Report on

Student Research Project Grant – SRPG

Experimental and Numerical Investigation on Thin Film Water Cooling for PV Solar Panels

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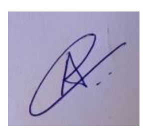
Aayush Kolamkar (ISHRAE mem no: S00112272) - 

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CERTIFICATE

The project titled "Experimental and Numerical Investigation on Thin Film Water Cooling for PV Solar Panels" submitted to the Symbiosis Institute of Technology, Pune submitted as completion of ISHRAE student research project grant – SRPG UG is based on my original work carried out under the guidance of Dr. Chandrakant Sonawane and Dr Anirban Sur. The report has not been submitted elsewhere.

The material borrowed from other sources and incorporated in the report has been duly acknowledged and/or referenced.

We understand that we all could be held responsible and accountable for plagiarism, if any, detected later on.

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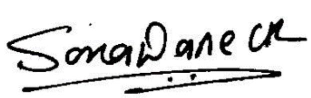

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1 Introduction

The escalation of population growth coupled with economic development has resulted in a heightened demand for energy, consequently leading to an increased reliance on fossil fuels, elevated costs, and augmented carbon emissions. It is imperative to investigate renewable energy sources as a substitute for fossil fuel dependency. Solar energy, particularly via photovoltaic (PV) panels, represents a highly promising renewable energy alternative. PV panels transmute solar radiation into electrical energy utilizing semiconductor materials, providing advantages such as diminished carbon emissions, rapid returns on investment, and adaptability across various applications.

1.1 Background Study

The global installed solar PV capacity over the past decade and the contributions of the top fourteen countries are detailed in Tables 1[1]. In the early stages of solar PV development, Europe was recognized as the leading contributor to global solar PV projects. In 2013, it was noted that sixty percent of the world's solar PV installations were attributed to this continent, as shown in Table 1. Since 2013, significant solar PV development has been observed in other regions, particularly in China. In 2017, it was established that China emerged as the largest solar PV market, surpassing Europe, with approximately 1/3 of the worlds installed capacity. By 2022, the world's cumulative installed solar PV power capacity was reported to have exceeded 1046 GW (IRENA, 2023). A remarkable increase of around 22% (192 GW) in solar PV installed capacity between 2021 and 2022 is illustrated in Table 1. While the top three installers are identified as China, the US, and Japan, it was found that China's relative contribution comprised nearly 37% of the total solar PV installation in 2022. In 2022, it was observed that the most significant expansion in the solar PV market took place in China, the US, and India, with increases of 86.1 GW, 17.8 GW, and 13.5 GW, respectively (IRENA, 2023).

Photovoltaic panels encounter efficiency impediments attributable to various determinants, including particulate matter, reflection, angle, orientation, shading, solar radiation, and temperature. Among these, temperature emerges as the most critical variable, since only the visible spectrum of light is transduced into electrical energy, while other wavelengths are converted into thermal energy, thereby compromising overall efficiency

Table 1: Global installed solar PV capacity from 2013 to 2022[1]

	Solar PV capacity (MW)									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
World	136 572	176113	224070	296112	390878	483495	585868	713918	855162	1046614
Africa	651	1544	1917	3030	4675	7165	8408	9734	855162	11556
Asia	36055	60346	90236	140125	211488	275827	332111	409433	10543484496	596530
Europe	81878	88783	97292	1033861	109987	119291	139951	160474	187822	225478
N.America	12358	18463	25285	36973	46070	55890	67881	84728	105695	124946
S.America	198	465	921	1589	3672	5512	8562	13164	20687	32665
Oceania	4607	5355	6076	6857	7574	8878	13290	8354	23339	27397

1.2 PV Technology & Temperature versus Performance Relationship

Photovoltaic are utilized to directly convert solar radiation into electricity. Each cell is formed from layers of a semiconducting material, consisting of p and n-Type. When light is incident upon the cell, an electric field is generated between the layers, resulting in an output voltage and current. The cells are classified as either polycrystalline, which are composed of fragments from multiple silicon crystals, or monocrystalline, which are sliced from a singular large crystal. The monocrystalline cells have a greater conversion efficiency and cost. An issue is presented by the fact that current PV technology exhibits relatively low conversion efficiencies, ranging from 6-20%. Meanwhile, it is noted that the remaining 80-94% of incident solar radiation is transformed into heat, which significantly raises the temperature of the PV cell, consequently reducing the efficiency. Higher temperatures slightly increase current but cause significant voltage drops, reducing solar panel efficiency by 0.5% per 1°C rise, and can also damage silicon cells and cause corrosion due to negatively charged stray currents.

