Research Journal of Engineering Technology and Medical Sciences (ISSN: 2582-6212), Volume 07, Issue 02, June-2024
Available at www.rjetm.in/

Optimizing Photovoltaic Panel Cooling: Insights from Computational Fluid Dynamics Simulations

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Abstract: *photovoltaic (PV) panel thermal management utilizing CFD (computational fluid dynamics) simulations, with an emphasis on different fin geometries' cooling efficiency. Maintaining PV panels at their ideal working temperatures is essential to ensuring their longevity and continued performance as the need for efficient renewable power solutions grows globally. The study investigates how adding fins with varying shapes and configurations to photovoltaic modules can improve heat dissipation and, consequently, increase overall efficiency and dependability. The study aims to aid in the design and optimization of cooling structures for PV installations by providing information about the thermal properties of rectangular, trapezoidal, and triangular fins at various environmental circumstances through the use of CFD simulations.The results show notable increases in cooling efficiency for various fin kinds and arrangements. For example, a percentage improvement of about 0.51% and 3.24% was obtained when the amount of rectangular fins was increased from 10 to 20, suggesting improved cooling performance in this study as compared to previous studies. Even more increases were shown by trapezoidal fins, which improved by roughly 6.82% and 7.59% for 10 and 20 fins, respectively, highlighting their better heat dissipation properties. Likewise, significant gains of roughly 5.13% and 5.74% for 10 and 20 fins, correspondingly, were demonstrated by triangular fins, highlighting their competitive effectiveness in cooling.*

Additionally, the study assesses how variables like fin length and thickness affect cooling efficiency. It was discovered that, in comparison to the vital function played by fin geometry, changing these parameters within specific ranges had little impact on cooling efficiency. The study also covers other aspects of cooling performance, such as material characteristics and airflow patterns, which are crucial things to take into account when designing fins for solar power plant cooling applications.sIn summary, this study offers significant new understandings into PV system passive cooling techniques, with the goal of advancing solar energy technology through improved performance, dependability, and sustainability of solar power systems across the globe. The findings of this research have important ramifications for the creation of effective cooling solutions suited to particular operating circumstances.

Keywords:*photovoltaic panels, photovoltaic panel cooling, Computational Fluid Dynamics (CFD) simulations, fin geometries, temperature optimization, environmental conditions, efficiency, reliability*.

I.INTRODUCTION

The exploration into the cooling efficacy of attached fins with diverse geometries on photovoltaic (PV) panels, facilitated by Computational Fluid Dynamics (CFD) simulations, arises from the pressing need for efficient cooling solutions in solar energy systems. As the global demand for PV panels escalates, maintaining optimal operating temperatures becomes paramount for their performance and durability. This research endeavors to scrutinize how different fin shapes and arrangements can amplify heat dissipation from PV panels, thereby augmenting their efficiency and reliability. Through the utilization of CFD simulations, the study aims to offer insights into the thermal dynamics of various fin geometries amidst fluctuating environmental conditions, providing invaluable guidance for the refinement and enhancement of cooling systems for PV installations.

This investigation delves into a pivotal facet of PV system performance: temperature regulation. As solar panels convert sunlight into electricity, they inherently generate heat, posing a challenge to their efficiency and lifespan if left unaddressed. The integration of attached fins onto panels has emerged as a promising avenue for dissipating surplus heat and upholding optimal operating temperatures. Nonetheless, the efficacy of fins is contingent upon their geometry, encompassing factors such as shape, dimensions, and alignment. By means of comprehensive CFD simulations, this study endeavors to unravel the intricate interplay between diverse fin configurations and their cooling efficacy. Through systematic scrutiny of various fin geometries under disparate environmental conditions—encompassing solar irradiance levels and airflow dynamics—the research aims to elucidate the most efficacious cooling strategies for PV systems. Ultimately, the insights garnered from this inquiry carry substantial implications for the advancement of solar energy technology, facilitating heightened performance, reliability, and sustainability of PV installations on a global scale.

A. Effect of solar irradiance

The short circuit (ISC) current is affected by the amount of photons absorbed by the semiconductor material and is thus related to the light intensity . The conversion efficiency is therefore fairly constant in such a way that the power output is usually associated with the irradiance, but the efficiency is reduced if the cell temperature rises Figure 1. The open-circuit voltage (VOC) varies only marginally with the light intensity [1].

