

Numerical Investigation of Inlet Positioning Effects on the Performance Efficiency of Hybrid Photovoltaic Thermal Systems with Reversed Circular Flow Jet Impingement Cooling

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ABSTRACT

The research investigates a dual-function photovoltaic thermal (PVT) cooling approach that employs an innovative reversed circular flow jet impingement system. PVT systems often exhibit uniform temperature distribution, thereby reducing the electrical and thermal performance. Conventional cooling designs cannot ensure homogeneous heat removal. While previous studies have explored the design of jet impingement geometries, the influence of inlet positioning remains largely unexplored. This research fills a gap by examining the effects of symmetric and asymmetric inlet positioning on jet impingement on PVT performance. Computational fluid dynamics (CFD) simulations were conducted in COMSOL Multiphysics at three irradiance levels (800, 900, and 1000 W/m²) while varying the Reynolds number from 1463.81 to 4415.51. The system was evaluated based on performance, examining thermal and electrical efficiencies, overall efficiency, and outlet air temperature. Enhanced performance metrics resulted from increased Reynolds number, which improved convective heat transfer and decreased PV surface temperatures. The asymmetric inlet configuration proved superior to symmetric setups across all test conditions, delivering up to 0.4% electrical efficiency gains and 2.5% thermal efficiency improvements, resulting in overall efficiency gains of up to 3% and reaching a peak overall efficiency of 92.48% under 1000 W/m² conditions. The outlet temperature trends showed that the asymmetric design extracted heat more effectively, confirming its advanced thermal transfer properties. The research demonstrates that asymmetric inlet placement is an effective passive strategy for enhancing the performance of hybrid PVT systems under high levels of sunlight.

Keywords: Reversed Circular Flow Jet Impingement (RCFJI); photovoltaic energy; thermal energy; hybrid PVT; PVT collector; dual inlet

INTRODUCTION

Global energy demand continues to escalate as populations grow, industries expand, and cities develop, placing mounting pressure on finite fossil fuel reserves (Tawfik et al. 2022). This over-reliance on conventional sources not only hastens resource depletion but also intensifies environmental concerns, including greenhouse gas emissions and climate change (Kularni et al. 2023). It is becoming critical to switch to renewable energy sources in order to reduce these effects and protect resources (El Alami, Baghaz, et al. 2026). In response, Renewable energy technologies are increasingly viewed as vital for sustainable energy generation (Cui et al. 2021). Within this domain,

solar energy stands out for its vast availability and the rapid technological progress in photovoltaic (PV) systems (Aktekeli et al. 2025). Both PV modules and solar thermal collectors are well-established technologies for harnessing solar radiation; integrating these systems to deliver both electrical and thermal energy has long been recognized as a viable concept (Khelifa et al. 2024; Luqman Azeez et al. 2024). However, PV modules face a persistent challenge: their efficiency declines as operating temperature rises. Elevated cell temperatures not only reduce electrical power output but can also shorten the system's operational lifespan (Ranjan et al. 2022). The challenge is more acute in areas with high solar intensity and elevated ambient temperatures, where heat accumulation can significantly degrade PV performance. To mitigate this, Photovoltaic

thermal (PVT) systems have been introduced, combining a thermal absorber with a PV module to capture and repurpose excess heat. This dual functionality improves both thermal and electrical outputs. PVT systems offer the advantage of producing both heat and electricity from a single solar unit (Pathak et al. 2022). For PVT to operate as efficiently as possible, the heat exchanger must be properly configured (El Alami, El Achouby, et al. 2026). However, one of their ongoing limitations is maintaining a uniform temperature distribution across the PV surface, particularly when environmental conditions vary (Ewe, Fudholi, Sopian, Asim, et al. 2021). This limitation reduces the electrical and thermal performance. Conventional cooling approaches often fail to deliver consistent or efficient heat extraction, which highlights the need for improved strategies to enhance both reliability and energy yield. In addition, previous studies lack a focus on inlet positioning, which remains largely unexplored. This research fills a gap by examining the effects of symmetric and asymmetric inlet positioning on jet impingement on PVT performance. When the PV surface gains heat, the PVT system's ability to generate electrical power declines. In addition to reducing power output, exposure to high temperatures expedites material deterioration. Lowering PV temperature is possible by effectively removing heat through improved airflow patterns enabled by strategically configured inlets. As a result, it can mitigate the heat recovery and enhance system efficiency.

A wide range of optimization techniques for PVT systems has been investigated in recent literature, with a strong focus on improving cooling methods for PV panels. Approaches have included phase change materials (PCMs), thermoelectric devices, and the incorporation of metallic fins to increase heat dissipation (Bayrak et al. 2020). The introduction of nanoparticles into PCMs or fluids has further enhanced thermal conductivity and cooling performance (Bassam et al. 2023). In general, a PVT unit comprises a PV panel coupled with a coolant flow channel (Al-Karbolý et al. 2025; Jha et al. 2025; Rostami et al. 2025). Many researchers prefer passive cooling for PV modules because it requires no additional energy (Farahani et al. 2025). Research has shown that the cooling nozzle significantly influences heat transfer behavior. Reported improvements include markedly higher uniformity and enhanced heat transfer efficiency (Shaeli et al. 2025). Similarly, jet impingement configurations, such as multi-nozzle or swirling arrangements, have also proven effective, as they spread the cooling air more evenly across the PV surface (Ewe et al. 2022). Another critical parameter is the coolant Reynolds number, which directly affects system cooling capacity. Higher flow rates generally lead to stronger heat transfer, although they also raise the associated energy demand and (M. A. A. B. Ishak, Ibrahim,

Fazlizan, et al. 2023). Researchers have experimented with a variety of cooling media ranging from simple air jets to water and nanofluid streams, demonstrating the adaptability of jet impingement methods for different PVT configurations (Chandrasekar & Senthilkumar, 2021; Noui et al. 2025). Enhanced absorber plate geometries have also been introduced, for example, by adding V-shaped protrusion ribs to induce turbulence and strengthen convective heat transfer (Çiftçi et al. 2021). Other design aspects that strongly influence system efficiency include the collector surface area, the number of fluid passes, and the spacing between the absorber plate and PV cells (Rani & Tripathy, 2022). Studies identified an optimal configuration that achieved a strong thermal-hydraulic performance with values above 3.44. Moreover, structural modifications, combined with varying air velocities, have been shown to significantly increase system efficiency. For instance, adding 108 fins at an airflow of 4.5 m/s yielded an increase in electrical efficiency of 12.02%. Optimizing nozzle Height is crucial for achieving the desired balance between heat transfer enhancement and energy consumption (Chaurasiya & Singh, 2023).

