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Embossed fins for improved PV module efficiency - A CFD study

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ABSTRACT The escalating global demand for renewable energy has propelled the adoption of Solar Photovoltaic (PV) panels. However, the efficiency of these panels is often compromised by elevated operating temperatures. This study aims to systematically investigate the influence of embossed fins on the thermal performance of solar PV modules using Computational Fluid Dynamics (CFD) simulations. The study also delves into the underlying mechanisms by which emboss geometries modulate fluid flow and induce turbulence, thereby affecting convective heat transfer efficiency. The simulations, when validated against experimental data, exhibited a high accuracy with a maximum difference of 4.45%. Results indicate that the triangular emboss fin is the most effective in enhancing heat transfer by convection, achieving the lowest average PV module surface temperature of 41.78 °C. This study gives vital insights on the impact of emboss fin in maximizing the thermal efficiency of solar PV systems, hence presenting a roadmap for design advances in PV module cooling methods.

KEYWORDS: Solar PV Cooling, Emboss fin, Turbulence, Reynold's Number, Nusselt Number
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INTRODUCTION

Solar energy is increasingly recognized as an eco-friendly alternative for both thermal and electrical energy production. The global adoption of Solar Photovoltaic (PV) panels has surged, primarily due to their reduced environmental footprint in electrical energy production compared to conventional fossil fuel-based power plants. Notwithstanding the environmental benefits, it is pertinent to highlight the substantial initial investment required for solar PV installation. However, with the escalating global demand for solar PV panels, a significant reduction in prices is anticipated (Haidar *et al.*, 2018). The efficiency of Solar PV remains a concern, as a substantial portion of incident solar energy is converted to heat rather than electricity. Elevated operating temperatures further exacerbate this efficiency challenge. It is documented that for every 1°C increase in the operating temperature of a solar PV module, there is a corresponding 0.5% decrease in its efficiency. Presently, commercial solar PVs convert only about 13%-20% of the incident solar radiation into electrical energy (Usama *et al.*, 2012). Cooling methodologies for solar PV panels can be broadly categorized into active and passive cooling. While active cooling necessitates energy consumption to facilitate cooling, passive cooling leverages natural mechanisms such as conduction, convection, and radiation, thereby eliminating the need for external energy sources (Kim & Nam, 2019). Research by Singh & Patil (2015) underscores the efficacy of embossed fins in augmenting the heat dissipation capacity of naturally cooled heat sinks.

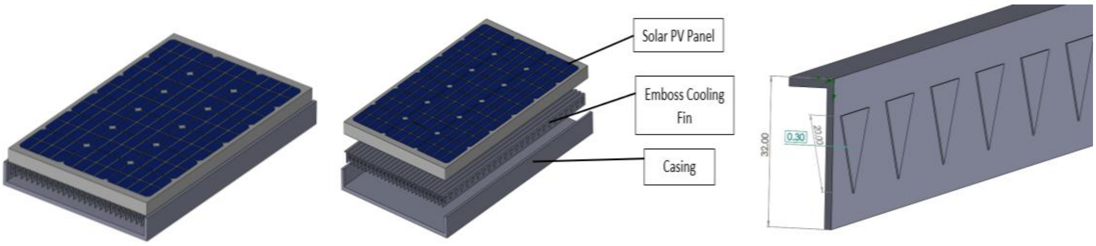
Furthermore, Photovoltaic cells exhibit constrained efficiency in the conversion of sunlight to electricity, particularly under conditions of intense solar radiation and high temperatures (Alkhalidi *et al.*, 2019). Computational Fluid Dynamics (CFD) simulations, as presented by Kim & Nam (2019), indicate a temperature reduction of approximately 15.13 °C upon the integration of fins to the PV module's underside. Hasan (2018) conducted an empirical study, emphasizing the role of fins as heat sinks in enhancing PV module performance. The findings reveal a significant temperature reduction, approximately 5.7 °C, leading to an average module output power increase of about 15.3%. A comparative analysis by Gupta & Thakur (2015) using ANSYS highlighted the superior temperature reduction capabilities of perforated and dimpled fins over plain fins

Previous research (Kim & Nam, 2019; Gupta & Thakur, 2015) showed that the implementation of fins with dimple or embossments is highly suitable as a cooling mechanism as it enhances the heat transfer. The primary objective of this paper is to conduct preliminary investigation into the influence of various emboss fins on the thermal performance of solar PV modules, utilizing Computational Fluid Dynamics (CFD) simulations. The study aims to explain the underlying mechanisms by which these emboss geometries modulate fluid flow and induce turbulence, thereby affecting convective heat transfer efficiency.

