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ARTICLE

Enhancing Solar Photovoltaic Efficiency: A Computational Fluid Dynamics Analysis

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ABSTRACT

The growing need for sustainable energy solutions, driven by rising energy shortages, environmental concerns, and the depletion of conventional energy sources, has led to a significant focus on renewable energy. Solar energy, among the various renewable sources, is particularly appealing due to its abundant availability. However, the efficiency of commercial solar photovoltaic (PV) modules is hindered by several factors, notably their conversion efficiency, which averages around 19%. This efficiency can further decline to 10%–16% due to temperature increases during peak sunlight hours. This study investigates the cooling of PV modules by applying water to their front surface through Computational fluid dynamics (CFD). The study aimed to determine the optimal conditions for cooling the PV module by analyzing the interplay between water film thickness, Reynolds number, and their effects on temperature reduction and heat transfer. The CFD analysis revealed that the most effective cooling condition occurred with a 5 mm thick water film and a Reynolds number of 10. These specific parameters were found to maximize the heat transfer and temperature reduction efficiency. This finding is crucial for the development of practical and efficient cooling systems for PV modules, potentially leading to improved performance and longevity of solar panels. Alternative cooling fluids or advanced cooling techniques that might offer even better efficiency or practical benefits.

KEYWORDS

PV module efficiency; water film thickness; reynolds number; CFD analysis; PV/T; renewable energy

Nomenclature

PV	Photovoltaic
a	Thickness of Water Film
b	Width of the Water Film/ PV Module

IV	Current Voltage
D_h	Hydraulic Diameter
Q	Heat Transfer per Unit Time
K	Thermal Conductivity of Material
dT	Temperature difference between hot and cold body
dx	Thickness of the body
hc	Coefficient of convective heat transfer
A	Area of heat transfer
ΔT	Temperature difference

Highlight

- Solar panel efficiency decreases due to high temperatures at midday.
- Water cooling the front surface of the panel improves efficiency.
- CFD tool is employed to analyze the water film thickness and Reynold number on temperature reduction.
- A water film thickness of 5 mm with a Reynolds number of 35 achieves optimal cooling.
- Water flow rate, Reynolds number, and diameter of the water channel affect heat transfer.

1 Introduction

Pakistan suffers from acute power shortages, with blackouts lasting up to eighteen hours a day in rural areas and twelve to thirteen hours in urban areas [1–3]. Economic limitations, the depletion of energy resources, and rising electrical consumption are the main causes of this dilemma [4,5]. The government has responded by enacting modest reforms to the power sector. Considering worries about global climate change, the nation also needs to guarantee energy security [6,7]. To tackle these issues, scientists are looking to renewable energy sources like solar energy. On the other hand, PV panel efficiency drops as temperature rises; for every degree Celsius above 25°C, efficiency drops by 5% [8]. Numerous investigations have investigated cooling techniques to help with this problem. For example, efficiency has increased in experimental setups using water cooling and ventilation systems [9–11].

The understanding and optimization of photovoltaic (PV) systems, with a focus on different cooling strategies and environmental interactions, have been greatly improved by contemporary advances in computational fluid dynamics (CFD) [12]. Research using ANSYS Fluent has shown that ground source and active air cooling can significantly lower PV operating temperatures, increasing efficiency [13]. An increasing number of reviews of CFD applications show that PV-environment interactions are being modeled, underscoring the need for improved parameterization techniques and more straightforward models for urban-scale simulations [14]. The use of phase change materials (PCM) and nanofluids in cooling systems has shown great potential in improving thermal efficiency [15]. Research on wind effects shows that strategic array topologies, especially those with inter-row spacing, can enhance PV performance under different wind situations. These findings emphasize the necessity of CFD in designing efficient cooling mechanisms and PV system designs for sustainability.

Attia et al. [16] conducted comparative analysis of two photovoltaic thermal (PVT) systems—one with a standard straight zigzag-gilded tube cooling conduit (Case A) and another with a novel three-section zigzag-plated tube cooling channel (Case B)—showed that Case B improved thermal efficiency by 7.23% (water) and 15.75% (air), and electrical efficiency by 4.0% (water) and 4.6% (air). This indicates that the innovative design significantly enhances PVT performance and ensures a more uniform coolant flow. However, Khelifa et al. [17] in his study analyzed the heat-based performance of photovoltaic thermal (PVT) collectors cooled with absorbent flax strings in water, finding the optimal configuration to be a 50 mm thick flax fiber layer with a 0.907 m/s water flow rate, which increased the Nusselt number by 173.46% compared to pure water. The PVT system's thermal efficiencies were 69.58% with water/flax fibers, 50.02% with pure water, and 34.60% with air.