Jet impingement techniques and cooling approaches have demonstrated strong potential for PVT Systems using air-atomizing nozzles, achieving a temperature reduction of 29.3°C while providing electrical output up to 14.5% (Juneja et al. 2025). More recent developments, such as the reversed circular flow jet impingement (RCFJI) configuration, have achieved notable improvements, with studies reporting significant increases in both electrical and thermal efficiency depending on nozzle arrangement and flow conditions (Khalili & Sheikholeslami, 2023; Shaeli et al. 2024). Furthermore, the addition of ribs opposite the impinging airflow increases local turbulence on the ribbed surface, thereby enhancing the thermal performance of the solar air heater (Promvong et al. 2021). Jet impingement methods to remove heat from the collector surface are achieved by directing concentrated air streams onto the absorber plate to accelerate cooling (Thapa et al. 2024). This study systematically investigates the effects of inlet configurations on the performance of the RCFJI-PVT system using COMSOL. Previous research on photovoltaic thermal (PVT) cooling has mainly focused on nozzle shapes and surface improvements, while neglecting important aspects of inlet positioning and quantity. To address this, we introduce an innovative Reversed Circular Flow Jet Impingement (RCFJI) design with precisely optimized inlet configurations. The research demonstrates through validated computational fluid dynamics (CFD) analysis that Asymmetrical inlet positioning results in better airflow coverage, simultaneously decreasing PV temperature and boosting thermal and electrical efficiency.

COMPUTATIONAL ANALYSIS

MODEL DESIGN

Numerical simulations were performed in COMSOL Multiphysics 5.6 to determine the cooling efficiency of a new hybrid photovoltaic thermal (PVT) design and to compare two inlet layouts: symmetric and asymmetric. COMSOL provides greater capacity to solve coupled heat transfer and fluid flow problems, which are crucial for assessing PVT performance. In addition, COMSOL provides more flexible mesh optimization, boundary condition customization, and physics interaction within a single interface. Due to these characteristics, COMSOL was used to evaluate the effects of inlet configuration on the PVT system's temperature distribution. The analysis aimed to identify which arrangement achieved the highest overall energy performance. Figure 1 shows the isometric view and side view of the PVT collector. The PV module is mounted on top of the collector, separated by a 25 mm air duct for airflow. The jet impingement is then mounted on the absorber plate, which serves as the cooling

mechanism. The air outlet is on both the left and right sides of the PVT collector. The dimensions of the PVT collector are 200 mm in length, 200 mm in width, and 25 mm in depth, as shown in Figure 1. The simulations for each model maintain a Reynolds number of 1463.81 to 4415.51 and apply irradiation levels of 800, 900, and 1000 W/m². The simulations for each model maintain a Reynolds number of 1463.81 to 4415.51 and apply irradiation levels of 800, 900, and 1000 W/m². In the air inlet configuration, the inlet configuration varies as indicated in Figure 1 (c) and (d). The collector employed a reversed circular flow jet impingement (RCFJI) design that included a circular flow cup with a 40 mm diameter, with air entering through 6 mm inlets and exiting via 3 mm jet holes in the plate, generating higher jet velocities and intensifying the impingement effect. The jet plate contained six openings, with the cup positioned behind it, spaced 113.4 mm apart in the stream wise direction and 126 mm apart in the span wise direction. In addition, Figure 1 (c) and (d) illustrates the different air inlet configurations and their respective positions. The different configurations of air inlet positions help establish the best (PVT) system.

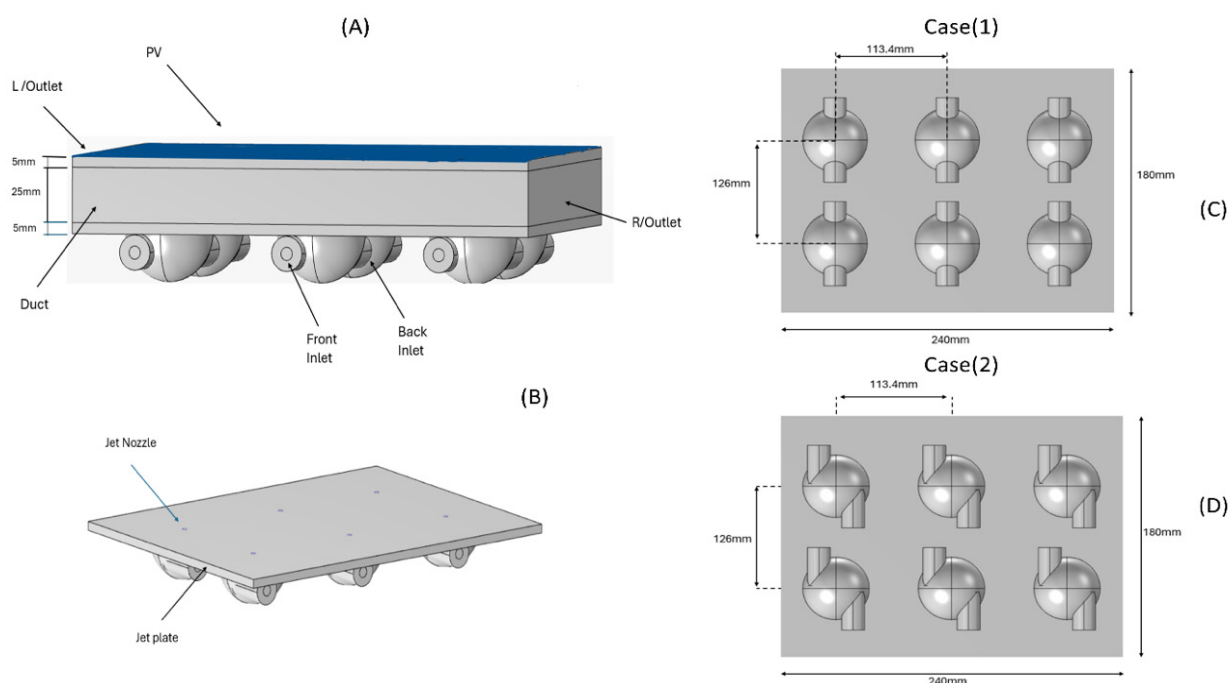


FIGURE 1. (a) 3D PVT collector, (b) Jet plate, (c) symmetry inlets, (d) Asymmetry inlets

MESH INDEPENDENT STUDY

To assess grid sensitivity, nine different mesh levels ranging from coarse to very fine were generated for the PVT collector geometry. For each configuration, the element count and average element quality were recorded to

evaluate the influence of mesh density on solution accuracy. A summary of the tested mesh configuration is provided in Table 1. The purpose of this mesh independence check was to ensure that the numerical predictions would remain consistent regardless of further mesh refinement.

