

Wavy jet plate induced turbulence for enhanced thermo-fluid performance of jet impingement photovoltaic thermal (PVT)

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ARTICLE INFO

Keywords:

Photovoltaic Thermal
Jet Impingement
Energy Performance
Jet Plate
Heat Transfer

ABSTRACT

A photovoltaic (PV) system suffers degradation as its operation temperature increases, which in turn limits the overall energy output. Although jet impingement cooling has been extensively studied, most research concentrates on the streamwise and spanwise aspects of a conventional flat plate jet impingement. The impact of jet plate geometry itself is often disregarded. This study fills the gap by providing a new wavy jet plate design to improve the thermo-fluid performance in a jet impingement PVT system. A hybrid approach using numerical analysis and indoor experiment was used to examine four different jet plate geometries, such as 60° equilateral, 45° isosceles, 50–70° scalene, and 30–60° right-angle configurations. The wavy jet plate was tested with a constant irradiance of 1000 W/m² and Reynolds numbers of 2105 to 10672. Key performance indicators, such as energy performance and system evaluation performance, including exergy, friction factor, and pressure drop, were assessed for each design. The findings show that the wavy jet plate has a significant impact on flow behaviour and heat transfer characteristics. The 45° isosceles design achieved the highest overall PVT efficiency around 86% due to an optimum balance between thermal enhancement and hydraulic losses. Meanwhile, the 60° equilateral design resulted in a better electrical performance due to even cooling. It was also discovered that higher Reynolds numbers cause performance improvement decreases due to turbulence saturation and higher pressure drop. The novelty of this work lies in the establishment of jet plate geometry as a new design parameter, which provides a practical pathway for optimizing jet impingement PVT systems.

1. Introduction

It should be noted that renewable energy markets have been witnessing an increase in their growth compared to fossil fuels in recent years. Such an upward trend may be attributed to environmental concerns related to carbon emissions and high prices on the latter [1]. An increase in the number of technologies designed to produce energy has caused a shift in demand for the former across the globe. Specialists around the world keep developing innovations in this sphere trying to make energy generation more ecological and effective [2]. For instance, the use of solar energy has become popular as one of the rapidly growing renewable sources. Issues of climate change, energy security, and economic stability have made a certain number of nations switch to solar

power as a secure and relatively low-risk replacement for fossil fuels [3]. Furthermore, the price of photovoltaic technology has decreased drastically by 82% in the last decade. Thus, making it extremely cheap [4]. As a result, its popularity has grown considerably, especially in Europe, where the capacity of PV installations rose from 100 GW to 270 GW in 2023. This accounts for approximately 10% total power generation. The increasing trend is expected to continue over the following years [4]. Solar energy has dominated the renewable energy production growth due to its sustainability and accessibility [5]. However, despite its advantages, PV modules suffer a drawback where their efficiency decreases by 0.4 to 0.65% for every 1 °C increase. Operating at high temperatures causes exposure to the sun, which hinders the electrical energy generation. This also indicates that higher solar irradiance does not necessarily contribute to higher electrical output [6].

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<https://doi.org/10.1016/j.tsep.2026.104826>

Received 5 May 2026; Received in revised form 16 June 2026; Accepted 2 July 2026

Available online 4 July 2026

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Nomenclature			
l	Length	k_{fluid}	Thermal conductivity
w	Width	μ	Dynamic viscosity
D_1	Lower duct	D_h	Hydraulic diameter
D_2	Upper duct	d	Duct depth
J_p	Wavy jet plate	$\dot{m}$	Mass flow rate
$k-\epsilon$	K-epsilon	Nu	Nusselt number
Re	Reynolds number	h	Heat transfer coefficient
T_a	Ambient temperature	T_s	Temperature surface
A_{PVT}	Area of PVT collector	T_f	Average air temperature inside the duct
I	Irradiance	Q_u	Useful heat gain
t_p	Jet plate thickness	f_f	Friction factor
$P_{max,ref}$	P_{max} at references	ΔP	Pressure drops
T_{ref}	Reference temperature	Nu^*	Baseline Nusselt number
C_p	Specific heat capacity	f^*	Enhanced friction factor

A hybrid photovoltaic thermal (PVT) system provides a more comprehensive approach to energy independence by integrating both electrical and thermal generation [7]. PVT key principle is its ability to generate energy while recovering useful heat from the PV module for thermal energy [8]. In a photovoltaic-thermal (PVT) system, thermal energy can be obtained from a conventional PV system by attaching a heat exchanger under the PV module. Because the PV module is cooled down during the process of thermal energy production, the efficiency of the PV module increases [9–11]. The performance of a PVT system is intrinsically associated with its solar module, which is the primary component of the system. According to established research, the PVT thermal efficiency can range as low as 10% and up to 90% depending on the system. Electrical efficiencies for PV technologies vary from 10% to 25%; hence, thermal systems based on such technologies may be operated at up to 90% efficiency under ideal conditions [12]. Despite such impressive figures, there are performance limitations inherent to PVT systems. Specifically, extended exposure to sunlight causes overheating in PV modules, which decreases their efficiency because of the temperature increase [13]. Besides, in case of insufficient heat removal because of ineffective heat transfer and temperature imbalance in the PVT system, the effectiveness of thermal energy usage becomes extremely low in spite of increasing electrical efficiency [14]. Many researchers all over the world have tried different means to address this problem and improve cooling in PVTs. One of these techniques includes using jet impingement cooling that can increase the efficiency of convective heat transfer in PVT systems [15–17].

A previous study experimentally compared a new v-corrugated absorber with the conventional design within a solar collector equipped with a jet plate system. It turned out that the efficiency of the proposed design always exceeded the efficiency of the standard design since thermal efficiency was up to 82.3%, depending on the mass flow rate of air. Gains reached up to 14% as well as higher outlet air temperatures and effective convective heat transfer could be observed within the proposed geometry. However, the experiment was limited to a particular range of conditions and did not involve further analysis of PVT performance over time [18]. Another technique used for improving PVT performance included using of thermoelectric cooling with confined nanofluid jet impingement. Under optimal irradiance of 700 W/m², the system achieved 85% electrical performance and 15% thermal efficiency. The results indicate the potential of the hybrid cooling approach by demonstrating high heat removal capability [19]. Almeshaal et al (2024) investigated the effects of combined fins with a conical ring on a jet impingement PV system. The research found a considerable increase of 82% thermal efficiency and 78% hydraulic efficiency. A comprehensive analysis was performed, including geometry optimization using MATLAB. However, from the study, the design geometry intricacy may

present fabrication and implementation issues. [20]. Furthermore, a recent study using conical jet impingement yielded an empirical correlation for the Nusselt number and friction factor with a variation of 10% from the reference value. The optimization of jet characteristics was proven to enhance thermal performance while reducing pumping loss. [21]. Another study numerically investigates jet impingement on solar air heaters. The study revealed a significant thermal-hydraulic performance improvement compared to conventional designs. The optimal jet pitch utilized was 1.30, and the angle was 0.094 m at Reynolds number 7500. While promising, the study is limited to simulations and lacks experimental validation for real-world reliability [22].

