by cooling the PV module eight times over duration of 2 months during multiple different days and then calculating the average value of the results. There is almost no wastage of water in this cooling system since the heat exchanger is watertight and all water used for cooling is recovered and reused in a closed loop.

The temperature of the solar panel with and without the cooling is compared to find the effectiveness of the cooling system. The graph in **Error! Reference source not found.**4.1 shows t hat the average temperature of the solar panel is significantly lower for the PV module with the cooling system than one without it. The temperature drop is relatively small, for low surface temperatures, because the temperature difference between the solar panel and the inlet water is minimal. Thus, less heat transfer takes place between the water and panel interface. The maximum temperature difference of 5.8° Celsius occurs when panel temperature is 57.8° Celsius. The average temperature difference of 4.2° Celsius was observed by installing the cooling system which represents an average decrease of 7.2%.

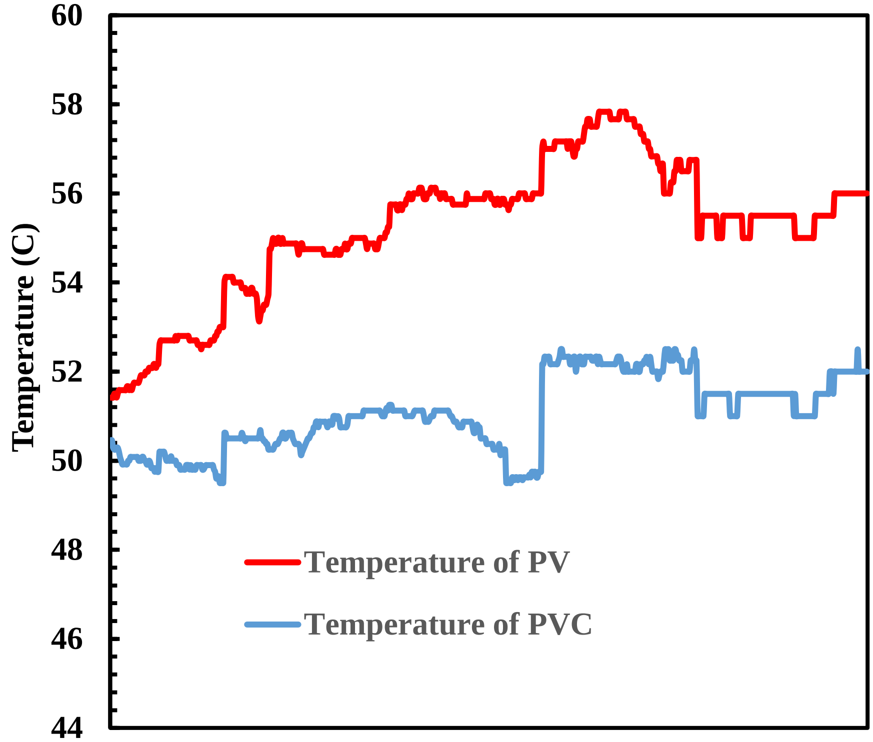

Figure 4.1 Temperature Comparison of PV and PVc System

To quantify the overall impact of decrease in the temperature, the power and the efficiency of the PV module is compared. The graph in figure 4.2 shows a notable increase in power by installing the cooling system. The overall maximum of increase in the power output of designed system is experimentally noted to be 6.1 Watt. This maximum increase in power output occurs at the same instance where maximum decrease in temperature is observed. The average increase in Power output is 2.8 Watts (7.95%), which is less than the power required for running the DC water pump, making this system not viable for a 40-Watt panel. However, the system is advantageous for PV modules with higher wattage since the overall system efficiency increases by cooling. The cooling system is viable for the PV module with more than 76-watt power rating. The graph in figure 4.3 shows the increase in efficiency observed during each experiment. The maximum increase in efficiency of 16.3% is observed while the average increase is 7.95%. The conditions for the different experiments and the temperature differences between inlet and outlet of the heat exchanger are given in Table IV. The standard deviation of the efficiency values is 4.1. The confidence interval at 95% is from 3.68% to 11.63% increase in efficiency.