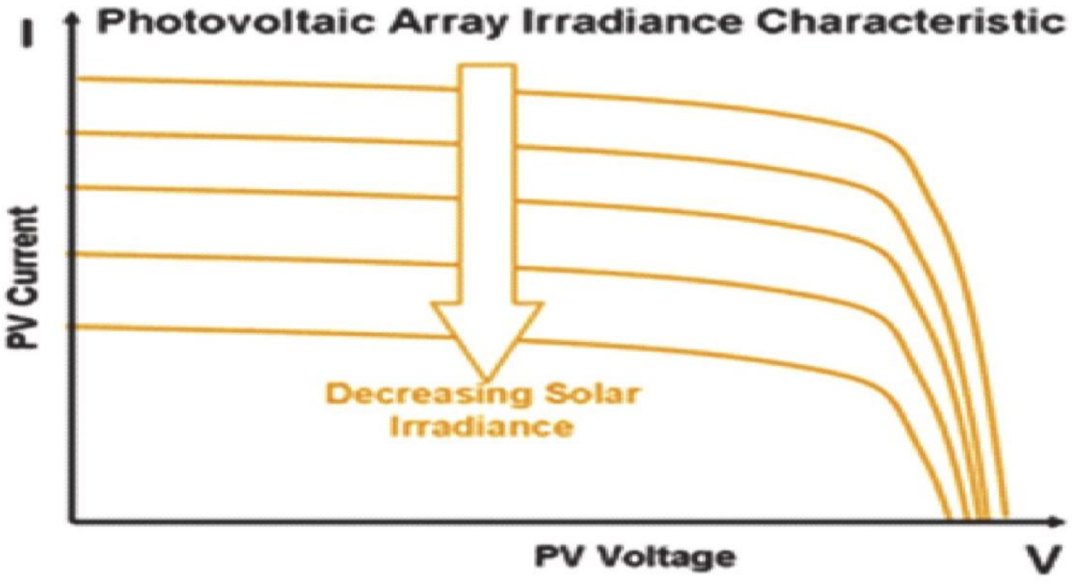

Figure 1. Characteristics of a solar P-V: Effect of solar irradiance[1]

B. Effect of ambient temperature

The VOC decreases so much with the rise in temperature of the panel above 25 oC but short-circuits current, Isc, increases only marginally Figure 2. The temperature effect on P.V. performance is identified as the temperature coefficient. The net result is a reduction in power output with temperature rise. The percentage of temperature coefficient indicates a shift in output as it rises or falls against the normal conditions of 25 degree Celsius.

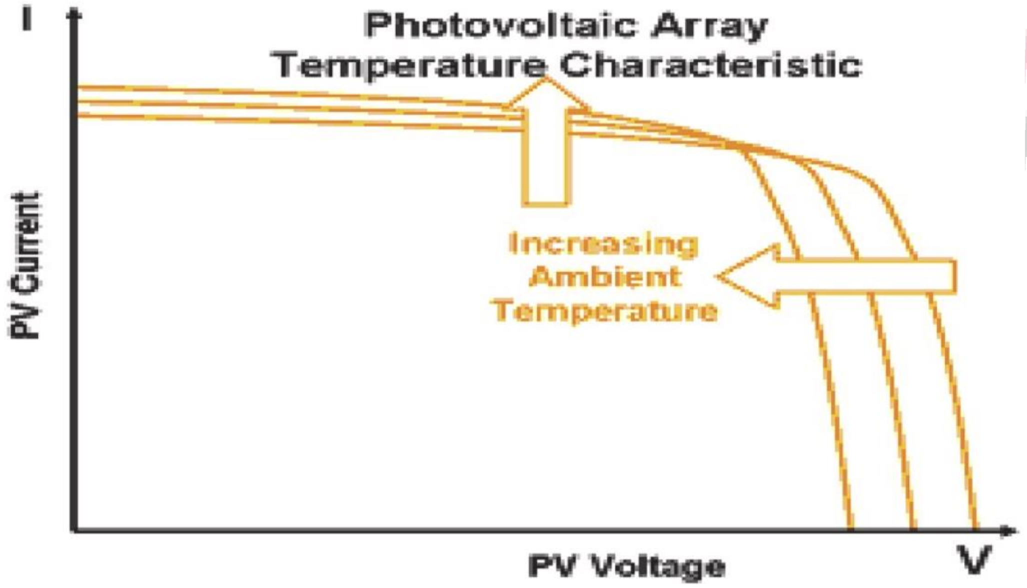

Figure 2. Characteristics of a solar P·V.: Effect of temperature[1]