Thapa et al. (2024) studied a jet impingement solar thermal collector with multi-arc ribs and obtained a considerable boost in exergy efficiency to a peak of 2.77 times the baseline geometry. The economic and environmental analysis also showed that the energy cost was relatively low as 0.08 \$/kWh and the reduction of CO₂ per year was about 51 tons. Nonetheless, in spite of such encouraging results, the system had a comparatively long exergy-based payback period of 14.9 years, which suggests that the system may have certain restrictions in its practical use [23]. Eng et al. (2024) investigated a jet impingement in a bifacial photovoltaic thermal system. The cooling effect not only lowers the panel temperature but also increases the rear-side irradiation by reflection. The results achieved a 33.8–62.3% thermal efficiency and 9.4–11.2% electrical efficiency. Though the numerical predictions were in good agreement with experimental outcomes, the more complex system and the higher requirements in pumping impose trade-offs between performance gains and operational costs [24]. Subsequent studies revealed that solar collectors with dimple roughening of jet impingement performed better thermally and economically compared to regular smooth jet impingement collectors. Exergy analysis provided optimal roughness parameters including an arc angle of 60°, roughness height of 0.027 m and pitch ratio of 0.27 m with the best exergy efficiency of 0.026. Nevertheless, to get these improvements requires more power in pumping [25]. Furthermore, previous studies have shown the performance of bifacial PVT collector with jet impingement configuration of reversed circular flow. The best exergy efficiency was recorded as 12.64% at 900 W/m² and flow rate of 0.14 kg/s while the highest performance was achieved at 0.06 kg/s flow rate. Although these advances have been made, the comparatively low exergy efficiency implies that there is more work that needs to be done to optimise it [26]. Also, experimental studies of an impinging jet solar air heater with stepped ribs showed that certain rib designs, especially ribs with dimensions of 2 × 4 cm, a pitch of 4 cm, and a jet diameter of 6 mm, can increase the Nusselt number by up to 31% and thermohydraulic performance by up to 19% over a smooth reference design. These results highlighted the need for optimization of the geometrical parameters of ribs to achieve

compromise between improved heat transfer and the effect of pressure drop [27].

All these results highlighted the need for optimization of the geometrical parameters of ribs to achieve a compromise between improved heat transfer and the effect of pressure drop [27]. Numerous studies have confirmed the advantages of jet impingement and its combined applications with other techniques like fin, ribs, wire mesh and corrugated absorber plate in solar air heaters and PVT systems. Some improvements in heat transfer coefficient and Nusselt numbers were reported along with significant increases in the overall performance of these devices. However, those improvements were usually associated with increased friction losses, greater pumping power requirements and higher system complexity. It is worth mentioning that the existing literature mostly uses numerical simulation and/or laboratory experiments, which may reduce the accuracy of generalization of results into practical operation. While numerous efforts have been made to change the absorber surfaces, the most widely used technique still remains plain jet plates. Therefore, the effect of changing the jet plate geometry on heat transfer has not been fully investigated yet. This highlights an important gap in the existing knowledge related to the impact of geometrical changes in jet plate on turbulence generation and heat transfer process. With this purpose in mind, the current research proposes a new configuration of jet plate, namely, wavy plate. The wavy plates are designed to increase turbulence in the flow and thus enhance mixing. The experiment methodically considers various wavy geometries, such as 30–60° right-angle, 45° isosceles, 50–70° scalene, and 60° equilateral geometries. The study was carried out by using a hybrid approach of computational fluid dynamics (CFD) and experimental confirmation. Key performance indicators evaluated are airflow characteristics, photovoltaic temperature distribution, electrical and thermal efficiencies, friction factor, pressure drop, and exergy performance, which give an in-depth analysis of the proposed design.

While previous studies have successfully enhanced jet impingement PVT performance through absorber modifications, rib roughness, fins, wire mesh inserts, corrugated surfaces, and optimization of jet operating parameters, the jet plate itself has generally remained a conventional flat configuration. In addition, existing research is mainly directed towards enhancing the heat transfer at the target surface, instead of controlling the flow structure before jet formation. The present work proposes a novel design of the jet plate, which incorporates an active flow-conditioning element instead of a conventional jet flat plate jet impingement. The wavy jet plate enhanced the fluid flow path before it reaches the surface of the photovoltaics, creating controlled flow separation, secondary vortices, and increased mixing before the jets impact the PV surface. This is a mechanism that is different from the existing enhancement methods that add roughness elements to the absorber. Also, the study quantitatively compares four different types of wave geometry by conducting CFD and experimental validation of the thermo-fluid behaviour of the different wave geometries. This makes the geometry of the jets a new design parameter to be optimized for PVT jet impingement systems.

The main contributions of this study are:

- Establishes jet plate geometry as a new design parameter in jet impingement PVT systems, moving beyond traditional absorber-focused modifications.
- Introduces a novel wavy jet plate concept with systematic evaluation of multiple geometries, demonstrating its effect on turbulence, flow separation, and heat transfer.
- Provides combined CFD and experimental validation, ensuring accurate assessment of thermal, electrical, and exergy performance.
- Quantifies the trade-off between heat transfer enhancement and pressure losses, enabling optimized design for practical and scalable PVT applications.

- Develops design guidelines for high-performance PVT systems, bridging the gap between theoretical research and real-world implementation.

2. Methodology

The methodology of this research is categorized into two Phases:

Phase 1: Numerical Analysis

In this Phase, four different wavy plate geometrical designs were analyzed using CFD simulation. The objective of phase 1 is to simulate the airflow distribution and temperature gradient through numerical analysis. Each design was simulated at a constant of 1000 W/m² with Reynolds numbers from 2105 to 10672.

Phase 2: Indoor Experiment

In Phase 2, an indoor experiment was carried out to analyze the energy performance, performance evaluation criteria, and exergy analysis. A PVT test rig is set up under a calibrated artificial solar simulator to maintain a consistent heat flux. Key parameters such as air inlet/outlet temperature, PV surface temperature, mass flow rate, and pressure drop are measured using appropriate sensors and data acquisition systems.

2.1. Phase 1: Numerical analysis

2.1.1. Geometrical configuration

Several systematic processes were applied in Phase 1 to ensure the accuracy of the methodology and data curation. The initial step involved defining and establishing the geometry of the wavy jet plate. The jet plate conceptual design was inspired by the research gap in the literature, which previous literature has only focused on flat plate jet impingement. Although these configurations have been extensively studied, there is a lack of knowledge applied to the jet plate in the current pool of knowledge. To address this limitation, the current study proposes a wavy jet plate for a jet impingement PVT system. The proposed wavy jet plate intends to improve flow disturbance and enhance convective heat transfer within the PVT system. By utilizing the wavy jet plate, fluid mixing will improve, which will also create local turbulence. As a result, the wavy plate will contribute to improved thermal management in the PVT system. However, one of the key uncertainties in the design lies in determining the most effective wave angle that can maximize the system efficiency. Therefore, four different angles of wavy jet plate designs were established: (a) Design 1: 60 deg equilateral wavy jet plate, (b) 45 deg isosceles wavy jet plate, (c) 50–70 deg scalene wavy jet plate, and (d) 30–60 deg wavy right-angle jet plate, as shown in Fig. 1. Each wavy jet plate was constructed with a standardized geometric specification to ensure accurate comparison of configuration. Specifically, each jet plate measures 180 mm in width, w , and 280 mm in length, l , with a thickness of 3 mm, as shown in Fig. 2. The spacing of each wave is set to 3 mm, only the angle of the wave varies according to the design.