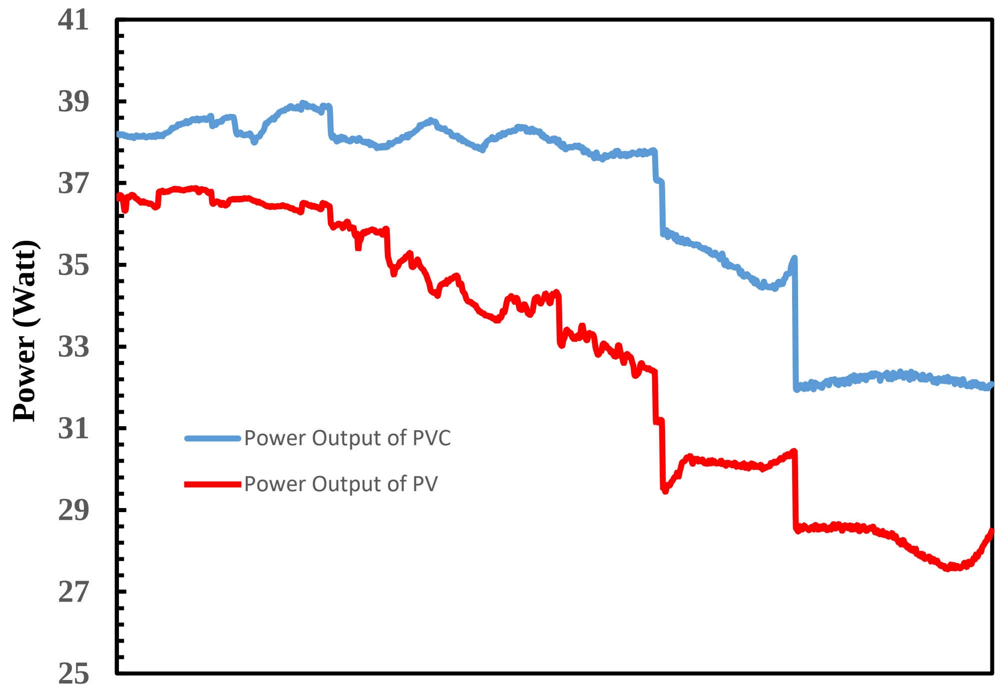

Figure 4.2 Power Comparison of PV and PVc system

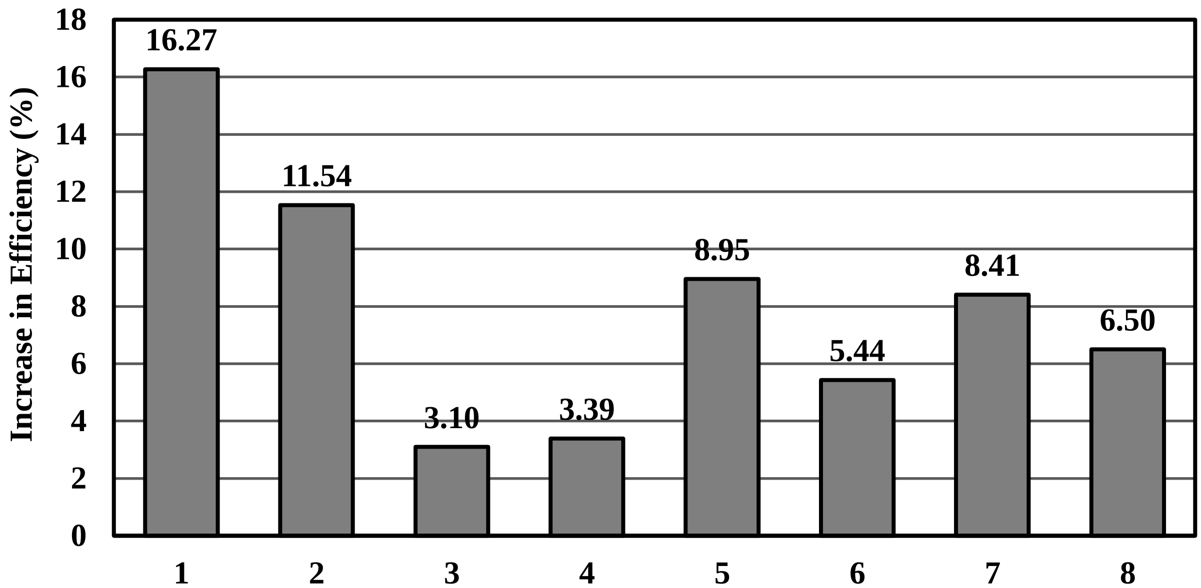

Figure 4.3 Increase in Efficiency for eight tests.

Table 4.1 Experiment Conditions

Experiment No.	Date	Time	Ambient Temperature	Water Tank Temperature
1	22/06/2023	12:30-13:30	42	39.4
2	22/06/2023	14:00-15:00	45	37.1
3	24/07/2023	11:30-13:30	34	33.9
4	26/07/2023	11:00-12:00	35	35.2
5	26/07/2023	13:00-14:00	35	35.5
6	7/8/2023	13:00-14:00	34	30.8
7	7/8/2023	14:30-15:30	34	34.7
8	8/8/2023	14:30-15:30	37	33.8

4.1.3 Economical Analysis

The total economic analysis of this cooling system has been done by comparing the cost of the power produced by the PV module and the cost for installing and operating the cooling system. The Cost of 40-watt PV module without cooling ($\boldsymbol{C_{PV}}$) system as mentioned in table 4.2 is 32 USD, however the cost of PV module with cooling system ($\boldsymbol{C_{PVc}}$) comprises of the very initial cost and the operational cost of the cooling system. The initial cost of the PV module with cooling system is 73.81 USD as stated in table 4.3. While the operational cost is due to running the 6-watt water pump. The worldwide average cost of electricity per kWh is 0.152 USD. Since the operating time of pump is 8 hours per day, cooling system would require **0.048 kWh** of energy per day. The cooling system will cost **0.21888 USD** to operate for one month. Eq (14) shows the total initial cost and operational cost of PV module with cooling system.

Table 4.2: Cost of PV Setups

System Components	Cost of 40-Watt PV module (USD)	Cost of 400-Watt PV module (USD)