II. LITERATURE REVIEW

Murtadha et al. (2023)[2] underscore the importance of addressing cost, durability, and simplicity in cooling systems to improve PV performance. Their study demonstrates that PV-3 equipped with longitudinal fins and forced air cooling achieved a remarkable temperature drop of 11.86% on the PV surface, coupled with a 5.42% increase in output power compared to baseline PV-1.

Kazem et al. (2023)[3] conducted a comprehensive review of active and passive thermal management solutions for PV technology, with a specific focus on the utilization of fins and their performance parameters. Their findings indicate that fins incorporated into various cooling systems, including air, fluid, nanofluid, and PCM-based systems, contributed to an 8-10% improvement in both electrical and thermal efficiency.

Elminshawy et al. (2022)[4] investigated novel passive cooling approaches for PV systems, comparing a modified floating PV system with attached fins to conventional systems. Their study revealed that the modified system outperformed conventional setups, achieving a substantial temperature reduction of 19.07% along with significant increases in output power and electrical efficiency.

Raina et al. (2022) [5]studied the effectiveness of a passive cooling system integrating fins into PV modules. Their research demonstrated that the passive cooling system with fins led to an average overall efficiency increment of 5.47% and exhibited efficacy in mitigating high module temperatures.

Amber et al. (2021)[6] conducted experiments to evaluate the efficacy of rectangular and circular fins attached to the rear surface of mono-crystalline PV modules. The results indicated that PV modules with rectangular fins exhibited significantly improved heat dissipation, resulting in a 10.6% decrease in module temperature and a 14.5% increase in efficiency compared to modules with circular fins.

Khan et al. (2020)[7] investigated the impact of hollow rectangular aluminum tubes as fins on the operating temperature and electrical output efficiency of silicon-based solar PV modules. Their experimental findings demonstrated that the attached fins reduced the average surface temperatures by up to 8.97% and 8.41% on the front and rear surfaces, respectively, leading to a notable increase in electrical output efficiency by up to 2.08%. These studies underscore the effectiveness of passive cooling techniques, particularly those utilizing rectangular fins, in enhancing the performance and efficiency of PV installations.

III. OBJECTIVE

- To analyse the thermal performance of fins and slits
- To analyse the temperature distribution of the fins and slits with different configurations of fin.
- To compare different configurations of fin for enhance performance of fins
- To suggest best configuration of fins

IV. METHODOLOGY

A. Computational Fluid Dynamics Analysis

Due to the advances in computational hardware and available numerical methods, CFD is a powerful tool for the prediction of the fluid motion in various situations, thus, enabling a proper design. CFD is a sophisticated way to analyse not only for fluid flow behavior but also the processes of heat and mass transfer.

Computational fluid dynamics is the analysis of systems involving fluid flow, heat transfer by use of computer-based simulation. The technique is very powerful and spans a wide range of industrial and non-industrial application areas. The phase shifting substance is used in the current work to do CFD evaluation utilizing ANSYS fluent for solar stills. This computerized study is carried out using mathematical model such as the following expression, conservation of momentum, as well as energy formulas.

Mathematical approaches for dealing address fluid flow difficulties are the heart of CFD. These Computational Fluid Dynamics software feature comprehensive user interfaces for entering variables and examining the details in order for providing immediate access to their solution capabilities. Hence three main elements are used to solve the Computational fluid dynamics problems.

a) Pre-processor,
b) Solver and
c) Post-processor

B. Boundary Conditions

In the present investigation, the commercial CFD software FLUENT 6.3, which is based on the finite volume method, is used for the numerical computation, and the SIMPLE algorithm is used for finding a solution for the coupling between the pressure and velocity. The finite-element model is built and meshed using the software Gambit, and unstructured grids are used. The tetrahedral grid is used for meshing the models, and the grid in the region near the tube wall, which is highly refined, is considered as the boundary layer. Figure 3.shows the meshing grid. In this study, a parameter study was conducted according to the shape of the fins to analyze the cooling performance of the fins attached at the bottom of the PV module.