TABLE 1. Element count and average element quality across different mesh settings

Mesh	No of Element	Average Element Quality	Average Difference Percentage
Extremely coarse	64,874	0.545	8.73%
Extra coarse	102,884	0.592	8.08%
Coarser	233,595	0.640	4.16%
Coarse	564,679	0.667	2.27%
Normal	2,022,723	0.682	0.96%
Fine	59,72,916	0.688	0.59%
Finer	19,436,379	0.693	-0.96%
Extra fine	27,092,230	0.686	-1.03%
Extremely fine	54,434,330	0.679	

The independent mesh analysis began with very coarse settings and progressed to the finest settings to achieve maximum detail. The total number of elements ranged from 64,874 to 54,434,330, while average element quality measurements varied between 0.545 and 0.6792. The difference in average element quality diminished as the mesh settings progressed from an extremely coarse to a fine configuration. After reaching finer mesh settings, the calculated difference reached a negative rate of -0.96%, indicating that results remain unaffected when using finer settings beyond the current standard, as demonstrated in Table 1. Figure 2 shows the mesh setting using finer mesh settings. The highest recorded average element quality of 0.693 was achieved with finer mesh settings, as demonstrated in Figure 3.



FIGURE 2. Finer mesh configurations used in the simulation settings

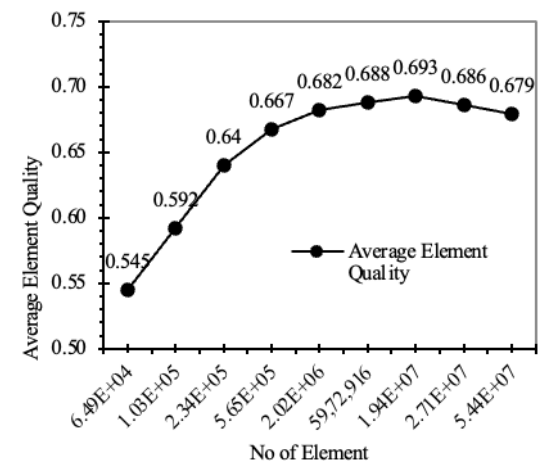


FIGURE 3. Mesh independence study correlation.

SIMULATION PARAMETERS AND BOUNDARY CONDITIONS

The simulations accounted for temperature-dependent variations in material properties, enabling the simultaneous analysis of fluid (air) and solid domains, such as aluminum and steel. Certain simplifying assumptions were made: the lamination, jet plate, and PV cell layers were treated as thermally homogeneous; the airflow was assumed confined within the collector channel; and no heat was lost through the collector edges. Turbulent heat transfer was modelled using the standard $k-\epsilon$ approach, which describes interactions between the fluid stream and solid boundaries (M. A. A. B. Ishak, Ibrahim, Sopian, et al. 2023). The $k-\epsilon$ model was selected as the approach for turbulent flow, as detailed in subsection 2.3.1. The simulation used Reynolds-averaged Navier-Stokes (RANS) equations to address turbulent flow. The simulation used non-isothermal flow coupling between a turbulent flow modelled by $k-\epsilon$ equations and heat transfer in both fluid and solid domains. The simulation used a reference temperature, T_{ref} , set at 303.15 K, and tested heat flux values ranged from 800 to 1000 W/m² for Reynolds numbers between 1463.81 and 5515.51. The heat transfer coefficient h was determined to be 9 W/m²·K, while the external temperature was set at 30°C for the analysis of convective heat flux. The analysis accounted for radiation transfer from the PV panel surface to the surrounding environment using an emissivity of 0.95. The simulation uses parameters and base values detailed in Table 2. The dimension was based on the PVT collectors, while other parameters were based on relevant parameter values from established studies.

TABLE 2: Simulation parameters and baseline values (Amir et al. 2025; Ewe et al. 2021; M. A. A. Bin Ishak et al. 2023).

Parameter	Value
Reynolds number, Re	1463.81 - 4415.51
Width of collector, W	240mm
Length of collector, L	180mm
Duct depth, d	25mm
Solar irradiance, I (W/m ²)	800, 900, 1000 W/m ²
Area of collector, A_c	0.0432 m ²
Temperature ambient, T_a	30°C
Absorptivity of PV cell, α_{pv}	0.91
Heat transfer coefficient, h	9 w/ (m ² .K)
External temperature, T_{ext}	30°C
Transmittance of lamination, τ_l	0.085
Reflectivity of jet plate, n_R	0.7
Electrical efficiency at reference condition, η_{ref}	0.16
Temperature Coefficient, β	0.0045 K ⁻¹
Temperature at reference condition, T_{ref}	303.15 k

REYNOLDS NUMBER

The Reynolds number was used to characterize the airflow inside the PVT channel. Based on the chosen mass flow rate (0.00078-0.00393 kg/s), the value ranged from approximately 1463.81 to 4415.51. The COMSOL simulations used a turbulent heat transfer framework, in which fluid flow and heat exchange were solved in a coupled manner. The Reynolds number (Re) is calculated as follows:

$$Re = (\dot{m} \times Dh) / (W \times \mu) \quad (1)$$

Where:

$\dot{m}$ = mass flow rate of the fluid (kg/s)
 Dh = hydraulic diameter (m)
 W = width of the flow channel (m)
 μ = dynamic viscosity of air (Pa·s)

The hydraulic diameter is given by (Amir et al. 2025):

$$Dh = (4 \times w \times d) / [2 \times (W + d)] \quad (2)$$

Where d is the depth of the flow channel (m). The dynamic viscosity μ as a function of air temperature T (in Kelvin) is estimated to use (Amir et al. 2025):

$$\lambda_B = \frac{2\eta_0\Lambda_0}{\kappa} \quad (3)$$

CONVECTIVE HEAT FLUX

Convective heat flux (q_0) represents the rate of heat transfer per unit area due to convection between the surface and the air. It is given by (Amir et al. 2025):

$$q^0 = h \times (T_a - T_i) \quad (4)$$

Where: h = convective heat transfer coefficient (W/m²·K)
 T_a = average outlet air temperature (°C or K)
 T_i = inlet air temperature (°C or K)

THERMAL EFFICIENCY

The thermal efficiency ($\eta_{thermal}$) quantifies the portion of incident solar energy converted into useful thermal energy. It is calculated as (Amir et al. 2025):

$$\eta_{thermal} = Qu / (I \times A_c) \quad (5)$$

Where:

Qu = useful thermal energy gained by the air (W)
 I = solar irradiance (W/m²)
 A_c = collector area (m²)

The useful energy Qu is defined as (Amir et al. 2025):

$$Qu = \dot{m} \times Cp \times (T_a - T_i) \quad (6)$$

Where Cp is the specific heat capacity of air (J/kg·K)

PHOTOVOLTAIC EFFICIENCY

The photovoltaic efficiency (η_{pv}) reflects the electrical efficiency of the PV panel and is influenced by the panel's temperature. It is given by (Amir et al. 2025):

$$\eta_{pv} = \eta_{ref} \times [1 - \beta \times (T_{pv} - T_{ref})] \quad (7)$$

Where:

η_{ref} = reference PV efficiency at standard test conditions (typically 25°C)
 β = temperature coefficient of efficiency (%/°C)
 T_{pv} = actual panel temperature (°C)
 T_{ref} = reference temperature (°C)