PV Panel (40-watt)	20	160
Steel Stand Frame	9	18.18
PV installation and commissioning	3	3.27
Total Initial Cost	32	181.45

Table 4.3: Cost of PVc Setups

System Components	Cost of 40-watt PVc Module (USD)	Cost of 400-watt PVc Module (USD)
PV Panel	20	160.00
Steel Stand Frame	9	18.18
DC Pump (6-watt)	1.81	1.81
Water Filter	1.45	1.45
Arduino and Wiring	9	9
Heat Exchanger Cost	29	58.29
PVT installation Cost	3.55	5.45
Total Initial Cost	73.81	254.18

$$C_{PVc} = 73.81 + 0.21888 \times t\ USD \qquad \text{where t is the duration in months} \qquad (14)$$

Additional cost stated in Eq (15) is the difference between cost of this PV module with (C_{PVc}) and without (C_{PV}) the cooling system. For average life of 25 years of the PV module, C_{addit} is calculated to be 107.5 USD. Additional increase in average energy is calculated to be $201.6\ kWh$ for 25 years, while the average cost of electricity per kWh (C_{kWh}) is 0.152 USD. While the operational cost is due to running the 6-watt water pump. The worldwide average cost of electricity per kWh is 0.152 USD. Since the operating time of pump is 8 hours per day, cooling system would require 0.048 kWh of energy per day. Cost recovered (C_{Recov}) is found to be 30.6 USD. The difference of cost recovered, and additional cost is ($C_{Recov} - C_{addit}$) is the total profit from the system. The difference of -76.8 USD displays that the cooling system designed is not initially feasible for the 40-watt solar panel**.**

$$C_{addit} = 41.81 + 0.21888 \times t\ \ USD \qquad \text{where t is the duration in months} \qquad (15)$$