The wavy jet plate is then placed inside a PVT collector with a length, l , of 240 mm and a width, w , of 180 mm. The air inlet will come through the lower duct D_1 with a 45 mm height to allow air distribution across the PVT collector. The air will then pass through the wavy jet plate, J_p , with each jet plate consisting of 54 holes each measuring 3 mm in diameter. The spacing of each hole is set to 28 mm based on a previous study, which shows a good energy performance enhancement in the jet impingement PVT system [28]. The air passing through the jet plate creates an impinging effect, thereby impinging on the PV module to enhance cooling, as illustrated in the schematic diagram in Fig. 3. The heat dispersed in duct D_2 will then be exhausted through the air outlet for thermal heat utilization.

2.1.2. Governing equation and boundary setup

ANSYS Fluent was utilized to assess the coupled fluid flow and heat transfer of each design. After establishing the geometry, the model was

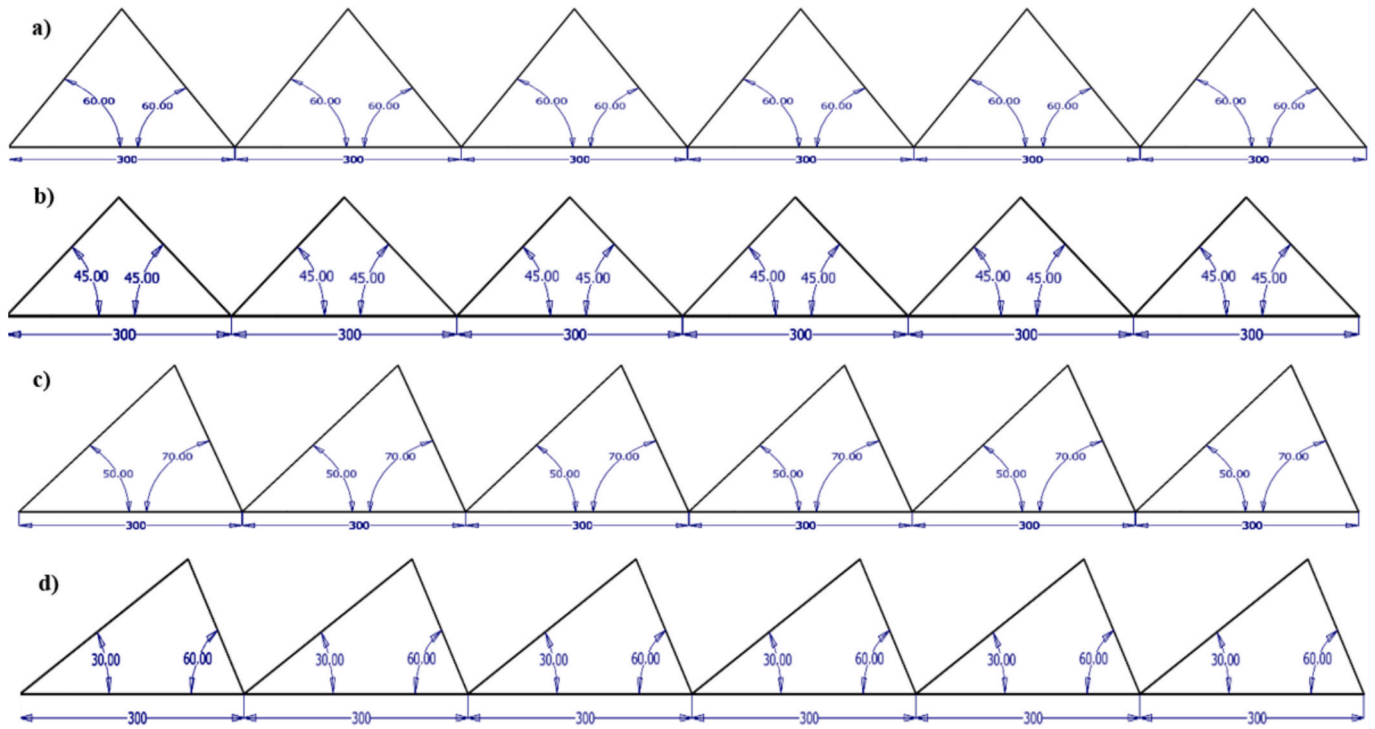


Fig. 1. Wavy jet plate design with varying angles. (a) Design 1: 60 deg equilateral wavy jet plate, (b) Design 2: 45 deg isosceles wavy jet plate, (c) Design 3: 50–70 deg scalene wavy jet plate, and (d) Design 4: 30–60 deg wavy right angle.

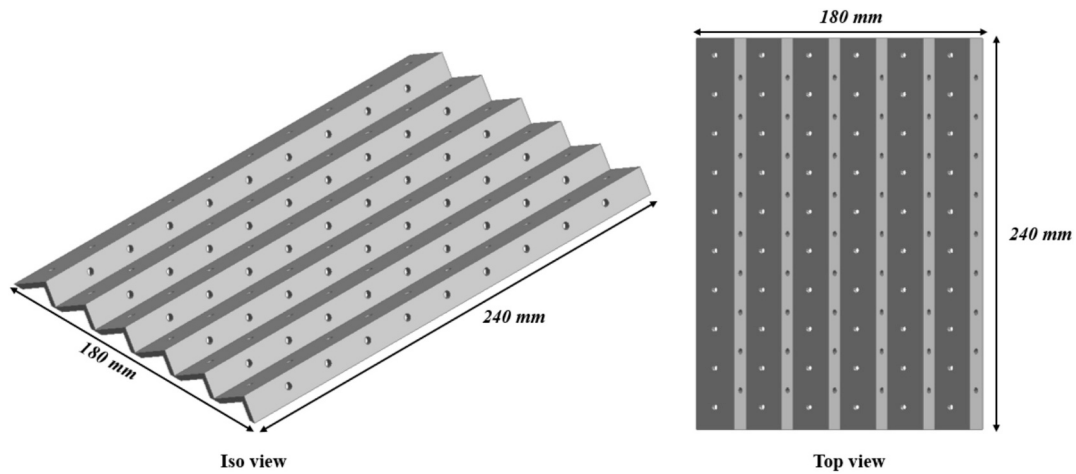


Fig. 2. Wavy jet plate dimension and view. Isometric view (left) and top view (right).