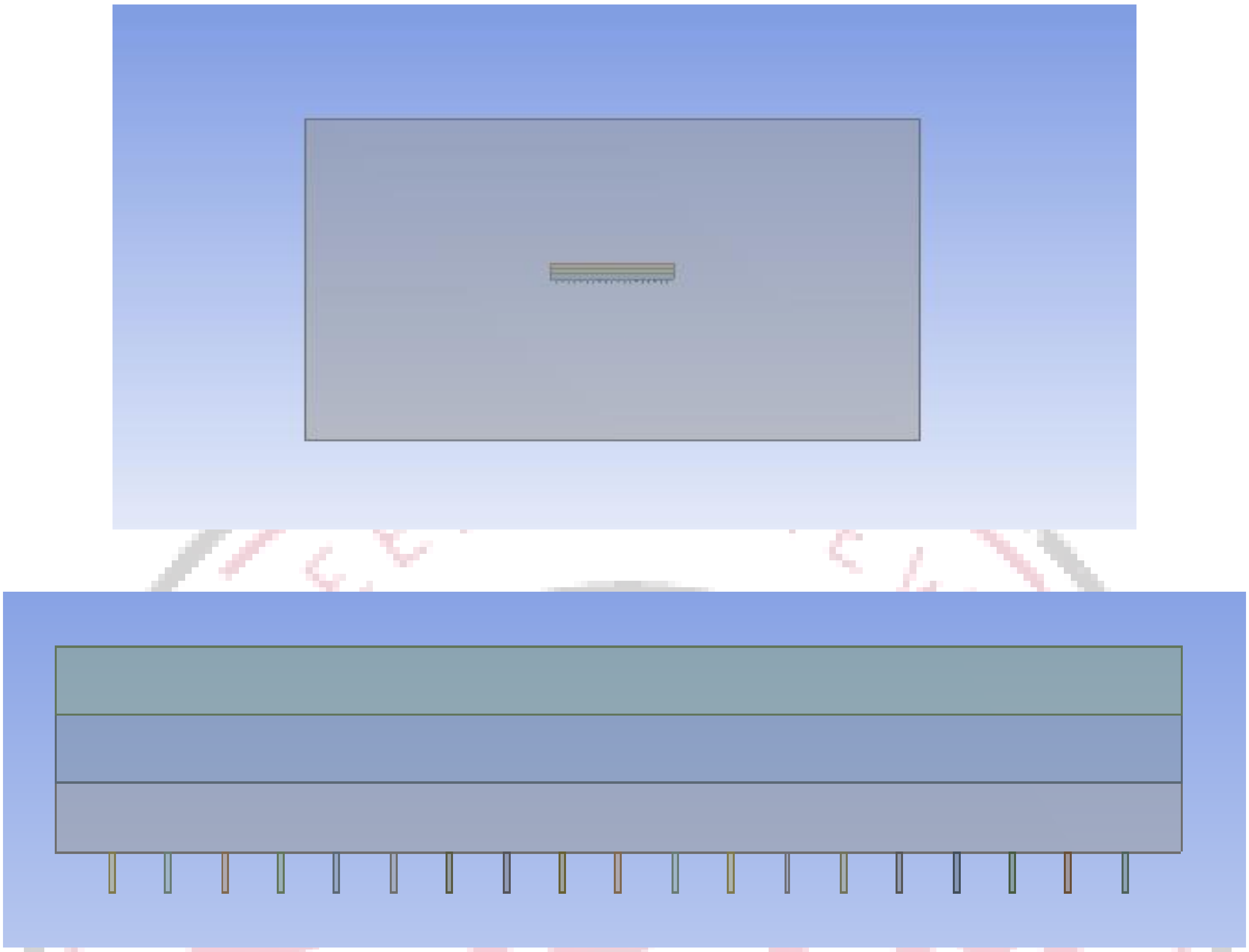

Figure. 3. CFD model[8]