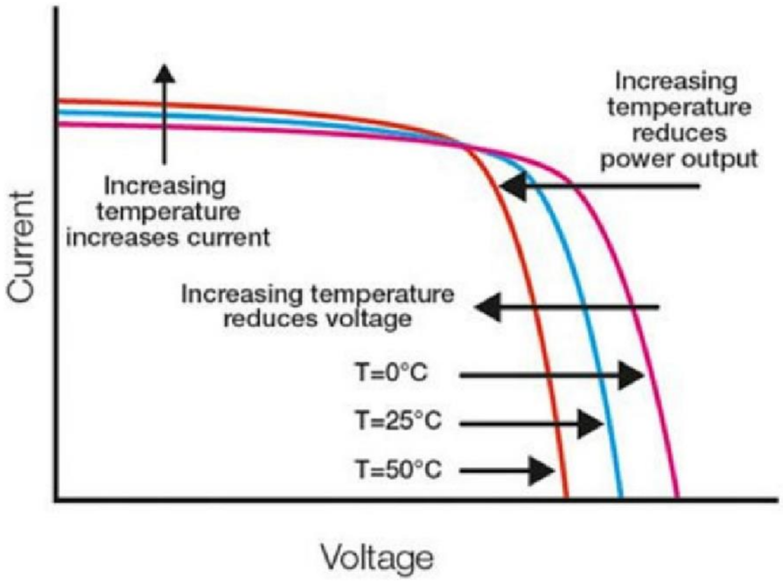


Figure 1: Impact of temperature on the current and output voltage profiles

1.3 Objectives

1. Assess the Effectiveness of Thin Film Water Cooling: Determine the extent to which thin film water cooling can reduce the operating temperature of PV solar panels under different environmental conditions and assess its impact on panel efficiency.
2. Compare Thin Film Water Cooling with Conventional Cooling Methods: Compare the thermal performance of thin film water cooling with traditional cooling methods such as air cooling or passive cooling techniques commonly used in solar panel applications.

3. Optimize Cooling System Parameters: Investigate the optimal parameters for thin film water cooling, including water flow rates, film thickness, and surface path configurations, to maximize cooling efficiency and energy yield.
4. Develop a Numerical Model for Cooling System Simulation: Create a comprehensive numerical model using computational fluid dynamics (CFD) software to simulate the heat transfer and cooling processes in PV solar panels with thin film water cooling.
5. Provide Practical Recommendations for Implementation: Based on experimental and numerical results, provide practical recommendations for implementing thin film water cooling systems in real-world PV solar panel installations. Consider factors like cost-effectiveness, ease of maintenance, and environmental considerations.

2 Literature Review

Cooling technology plays a pivotal role in augmenting the performance and efficiency of photovoltaic (PV) systems, as it mitigates the adverse repercussions of elevated operating temperatures on solar panels. Increased temperatures can markedly diminish the electrical efficiency of PV modules, thereby rendering effective cooling methodologies indispensable for sustaining optimal performance and extending the operational lifespan of these systems [2].

Cooling technologies are typically classified into passive, active, and hybrid systems, each possessing unique advantages and constraints. Various cooling techniques employed in PV cooling are discussed in the subsequent sub-sections and are illustrated in Fig.2

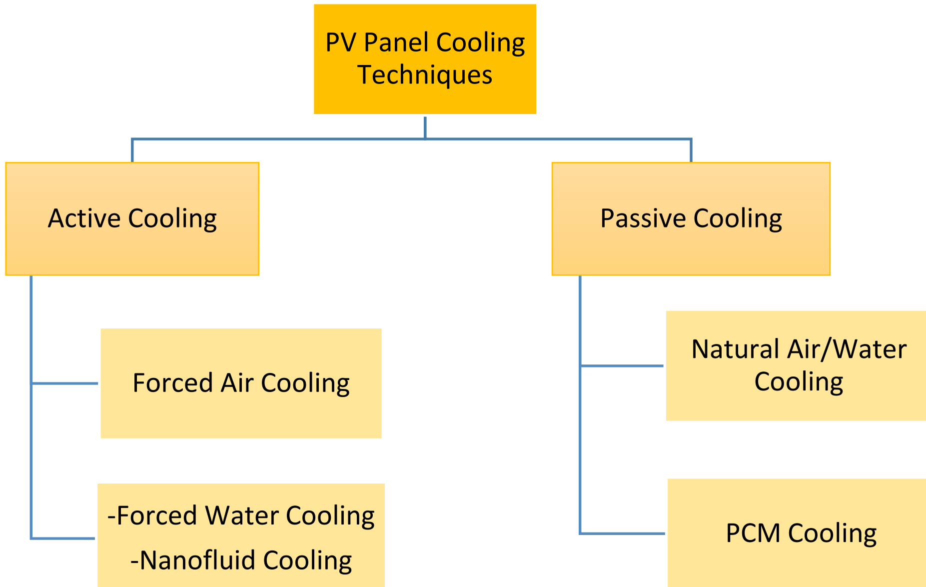


Figure 2 the different Cooling Techniques

2.1 Bibliometric Analysis

2.1.1 Trend Analysis

Year-wise publications in recent years have been analyzed. Table 2 is presented, showing the number of publications that have been issued from 2000 to 2024 in the domain of Cooling of photovoltaic solar panels. An upward trend is observed, indicating that research has been gradually increasing over the years, particularly during 2022, 2023, and 2024. Therefore, more focus could be placed on the research in the area of Cooling of photovoltaic solar panels. Figure 2 is displayed, illustrating the number of publications year-wise over the last 24 years. A significant increase in publications is noted in 2022 and 2023. Being a critical social concern for research, the graph indicates an upward trend over recent years. The highest number of publications was recorded in the year 2023.