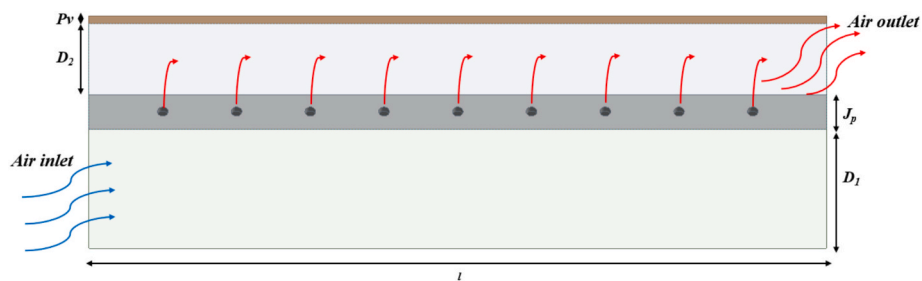


Fig. 3. Cross-sectional view of the PVT system with a wavy jet plate.

defined into three distinct bodies, which are the jet plate, PV module, and air, to ensure proper definition of interaction. The numerical

domains were then characterized into two categories, which are the solid domain and the air domain. The solid domain includes the PV

module and the wavy jet plate. The solid domain material was set to aluminium due to its high thermal conductivity and widespread use in thermal systems. Meanwhile, the fluid domain presents the air inside the PVT collector, which also serves as the working fluid for heat removal. The primary function of the wavy jet plate in the present study is to condition the airflow before impingement rather than to serve as a major heat transfer medium. The thermo-fluid enhancement mechanism is mostly controlled by the acceleration of flow due to geometry, flow separation, generation of vortices, and later the disruption of the thermal boundary layer at the PV surface. The numerical model assumed aluminium to be part of the jet plate, but most of the thermal energy transferred between the PV module and the working fluid is by forced convection. In the numerical model, aluminium was assumed to be attached to the jet plate, and most of the thermal energy transfer between the PV module and the working fluid was assumed to be by forced convection. Therefore, the geometric effects studied in this work are expected to have a larger effect than the effect of the jet plate material. However, the experimental jet plates were fabricated with the additive manufacturing of PLA, which led to a discrepancy in thermal conductivity between the experimental model and the numerical model. This restriction should be taken into account in the interpretation of the quantitative comparison of the CFD predictions and experimental measurements. Double precision was used in the solver configuration to allow numerical stability and eliminate rounding mistakes during iterative calculations. The energy equation was turned on to incorporate the heat transfer process and allow temperature-dependent fluid attributes to be evaluated throughout the simulation. The typical $k-\epsilon$ turbulence model was implemented to simulate turbulent flow induced by the wavy surface effects from the jet plate. This model is widely used in engineering applications requiring internal flow as it demonstrates an appropriate balance between computational performance and adequate precision in estimating turbulent kinetic energy and dissipation [29]. The standard $k-\epsilon$ turbulence model was used because of its robustness, numerical stability, and its useful application in engineering analysis related to jet impingement and forced convection heat transfer. Flows in the PVT collector are turbulent, recirculating, and wall-bound, with Reynolds numbers between 2105 and 10672. Advanced turbulence models like the RNG $k-\epsilon$ model, Realizable $k-\epsilon$ model, and $k-\omega$ SST model are potentially capable of predicting complex near-wall phenomena. However, past research has shown that the standard $k-\epsilon$ model is able to accurately describe the overall flow behaviour and heat transfer trends in jet impingement applications. The primary aim of this study is to compare the thermo-fluid performance of various wavy jet plate designs that are operating under identical conditions, for this reason, the standard $k-\epsilon$ model was deemed appropriate for analysing the relative performance of the various jet plate designs. In addition, the CFD predictions were found to be in good agreement with the experimental measurements, which gave confidence in the use of the selected turbulence model. However, future studies could use higher fidelity turbulence models to better explore finer details such as the structure of the vortices and the local heat transfer. A conjugate heat transfer model was used to address the dynamic relationship of thermal and flow fields. This also allows concurrent solution of heat conductivity in the solid domain and convective heat transfer in the fluid domain. In addition, the governing equations for the system included the continuity equation, the Navier-Stokes momentum equation, and the energy equation. The continuity equation retains mass conversion while the momentum equation quantifies fluid motion in the presence of pressure and viscous factors. The following assumptions were made to simplify the model:

- The system is assumed to run in steady state upon initial convergence.
- Air characteristics are temperature-dependent except for a uniform air inlet.
- No heat loss or leakage occurs within the PVT system.

- Solar irradiance is steady and evenly distributed across the PV surface.

The Reynolds number, Re , for this study varies from 2105 to 10672, which starts from the laminar region at low mass flow rate and develops to the turbulent region as the mass flow rate increases. Each of the designs was simulated at a constant irradiance of 1000 W/m^2 . The objective of Phase 1 is to simulate the airflow distribution and temperature gradient through numerical analysis. The input variables and values are listed in Table 1.

The Reynolds Number, Re , was calculated based on the equation below [30,31]:

$$Re = \frac{\dot{m}D_h}{W\mu} \quad (1)$$

In which $\dot{m}$ represents the mass flow rate, while w denotes the width of the PVT collector, and d refers to the duct depth. The dynamic viscosity of the air is represented by μ , while D_h is the hydraulic diameter, defined as:

$$D_h = \frac{2Wd}{W+d} \quad (2)$$

The dynamic viscosity (kg/m.s) is calculated based on the equation below [32]:

$$\mu = [1.983 + 0.00184(T - 300K)] \times 10^{-5} \quad (3)$$

The Nusselt number is used to evaluate convective heat transfer performance in this study, and is defined by the following equation:

$$Nu = \frac{hD_h}{k_{fluid}} \quad (4)$$

where k_{fluid} is the thermal conductivity and h is the convective heat transfer coefficient expressed as:

$$h = \frac{\dot{Q}}{Ac(T_s - T_f)} \quad (5)$$

Ac represents the PVT collector area, and T_s is the temperature surface of the PV module, and T_f is the average air temperature inside the duct.

2.1.3. Mesh independence analysis

Mesh selection is important in numerical analysis to ensure that the level of differentiation has no influence on the expected outcomes. This approach divides the physical domain into discrete governing dimensions where the average element of quality and no of elements have a direct impact on the solution precision. Thus, mesh independence and mesh setup were performed to ensure that the results were consistent and independent of mesh refinement. The seven mesh setup was

Table 1
Input variables and values.