C. Meshing Of Domain

In this study, a general curve linear coordinate grid generation system based on body–fitted coordinates was used to discrete the computational domain into a finite number of control volumes. The geometries of the problems are carefully constructed. All cases were modelled and meshed with the ANSYS 16 shows inFigure 4 Mesh model.FLUENT also comes with the CFD program that allows the user to exercise the complete flexibility to accommodate the compatible complex geometries. The refinement and generation of the grid system is important to predict the heat transfer in complex geometries. In other words, density and distribution of the grid lines play a pivotal role to generate accuracy. Due to the strong interaction of mean flow and turbulence, the numerical results for turbulent flows tend to be more dependent on grid optimisation than those for laminar flows [8].

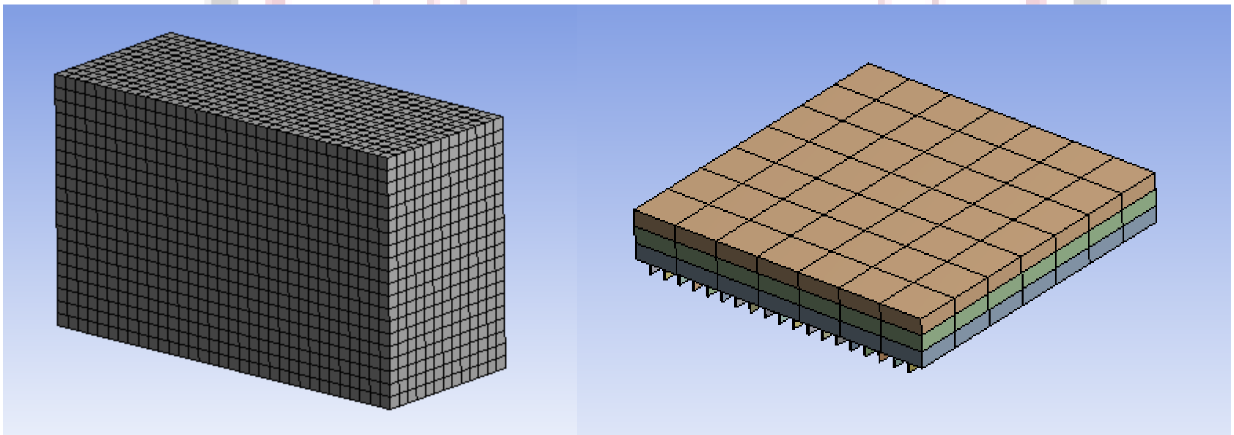

Figure. 4 Mesh model[8]

D. Choosing the Physical Properties

The definition of physical properties (thermal conductivity, density, viscosity, specific heat) of fluids and solids is a necessary factor for setting up the model. The PV module implemented through simulation consisted of cells, EVA (ethylene vinyl acetate),a back sheet, and fins, except glass. In other words, the effects of transmission bodies, such as glass andEVA, on the transmissivity of solar irradiance were ignored. The two sides of the domain were set asthe velocity inlet and pressure outlet for the airflow. On the top surface, the heat flux was set as theboundary condition Table 2. The values of the heat flux and velocity were set to 600W/m^2 and 0.5 m/s, which were in the effective range under the NOCT condition. In addition,the interface of each layer was assumed to be in full contact, and the contact resistance was set to 0 m^{2}K/W. Table 1. shows the thermal properties of each component entered into the simulation of the PV module

Table 1. Simulation conditions

Heat flux, W/m^2	Velocity inlet (m/s)	Ambient temperature, °C	Initial temperature, °C	Contact Resistance, m^{2}K/W
600	0.5	26.84	26.84	0

Table 2. Thermophysical properties

Components	Density (Kg/m^3)	Thickness, mm	Specific heat (J/Kg°C)	Thermal conductivity, (W/mk)
Cell (Si)	2330	10	677	148
EVA	960	10	2090	0.35
Frame (Al)	2702	60	903	237
Back sheet	1200	1	1250	0.2
Fin (Cu)	8900	3	385	400

V. RESULT ANALYSIS

A. Model Validation

In the present study, a CFD (computational fluid dynamics) simulation model was developed to analyze a passive cooling technology using fins attached to the back of the PV module. The heat transfer results obtained from the present study were first validated with the Kim and Nam (2019), as shown in Figure 5. It is evident from the figure that the average temperature is reasonably well within the range of ±5%.