Prior research has mostly concentrated on experimental configurations and particular cooling techniques as illustrated in Table 1, with a dearth of thorough simulation-based assessments that can be applied to various scenarios. Despite these developments, there is still a clear research deficit in using computational fluid dynamics (CFD) simulations to improve PV panel cooling. By using ANSYS Fluent for CFD simulations, this study seeks to lower the surface temperature of PV modules and increase their efficiency. The objective of this study is as follows:

- To offer a scalable method for utilizing sophisticated simulations to enhance cooling parameters.
- To determine the ideal parameters for maintaining surface temperatures of PV between 20 and 25°C using CFD analysis.
- To optimize heat transfer by adjusting Reynolds numbers and water film thickness.

Table 1: Literature review

Cooling agent	Simulation or experimental	Results	References
Air	CFD analysis	Varying air mass flow rates significantly impact the temperature and efficacy of the PV/T system under a solar irradiance of 800 W/m^2.	[18]
Air and water	CFD simulation	Authors disclosed water velocity affects the temperature of floating photovoltaic (FPV) systems, finding that forward water flow reduces FPV temperature. In contrast, reverse flow increases it, with a nominal water velocity of 1.1 m/s yielding a significant temperature drop.	[19]
Air-based	Numerical + Experimental	This study demonstrates that cooling photovoltaic (PV) panels with small backside fans resulted in a 2.1% increase in efficacy and a 7.9% energy savings while employing a blower through a lower duct led to a 1.34% increase in efficiency and a 4.2% energy savings.	[20]
Air	CFD analysis	This study used 3D CFD simulations to analyze the flow of air around ground-attached PV panel arrays, validated with field data. Results suggest optimal wind resistance with a 35° panel inclination, 0 m line spacing, and 3 m line spacing. Adjusting the inclination angle for higher wind velocities is advised to prevent damage and enhance resistance efficiency, offering valuable insights for PV power plant design.	[21]

(Continued)

Table 1 (continued)

Cooling agent	Simulation or experimental	Results	References
Air and a water-ethylene glycol solution	CFD analysis	A novel computational fluid dynamics algorithm is developed and applied to compare finned and unfinned collectors using air and water as working fluids, assessing solar segment, electricity division, and consumption factor. Results show that an air-based finned collector achieves the highest solar fraction and proves most effective for meeting concurrent heat and energy loads.	[22]

2 Design and Methodology

2.1 Computational Fluid Dynamics (CFD)

With the rise of computational fluid dynamics, it is widely used techniques to solve challenging issues in the current age of Engineering, Technology, and Innovation. CFD was originally motivated by a scientific understanding of the mechanics of fluids and heat transfer. It has cut costs and improved the performance of the equipment which has culminated in greater quality discoveries through computational simulation [23,24]. It is a multidisciplinary tool that led to the evolution of computer science, mathematics, and fluid mechanics. The dedication of CFD is only for the fluids that are in movement. Mathematical simulations of any fluid flow fall under the umbrella of the computational part [25,26].

2.2 Geometrical Drawing

ANSYS Fluent has a built-in design tool for creating 3D sketches, which can be used to draw different geometric specifications which is known as Space-Claim. A 3.4 mm-thick sketch of a photovoltaic PV panel's glass was drawn. Nevertheless, as shown in Fig. 1, a rectangle that resembled a duct was also constructed above the glass [15,27].

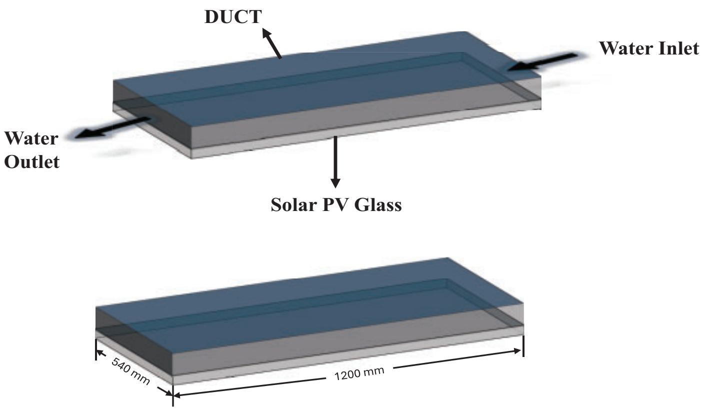

Figure 1: Solid model of glass with duct

2.3 3D Model Meshing

It is the important phase in CFD which arises after geometry. In this step simply, cells are built on which the flow variables are computed in a computational globe. There are distinct forms of cells, such as (Triangles, Quadrilateral, tetrahedrons, hexahedrons, etc.) out of which a fine mesh has been created of 5 mm.

