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Experimental and CFD Simulation Study of Heat Transfer Enhancement in a Flat-Plate Photovoltaic Thermal Collector with Spiral Cooling Channels

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Abstract

Photovoltaic (PV) cells convert solar radiation into electricity, but elevated operating temperatures significantly reduce their efficiency. This study numerically investigates a novel flat-plate photovoltaic-thermal (PV/T) collector featuring a spiral cooling channel beneath the plate using Computational Fluid Dynamics (CFD). Operating under laminar flow conditions with water as the working fluid, the research evaluates the individual and combined effects of turbulators at angles of 15°, 30°, 45°, 60°, 75°, and 90° and alumina nanofluids at volume fractions ranging from 1% to 4%. Performance is assessed using two main criteria: the ratio of total heat transfer rate to the required pumping power, and the standard deviation of surface temperature distribution to measure thermal uniformity. The CFD results demonstrate that incorporating turbulators significantly enhances heat transfer characteristics. Specifically, the configuration utilizing a 15° turbulator angle achieves superior overall thermal and hydraulic performance, outperforming the baseline design, the standalone nanofluid system, and the combined turbulator-nanofluid configurations.

Keywords:

Heat transfer, Computational fluid dynamics (CFD), Photovoltaic thermal collector, Turbulator, Aluminum-oxide nanofluid.

1. Introduction

The growing concerns over fossil fuel costs, resource depletion, and environmental issues have intensified the global shift toward renewable energy sources [1]. Among various technologies, photovoltaic (PV) systems directly convert solar radiation into electricity; however, they typically absorb only a fraction of incoming solar energy and exhibit relatively low efficiencies ranging from 4% to 17% [2, 3]. Moreover, as PV cells convert radiation into electrical energy, their operating temperature rises significantly, leading to a substantial drop in conversion efficiency.

Photovoltaic-thermal (PV/T) collectors address this issue by simultaneously generating electricity and thermal energy. Because PV performance improves at lower temperatures, effective cooling is crucial. One effective passive strategy involves modifying the cooling channel geometry or incorporating turbulators to enhance fluid mixing and heat transfer [4-7]. Additionally, conventional base fluids like water or air often exhibit limited thermophysical properties. To overcome this, the integration of nanofluids, suspensions of nanometer-sized metallic or metal-oxide particles, has been widely studied to enhance thermal conductivity and overall heat transfer performance [5, 7-9].

This study numerically evaluates the thermal performance of a flat-plate PV/T system equipped with a bottom cooling channel using Computational Fluid Dynamics (CFD). The investigation examines three main configurations: first, the incorporation of turbulators to promote fluid mixing and surface temperature uniformity; second, the use of alumina (Al_2O_3) nanofluids to improve fluid thermophysical properties; and third, a combined system integrating both turbulators and nanofluids.

2. Methodology

Computational Fluid Dynamics (CFD) was employed to evaluate the flow patterns in the cooling channels and the enhancement of heat transfer in the photovoltaic-thermal (PV/T) system. Building upon previous studies [1, 10] that demonstrated the benefits of cooling channels for overall efficiency, this research investigates the combined effectiveness of flow channels, turbulators, and nanofluids on thermal performance. Finally, based on the simulation

results, the optimal operating conditions are identified using performance criteria and temperature uniformity across the PV panel.

2.1. Experimental Setup and CFD Method

To validate the CFD model, experimental data were obtained from a laboratory-scale PV/T setup. Pure water entered a spiral cooling channel beneath the collector plate and absorbed heat before exiting. Surface temperatures at nine points were measured using a TES-1327K laser thermometer, while inlet/outlet fluid temperatures, solar radiation (constant at 400 W/m^2), and flow rates (400, 750, and 1200 mL/min) were recorded using appropriate instruments.

For the numerical simulations, the maximum Reynolds number in the $10 \times 10 \text{ mm}$ square channel was 1994, confirming laminar flow. Although turbulators do not trigger a full turbulent transition in laminar flow, they induce local boundary-layer disturbances, secondary flows, and small vortices that enhance heat transfer and temperature uniformity with minimal pumping power. Consequently, a laminar flow model was sufficient and computationally efficient. Governing equations, including conservation equations of mass, momentum at steady, incompressible, and laminar conditions, were solved using the finite volume method via the SIMPLE algorithm and second-upwind discretization schemes, with a convergence criterion of 10^{-6} . The numerical simulations were established using a uniform inlet velocity at 300 K for the cooling channel, an atmospheric pressure outlet, and a constant solar heat flux applied to the photovoltaic collector surface.