METHODOLOGY

Geometry and Computational Model

In this project, SolidWorks software was used to create 3D virtual prototypes of the design that were chosen. The design of the solar PV module was based on the experimental research conducted by Aswad (2021). The dimensions of the solar PV module, the aluminum fin, and the casing were all derived from this foundational work. The geometric design can be viewed in Figure 1, and the dimensions of the solar panel are detailed in Table 1. The aluminum fins were mounted on the back of the solar panel and had a height of 32 mm and 800 mm in length, with a thickness of 1.5mm respectively. The primary purpose of the casings is to ensure that the directed air flows precisely along the axis of the fin surface. This design approach aligns with the experimental setups previously conducted (Aswad, 2021), serving as a benchmark to validate subsequent simulation work.



(a) (b) (c)

Figure 1. (a) The 3D Model of the Solar PV Module (b) The Exploded View of the Solar PV Module (c) Emboss Triangular Fin shown

Table 1. Solar Panel Specifications

Characteristics	Solar Panel
Model	Monocrystalline 55wp 36 cells
Size	845mm x 515mm x 35mm
Type	Mono Crystalline Silicon

Governing Equation

Computational Fluid Dynamics (CFD) uses the following laws of conservation of mass, momentum and energy.

Continuity equation (Equation 1):

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (p\vec{v}) = 0 \qquad (1)$$

Momentum conservation equation (Equation 2):

$$\rho\frac{\partial u}{\partial t}=\frac{\partial(-p+\tau_{xx})}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial y}+S_{Mx}{}' \tag{2}$$

Navier Strokes equation (Equation 3):

$$\frac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\vec{\nabla})\vec{v}=\frac{-\nabla p}{\rho}+\frac{u}{\rho}(\vec{\nabla}\cdot\vec{\nabla})\vec{v} \tag{3}$$

ρ = density, p = pressure, t = time, τ = shear stress, u = fluid velocity, coordinates: (x,y,z)

Boundary Condition

In the computational simulation to describe the thermal behavior of the solar PV system, several critical assumptions were included into the formulation of the energy balance equations. Specifically, the system was considered to run at steady-state conditions, hence eliminating temporal changes. Heat transmission is one-dimensional, allowing for a more tractable computational technique. Finally, the heat capacity of the solar PV module was deemed negligible, thereby eliminating its impact on transient thermal behavior. Within this framework, exact boundary conditions were meticulously defined. The boundary conditions implemented were grounded in the study conducted by Aswad (2021) during his experimental work. A consistent velocity inlet was assumed at the entrance of the cooling fins, maintaining a steady velocity of 4 m/s. This specific value was chosen in alignment with the capabilities of the blowers that were available for empirical validation. Simultaneously, the outlet pressure was standardized to a constant gauge pressure of 101,325 Pa. To simulate the solar irradiance, an external heat flux of 1175 W/m^2 was uniformly applied to all facets of the solar panel. This was done under the premise of an ambient environment maintained at a temperature of 35.1°C. These parameters ensured that the simulation closely mirrored the real-world conditions Aswad (2021) encountered in his experimental work, thereby enhancing the reliability and relevance of the findings. To guarantee the robustness of the computational results, a mesh independence analysis was done. It was discovered that the temperature of the solar panel remained consistent and that there was a minor difference in pressure distribution for mesh sizes reaching 5.0 (3.1 million Nodes and 11.1 million Cells).

Result Verification

The simulation result was compared with the experimental result reported by Aswad (2021) to compare the accuracy of the simulation model and results from the SimScale simulation and SolidWorks software with the real-life experiment conditions. The experimental data shows a maximum temperature of solar panel which was 45.27 ^{o}C. The simulation result showed an acceptable level of confidence and accuracy, with the maximum temperature obtained from the simulation being 43.31 ^{o}C lower than the experimental value of 45.27 ^{o}C resulting in a percentage difference of 4.45%.

RESULT AND DISCUSSION

In the analysis, for simulating the different shape of emboss parameter, the other parameters were kept constant. The number of emboss was set at 26 per total length of the fin (800 mm), the depth of emboss was set at 0.30 mm, the size of emboss was set at 20 mm, the number of fin was set at 20 fins, and the velocity of flow was set as 4m/s. This approach allowed for a targeted analysis of the sole effect of the emboss fin, enabling an understanding of its impact on the cooling performance of the solar PV module.