Following the geometry phase, mesh generation represents a pivotal step in Computational Fluid Dynamics (CFD) as depicted in Fig. 2. During this stage, cells are intricately designed to facilitate the calculation of flow variables within a computational domain. Various cell shapes, including triangles, quadrilaterals, tetrahedral, and hexahedrals, are available for this purpose. The selection of an appropriate cell shape is contingent upon the specific characteristics of the flow under consideration. In this context, a fine mesh with a nominal size of 5 mm was employed to ensure a detailed representation of the computational domain. This meticulous mesh refinement is crucial for accurately capturing the intricacies of fluid flow and enhancing the reliability of the CFD simulations [28].

$$q_k = -kA\frac{dT}{dx} \tag{1}$$

$$q = hc\mathrm{A}\Delta\mathrm{T} \tag{2}$$

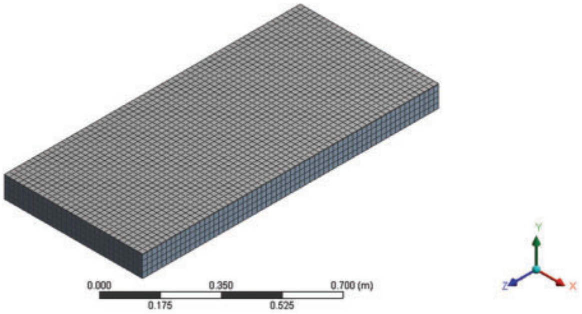

Figure 2: Structure mesh of the 3-D model

Eqs. (1) and (2) were the basic equations to be considered for the heat transfer from PV module glass to water (Coolant). However, the following parameters for the glass were considered as a standard to calculate heat transfer. Table 2 shows data for the glass. Whereas properties of glass and water are the standard values for calculating the effect [29–31].

Table 2: Properties of glass and water

Type	Thermal conductivity W/m. K	Density kg. m^{-3}	Sp. heat capacity J/kg. K	Temperature K
Glass	1.8	3000	500	50
Water	0.6	998.2	4182	25

2.4 Boundary Condition

Boundary conditions are applied without any reluctance. Velocity in any application of equipment can be varied by the variation in Boundary conditions. Besides, in real-time applications, it gets changed by the change of equipment of higher power as in the pump for variation flow rate and velocity. Altogether the same procedure is recalled for temperature and pressure whereas for many other conditions. Above mentioned technique reduces the cost of the system. CFD helps to simulate multiple conditions at different rates and variations in different parameters [32]. However, boundary conditions are also illustrated in tabular form in Table 3.

Table 3: Boundary conditions

Solver type	Pressure-based
Time	Steady-state
Velocity	Absolute
Model	Energy equation
Viscous	Laminar

2.5 Input Variables

The most useful and dynamic input variable that immediately gets affected by the flow includes velocity. Remember that a temperature of 323 K is fixed at the glass's surface. Even variations in Reynolds number have an impact on velocity. Therefore, velocity was computed at various Reynolds numbers between 5 and 50 as an input parameter [33].

2.6 Calculations

Considering the duct as a rectangular shape over the surface of the PV Glass it was considered that velocity will be the primary input variable. So, the hydraulic diameter was taken in the Reynolds number formula and calculations were done as given in following Table 4 and these calculations were carried out by Eq. (3).

$$D_h = \frac{2ab}{a+b} \tag{3}$$

Table 4: Hydraulic diameter

Hydraulic diameter	Thickness of water film	The breadth of the PV module
D_h	**m**	**m**
0.0918	0.05	0.56
0.08331	0.045	0.56
0.07467	0.04	0.56
0.06588	0.035	0.56
0.05695	0.03	0.56
0.04786	0.025	0.56
0.03862	0.02	0.56
0.02922	0.015	0.56
0.01965	0.01	0.56
0.00991	0.005	0.56