Table 2: Publication trend from year 2000 to 2024 (Source: www.scopus.com accessed on august 13, 2024)

Year	No of Documents	Year	No of Documents
2024	291	2011	27
2023	444	2010	24
2022	340	2009	14
2021	233	2008	13
2020	183	2007	6
2019	163	2006	9
2018	124	2005	6
2017	106	2004	6
2016	84	2003	2
2015	47	2002	1
2014	47	2001	3
2013	37	2000	1
2012	37		

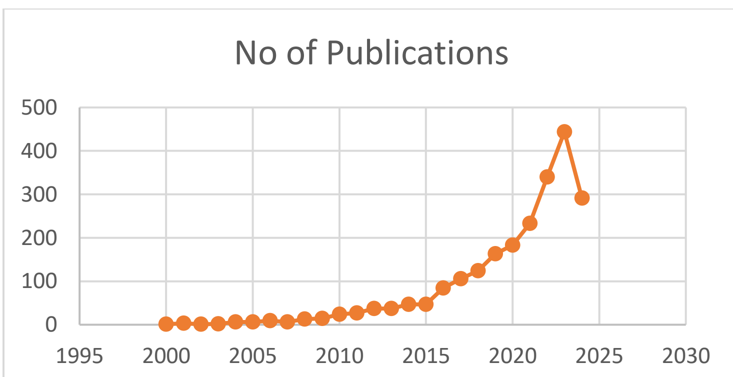


Figure 3 Year-wise trend of publication for the last 24 Years

(Source: www.scopus.com accessed on august 13, 2024)

2.1.2 Country Wise Publications

Table 2. Describes the country-wise distribution of research publications dealing with cooling photovoltaic solar panels. India is the forerunner with 372 publications on it, marking a high contribution in this field of study. China, with 261 publications, means that interest in research in this area is strong in that nation. Coming third is Iran, with 190 publications on a subject that means there has been some active effort in researching the domain under study. The United States, Malaysia, and Saudi Arabia are other important contributors with 151, 145, and 135 publications, respectively.

Other countries most interested in this field of research include Egypt, which published 127 publications on this field, Iraq published 123 publications, the United Kingdom published 119 publications, and Turkey published 118 publications. The figure clearly shows that the trend of working towards the future, in terms of the cooling of photovoltaic solar panels, is universal across countries from diverse parts of the world in the quest to enhance the efficiency and performance of solar energy systems.

Table 3 Country Wise No of Documents Published (Source: www.scopus.com accessed on august 13, 2024)

Country/Territory	No of Publications
India	372
China	261
Iran	190
United States	151
Malaysia	145
Saudi Arabia	135
Egypt	127
Iraq	123
United Kingdom	119
Turkey	118

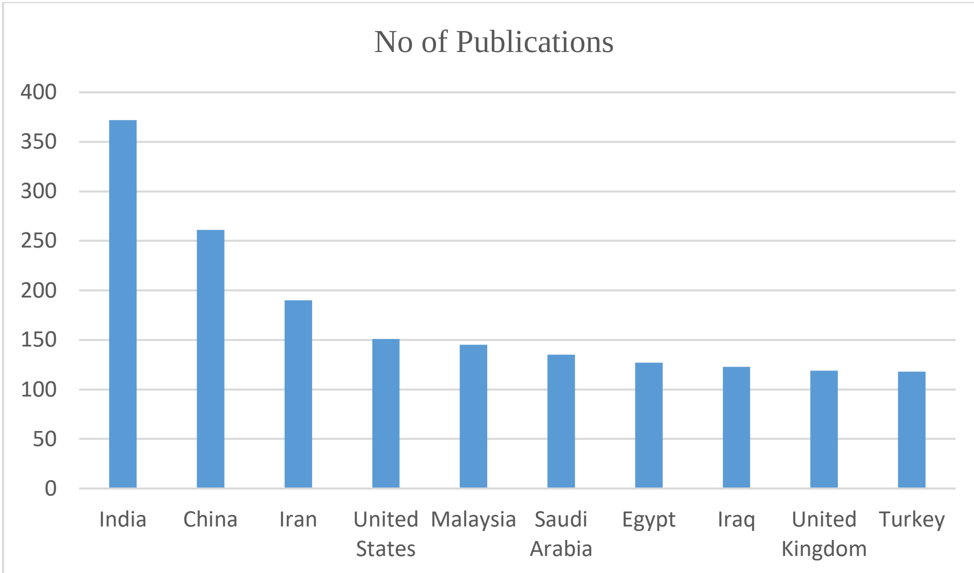


Figure 4 Research on Cooling of photovoltaic Solar panels in different countries

(Source: www.scopus.com accessed on august 13, 2024)

2.2 Active Cooling Method

Active cooling methodologies, which involve the utilization of pumps, fans, or blowers, can further optimize heat dissipation by utilizing water, air, or Nano fluids as coolants. Empirical evidence indicates that these methods can significantly enhance electrical efficiency, with Nano fluids such as silver and aluminum oxide improving both thermal and electrical performance due to their exceptional heat transfer characteristics [3] [4].