OVERALL EFFICIENCY

The overall efficiency ($\eta_{overall}$) of the photovoltaic thermal (PVT) system accounts for both thermal and electrical contributions. It is defined as (Amir et al. 2025):

$$\eta_{overall} = \eta_{thermal} + \eta_{elec} \quad (8)$$

Where η_{elec} is the electrical efficiency (same as η_{pv} if no storage or inverter loss is considered)

MASS FLOW RATE

$$\dot{m} = \rho \cdot A \cdot v \quad (9)$$

where:

ρ = Air density $\approx 1.16 \text{ kg/m}^3$

v = velocity of air

A = the cross-sectional area of a pipe

VALIDATION OF MODEL

The simulations accounted for temperature-dependent variations in material properties, enabling the simultaneous analysis of fluid (air) and solid domains, such as aluminum and steel. Certain simplifying assumptions were made: the lamination, jet plate, and PV cell layers were treated as thermally homogeneous; the airflow was assumed confined within the collector channel; and no heat was lost through the collector edges. Turbulent heat transfer was modelled

using the standard k- ϵ approach, which accounts for interactions between the fluid and solid boundaries. The COMSOL model was validated against previously published data to confirm its accuracy.

The same operating conditions and boundary parameters reported in bin Ishak's model, experimental, and numerical studies were adopted for comparison. By reproducing their test scenario, the present simulation could be benchmarked against well-documented performance results, thereby ensuring that the model provides reliable predictions of thermal behavior under similar conditions. Figure. 4 compares the overall efficiency between the current simulation and confirmed previous research by Bin Ishak et al. (2023) for mass flow rates from 0.01 to 0.14 kg/s for comparison, the current simulation employed the exact collector dimensions as in their paper: a collector width of 0.684 m, a length of 0.704 m, and a duct depth of 0.025 m. As depicted, the current model closely matches the old model, indicating a high correlation across the entire mass flow rate range, with a maximum deviation of less than 2.2%. Table 3 compares the calculated thermal efficiency values from the current simulation for both cases with those reported by Bin Ishak et al. The average percentage error between the current model and their numerical data is identified as 1.98%, deviating slightly from their experimental data by 1.89%. The related average accuracy are 98.01% and 98.11%, respectively. These values confirm the validity and credibility of the constructed COMSOL model for overall efficiency performance estimation.

TABLE 3. Simulation accuracy was validated by comparing overall efficiency results with those of Ishak et al. (2023).

Mass flow rate (kg/s)	(Ishak et al. 2023) Model	Current Work	Error (%)	(Ishak et al. 2023) Experiment	Current Work	Error (%)
0.01	52.57	53.71	2.17	52.57	53.71	2.20
0.04	54.50	55.73	2.24	54.52	55.70	1.81
0.07	56.42	57.44	1.81	56.42	57.44	1.98
0.10	61.01	62.22	1.98	61.01	62.22	1.75
0.14	65.16	66.34	1.75	65.16	66.32	1.75
Average percentage error (%)				1.98%	1.89%	1.89%
Average percentage accuracy (%)				98.01%	98.11%	

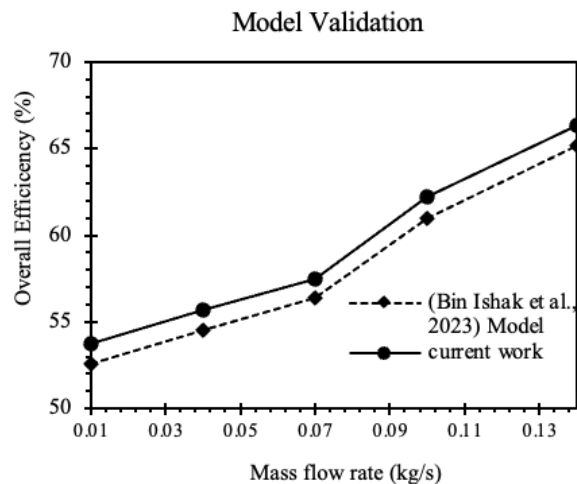


FIGURE 4. Validation of the simulation model through comparison of overall efficiency with previous results from Ishak et al (2023) (M. A. A. B. Ishak, Ibrahim, Sopian, et al. 2023).

RESULTS AND DISCUSSION

This section discusses the outcomes obtained for different inlet positions (symmetric and asymmetric), irradiance intensities (800, 900, and 1000 W/m²), and Reynolds numbers (1463.81 to 4415.51). The discussion is presented through thermal efficiency, electrical efficiency, PV surface temperature, outlet temperature, overall efficiency, and streamlines. The analysis is presented alongside the appropriate physical behavior and flow mechanisms to justify the observed trends.

PV TEMPERATURE

The results for PV surface temperature are presented in Figure 5, which shows the expected continuous decrease with increasing flow rate. This is expected because of enhanced convective heat transfer from the PV surface to the cooling air stream. For instance, at 1000 W/m², the surface temperature decreased from 72.86°C to 50.22°C for the symmetric case and from 69.01°C to 46.92°C for the asymmetric case. At 900 W/m², the temperature decreased from 68.82°C to 48.19°C in the symmetric configuration, while the asymmetric configuration ranged from 67.03°C to 46.46°C. Similar trends were also observed at 800 W/m², where the symmetric layout decreased from 68.54°C to 52.34°C, and the asymmetric arrangement further reduced the temperature from 64.91°C to 46.42°C. In all the presented cases, the asymmetric inlet consistently experiences lower PV temperatures than the symmetric case, due to stronger, more uniform airflow over

the PV surface, leading to lower thermal resistance in the PV module.

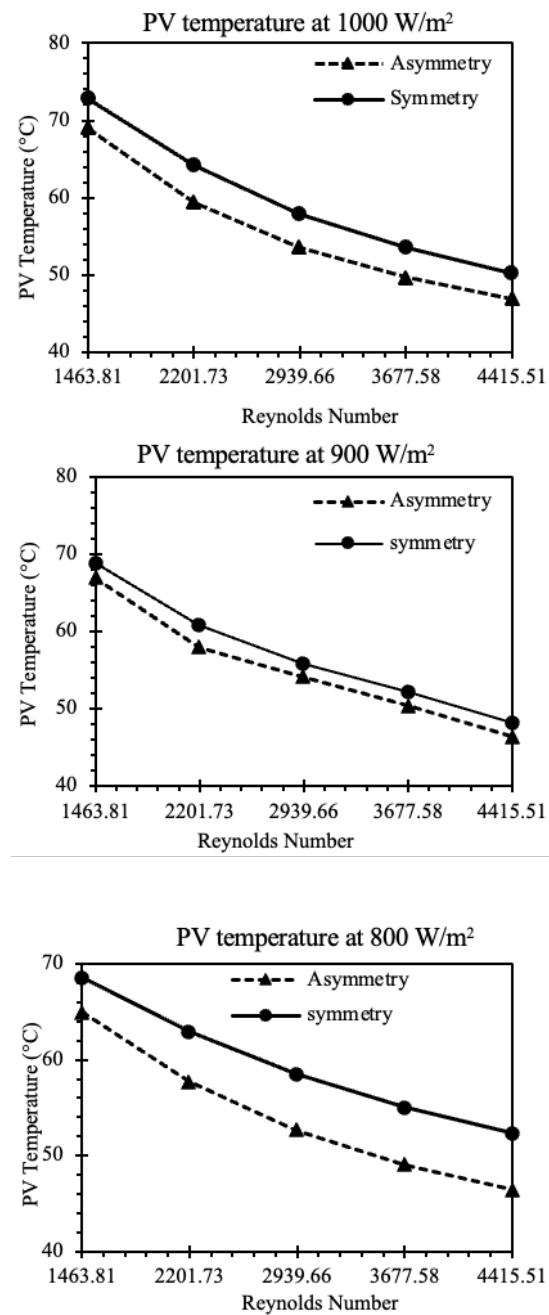


FIGURE 5. PV temperature for different dual-inlet asymmetric-symmetric inlets.