But here, the idea of generating a cost efficient system does not succeeds completely, hence this problem needs to be addressed. In this regard, a 400-watt panel is selected, and economic analysis is done by taking the same efficiency criteria to check the feasibility of the system. The cost of PV module without cooling system is 181.45 USD for 400-watt PV module. The initial cost of PV module with cooling system is 254.18 USD as shown in Table . Additional cost and cost recovered for 400-watt system is calculated to be 138.4 USD and 348 USD, respectively. By installing cooling system on a 400-watt PV module, a total profit of 209.6 USD is gained. The graph in figure 4.4 shows the cost benefit diagram of PV system and PVc system. The total cost analysis and estimation of the PV module system has been displayed below in table 4.4.

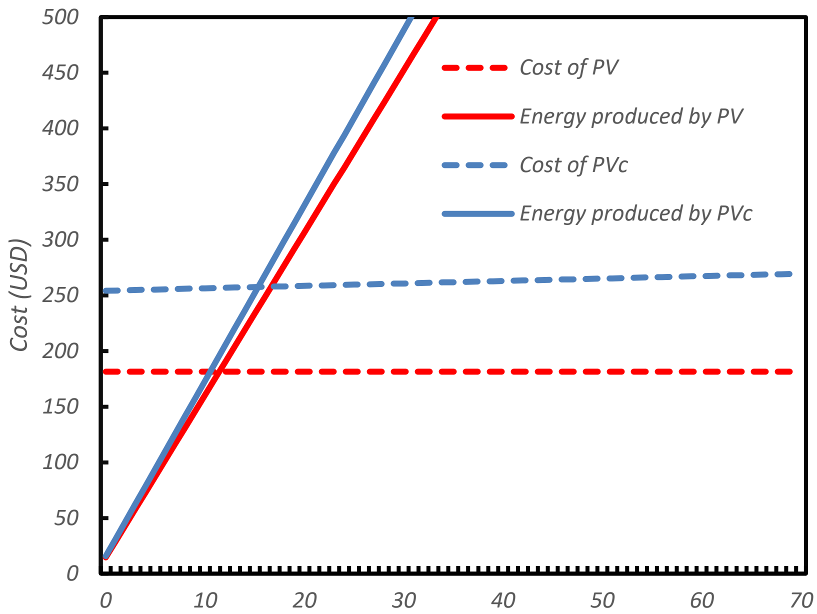

Figure 4.4: Benefit-Cost Graph for PV and PVc system

Table 4.4: Cost analysis

Costs	Cost of 40-watt PVc Module (USD)	Cost of 400-watt PVc Module (USD)
C_{addit}	107.5	138.4
C_{Recov}	30.6	348
C_{profit}	-76.8	209.6

4.2 Simulations

4.2.1 Temperature Contours

The temperature contours obtained through the CFD analysis are shown in the following figures