The thermal characteristics and efficiency of a solar PV module were examined by K. M. Alsayegh [5], where a combination of active and passive cooling mechanisms was investigated. The experimental setup was comprised of aluminum fins and an ultrasonic humidifier, and a reduction in the temperature of the PV panel was observed, averaging 14.61°C due to the cooling process. This observed temperature reduction was associated with a 6.8% enhancement in the electrical efficiency of the module.

The performance of photovoltaic (PV) modules has been studied in tropical climates using aluminum heat sinks and forced cold-air circulation methods. N. M. A. Rahman et.al[3], It is demonstrated by the study that the surface temperature of PV modules is significantly reduced by using aluminum fins as heat collectors. For example, the surface temperature was lowered from 64.3 °C without cooling to 39.73 °C with 200 mm high fins, showing effective heat management The heat transfer characteristics of a water-cooled photovoltaic/thermal (PV/T) system featuring a cooling channel positioned above the PV panel were examined by S. Y. Wu et al.[6]. It was indicated by the study that the mass flow rate (ranging from 0.001 to 0.05 kg/s), cooling channel height (3 mm to 14 mm), inlet water temperature (288.15 to 302.15 K), and solar radiation intensity (100 to 1000 W/m²) are significantly influenced by the heat transfer characteristics of the cooling channel and the overall performance of the PV/T system.

2.3 Passive Cooling Method

Passive cooling is a technique that is employed to improve the efficiency of photovoltaic (PV) panels by having their operating temperature lowered without relying on external power sources. Natural cooling mechanisms such as air and water cooling, as well as radiative and evaporative cooling, are primarily involved in this technique. By incorporating air ducts or metal fins at the back of the PV cells, natural air cooling can be facilitated to increase the surface area that is exposed to air, thus improving the cooling rate.

Table 4 Summary of most of the studies on Active Cooling

Author	**Cooling Method**	**Type of Study**	**Findings**
Bhaidara et al.[7]	Active (Water cooling system installed on the back surface of the PV panel)	Numerical & Experimental	Temperature reduced to 20%
Llhan ceylan et al.[8]	Active (A cooling system consisting of a simple tube placed on a PV module)	Experimental	Electrical efficiency improved by 3%
McColl et al.[9]	Active (Water Cooling & Sun tracking system)	Experimental	Electrical Energy production increased by 22%

Kabeel et al.[10]	Active (Reflectors with water & air cooled)	Experimental	Power improved by 16.81% & 21.62%
Kamal singh et al.[11]	Active (Copper tubes attached behind conventional PV panel)	Experimental	Temperature was decreased by 15.23% & electrical efficiency increased by 6.08%
Yingbo Zhang et al.[12]	Active (Porous cooling Channel)	Numerical & Experimental	electrical efficiency increased by 6%

An experiment was conducted by Study et al.[13], in which a modified aluminum fin heatsink was included in the experimental setup to enhance cooling. The fins were made from 22-gauge aluminum, which was bent manually to the required angles, and it was found that the implementation of an aluminum fin heatsink could lead to a reduction in the temperature of the photovoltaic (PV) cells by up to 10 °C. An enhancement in the efficiency of the panels is expected to be seen by approximately 5% as a result of the significant temperature drop.

Table 5: Summary of most of the studies on Passive Cooling technique

Author	Cooling Method	Type of Study	Findings
Hernandez-Perez et al.[15]	Passive New Passive heat sink design	Numerical & Experimental	An improvement if electrical efficiency by 4%
Laura Maturi et al.[16]	Passive Heat sink system on backside of the PV module	Numerical & Experimental	Temperature decreased by 5.2 ^{0}C & output power increased by 2.3%

Faith Bayrak et al.[17]	Passive Different fin parameters	Experimental	Energy efficiency calculated as 11.55%
Ellis Johnston et.al [18]	Passive Different fin height & different fin inclination	Numerical & Experimental	Output power increased by 15.3%

Numerical studies were performed by H. Elarga et al. [14] regarding the performance of an integrated photovoltaic (PV) and phase change material (PCM) system within double skin façades (DSF), where a comparison was made of the yearly solar energy conversion for two different façade configurations. It is emphasized by the study that the incorporation of the PCM layer results in a stabilization of the PV module temperature, leading to an increase in the electrical energy conversion efficiency by 5% to 8% when the DSF is outfitted with the PCM-PV configuration. This enhancement is deemed particularly significant for improving the overall performance of the PV modules.