2.7 *Numerical Analysis*

The supposed geometry was meshed, allowing for simulations in ANSYS Fluent Academic Version V18R2. The laminar flow pattern was picked for the current shape due to its transparency throughout the PV module surface, enabling maximum irradiance absorption for electricity generation. So, the framework was solved using Energy Eq. (4) under steady-state circumstances [1–3].

$$\begin{aligned}\frac{\partial}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right]+\nabla.\left[\rho\left(e+\frac{V^2}{2}\vec{V}\right)\right]=\rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\frac{\partial up}{\partial x}\\ -\frac{\partial vp}{\partial y}-\frac{\partial wp}{\partial z}+\frac{\partial u\tau xx}{\partial x}+\frac{\partial u\tau yx}{\partial y}+\frac{\partial u\tau zx}{\partial z}+\frac{\partial v\tau xy}{\partial x}\\ +\frac{\partial v\tau yy}{\partial y}+\frac{\partial v\tau zy}{\partial z}+\frac{\partial w\tau xz}{\partial x}+\frac{\partial w\tau yz}{\partial y}+\frac{\partial w\tau zz}{\partial z}+\rho\vec{f}.\vec{V}\end{aligned} \tag{4}$$

3 Results and Discussion

3.1 *Maximum Heat Transfer*

The calculations were performed On ANSYS FLUENT software at different Reynolds numbers ranging from 5 to 45 as shown in Table 5. Geometry and meshing were done with the help of ANSYS workbench. Water was used as a fluid and the solid was modeled as Glass of photovoltaic. The flow was modeled as laminar and incompressible. Because of incompressible flow, the solver was used as pressure-based in ANSYS fluent. Then calculations were run on various Reynolds numbers. It was observed that with the increase of Reynolds number, the temperature change also increases. However, From Re = 35 the change in temperature becomes constant as clearly visible in Fig. 3.

Table 5: Heat transfer *vs*. Reynolds number

Hydraulic diameter	Velocity	Change in temperature	Reynolds number
m	m/s	K	
0.0918	2.0202	2.2398	5
0.08331	4.040404	2.2405	10
0.07467	6.060606	2.2408	15
0.06588	8.080808	2.2409	20
0.05695	10.10101	2.241	25
0.04786	12.12121	2.241	30
0.03862	14.14141	2.2411	35
0.02922	16.16162	2.2411	40
0.01965	18.18182	2.2411	45

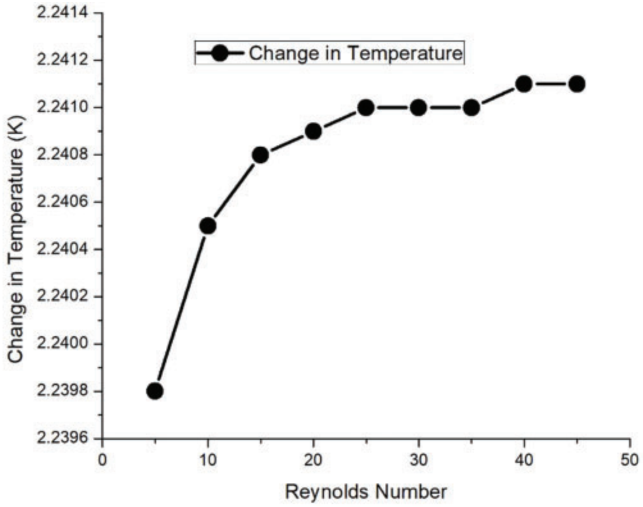

Figure 3: Reynolds number *vs*. Change in temperature

Therefore, the value of Reynolds is suggested as 35 at hydraulic diameter 0.04786 for maximum heat transfer.

3.2 Optimum Thickness of Film

After calculating optimum Reynolds number 35, for maximum heat transfer. Secondly, the optimum thickness was calculated. For the calculation of optimum thickness, different values of thickness were taken ranging from 5 to 50 mm. Based on thickness, the hydraulic diameter was calculated. Wherein the Change in temperature between the inlet and outlet was calculated on different thickness values as shown in Table 6. It can be observed from Fig. 4 and Table 6 that the maximum change in temperature occurs at 5 mm thickness of water. Moreover, as the value of thickness is increased the change of temperature is decreased. The maximum heat transfer occurs at Re = 35 and thickness = 5 mm in comparison to Re = 30, thickness = 30 mm. Therefore, it has been selected as the optimum value of Reynolds and the optimum value of thickness.