2.2. Performance Evaluation Criterion

To evaluate the thermal-hydraulic performance of the spiral channel, a quality factor (η) is defined as the ratio of the total heat transfer rate during cooling (Q) to the pumping power (W_p) required for fluid circulation [11]:

$$\eta = \frac{Q}{W_p} = \frac{\dot{m} C_p \Delta T}{\frac{\dot{V}}{\eta_p} \Delta P} \quad (1)$$

where $\dot{m}$ is the mass flow rate, C_p is the specific heat capacity, ΔT is the fluid temperature difference between the inlet and outlet, $\dot{V}$ is the volumetric flow rate, η_p is the pump efficiency, and ΔP is the pressure drop across the channel.

2.3. CFD Collector Geometry

The simulated PV/T collector comprises several layers from top to bottom: glass, the photovoltaic cell, EVA and Tedlar encapsulants (effective thermal conductivity of $0.55 \text{ W/(m} \cdot \text{K)}$), an aluminum absorber plate, and a spiral cooling channel (Fig. 1), matching the experimental dimensions.

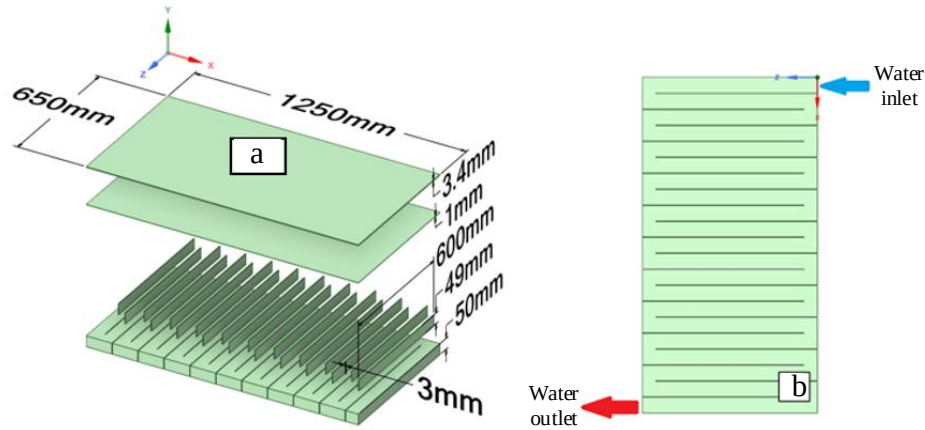


Figure 1. (a) Geometry of the photovoltaic collector showing the layers from top to bottom: glass and PV cell, EVA encapsulant, Tedlar backsheet, aluminum absorber plate, and flow channel; (b) Geometry of the spiral channel.

3. Results and Discussion

3.1. CFD model validation

To validate the numerical model, the CFD-predicted friction factor inside the channel was compared with the empirical correlation by Shah and London [12], yielding an average error of 5%. Furthermore, a comparison between the numerical results and experimental data across various Reynolds numbers showed a good agreement with an

average error of 1.6%.

3.2. Nanofluid Effect

To enhance heat transfer, the effect of alumina (Al_2O_3) nanofluid at volume fractions of 1% to 4% was investigated at a flow rate of 600 mL/min and solar flux of 600 W/m^2 . The performance evaluation criterion and the standard deviation of surface temperature were utilized to quantify the effects. The results demonstrate that while nanofluids increase thermal conductivity and specific heat capacity, they reduce the performance criterion (Eq. 1) by 12.5%. Furthermore, the standard deviation of the PV surface temperature remains nearly unchanged (by about 0.1%) across different nanoparticle concentrations. This is attributed to the persistence of laminar flow, where the flow pattern and thermal uniformity do not undergo significant alterations.

3.3. Turbulators Effect

To further enhance heat transfer, turbulators (Fig. 2) were integrated into the cooling channel at angles of 15° , 30° , 45° , 60° , 75° , and 90° to direct fluid toward the upper plate. CFD results reveal that the 15° turbulator yields the optimum thermal-hydraulic performance, providing a 6.5% improvement in the performance criterion compared to the smooth channel without turbulators. Although the turbulator enhances fluid mixing, the standard deviation of temperature for the 15° configuration increases slightly by 4.9%, though this marginal increase has a negligible impact on the overall temperature distribution pattern across the PV surface.