Figure 2 and 3 gives insights into the influence of emboss fin on both surface temperature and convective heat transmission, as evaluated by the Nusselt number. The data reveals a tiered performance among the embossed fins. The triangular embossed fin emerged as the most efficient, recording the lowest average PV module surface temperature of 41.78°C. This was closely trailed by the square embossed fin at 41.9°C and the circular embossed fin at 42.56°C. Conversely, the smooth fin configuration proved to be the least effective in cooling, registering the highest average surface temperature of 44.37°C.

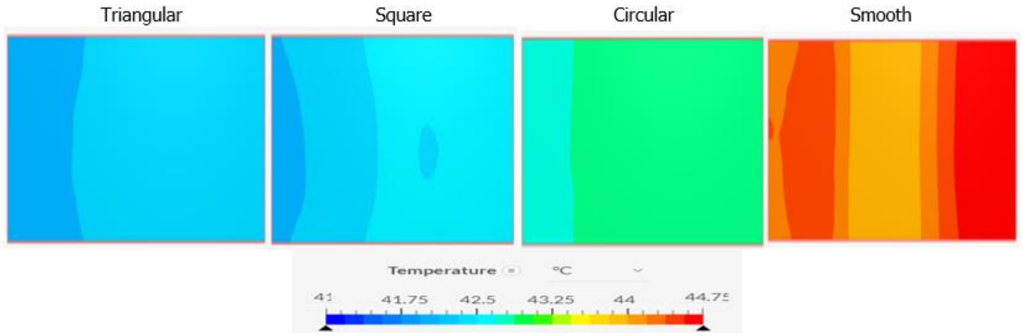
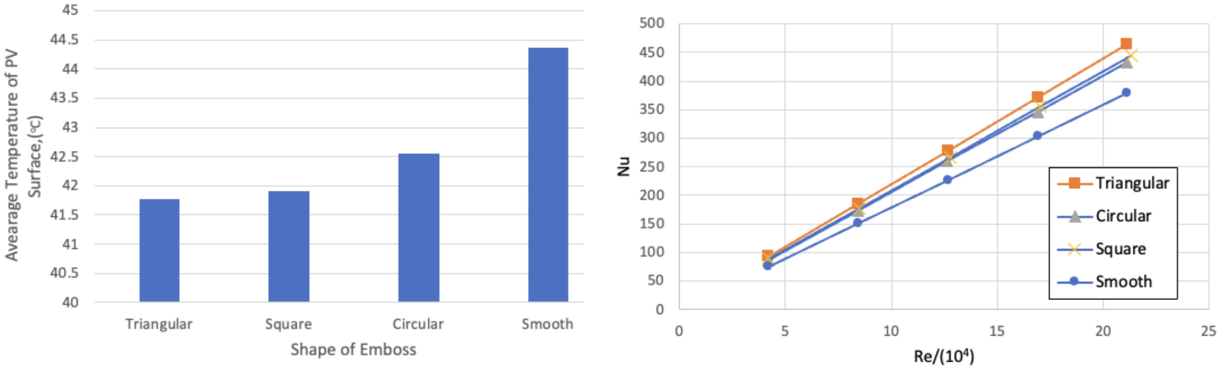


Figure 2. Temperature Distribution on Solar PV Surface for Different Emboss Fins



(a) (b)

Figure 3. (a) Graph of Average Temperature of PV module, (°C) against Different Emboss Fins (b) Graph of Nusselt against Renault/(10^4) for Different Emboss Fins

This temperature hierarchy is further corroborated by the corresponding Nusselt numbers, which serve as a reliable indicator of convective heat transfer efficiency. A marked and sharp increase in the Nusselt number was observed as the Reynolds number escalated for all emboss fins (Ozisik, 1985; Cengel, 2002). Intriguingly, the triangular emboss fin exhibited the highest Nusselt number, thereby confirming its superior heat transfer capabilities via convection.