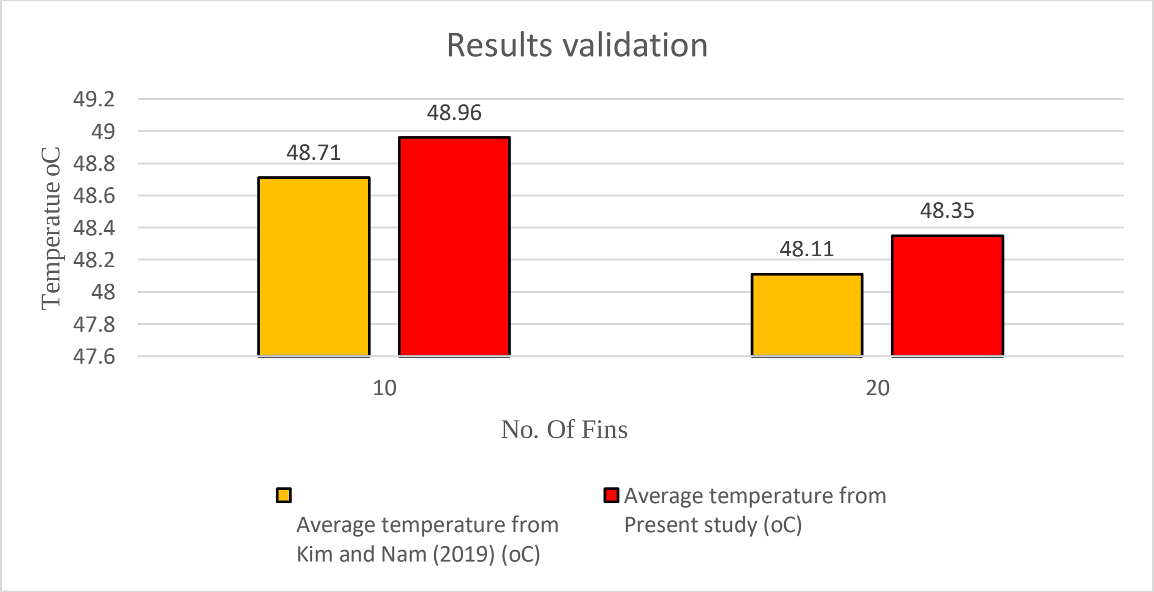

Figure 5. CFD validation results and comparison

B.Analysis of Average Temperature in Fins

This comparison suggests that the rectangular fins had a similar cooling performance in both studies, with a slightly higher average temperature recorded in the present study. The difference could be attributed to variations in experimental conditions, such as airflow velocity, ambient temperature, or fin dimensions, which may have influenced the heat transfer characteristics.For rectangular fins, there was a marginal percentage improvement of approximately 0.51 to 5.15% in the present study compared to Kim and Nam's study that shows in figure 6. variation of no. of fins temperature