Input Variables	Values
Reynolds number, Re	2105–10672
Ambient temperature, T_a	25 °C
Area of PVT collector, A_{PVT}	5000 mm ²
Duct 1, D_1	45 mm
Duct 2, D_2	40 mm
Irradiance, I	1000 W/m ²
Length of PVT collector, l	280 mm
PV Module thickness	3 mm
Jet plate thickness, t_p	3 mm
P_{max} at references, $P_{max, ref}$	7 W
Reference temperature, T_{ref}	25 °C
Specific heat capacity, C_p	1007 J/kg.K
Thermal conductivity, k_{fluid}	0.026 W/m.K
Width of PVT collector, w	180 mm

evaluated as tabulated in Table 2. The evaluation took into account variables such as nodes, no of elements, average element quality, difference between average element quality, skewness, and orthogonality. The grid independence study was conducted with different mesh densities from coarse to fine to make sure that the numerical results do not depend on the mesh size. Seven different mesh densities were used in a mesh independence study, ranging from 77,454 elements to 564,196 elements. Average Nusselt number and pressure drop were chosen as the monitoring parameters. With increased mesh density, both parameters tended to approach constant values. The difference in the mean Nusselt number and pressure drop between Mesh 6 and Mesh 7 was only 0.38% and 0.39%, respectively. Since the improvements achieved with further mesh refinement were negligible, and the costs of simulating Mesh 7 were significantly higher due to its higher number of elements. Consequently, mesh 6 with 332,822 elements was chosen for all further simulations. Element quality, skewness, and orthogonal quality were also employed to measure the mesh quality. The selected mesh has an average element quality of 0.806, a skewness of 0.271, and an orthogonal quality of 0.728, which are all within the recommended range for CFD simulation and assure numerical stability and solution accuracy. In order to ensure accuracy of the solution and cost of calculations, the selected mesh was found to be sufficiently fine to capture the flow structures, heat transfer characteristics, and the pressure drop in the jet impingement PVT collector. For all further simulations, it was therefore decided to use the same mesh. Fig. 4 displays the mesh setup using mesh 6 selection.

2.1.4. Model validation

Model validation is an essential procedure in CFD to ensure the accuracy of numerical outputs. In this phase, the CFD model established for the jet impingement solar PVT system was evaluated against experimental data given by Ewe Wing Eng et al (2022), as shown in Fig. 5 [33]. The validation was executed using a fixed irradiance of 1000 W/m² with Reynolds numbers ranging from 982.67 to 2465.66. A comparative analysis of electrical efficiency Fig. 5, left) and thermal efficiency. Fig. 5 (right) reveals a good correlation between the current simulation and experimental data. Both datasets show a steady upward trend in electrical and thermal efficiency as the Reynolds number increases. This agreement validates the numerical model's tendency to accurately describe the air flow configuration and thermal behaviour of the system. It should be noted that the investigated Reynolds number range extends from 2105 to 10672, encompassing both transitional and fully turbulent flow regimes. The current operating range corresponds to real airflow conditions typically used in PVT cooling systems. To ensure consistency between model development and application, the validation procedure was done in the same range of Reynolds numbers as those of the numerical and experimental investigations. The turbulence model selected has also been extensively reported in the literature for predicting the behaviour of heat transfer in jet impingement flows under transitional and turbulent conditions. Hence, the range of validation is deemed suitable for the purposes and operating conditions studied in the present study [33].

2.2. Phase 2: Indoor experiment

Phase 2 indoor experiment was performed to analyze the energy performance, performance evaluation criteria, and exergy analysis of the four distinct wavy jet plates. An advanced solar simulator from the Solar Energy Research Institute, National University of Malaysia, was used in this indoor experiment. The solar simulator consists of two metal halides with a high precision of replicating the solar irradiance. The advanced solar simulator is equipped with thermocouples, a data logger, and a pyranometer, all centralized and controlled by one computer. All of the parameters are input through the software built into the computer, along with the recorded data. The wavy jet plate fabrication was outsourced using a 3D printer and made out of Polylactic acid (PLA) material. The wavy jet plate is then inserted inside the PVT collector to produce a jet impingement PVT system. A PV module with a specification as indicated in Table 3 was placed on top of the PVT collector, which is used to produce the electric energy for the PVT collector. The electrical performance of the PV module was monitored using an IV checker, which was also integrated into the centralized advanced solar simulator computer software. The temperature reading was captured using a K-type thermocouple, which is strategically placed around several points of the PVT collector. The temperature reading was logged for every 5-second intervals until the PVT system reached a steady state condition, approximately around 40 to 45 min. The temperature reading, solar irradiance, and controlled real-time monitoring are recorded using the centralized advanced solar simulator computer. The solar irradiance is fixed to 1000 W/m² for all designs to keep the variable constant and to ease the comparison of the performance of the four-geometry design. Airflow was channeled to the PVT collector using a high-speed compressor connected to a 3 mm hose. The hose is then connected to the lower duct 1, D_1 , to distribute air throughout the system. The air then passes through the wavy jet plate too and produces impinging effects on the PV module to cool it off. Excess heat is removed from the upper duct, D_2 , through the air outlet. A thermocouple is also placed at the air outlet to measure the outlet temperature for thermal performance. Air flow is then adjusted to the desired mass flow rate according to the Reynolds number calculated. The experiment procedures were in adherence with the outline from previous researchers [34,35]. After the system was fully assembled and operational, as shown in Fig. 6, the measurement was recorded. Within 40 to 45 min, the thermal and electrical steady state was reached. The system, along with the solar simulator, was left to cool down to its initial temperature after each set of data.

In Phase 2, key performance was evaluated for each geometry design, such as the energy performance, performance evaluation criteria, and exergy analysis. The first key performance evaluated was the energy performance, which includes the PV temperature, outlet temperature, PV efficiency, and thermal efficiency. The electrical efficiency, $Electrical_{eff}$, was evaluated using the following equation:

$$Electrical_{eff} = \frac{P_{max}}{I \times A_c} \quad (6)$$

Where the solar irradiance is denoted by I , A_c represents the PVT collector area, and P_{max} is obtained from the IV curve recorded.

Table 2
Mesh selection comparison.

Mesh	Elements	Average Nu	Error (%)	Pressure Drop (Pa)	Error (%)	Skewness	Orthogonal
1	77,454	19.34	8.25	8.82	8.98	0.485	0.515
2	101,821	19.98	5.22	9.06	6.5	0.418	0.582
3	134,538	20.36	3.42	9.25	4.54	0.404	0.877
4	174,619	20.63	2.14	9.4	2.99	0.383	0.616
5	203,070	20.84	1.14	9.55	1.45	0.312	0.688
6	332,822	21	0.38	9.6519	0.39	0.271	0.728
7	564,196	21.08	0	9.69	0	0.232	0.767

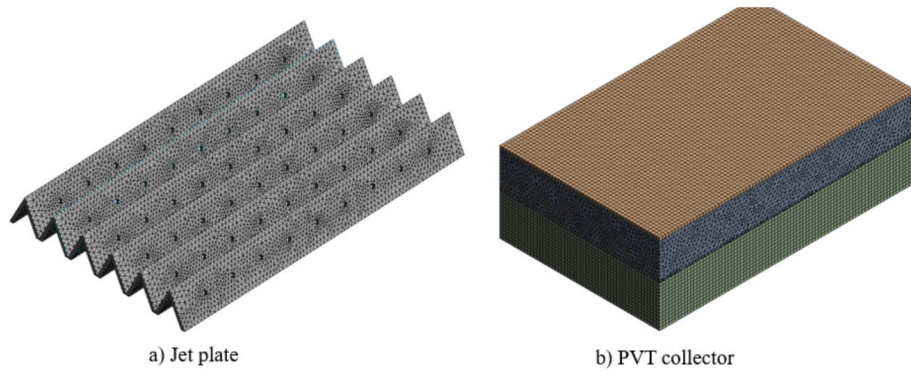


Fig. 4. Mesh samples of (a) jet plate and (b) PVT collector.