A critical analysis of these findings suggests that the emboss fins contribute to turbulence generation within the fluid flow, which is a pivotal factor in enhancing heat transfer. The triangular emboss, with its angular geometry, is particularly effective in disrupting the laminar sub-layer of the flow, thereby inducing a higher degree of turbulence. This heightened turbulence augments the convective heat transfer coefficient, as evidenced by its highest Nusselt number, and consequently results in a lower average surface temperature of the PV module. The square and circular emboss fins, although less effective than the triangular emboss fin, also contribute to turbulence but to a lesser extent, which is reflected in their marginally higher surface temperatures and lower Nusselt numbers.

The introduction of emboss shape on cooling fin will create an airflow that is irregular, swirling and chaotic along the fin compared to smooth cooling fin as shown in Figure 4. Turbulent flows are when the flow is highly chaotic and irregular (Islam & Hossain, 2021). The air swirling and vortices formed around the fin due to the emboss shape will enhance the mixing of air flow region as it transfers the air packets from the near-wall region of the channel to the central region and the other way around in which can improve the heat transfer (Nasiruddin & Siddiqui, 2007). It is observed that the triangular emboss fin has the most irregular and chaotic airflow followed by square emboss fin, circular emboss fin and smooth fin part. Consequently, this suggests that the triangular embossed fin induces the greatest turbulence, succeeded by the square embossed fin, the circular embossed fin, and lastly, the smooth fin. It is also observed that the temperature of airflow particles in the triangular emboss fin is the highest compared to the others. It has the highest heat transfer rate because the more heat from the fin is transferred to the surrounding air through convection (Cengel, 2002). Apart from that, the higher temperature around fin in triangular emboss fin is influenced by the recirculation and swirling flow as it causes better mixing of the air in the area between the hot fin surface and flow area (Menni *et al*., 2019).

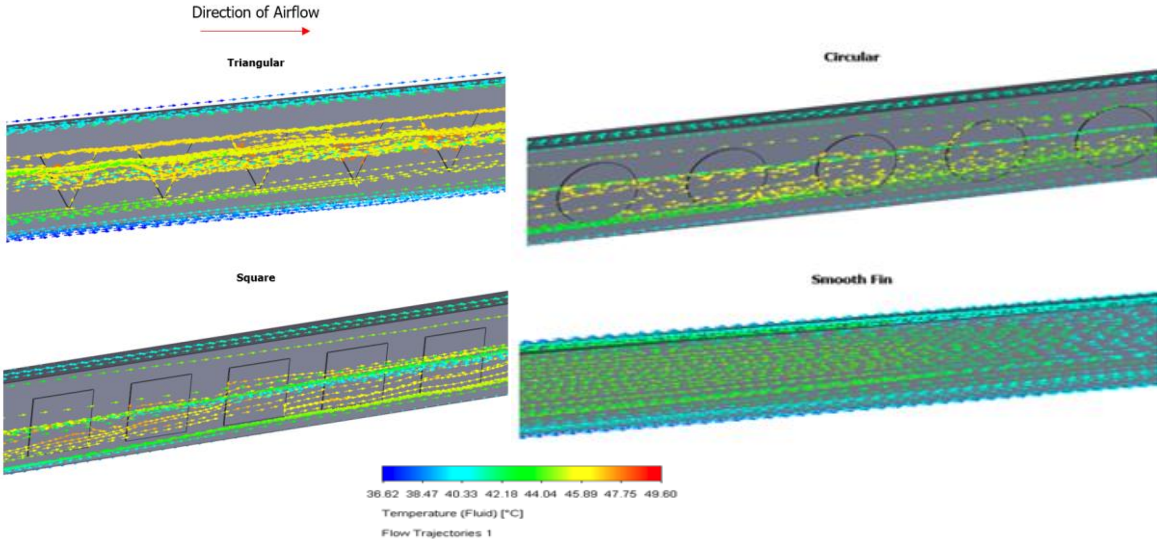


Figure 4. Flow with Arrow Representation of Embossed Part of the Fin with Different Emboss fins with Shaded View of the Model

CONCLUSION

In conclusion, the study systematically isolated the effect of emboss fin on the cooling performance of a solar PV module by keeping other parameters constant. The findings reveal that the triangular emboss fin is the most effective, achieving the lowest average PV module surface temperature of 41.78°C and the highest Nusselt number, indicative of enhanced heat transfer by convection. These results show the essential impact of emboss fin in enhancing the thermal performance of solar PV systems. Future research endeavors could delve deeper into the nuanced interactions between different embossed geometries and fluid dynamics to further refine and enhance the cooling mechanisms for solar PV modules.

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