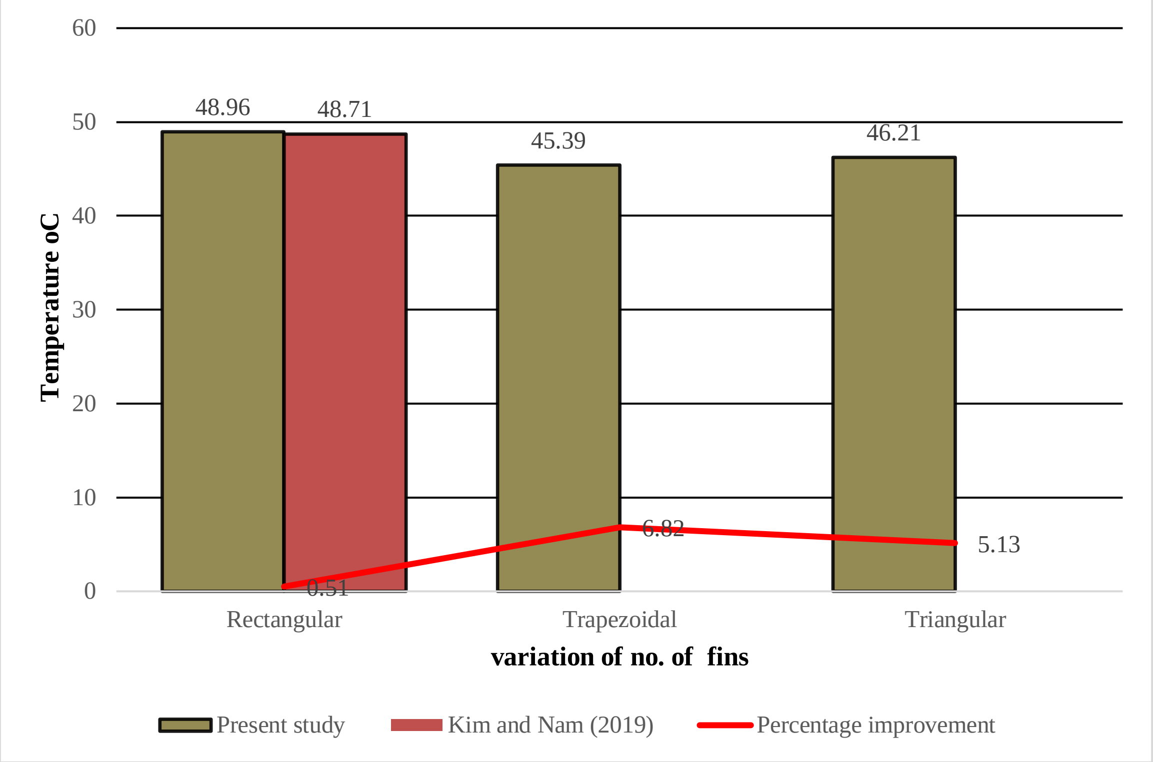

Figure 6. Comparison of average temperature

C. Parametric Study

A parametric study was performed for each fins by varying no. of fins, fins thickness and fins length.

Table 3. Variation of no. of fins (rectangular)

No. of fins	Average temperature from Kim and Nam (2019) (^oC)	Average temperature from Present study (^oC)
10	48.71	48.96
20	48.11	48.32

For the case with 10 fins, there was a marginal percentage improvement of approximately 0.51% in the present study compared to Kim and Nam's study shows in table 3..For the case with 20 fins, there was a more substantial percentage improvement of approximately 3.24% in the present study compared to Kim and Nam's study are also described in table 3.These percentage improvements indicate that as the number of fins increased from 10 to 20, the cooling effectiveness improved more significantly in the present study. This suggests that increasing the number of fins can lead to better heat dissipation and lower average temperatures in the PV panel.

Table 4.Variation of no. of fins (trapezoidal)

No. of fins	Average temperature from Kim and Nam (2019) (^oC) for rectangular fin	Average temperature from Present study (^oC)	Percentage improvement, %

10	48.71	45.39	6.82
20	48.11	44.46	7.59

Table 4. shows the case with 10 fins, there was an improvement of approximately 6.82% in the present study. For the case with 20 fins, there was a significant improvement of approximately 7.59% in the present study compared to Kim and Nam's study.These percentage suggest that increasing the number of fins from 10 to 20 led to a more substantial improvement in cooling effectiveness in the present study. This indicates that a higher number of trapezoidalfins can enhance heat dissipation and reduce the average temperature of the PV panel more effectively.

Table 5 Variation of no. of fins (triangular)

No. of fins	**Average temperature from Kim and Nam (2019) (oC) for rectangular fin**	**Average temperature from Present study (oC)**	**Percentage improvement, %**
10	48.71	46.21	5.13
20	48.11	45.35	5.74

Table 5. shows that the case with 10 fins, there was an improvement of approximately 5.13% in the present study compared to Kim and Nam's study.For the case with 20 fins, there was a more significant improvement of approximately 5.74% in the present study compared to Kim and Nam's study.These calculations suggest that increasing the number of triangularfins from 10 to 20 led to a more substantial improvement in cooling effectiveness in the present study compared to Kim and Nam's study. But the average temperature with triangular fins is smaller than that of trapezoidal fins.