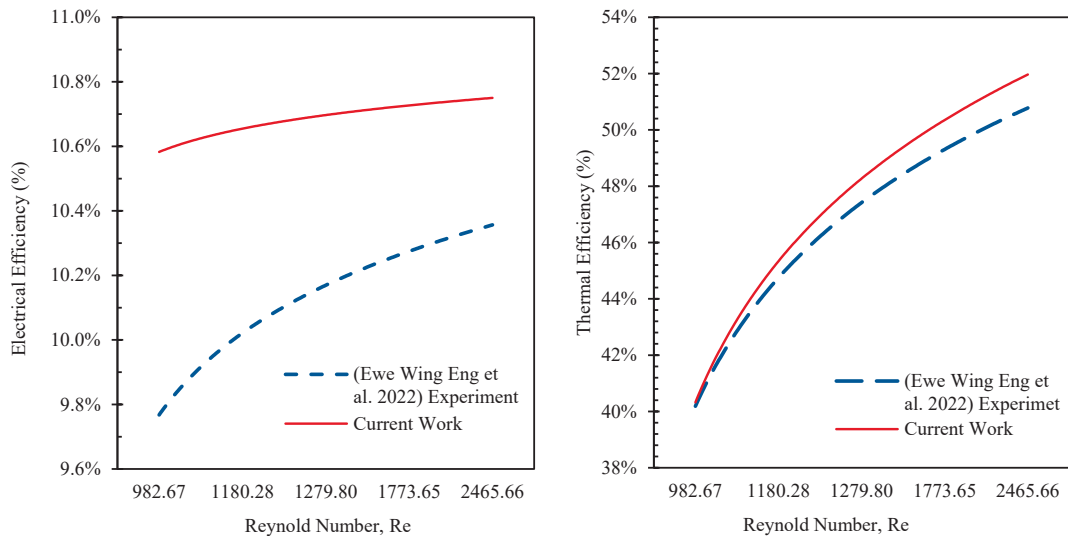


Fig. 5. Model validation result of electrical efficiency comparison (left) and thermal efficiency comparison (right) of the current study and pass study.

Table 3
Solar module specifications.

Parameters	Value
Rated peak power (PMAX)	7 W
Voltage at maximum power (VMP)	17.5 V
Current at maximum power (IMP)	0.4 A
Open circuit voltage (VOC)	21.5 V
Short circuit current (ISC)	0.45A

Meanwhile, the thermal efficiency, $Thermal_{eff}$, was analysed using the following equations:

$$Thermal_{eff} = \frac{Q_u}{(I \times A_c)} \quad (7)$$

Where Q_u represents the useful heat gain from the PVT collector, which is derived from the following equation:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \quad (8)$$

And the total PVT efficiency is calculated by:

$$PVT_{eff} = Electrical_{eff} + Thermal_{eff} \quad (9)$$

After than the system evaluation was further explored to assess the friction factor, pressure drop, exergy efficiency and performance evaluation criteria, PEC. The friction factor was evaluated to measure the fluid flow resistance due to wall friction in PVT system. Friction factor

assessment is essential as it affects the pressure drop and pumping power needed to supply to the PVT system. The friction factor, f_f , was determined using the following equation [36]:

$$f_f = 0.085 \times (Re^{-0.25}) \quad (10)$$

Meanwhile, the pressure drops, ΔP , was determined by the governing equation [36]:

$$\Delta P = \frac{2f_1 \times LG_1^2}{D_h \times \rho} \quad (11)$$

In addition, the exergy performance of the four wavy plates was also assessed to evaluate the beneficial energy obtained from the PVT system employing the wavy jet plate. The greater exergy value obtained reflects more effective energy consumption [37]. Exergy analysis was evaluated to allow a comprehensive assessment of all four wavy jet plates by considering irreversibility and associated losses within the PVT system. The electrical exergy, $Electrical_{exe}$, was evaluated by the following equations:

$$Electrical_{exe} = P_{max} \left[1 - \left(\frac{4}{3} \right) \left(\left(\frac{T_a}{T_s} \right) + \left(\frac{1}{3} \right) \left(\frac{T_a}{T_s} \right)^4 \right) \right] \quad (12)$$

Meanwhile, the thermal exergy, $Thermal_{exe}$, was evaluated by the given equation:

$$Thermal_{exe} = Q_u \times \left(1 - \frac{T_a}{T_{out}} \right) \quad (13)$$

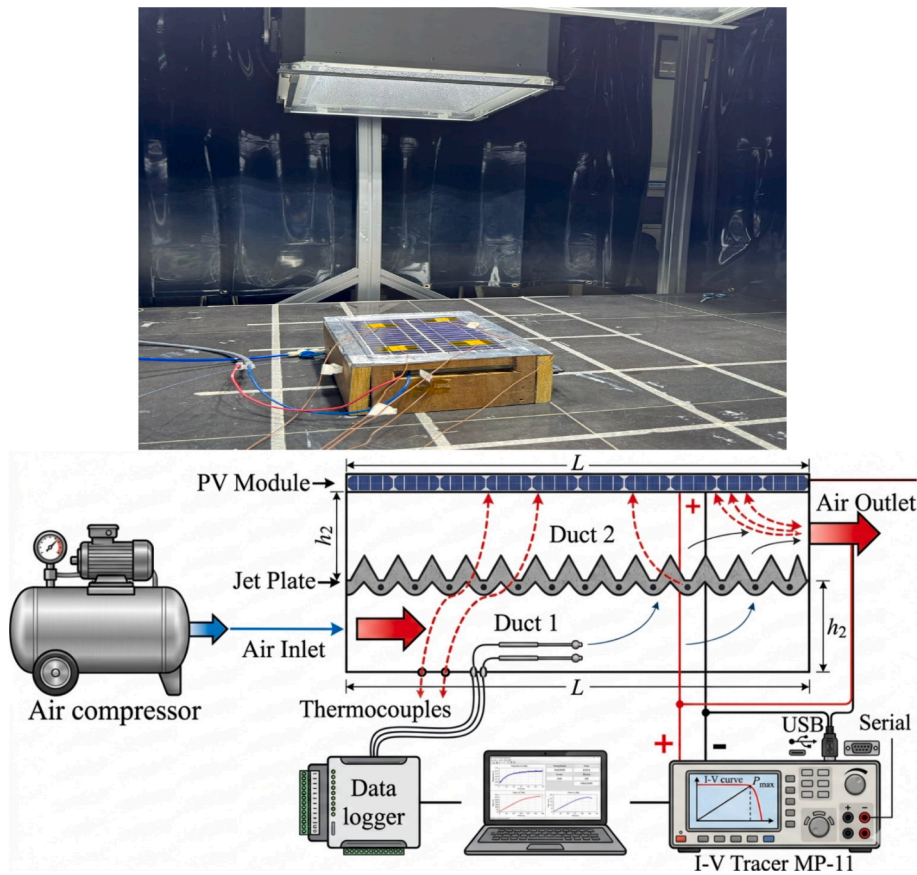


Fig. 6. Experiment setup (top) with schematic diagram (bottom).