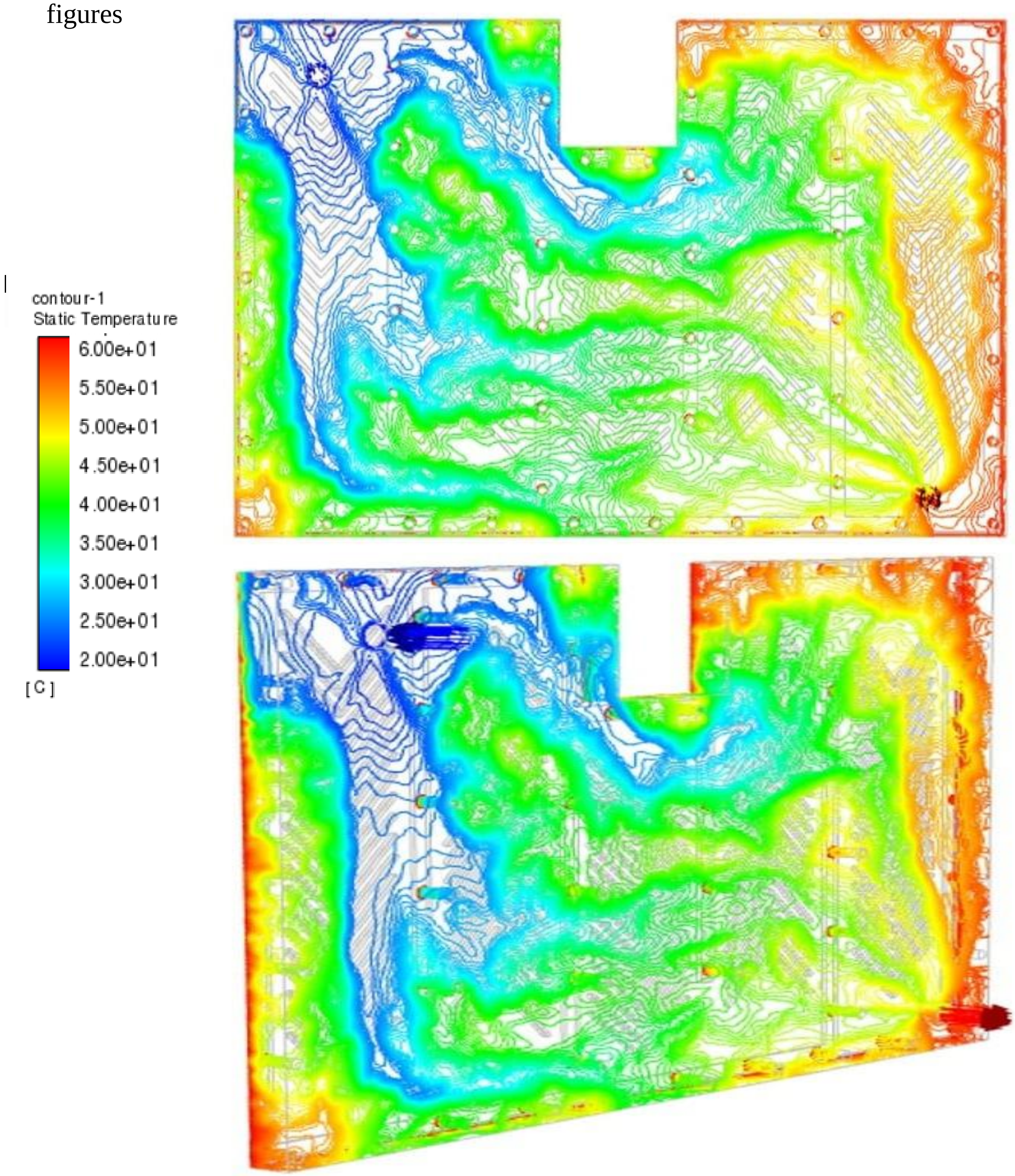

Figure 4.5 Temperature Contours 1

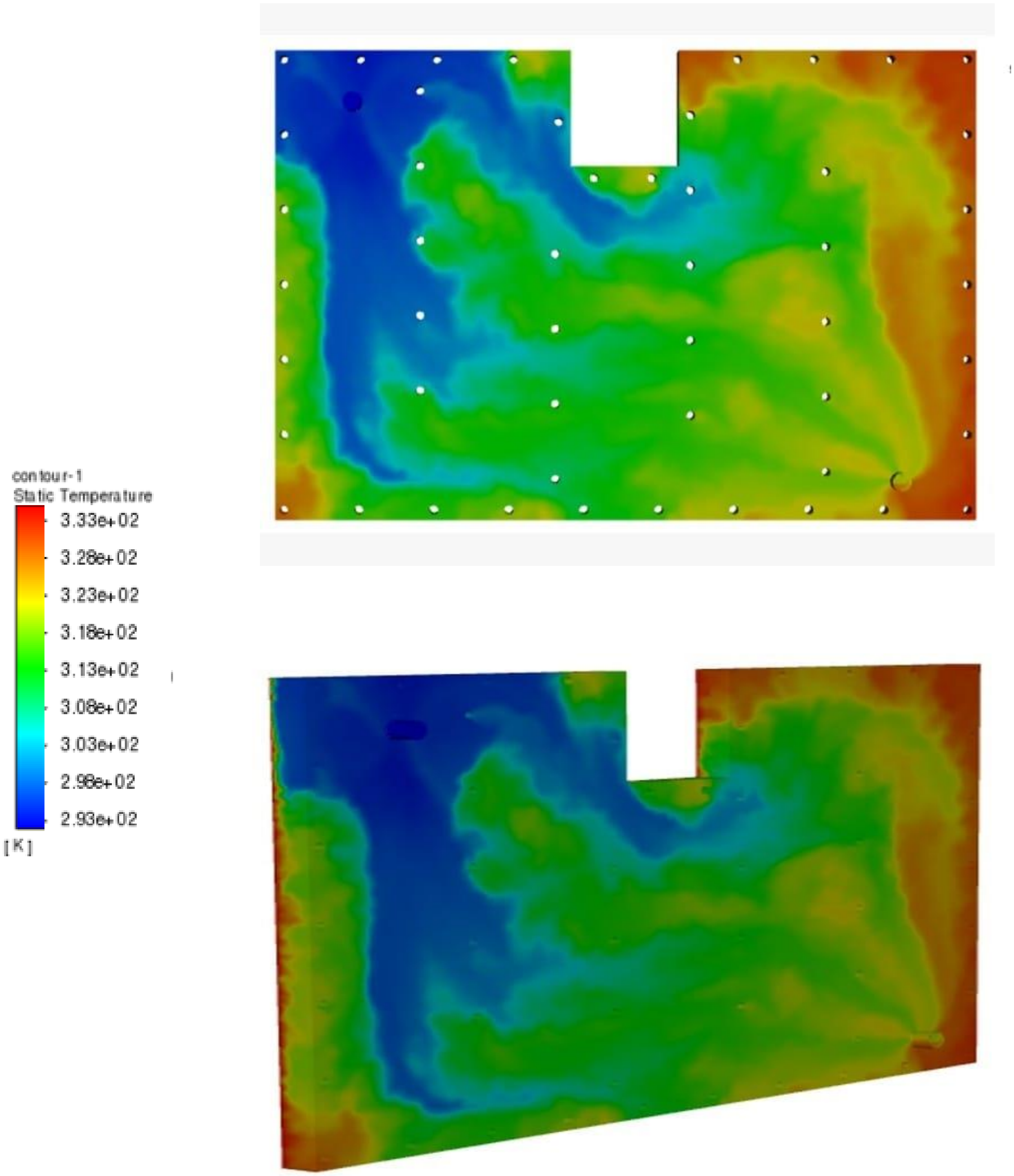

Figure 4.6 Temperature Contours 2

Table 4.5: CFD Results.

Boundary Conditions	**Mass flow rate (kg/s)**	**Surface Heat Transfer Coef. (h) [W/(m^2 K)]**	**Total Surface Heat Flux (q_{Conv}'') [W/m^2]**	**Temp (C^O)**
Water Inlet	0.138	------	------	20^o
Water Outlet	0.138	------	------	46^o
Chevron	------	181.91	8156.85	------
Chevron Border	------	154.55	6930.14	------
Chevron side	------	145.38	6519.15	------

CHAPTER 5: CONCLUSIONS

The development of a smart solar panel cooling system is essential for maximizing the overall efficiency and performance of the solar panels. By effectively reducing panel temperature when it exceeds a predefined threshold, the system ensures optimal power generation and overall panel efficiency. The system's objectives of cost-effectiveness, energy efficiency, scalability, intelligent control, reliability, durability, compatibility, and integration work together to create a solution that is accessible, sustainable, and adaptable. With the implementation of this smart cooling system, solar panels can operate at their peak efficiency, contributing to the wider adoption of the natural solar energy as a sustainable and renewable source of power generation.