ELECTRICAL EFFICIENCY

Figure 6 clearly shows a strong correlation between temperature and PV module performance. The PV temperature decreases due to the inverse temperature coefficient behavior, which is affected by the inlet configuration. As the PV temperature decreases with

increasing flow rate, the PV surface resistance decreases. This results in reduced internal resistance to carrier mobility and increased electrical efficiency. At 1000 W/m², efficiency increased from 11.76% to 13.45% for the symmetric configuration and from 12.02% to 13.70% for the asymmetric configuration. At 900 W/m², the symmetric efficiency improved from 12.0% to 13.5%, while the asymmetric efficiency improved from 12.2% to 13.8%. At 800 W/m², the symmetric layout improves from 12.0% to 13.2%, while the asymmetric design shows values of 12.4% to 13.6%. This indicates that the reduction in the PV surface temperature due to efficient cooling increased electrical efficiency, and the asymmetric inlet has an edge because of better airflow distribution and localized cooling. The asymmetric configuration exhibits non-uniform inlet positioning, resulting in more vigorous lateral jet mixing and broader air coverage. This enhances convective heat transfer over the active surface. As a result, the asymmetric configuration produces a more uniform and lower cell temperature than the symmetric configuration. In a symmetrical way, the airflow remains relatively confined and less turbulent. The improved cooling in the asymmetric configuration minimizes thermal resistance and suppresses localized hot spots. The results indicate that the inlet configuration significantly improves electrical performance by maintaining thermal stability.

OUTLET TEMPERATURE

The outlet temperature results are presented in Figure 7, showing the correlation between the inlet configuration and heat extraction performance. This is a clear indication that the heat is being extracted from the system to the ambient more effectively at higher flow rates. At 1000 W/m², the asymmetric obtained a temperature range of 50.3°C to 38.4°C, and the symmetric obtained a temperature range of 48.2°C to 36.5°C. At 900 W/m², the asymmetric had a temperature range of 48.9°C to 36.7°C, and the symmetric had a temperature range of 46.6°C to 34.9°C. Meanwhile, at 800 W/m², the values range from 44.3°C to 36.1°C for asymmetric and from 42.1°C to 33.7°C for symmetric. The outlet temperature of the asymmetric configuration is consistently higher than that of the symmetric configuration at all irradiance levels. This is due to the cooling air stream absorbing more heat from the PV module, resulting in more vigorous mixing and, hence, enhanced turbulence. In addition, an asymmetric inlet promotes stronger jet interaction and lateral mixing within the flow channel. The turbulence intensity increases, strengthening convective heat transfer between the air and the PV surface. Meanwhile, the symmetric configuration produces a more uniform but weaker jet flow, leading to less effective energy

absorption.

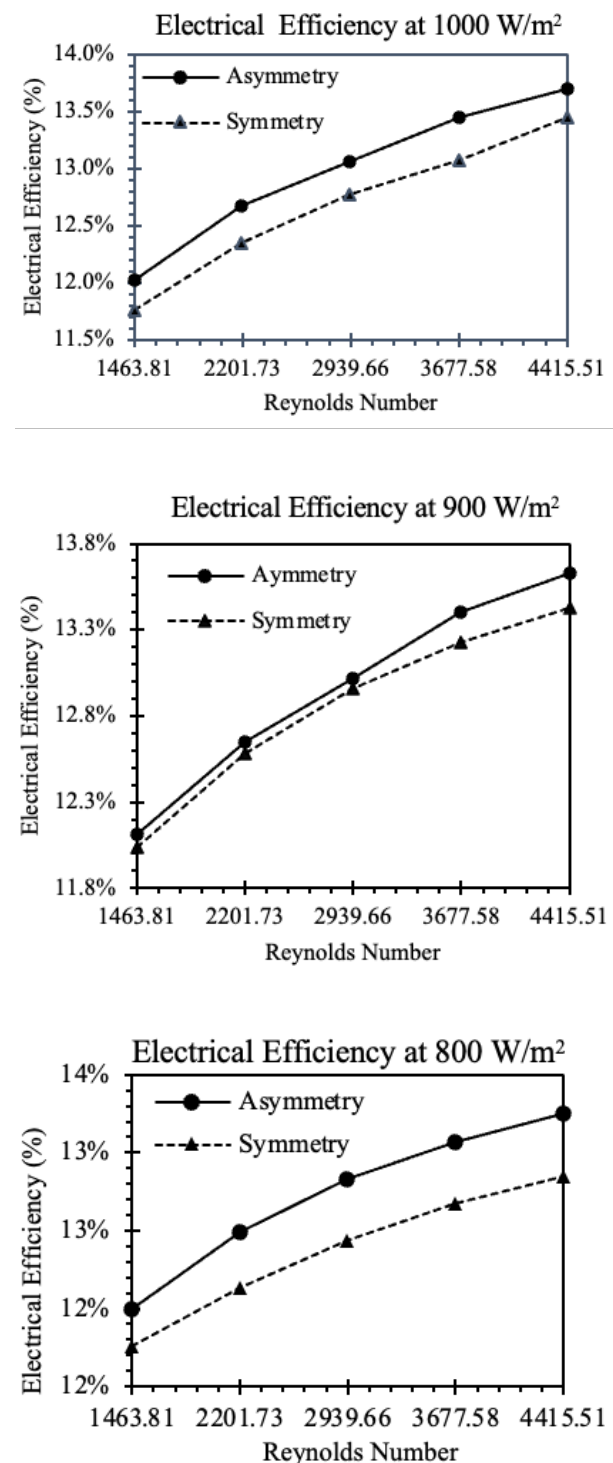


FIGURE 6. Variation of photovoltaic (electrical) efficiency for symmetric and asymmetric inlets