Active cooling methods offer several advantages over passive cooling techniques when it comes to enhancing the performance of photovoltaic (PV) systems. Here is a summary based on the provided contexts:

1. Enhanced Heat Dissipation: Active cooling methods utilize pumps, fans, or blowers to optimize heat dissipation. This approach allows for more effective cooling compared to passive methods, which rely on natural processes like air or water flow without external power sources
2. Use of Advanced Coolants: Active cooling can incorporate advanced coolants such as Nano fluids, including silver and aluminum oxide. These Nano fluids have exceptional heat transfer characteristics, significantly enhancing both thermal and electrical performance of PV modules
3. Greater Temperature Reduction: Empirical evidence suggests that active cooling can achieve a more substantial reduction in PV panel temperatures. For instance, a combination of aluminum fins and an ultrasonic humidifier in an active cooling setup resulted in an average temperature reduction of 14.61°C, which is more significant than typical passive cooling results

4. Improved Electrical Efficiency: The enhanced cooling provided by active methods can lead to significant improvements in electrical efficiency. The use of Nano fluids in active cooling systems has been shown to improve both thermal and electrical performance, which is crucial for maximizing the energy output of PV systems
5. Flexibility and Control: Active cooling systems offer greater flexibility and control over the cooling process. By adjusting the operation of pumps, fans, or blowers, these systems can be tailored to specific environmental conditions and performance requirements, unlike passive systems that are limited by ambient conditions

In summary, while passive cooling methods are beneficial for their simplicity and lack of energy consumption, active cooling methods provide superior heat dissipation, greater temperature reduction, and improved electrical efficiency, making them a more effective choice for optimizing the performance of PV systems.

3 Numerical simulations

In this project, a single PV panel is assessed through the use of COMSOL Multiphysics FEA software, from which results may be derived for an array of similar PV panels. An aluminum reservoir will be designed in COMSOL for the specified PV panel, through which water at a set inlet temperature will be directed. As forced convection is being investigated in this study, with water serving as the coolant or heat transfer fluid, various water flow rates will also be assessed for their influence on cooling performance.

3.1 Simulation set up

The simulation was carried out using COMSOL Multiphysics. The system involved a PV panel cooled by a flow of water passing through an array of holes, which facilitated heat exchange. The parameters for this simulation are as follows:

- Hole diameter (d): 2 mm
- Number of holes (N): 16
- Mass flow rate (m): 0.01, 0.03, 0.05 kg/s (swept parameters)
- Water density (ρ): 1000 kg/m³
- Heat flux (P): 1000 W/m³

- Fluid velocity (u): 0.19894 m/s

3.1.1 Geometry and Materials

The simulation modeled a 3D geometry with aluminum as the primary material for the PV panel and water as the cooling fluid. The cooling holes were explicitly defined in the model, with flow inlet and outlet boundaries assigned to ensure proper fluid flow over the PV panel surface.

- Material 1 (Solid): Aluminum
- Material 2 (Fluid): Water

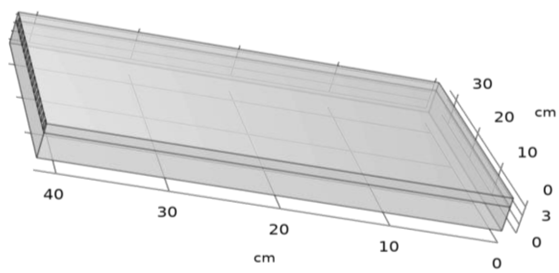


Figure 5 PV Panel geometry

3.1.2 Physics

The following physics interfaces were included in the model:

- Heat Transfer in Solids and Fluids: This interface was used to model the thermal behavior of the PV panel and the fluid.
- Laminar Flow: The fluid flow through the holes and over the panel was modeled using laminar flow equations.
- Nonisothermal Flow: This multiphysics coupling was employed to account for the interaction between heat transfer and fluid flow.

3.1.3 Mesh and Computation

A fine mesh was used for accurate results, and solved using a parametric sweep with mass flow rates of 0.01, 0.03, and 0.05 kg/s.

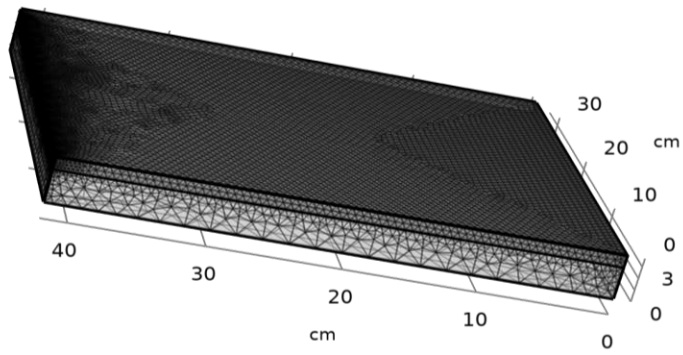


Figure 6 Meshing

3.1.4 Temperature Distribution**:**

The heat transfer analysis showed a significant reduction in temperature with increasing mass flow rate. The surface temperature distribution indicated that the cooling water efficiently dissipated heat across the PV panel.