In addition, performance evaluation criteria, PEC was also carried out to quantify efficiency, effectiveness and pressure drop which ensures that the selected geometric design delivers optimal performance. The PEC was assessed by employing the following equation [38]:

$$PEC = \frac{\left(\frac{Nu^*}{Nu} \right)}{\left(\frac{f}{f^*} \right)^{\frac{1}{3}}} \quad (14)$$

where Nu is the enhanced design Nusselt number, Nu^* is the baseline Nusselt number, f is the enhanced friction factor and f^* is the baseline friction factor.

2.2.1. Data reliability analysis

Although the indoor experiment was conducted using an advanced solar simulator that centralized all the measurements in one computer, data reliability was still ensured to ensure the reliability of the measurement. Data reliability is a statistical approach to evaluate uncertainty and variation in experimental measurements. Hence, it is essential to carry out data reliability to ensure the accuracy and reliability of the data. Table 4 tabulates the results of the measurement uncertainties, which are below 5%, indicating a strong and reliable data measurement:

Table 4

Data uncertainties result.

Equipment	Unit	Error (%)
Data logger	°C	± 0.4 °C
Thermocouples	°C	± 1.3 °C
Solar pyranometer	W/m ²	± 2.5 %
Anemometer	m/s	± 0.65 %

3. Results and discussion

The result and discussion section are breakdown into two, which are Phase 1 Numerical analysis and Phase 2 Indoor Experiment. Phase 1 of the results discusses the flow behaviour of all four distinct geometries, which includes the velocity contour and streamline. In addition, the heat transfer behaviour is also discussed in this section involving the Nusselt number, the Reynolds number, and the temperature contour. Meanwhile, in Phase 2, a more in-depth discussion on the performance is made, which includes the energy performance and system evaluation, such as the exergy performance and performance evaluation criteria.

3.1. Phase 1: Numerical analysis

3.1.1. Flow behaviour

Based on the velocity contour in Fig. 7, it clearly indicates that the geometric parameters of the wavy jet plate have a significant impact on the impinging effects and air flow. The 60° equilateral wavy jet plate produces a symmetric velocity stream that demonstrates steady flow behaviour with minimal momentum and negligible transverse divergence. Thus, maintaining a uniform and recurring structure. The 45° isosceles, on the other hand, produces a sharper velocity gradient, which contributes to improving the mixing due to the jet deflection. One of the significant changes that have been noted is in the case of the 50-70° scalene wavy jet plate due to the geometric structure resulting in non-uniformity in terms of spacing, directionality, and even the non-uniformity in jet impingement homogeneity. As a result, this leads to an increase in acceleration and breakdown of wall-jet coherency. While turbulence formation is possible, this may affect the uniformity of thermal efficiency of the plate. In regard to the 30-60° right-angled plates, these have displayed a high amount of velocity contours in the

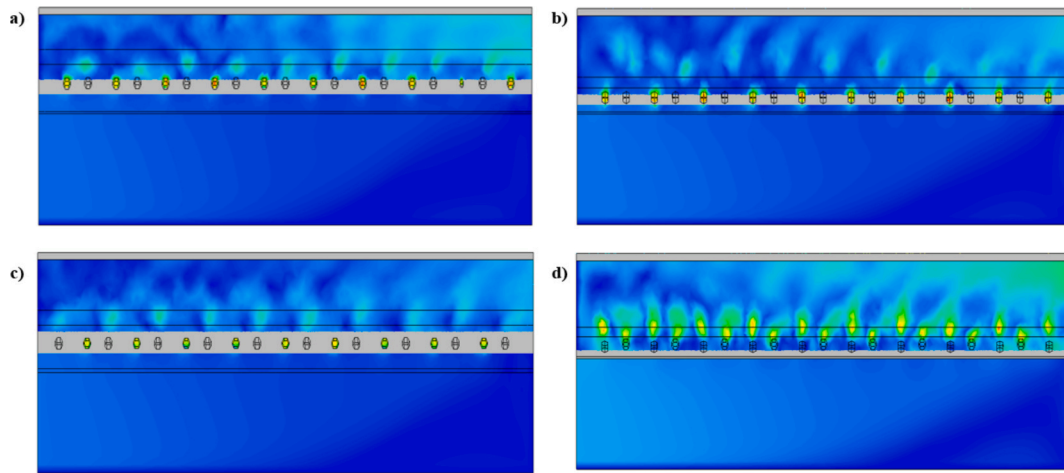


Fig. 7. Velocity contour of (a) Design 1: 60 deg equilateral wavy jet plate, (b) Design 2: 45 deg isosceles wavy jet plate, (c) Design 3: 50–70 deg scalene wavy jet plate, and (d) Design 4: 30–60 deg wavy right angle.

form of higher velocity cores and wider impingement areas. This implies that the jets will be penetrating deeper and thus losing less energy before impacting the surface target. This is probably because the geometric design has improved the ability of the jet in interacting with the other flow elements. The plates that consist of the 50–70° scalene and the 30–60° right-angle plates show increased turbulence, which is ideal for heat transfer in the PVT system. However, the 30–60° right-angled design seems better in balancing these needs.

Streamline flow behavior further explains the relationship between jet plate configuration and the flow behavior in the PVT collector, as shown in Fig. 8. For a 60-degree equilateral configuration, incoming flow enters the lower duct via a gradual streamline flow behavior, before exiting through the upper duct in a relatively structured jet path, with only low turbulence associated with the interaction, signifying jet momentum dominance. For the 45-degree isosceles, the lateral component is accentuated, leading to a larger vortex formation. As a result, there will be a high rate of entrainment of the fluid for efficient mixing. The 50-to-70-degree scalene jet plate configuration produces an unstable flow behavior, which results in turbulence but is likely to create more friction loss. For the 30-to-60-degree right-angle configuration (design 4), there is significant flow interaction behavior that results in jet impingement effects going deep into producing elongated streamwise motion behavior.

The improved thermal fluid performance noted in the case of the isosceles triangle at an angle of 45 degrees and the right-angled triangle at angles of 30 to 60 degrees is due to the combined effect of jet momentum, flow separation, and vortex formation. The angled surfaces result in acceleration of flow as well as the creation of pressure gradients when it flows across the wavy jet plate. The vortices created increase momentum transfer between the core of the high velocity jet and the near-wall fluid layer, leading to increased disruption of the thermal boundary layer. Thus, the local convective heat transfer coefficient will also rise because the fluid is continuously renewed and is cooler at the PV surface. On the contrary, in terms of geometry, the scalene angle of 50–70° is too asymmetric, thus generating asymmetric trajectories of the jet leading to a quick dissipation of its kinetic energy. As a result, the coherence of the jet is weakened prior to its impacting the plate surface, while the effect of disrupting the boundary layer is reduced. This fact can be explained by the more symmetric geometry of 60° and low turbulence intensity generated in that configuration, thus creating a stable jet. Based on the findings, one should note the dependence of the optimal geometry not only on the turbulence generation ability, but on maintaining coherent jet structure maximizing heat transfer and minimizing hydraulic losses.