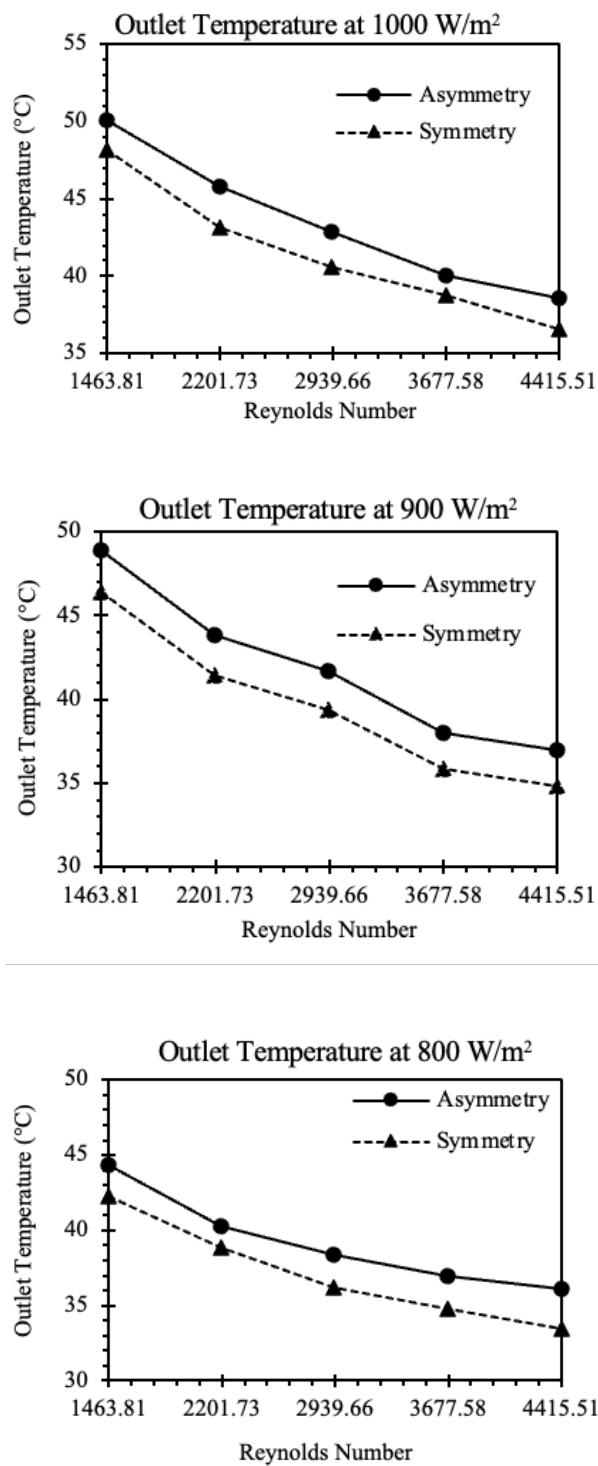
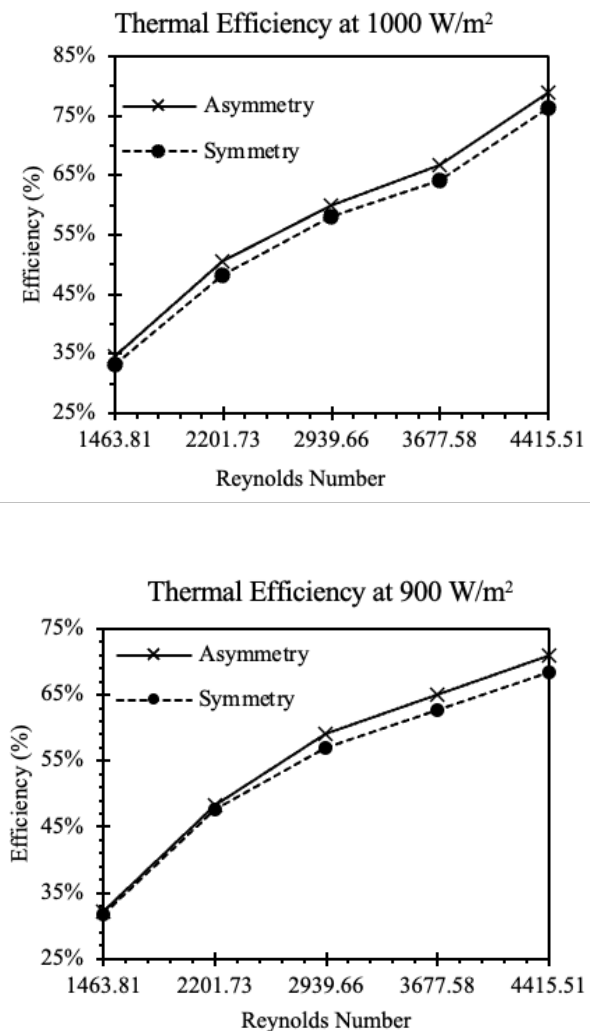


FIGURE 7. Outlet air Temperature variation for dual symmetric and asymmetric inlets.

THERMAL EFFICIENCY

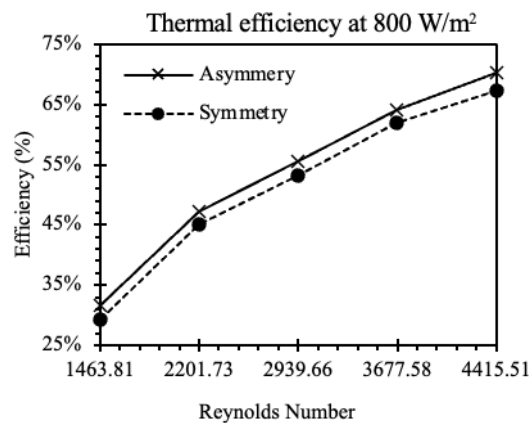
In Figure 8, the thermal efficiency increases with Reynolds number for both symmetric and asymmetric configurations, due to greater heat recovery from the PV surface. At 800 W/m², thermal efficiency ranges from 30.1% to 66.4% for

symmetric and from 31.8% to 69.2% for asymmetric. At 900 W/m², the values for symmetric range from 33.0% to 69.3% and from 33.2% to 71.4% for asymmetric. At 1000 W/m², the thermal efficiency was 76.2% for the symmetric case and 78.3% for the asymmetric case. The improvement in thermal efficiency can be attributed to the decrease in thermal boundary layers and, hence, to an increase in the convective heat transfer coefficient with increasing flow rate. At a higher Reynolds number, the thermal boundary layer becomes thinner. This helps to improve the heat transfer coefficient and improve heat removal from the absorber plate. As more heat was removed from the absorber plate, the outlet temperature increased, thereby increasing the PVT's thermal efficiency. In the asymmetric case, flow impingement is better with enhanced turbulence intensity, which plays a vital role in effective energy absorption.