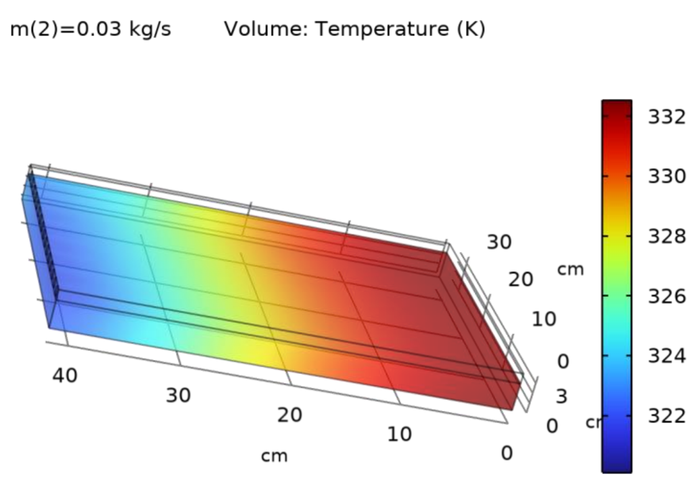


Figure 7 Temperature distribution

3.1.5 Velocity Distribution

The velocity of water was highest near the inlet and gradually reduced as it flowed across the PV panel. At the highest mass flow rate (0.05 kg/s), the velocity magnitude increased accordingly, improving the cooling effect.

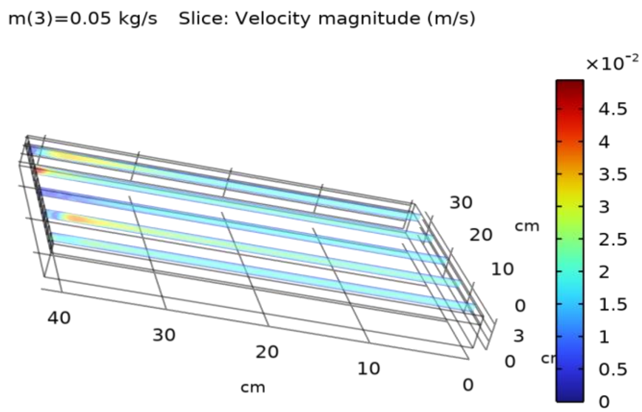


Figure 8 Velocity Distribution

3.1.6 Pressure Distribution

Pressure contours showed higher values near the inlet of the water flow. The pressure drop was uniform across the surface, indicating stable laminar flow.

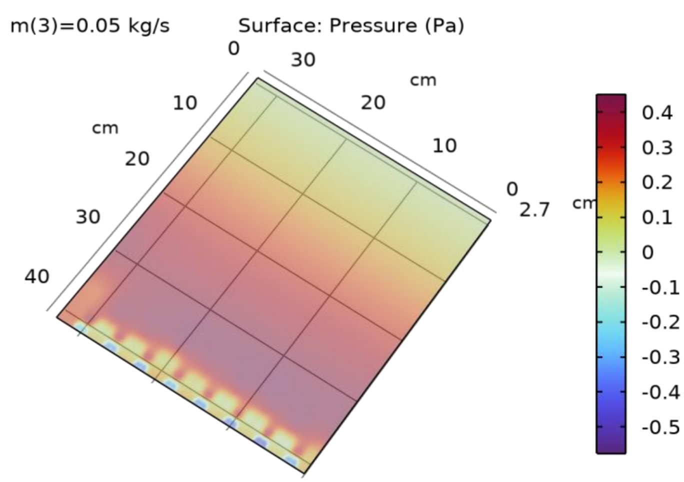


Figure 9 Pressure Distribution

4 Experimental Validation

Computer based simulation would be able to provide the solutions for the engineering design challenges faster and they are typically more efficient. They also help in reducing product development time as well as cost. However, it is always recommended to validate the results that were obtained from the numerical simulations with the experimental studies. Also, the experimental studies re-produce the actual working conditions and hence the performance evaluation data are more reliable as against the computer based simulations such as (CFD/FEA) which normally apply lots of assumptions and / or having modeling limitations. So, an experimental study must be carried out to validate the results from the numerical simulations.

4.1 Experimental set up

The experimental setup for the active cooling of solar photovoltaic (PV) panels involves several key components designed to evaluate the cooling effects on the PV panel's performance. Below is a detailed explanation of each part of the setup, including the equipment used, configurations, and procedures followed to ensure accurate results.

4.1.1 PV Panels

A single PV panel was selected for the experiment, measuring approximately 37 X 48 CM in size. The PV panel is installed on a flat surface, with a tilt angle of 30 degrees to simulate realistic solar exposure conditions. The panel is composed of monocrystalline silicon cells, chosen for their high conversion efficiency.

4.1.2 Cooling System Components

The active cooling system is a water-based setup, designed to reduce the temperature of the PV panel by circulating water over the surface of the panel. The system includes the following components:

- Water Tank: A 50-liter water tank serves as the reservoir for the cooling system. The water tank is filled with clean tap water and placed adjacent to the PV panel for ease of water flow and recirculation
- Water Pump: A submersible water pump with a flow rate of 10 liters per minute is used to drive water from the tank to the surface of the PV panel. The pump is connected to a pipeline system that allows the water to flow smoothly over the PV panel surface

- Piping and Valves: Piping made of high-quality, corrosion-resistant materials (such as PVC) is used to transport water from the tank to the PV panel. Flow regulators and control valves are installed to manage the water flow rate and pressure, ensuring optimal cooling performance
- Nano-fluid Additive**:** Al_2O_3 nanofluid is used. The nano-fluid enhances the heat transfer properties of the water, further improving the cooling efficiency of the system