Table 6: Change in temperature *vs*. Thickness when Re = 5

Hydraulic diameter	Thickness (mm)	Change in temperature (K)	Velocity (m/s)
0.0918	50	2.227	0.217865
0.083306	45	2.2284	0.240067
0.074667	40	2.2298	0.267845
0.065882	35	2.2312	0.303571
0.056949	30	2.2326	0.35119
0.047863	25	2.234	0.417885
0.038261	20	2.2354	0.517866
0.029217	15	2.2369	0.684463
0.019649	10	2.2383	1.017812
0.009912	5	2.2398	2.0202

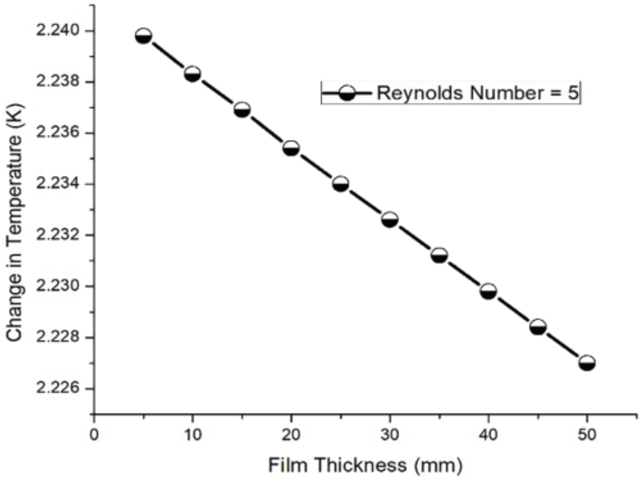

Figure 4: Thickness *vs*. Change in temperature

The rapid cooling of photovoltaic (PV) modules is essential for enhancing overall performance as shown in Fig. 5a–d, particularly electrical output during midday operations at peak temperatures. Various methods are employed to reduce working temperature, including the use of water as a cooling medium above the module's front transparent glass to extract surface temperature generated by irradiance. Water flow is regulated using the fundamental principles of the Reynolds number and hydraulic diameter as drawn in Table 6. Importantly, empirical observations reveal that the most significant temperature reduction occurs at a Reynolds number of 35 and a film thickness (T) of 5 mm demonstrated in Fig. 5c. The analysis in Fig. 5a–d implies a marked advancement in electrical efficiency by reducing the surface temperature of the PV Glass. Fig. 5b,d is the contours of the Glass surface and Fig. 5a,c is the contours of the Duct. when these optimal cooling parameters are applied, confirming the efficacy of this cooling strategy. Additionally, Table 6 focuses on the correlation between hydraulic parameters and cooling performance, providing a comprehensive framework for optimizing PV module cooling under varying operational conditions.

Fig. 6a,b displays the CFD study of the system including duct and PV glass. It is observed that the flow of water extracts the heat from the solar PV glass. From Fig. 6b, the contours of PV glass and interaction surface are illustrated. At Point 1, PV glass has the highest temperature, but water is very cold as compared to glass. However, with the optimal parameters the same contour shifts and takes place in opposite directions. At Point 2, the water is very hot, and the PV glass becomes very cold by achieving the standard temperature and pressure (STP) condition and maintaining room temperature at 25°C or 298 K.