D.Thickness of fins

Table 6 Variation of thickness of fin (rectangular)

Thickness of fins	**Average temperature from Kim and Nam (2019) (oC) for rectangular fin**	**Average temperature from Present study (oC)**
5	48.71	48.96
10	48.71	48.82

Analyzing the data in terms of the thickness of fins and the average temperatures from Kim and Nam's study (2019) compared to the present study for rectangular fins allows us to assess the impact of fin thickness on cooling effectiveness.In Table 6. Shows the case with 5mm thickness, there was a slight improvement of approximately 0.51% in the present study compared to Kim and Nam's study.For the case with 10mm thickness, there was an even smaller improvement of approximately 0.23% in the present study compared to Kim and Nam's study.These calculations suggest that varying the thickness of the fins from 5mm to 10mm had a minimal impact on cooling effectiveness, as indicated by the marginal percentage improvements in temperature. It's important to note that other factors such as fin geometry, material properties, and airflow conditions may also influence cooling performance and should be considered in optimizing fin design for PV panel cooling..

E. Length of fins

Length of fins were increased from 30 to 60 mm and simulation was conducted for different fins.

Table 7. Variation of length of fins (rectangular)

Length of fins, mm	**Average temperature from Kim and Nam (2019) (oC) for rectangular fin**	**Average temperature from Present study (oC)**	**Deviation, %**
30	48.71	48.96	0.51
60	47.65	47.73	0.17

For the case with 30mm length, there was a slight improvement of approximately 0.51% in the present study compared to Kim and Nam's study. As we see table 7. For the case with 60mm length, there was an even smaller improvement of approximately 0.17% in the present study compared to Kim and Nam's study. These calculations suggest that varying the length of the fins from 30mm to 60mm had minimal impact on cooling effectiveness, as indicated by the marginal percentage improvements in temperature. It's important to note that other factors such as fin geometry, material properties, and airflow conditions may also influence cooling performance and should be considered in optimizing fin design for PV panel cooling.

Table 8. Variation of length of fins (trapezoidal)

Length of fins, mm	**Average temperature from Kim and Nam (2019) (^{o}C) for rectangular fin**	**Average temperature from Present study (^{o}C)**	**Percentage improvement, %**
30	48.71	46.04	5.48
60	47.65	44.29	7.05

For the case with 30mm length, there was a notable improvement of approximately 5.48% in the present study compared to Kim and Nam's study. As we see table 8. for the case with 60mm length, there was an even more significant improvement of approximately 7.05% in the present study compared to Kim and Nam's study.These calculations suggest that increasing the length of the fins from 30mm to 60mm led to a substantial improvement in cooling effectiveness in the present study compared to Kim and Nam's study. It implies that longer fins may enhance heat dissipation and lower the average temperature of the PV panel more effectively.

Table 9. Variation of length of fins (triangular)

Length of fins, mm	**Average temperature from Kim and Nam (2019) (^{o}C) for rectangular fin**	**Average temperature from Present study (^{o}C)**	**Percentage improvement, %**
30	48.71	46.13	5.30
60	47.65	45.34	4.85

For the case with 30mm length, there was a modest improvement of approximately 5.3% in the present study compared to Kim and Nam's study.As we see table 9. for the case with 60mm length, there was a more substantial improvement of approximately 4.85% in the present study.These calculations suggest that increasing the length of the fins from 30mm to 60mm led to an improvement in cooling effectiveness in the present study compared to Kim and Nam's study. It implies that longer fins may enhance heat dissipation and lower the average temperature of the PV panel more effectively.

V.CONCLUSION

This study examined the effect of fin geometry on PV panel cooling performance using extensive CFD simulations. The findings show that, irrespective of form, adding fins improves heat dissipation and lowers average panel temperatures. Increasing the number of fins from 10 to 20 for rectangular, trapezoidal, and triangular shapes led to average temperature decreases ranging from 3.24% to 7.59% when compared to baseline experiments. In addition, variations in fin length and thickness only slightly affected the efficiency of cooling, highlighting the primary function of fin geometry in improving heat transmission. These results highlight how fin-based cooling systems can maximize PV panel performance, advancing renewable power technology and global environmental initiatives.

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