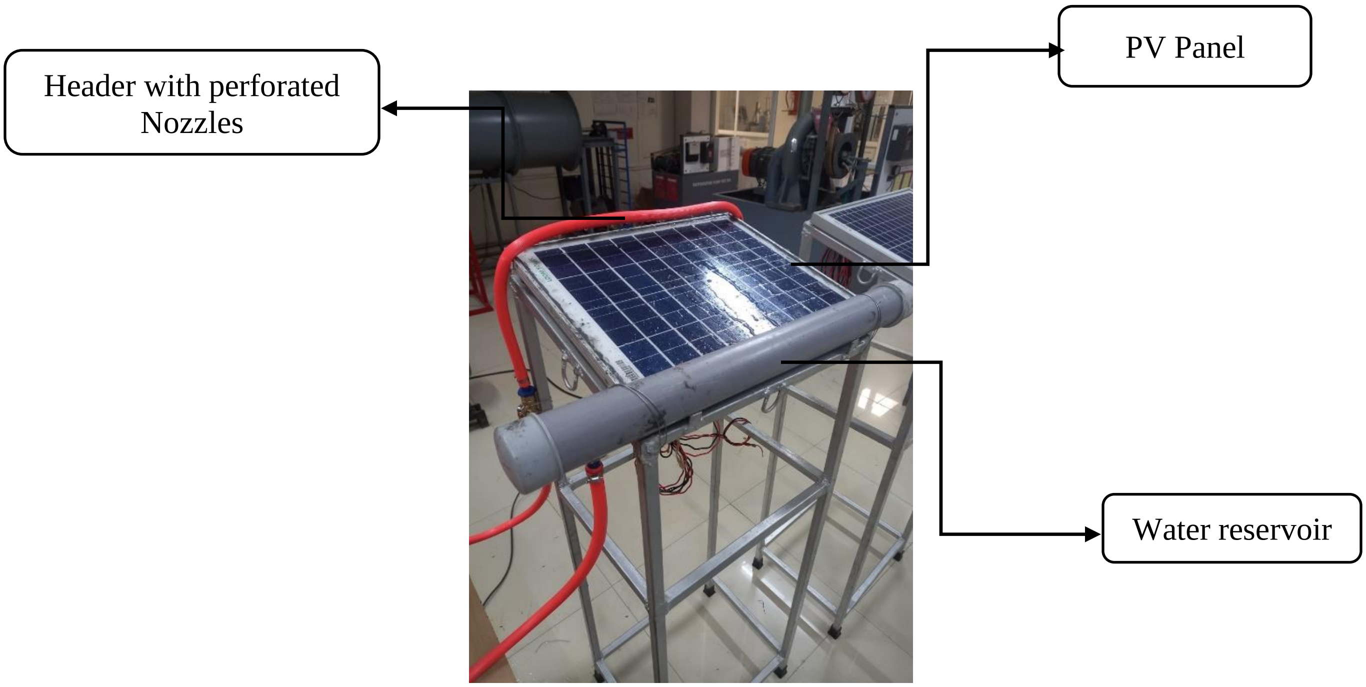


Figure 10 Experimental set up

4.1.3 Water Distribution System

Water is circulated through a network of pipes that leads to a perforated manifold positioned above the PV panel. The manifold is designed with small holes to evenly distribute water across the entire surface of the panel. The water flows from the top of the panel, creating a thin film that covers the PV cells and cools the surface through convective heat transfer. The water is collected at the bottom of the panel in a drainage channel, where it is filtered and recirculated back to the water tank.

5 Result & Discussion

5.1 Validation

It is necessary to compare the results obtained from a project solution methodology with another method to achieve the validation. For this project work, the results from numerical simulations (CFD) and experimental data had been compared in this section. The experimental studies for this project work were carried for the mass flow rate of 0.01, 0.03, and 0.05 kg/s. And hence the CFD simulation results for the same geometry configuration had been compared.

Water Cooling			
Mass flow rate kg/s.	Average Surface temperature (K)		% Difference
	Experimental Data	CFD Data	
0.01	315	306.70	2.63
0.03	312	303.52	2.72
0.05	310	303.38	2.14