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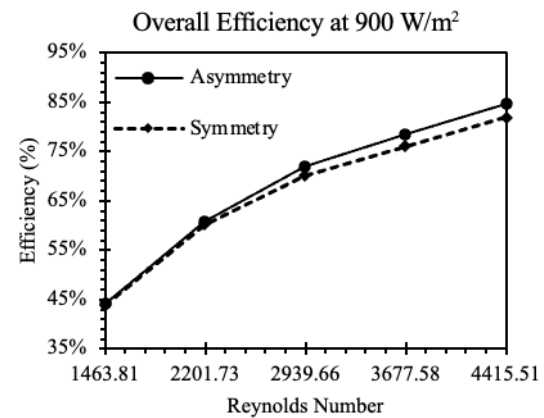


FIGURE 8. Thermal efficiency for dual asymmetric-symmetric inlets.

OVERALL EFFICIENCY

The overall efficiency, which represents the combined effect of electrical and thermal energy, is presented in Figure 9. The highest performance is observed at the higher flow rate. At 800 W/m², the efficiency of the asymmetric case increased from 43.91% to 83.74% and from 41.28% to 80.35% for the symmetric case. At 900 W/m², the asymmetric efficiency improves from 44.19% to 84.67%, while the symmetric efficiency ranges from 43.84% to 81.93%. At 1000 W/m², the efficiency of the asymmetric case is 92.48%, while the symmetric case is 89.80%. The observed trend toward asymmetric performance is superior to the symmetric layout due to improved fluid dynamics associated with vortex penetration and lateral jet spreading. This leads to improved overall heat extraction and cooling uniformity, thus improving the overall heat transfer environment. This not only helps reduce the PV surface temperature but also maintains a higher level of outlet air energy content and increases overall energy utilization.

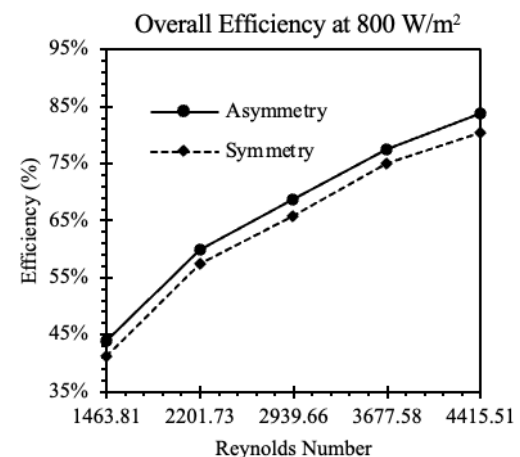
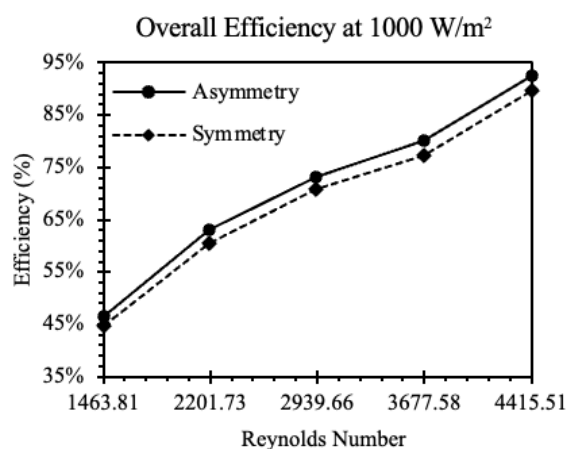


FIGURE 9. Overall efficiency for asymmetric and symmetric inlets.

OVERALL EFFICIENCY OF OPTIMUM DESIGN

Figure 10 compares the overall efficiency of the PVT system with the asymmetric inlet configuration at three irradiance levels (800, 900, and 1000 W/m²) and varying Reynolds numbers. A clear trend is observed: system performance improves with higher irradiance and Reynolds number, leading to better heat extraction and greater overall system efficiency. The system performance at the minimal Reynolds number of 1463.81 resulted in efficiencies of 43.91% at 800 W/m² and 44.19% at 900 W/m² before rising to 46.66% at 1000 W/m². When the Reynolds number reached 4415.51, the system efficiency reached 83.74% at 800 W/m². It improved to 84.67% at 900 W/m² before achieving 92.48% at 1000 W/m², the highest efficiency points on the graph corresponding to the maximum levels of both irradiance and flow rate. The asymmetric inlet design demonstrated exceptional performance, with the system maintaining efficiency above 83% at 800 W/m².

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Higher flow rates make the difference in irradiance levels more noticeable, showing how solar input combined with airflow power improves performance. The findings demonstrate that asymmetrically placing inlets enhances energy recovery effectiveness by boosting convective cooling, helping maintain reduced PV temperatures. The solar thermal system demonstrates exceptional responsiveness and efficiency across diverse environmental conditions, positioning it as an excellent option for practical applications.

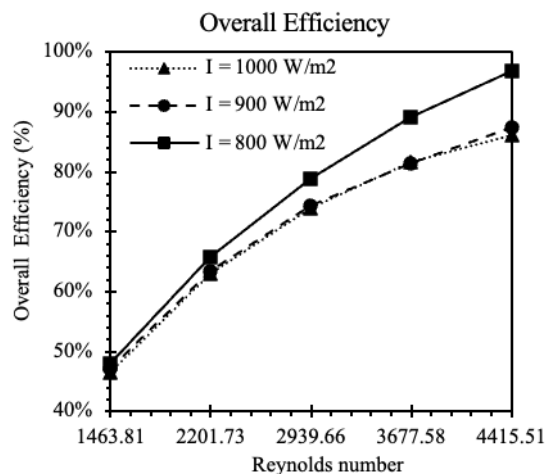


FIGURE 10. Overall efficiency of dual inlets at an asymmetric position

STREAMLINE AND FLOW PATTERN ANALYSIS

The velocity contour in the Figure. 11 (a) shows a stronger jet impingement near the offset inlet region in the asymmetric case, resulting in a higher localized velocity gradient. It can also be observed that the air stream has a wider lateral spread. The uneven inlet positioning promotes enhanced turbulence and better mixing within the flow channel. The streamline pattern in the symmetric case, shown in Figure 11 (b), reveals well-ordered vortex structures beneath each cooling jet, with limited lateral fluid penetration. The fluid flow pattern in the asymmetric configuration is not only unsteady in nature but also has a more lateral mixing tendency due to the combined effects of the secondary vortices and jet spreading behavior, which results in more vigorous mixing and fluid penetration over the surface. These dynamic flow features, as a result, help in reducing the thermal resistance of the PV surface, and thus, resulting in a more rapid heat removal. This improves performance, as discussed above, due to better flow mixing enabled by the asymmetric inlet layout. This is very important, especially at high solar irradiance loading when a large amount of heat is rejected from the PV surface.