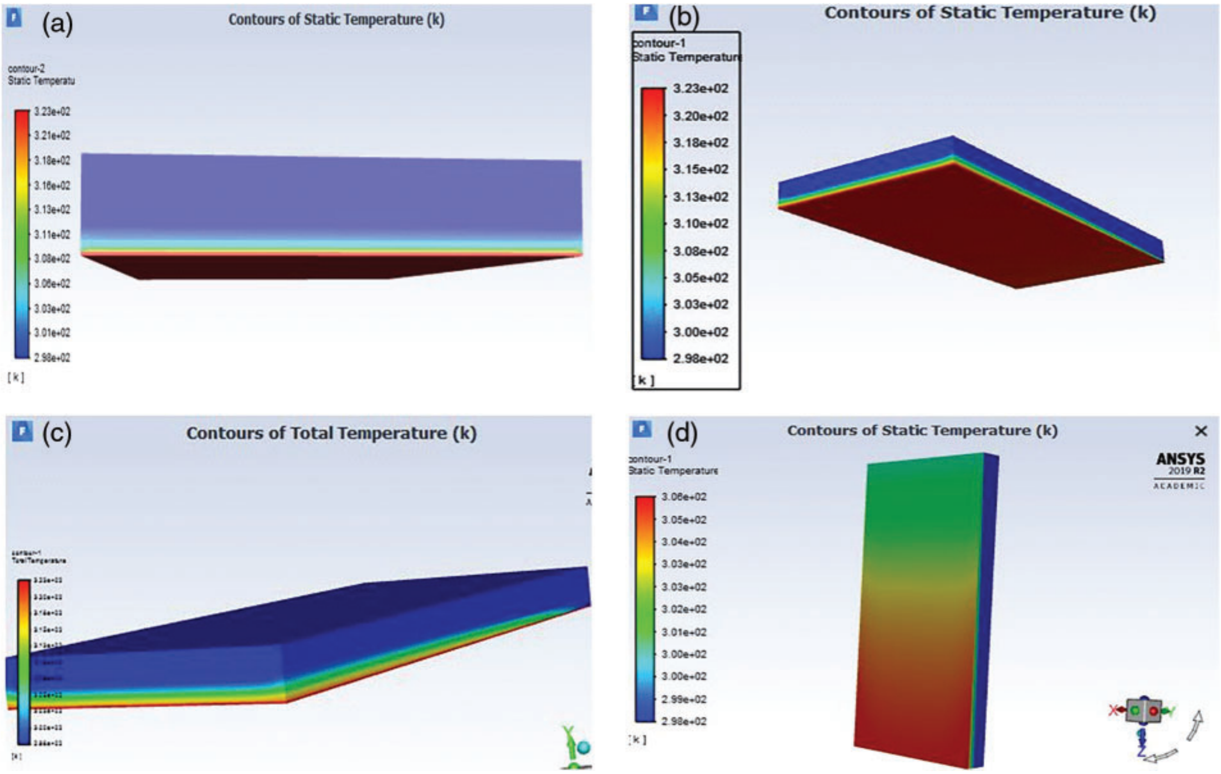

Figure 5: Contours of simulated model

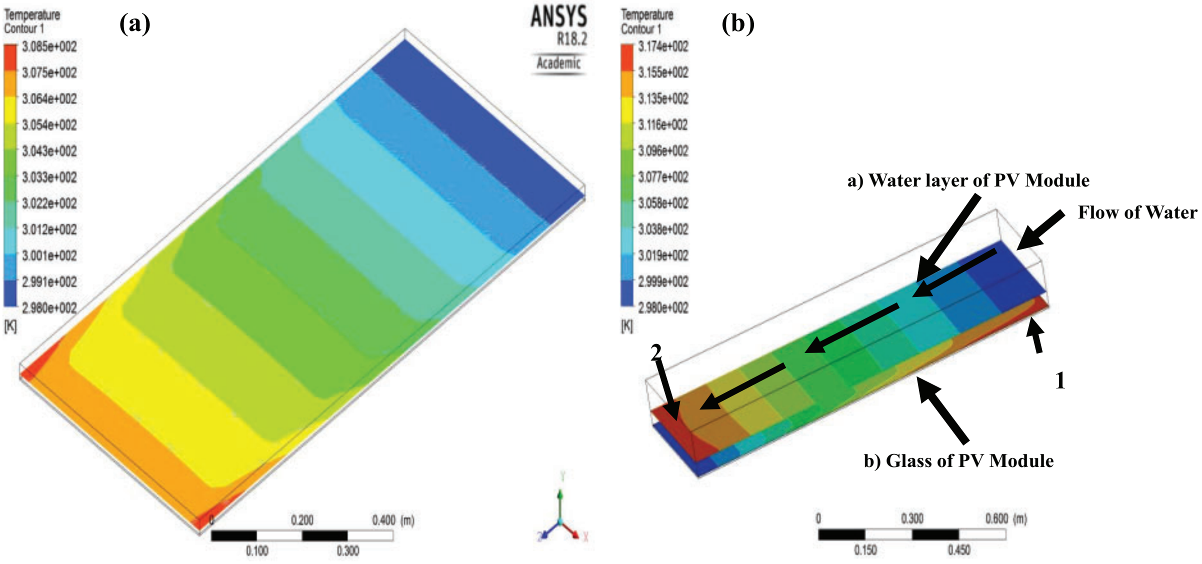

Figure 6: Interacting layer of water and PV glass

3.3 Validation of the Results

Our study molded the optimal cooling conditions for photovoltaic (PV) modules, with a Reynolds number of 35 and a water film thickness of 5 mm. Which ultimately increases the electrical power of the PV module [34]. This discovery aligns with previous research by Hosseini et al. [35] which also identified water cooling as an effective method for temperature control in PV modules. However, our study extends this research by pinpointing specific optimal parameters, whereas Smith et al. provided a broader range of effective Reynolds numbers (500–1500) without specifying the exact optimal point, and his study concluded the turbulent flow. Whereas, our study focused on laminar flow.

In contrast, Raju et al. [36] suggested a three-dimensional computational model for water spray cooling of photovoltaic panels, which reduced operating temperatures and enhanced performance, validated by an average deviation of 1.4 K from experimental data. The optimal flow rate of 170 L/h achieved an electrical efficiency of 15.73%, a panel power output of 40.25 W, and a pump power requirement of 0.77 W, with a maximum system power output of 39.48 W.

However, Patil et al. [12] disclosed the operating temperature of the PV panel significantly impacts its conversion efficiency, with high temperatures reducing output power under identical solar radiation conditions. His CFD Analysis with ANSYS Fluent software presents a solar PV/T system with a bottom active air-cooling system, finding that at an airflow rate of 0.1 kg/s and 800 W/m^2 irradiance, the maximum temperatures of the PV/T system's top surface, cell, bottom surface, and air inlet/outlet were 48.8°C, 48.4°C, 47.3°C, and 24.5°C, respectively. So, the discrepancies between our findings and those of Martin Raju and Malagouda Patil may be attributed to differences in experimental setups, such as the Martin Raju sprayed water with sprinklers, and we used free flow. Malagouda Patil tested the system with air as a fluid, but we used water as the fluid. Our study's improvements in cooling efficiency underscore the importance of fine-tuning cooling parameters, which had not been as precisely addressed in previous research.

4 Conclusion

The rapid advancement of cooling techniques for photovoltaic (PV) panels is crucial for enhancing their performance and electricity output, particularly during peak daytime temperatures. This research focuses on enhancing the performance of photovoltaic (PV) modules by effectively cooling them using a water film applied to the front transparent glass, thereby reducing surface temperature. The following are the main findings from the study:

- This study demonstrates a significant breakthrough in cooling photovoltaic (PV) panels. By strategically applying water film cooling to the front surface, we successfully mitigated the detrimental effects of irradiance-induced heat, particularly during peak daytime temperatures. This translates to a notable enhancement in PV performance and electricity output.
- Simulations reveal that the best cooling conditions occur at a Reynolds number of 35 and a film thickness of 5 mm for this particular geometry.
- This study demonstrates that optimal cooling can be achieved by adhering to fundamental engineering principles, specifically the Reynolds number and hydraulic diameter.

Implementing effective cooling methods, such as applying water over the front glass of the PV module, helps mitigate heat generated by irradiance. This research provides a practical and scalable approach to improving PV technology, establishing a foundation for further innovation and exploration in the field. Implementing these parameters in the design of cooling systems can lead to maximized temperature reduction and superior cooling efficiency. This research paves the way for substantial advancements in PV technology, offering a robust foundation for further exploration and innovation.

Future Scope

Future research could explore additional parameters and their impact on the cooling process, offering comprehensive insights for refining cooling techniques in PV technology. Investigating variables such as different cooling mediums, flow rates, ambient temperature conditions, and the potential of advanced materials holds immense promise for significantly improving PV module efficiency. Integrating computational modeling with real-world testing will be essential to optimize these parameters, driving the development of more effective and sustainable cooling strategies. By synergistically integrating computational modeling with real-world testing, we can optimize these parameters, paving the way for the development of even more effective and sustainable cooling strategies. This continuous exploration will ensure that PV technology evolves to meet the growing demands for renewable energy solutions.

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Availability of Data and Materials: The authors confirm that the data supporting the findings of this study is available within the article.

Conflicts of Interest: The authors disclose conflicts of interest about authorship, Dr. Sudhakar Kumarsamy is the member of the Editorial Board of Energy Engineering Journal. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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