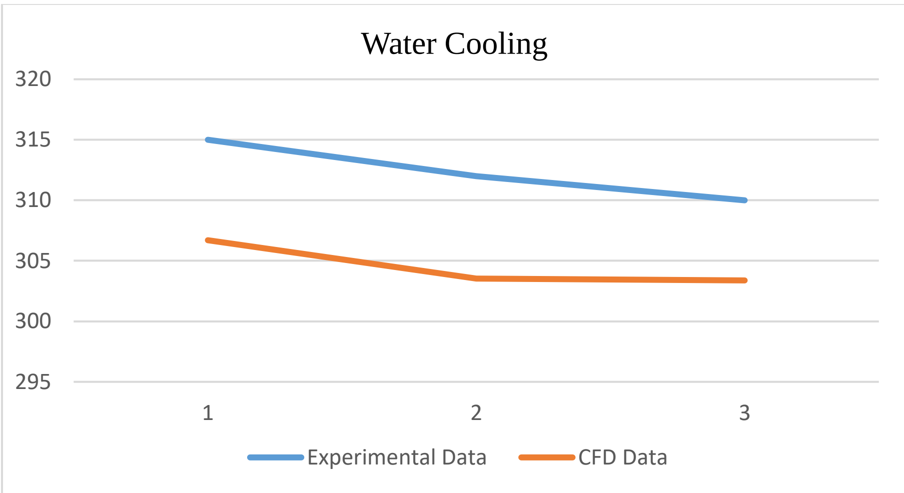
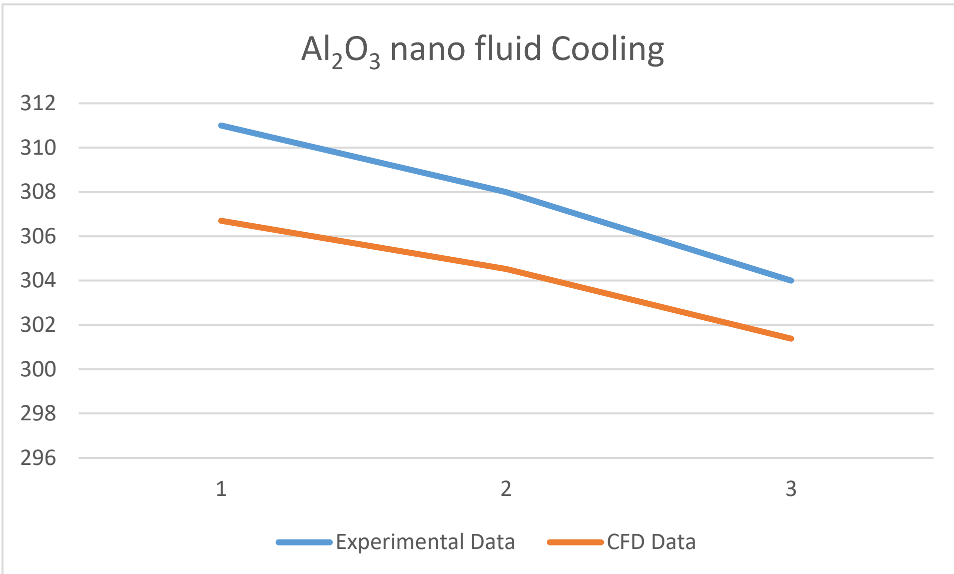


Figure 11 Average surface temperature for 1) 0.01 kg/s 2) 0.03 kg/s 3) 0.05 kg/s

Al$_2$O$_3$ nano fluid Cooling (Concentration 0.01%)			
Mass flow rate kg/s.	Average Surface temperature (K)		% Difference
	Experimental Data	CFD Data	
0.01	311	306.70	1.38
0.03	308	304.52	1.12
0.05	304	301.38	1.10



The results of the simulation & Experimentation demonstrate that cooling a PV panel using Nano fluid can be effective in managing heat. The temperature of the panel decreases as the mass flow rate increases, resulting in better heat dissipation and, consequently, enhanced performance of the PV panel.

- **At 0.01 kg/s**: The cooling effect was moderate, and while the temperature reduced, it did not uniformly cool the entire panel.
- **At 0.03 kg/s**: A more noticeable reduction in temperature was observed, with better cooling across the panel.
- **At 0.05 kg/s**: The best cooling effect was observed, as the water flow removed more heat, keeping the panel at a lower and more uniform temperature.

The velocity profiles showed that increasing the mass flow rate improved heat transfer, but it also required higher pumping power to maintain the flow. Pressure drop analysis suggests that the design can handle increased flow rates without significantly affecting the cooling performance.

6 Conclusion

The validation of the computational fluid dynamics (CFD) results with experimental data in this study has demonstrated the effectiveness of cooling a photovoltaic (PV) panel using both water and Al_2O_3 nanofluid. The CFD simulations showed a close agreement with experimental data across different mass flow rates, confirming the reliability of the proposed model.

Key findings include:

- The average surface temperature of the PV panel decreased as the mass flow rate increased, confirming that higher flow rates lead to better heat dissipation.
- Al_2O_3 nanofluid, with a concentration of 0.01%, proved to be more effective in cooling the PV panel compared to water. At all tested mass flow rates (0.01, 0.03, and 0.05 kg/s), nanofluid cooling exhibited lower temperature differences and improved heat transfer.
- The most effective cooling was achieved at the highest flow rate of 0.05 kg/s for both water and nanofluid, ensuring more uniform temperature distribution across the panel.
- However, an increase in mass flow rate also required higher pumping power, which needs to be balanced with the performance gains in practical applications.

The results confirm that nanofluid-based cooling offers a promising approach to enhancing the thermal management of PV panels, potentially improving their efficiency and performance. Further research could focus on optimizing nanofluid concentrations and flow rates for different PV panel configurations and environmental conditions.

7 References

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