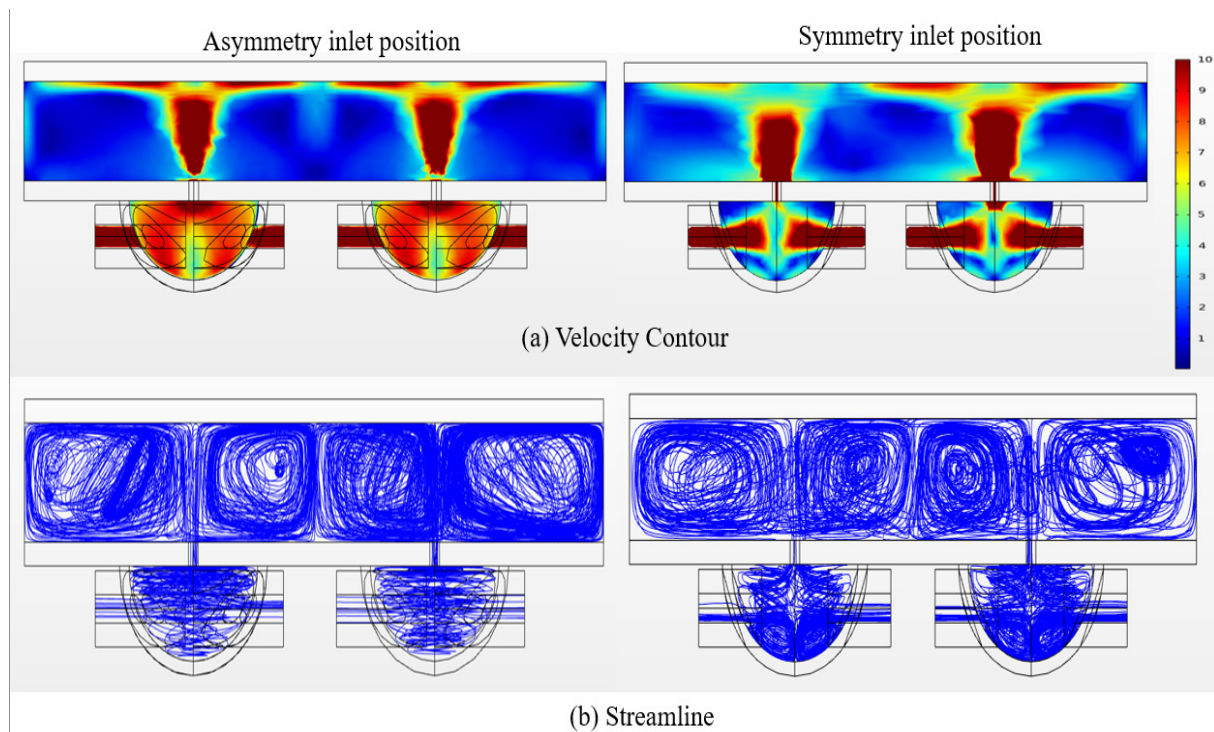


FIGURE 11. (a) velocity contour of asymmetric and symmetric inlet position and (b) velocity streamline

PRELIMINARY COST ESTIMATION

Table 4. shows the cost of presented proposed (RCFJI) system to be fabricated. The system is mostly made of simple parts such as aluminum jet plate, a circular flow cup, air inlet pipes, and Nozzle openings. These parts can all be made using standard machining methods. For a laboratory-scale PVT collector, the extra cost of the cooling structure is estimated to be between \$25 and \$40. This setup is about 5–10% more expensive than regular air-cooled PVT collectors. The asymmetric inlet configuration increased the overall efficiency by up to 3%. This means that the extra money spent may be worth it if the system produces more energy over its lifetime. So, the proposed cooling design looks like it could be useful and cost-effective in real life.

TABLE 4. Estimated additional cost of the proposed jet impingement cooling system

Component	Material	Estimated Cost (USD)
Jet Impingement Plate	Aluminum	8-12
Circular Flow Cup	Aluminum	5-8
Air Inlet Pipes	Plastic	2-5
Nozzle Openings	Aluminum	3-5
Assembly and Fabrication	Not Applicable	10-15
Total Cost		28-40

CONCLUSION

The performance of a hybrid photovoltaic thermal (PVT) system with reversed circular flow jet impingement (RCFJI) cooling was evaluated using two inlet designs as variables: symmetric and asymmetric. CFD simulations were used to test the system performance at three different solar irradiance levels (800, 900, and 1000 W/m²) and Reynolds numbers ranging from 1463.81 to 4415.51. System performance optimization was achieved through increased Reynolds number, which enhanced convective cooling and reduced PV surface temperatures. Across all performance metrics, the asymmetric inlet configuration outperformed the symmetric design. Greater electrical efficiency was achieved by increasing the flow rate. At all irradiance levels, the asymmetric configuration delivered increase in electrical efficiency improvements of 0.2% to 0.4% compared to the symmetric setup. Thermal efficiency also benefited from improved cooling. The asymmetric configuration achieved superior thermal recovery performance at all irradiance levels due to better flow mixing and higher impingement pressure, resulting in efficiency enhancements of 1% to 2.5% compared to

the symmetric design. Analysis of the outlet temperature showed that while symmetric designs produced cooler exhaust air, the asymmetric design yielded higher outlet temperatures, demonstrating more efficient heat removal from the PV surface due to enhanced thermal transfer effectiveness. The asymmetric design demonstrated superior combined electrical and thermal efficiency improvements. The asymmetric design maintained a higher overall efficiency between 1.5% and 3% above the symmetric design while reaching 92.48% efficiency at the highest flow rate under 1000 W/m² conditions. The significant findings from the study are as follows:

The asymmetric inlet configuration performed better than the symmetric design in both electrical and thermal efficiency.

1. Low PV temperature was attributed to the increasing Reynolds number, which enhanced convective cooling and increased energy production.
2. The asymmetric configuration increased the overall efficiency by up to 3%, peaking at 92.48 % at 1000 W/m².
3. Higher air outlet temperatures in asymmetric configurations demonstrate enhanced thermal energy recovery and more efficient heat extraction.
4. The asymmetric intake produced wider jet spreading and more vigorous mixing, improving temperature uniformity and decreasing thermal resistance for enhanced heat transfer.

Overall, the limitation of this study is its reliance on CFD simulations, which may not account for real-world factors such as varying ambient temperatures, weather conditions, and solar exposure intensity. However, the simulation was validated with a previous study to strengthen the reliability and accuracy of the data obtained. The airflow in the simulation was assumed to be uniform to avoid turbulence and transient effects, and the parameters were held fixed. Further lab-scale experiments are recommended to assess the inlet configuration, using this study as a benchmark. The simulation was conducted using air as the working fluid; other possible working fluids could be examined in future research. In addition, the inlet geometry can be further explored in future research.

FUTURE WORK

Future research may enhance the current study by experimentally validating the suggested asymmetric inlet arrangement in actual operating settings. Further

investigations may potentially explore other working fluids, like nanofluids or water-based cooling systems, to augment thermal performance. Furthermore, optimization analyses incorporating various inlet geometries, jet diameters, and nozzle configurations may yield enhanced understanding of heat transfer properties and system efficacy.

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DECLARATION OF COMPETING INTEREST

None.

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