The development of a cooling system for PV modules is essential for efficient operation under the hot climate of Pakistan. This study has investigated that by reducing the panel temperature optimal power generation can be achieved. Furthermore, the ability to cool through our flat plate cooling system is also investigated. This experiment involves building an experimental setup to observe output power losses due to heat, cooling through a flat plate heat exchanger, performing numerical simulation to calculate the effect of turbulators and performing economic analysis to ensure feasibility of the system. The main points of this study are tabulated below:

- An inverse relationship is found between surface temperature of the panel and the efficiency of the PV module. A 1.3% loss in efficiency per Celsius is observed for a 40-Watt polycrystalline Photo Voltic Module.
- Panel Temperature Reduced (CFD Analysis)= 5.16 ^{o}C
- Panel Temperature Reduced (Experimental Setup)= 4.20 ^{o}C
- Average Increase in Power Output = 2.8 Watts
- Cooling recovers 7.95% efficiency of this solar PV module in 15 minutes using the water at 30 degrees Celsius with a water flow rate of 8.3 LPM. The cooling system has a water requirement of 11.7 L/m^2.
- The cooling system provides the net positive value for PV modules with power rating higher than 76 Watt.

- An increase in heat transfer coefficient of 8.4% by adding V-shaped turbulators is found numerically.
- For a 400-Watt PV module, a net profit of 209.6 USD is obtained over a period of 25 years due to the installation of the cooling system.

The cooling system is more economical for high power rated PV modules. The system can be made more efficient by utilizing thermal energy from the exit temperature of the heat exchanger. For large PV setups, the water tank can be built underground to avoid heating the tank by sunlight. The proposed heat exchanger has the potential to overcome the shortcomings of a normal flat plate heat exchanger. However, the actual efficiency of the PV module was not quantified due to the lack of pyranometer. Furthermore, the study did not cover the winter season to find the effect of low ambient temperature on the feasibility of the system. Hence, further studies and research can be carried out to observe the impact of cooling in winter season and compare the power output by the variation in solar irradiance throughout the day and hence this study can be further improved.

CHAPTER 6: FUTURE WORK/RECOMMENDATIONS

By addressing critical factors such as temperature control and dust accumulation, these systems enable solar panels to operate at their highest efficiency levels, leading to increased power generation and enhanced sustainability. The combination of intelligent control, cost-effectiveness, scalability, reliability, and compatibility ensures that these systems offer practical and efficient solutions for the maintenance and optimal performance of solar panels. Through the implementation of these technologies, solar energy continues to be a viable and environmentally friendly solution for meeting our energy needs.

Following are the recommendations for the room of improvement in cooling system:

- The cooling system is more economical for high power rated PV modules. The system can be made more efficient by utilizing thermal energy from the exit temperature of the heat exchanger. For large PV setups, the water tank can be built underground to avoid heating the tank by sunlight. The proposed heat exchanger has the potential to overcome the shortcomings of a normal flat plate heat exchanger. However, the actual efficiency of the PV module was not quantified due to the lack of pyranometer. Furthermore, the study did not cover the winter season to find the effect of low ambient temperature on the feasibility of the system. Therefore, further studies can be carried out to observe the effect of cooling in winter season and compare the power output by the variation in solar irradiance throughout the day and hence this study can be further improved.
- The incorporation of Artificial Intelligence (AI) within the control system of the cooling system offers the potential to establish temperature thresholds at which the efficiency of the solar panels begins to decrease, based on factors such as light intensity and ambient conditions. By integrating AI algorithms into the control system, it becomes possible to dynamically adjust the cooling mechanisms in response to real-time data and optimize the panel's performance. This intelligent approach allows for more precise and efficient cooling, ensuring that the panels operate within the optimal temperature range and maintain their highest level of efficiency.

- The Junction box is fitted at the back of the panel and that was the place where fluid cannot be flowed. And we know that the efficiency is limited at the maximum temperature of the solar panel plate. So, it can be fixed at the frame in such a way that space optimality satisfied along with the cooling.

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