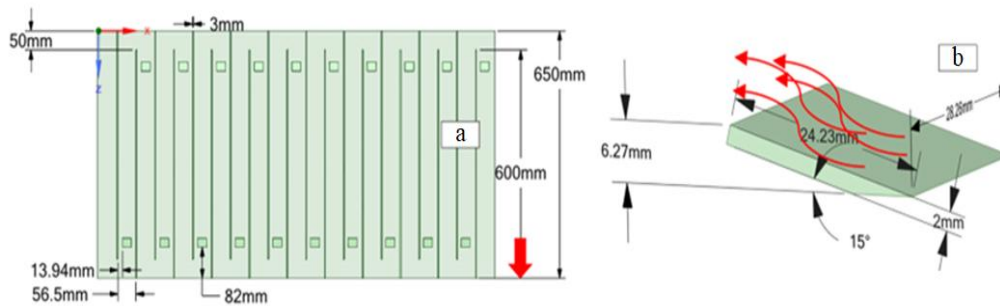


Figure 2. (a) Positioning of the turbulator inside the fluid flow channel; (b) Turbulator inside the fluid flow channel.

3.4. Combined Effect of Nanofluid and Turbulator

To evaluate the combined system, three configurations were compared: 1) 4 vol% Al_2O_3 nanofluid, 2) 15° turbulator, and 3) 15° turbulator combined with 4 vol% nanofluid. As shown in Fig. 3 and Table 1, the outlet fluid temperature for the combined system reached 312 K, showing a negligible difference compared to the base fluid (311.7 K) and turbulator-only (311.88 K) cases. However, the standard deviation of temperature in the combined system decreased by 5.7%, while its performance criterion dropped by 13.6% and 9.2% compared to pure water and the turbulator-only case, respectively, due to increased hydraulic resistance and pumping power. These findings indicate that simultaneous employment of both techniques does not necessarily improve overall performance, highlighting that single optimization methods (nanofluid or turbulator alone) are more efficient than their combination due to the trade-off between heat transfer enhancement and pressure drop.

Table 1. Performance evaluation criterion and standard deviation percentage of the combined system

System Configuration	Outlet Temperature (K)	Standard Deviation Percentage (%)	Performance Evaluation Criterion (PEC)
Nanoparticle 4%	311.89	14.56	350,000
Turbulator 15°	311.74	14.65	4,279,335
Nanoparticle 4% + Turbulator 15°	311.88	14.66	303,782.2

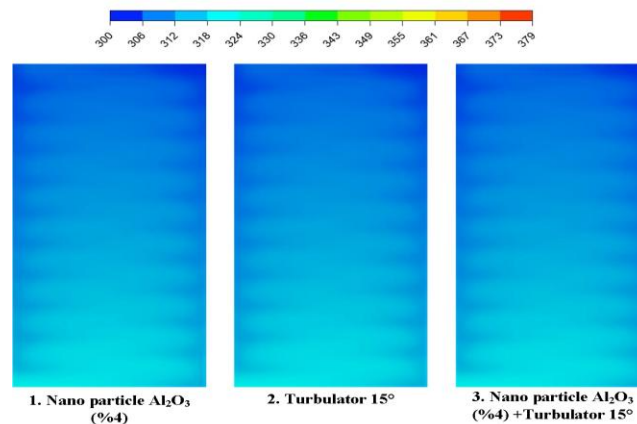


Figure 3. Comparison of photovoltaic plate temperature contours (in Kelvin) under different operating conditions: (1) presence of 4 vol% Al_2O_3 nanoparticles, (2) 15° turbulator, (3) 15° turbulator combined with 4 vol% Al_2O_3 nanoparticles.

4. Conclusion

In this study, the performance of a photovoltaic-thermal (PV/T) system incorporating turbulators, nanofluids, and their combination was numerically investigated using CFD. The main findings are summarized as follows:

- **Nanofluid Performance:** The 4 vol% nanofluid yielded the highest heat transfer effect.
- **Turbulator Impact:** Integrating a 15° turbulator improved the performance criterion by 5.5%, 22.2%, and 12% compared to the pure fluid without turbulator, the nanofluid case, and the combined system, respectively.
- **Overall Trade-off:** The 15° turbulator configuration provides an optimal balance between thermal efficiency and energy consumption.

5. References

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