Another way to analyze the results in question is to assess the vorticity and Q criterion distribution. Given the geometry of the wavy jet

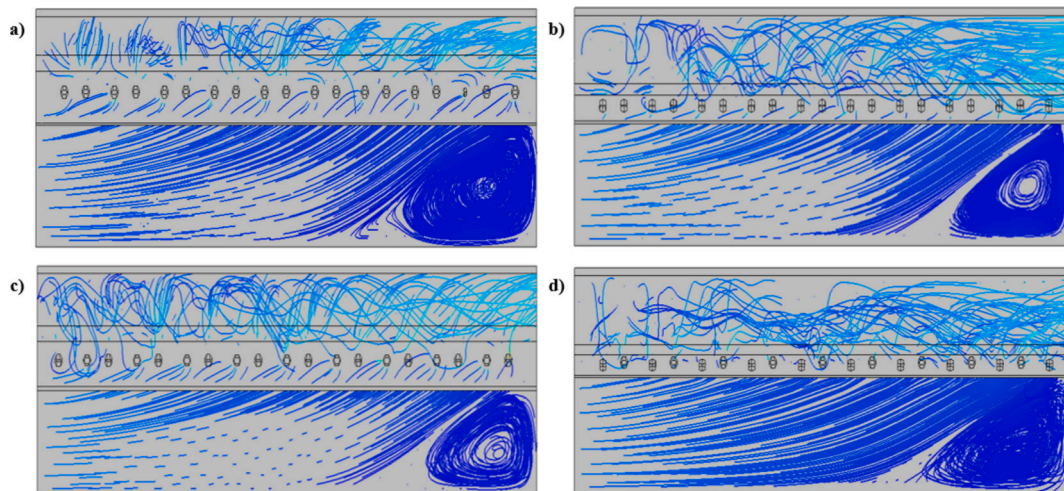


Fig. 8. Streamline of (a) Design 1: 60 deg equilateral wavy jet plate, (b) Design 2: 45 deg isosceles wavy jet plate, (c) Design 3: 50–70 deg scalene wavy jet plate, and (d) Design 4: 30–60 deg wavy right angle.

plate, the presence of the flow separation caused by the increasing velocity of airflow along the wave crest and meeting adverse pressure gradients in the vicinity of air descending segments, leads to flow separation and generation of vortex pairs downstream each wave fragment. The process of momentum exchange between the vortices and the core flow leads to carrying high-momentum fluid outwards the center of the jet and moving low-momentum near-wall fluid to the center. Thus, the mixing becomes intensified in the impingement area. In the case of the geometry characterized by the angles of 45° isosceles and 30-60° right-angle, the vortices formed are quite coherent and reach a considerable distance downstream. In terms of Q criterion, the vortex structures are clearly defined by the presence of the purely rotational regions relative to the strain rate, indicating their interaction with the wall jet. Consequently, the coherent vortical structures inhibit redevelopment of hydrodynamic and thermal boundary layers, promoting enhancement of heat transfer coefficient and wall shear stress. Contrarily, the vortices created at the scalene geometry are unstable due to asymmetric flow acceleration and trajectory of the jets. While turbulence intensity is higher, the vortices dissipate very fast, meaning that they do not affect the wall heat transfer process. At the same time, it should be noted that while there occurs the dissipation of the kinetic energy into turbulence, not all of it contributes to heat transfer enhancement.

3.1.2. Heat transfer

From Fig. 9, it is apparent that the variation between the Nusselt and Reynolds numbers demonstrates an enhancement in the effectiveness of convective heat transfer in line with increasing air flow for all wavy jet plates designs. The Nusselt number rises gradually from 2105 to 10672, indicating turbulent flows. This feature comes in handy, especially in the case of effective turbulence in thermal boundary layer deformation. For lower values of Reynolds numbers, the isosceles triangle angle of 45° and the right angles of 30-60° show greater Nusselt numbers than those from design 1. This shows that geometrical asymmetry is capable of encouraging earlier turbulence flow and mixing. The wavy jet plates with angles of 60° showed the greatest Nusselt number value of 16.36 at the maximum value of Reynolds number. Design 2 consistently demonstrates that its geometry achieves a balance between jet dispersion and turbulence creation. However, design 2 is marginally less effective at higher velocities than the equilateral design. In contrast, design 3 with the 50-70° scalene geometry produces the lowest Nusselt number due to uneven flow distribution and irregular vortex generation. Thus, reduces the localized heat transfer coefficient. Design 4 concludes that the flows formed are not as powerful and uniformly dispersed. Increasing the Nusselt number is caused by higher Reynolds stresses and lowering the viscous sublayer, which decreases heat resistance. Overall, the findings

indicate that all designs benefit from a higher Reynolds number. However, geometric symmetry and controlled impinging jet interaction are crucial in optimizing heat transfer performance in a jet impingement PVT system.

As the Reynolds number increases, the hydrodynamic and thermal boundary layer decreases, which causes the increase of the Nusselt number with Reynolds number, as inertial forces take over from viscous forces. The wall shear stresses and turbulent kinetic energy near the PV surface are higher at higher Reynolds numbers due to stronger momentum transfer from the impinging jets. This increases the amount of fluid entrainment and ensures that hot fluid near the wall is continually replaced by cold fresh air. However, the enhancement of the Nusselt number decreases slowly with the highest Reynolds numbers, indicating the approach to turbulence saturation. In such conditions, further increments in flow rate lead to only a marginal disruption of the boundary layer, but at the same time lead to further increases in the pressure loss. Thus, they experience low turbulence production gains for the thermal enhancement mechanism, leading to a performance plateau at high Re , as observed.

The relationship between the vortex dynamics and the development of the thermal boundary layer can further explain the observed heat transfer behaviour. For low and moderate Reynolds numbers, the wavy jet plate vortices reach far into the near-wall region and constantly sweep in cooler fluid to replace the heated fluid near the PV surface. In this way, the thickness of the thermal boundary layer is reduced, and the temperature gradient near the wall is enhanced, leading to higher Nusselt numbers. The generation of turbulent kinetic energy is significantly increased, and the strength of the vortex is increased as the Reynolds number increases. However, when the flow becomes sub-critical, the near-wall region tends to become fully turbulent with a very turbulent thermal boundary layer. In this scenario, further generation of vortices results in just a slight extension of the thinning of the boundary layer. Rather, a higher percentage of the kinetic energy provided is lost due to turbulent eddies and viscous interactions. This phenomenon is called turbulence saturation. The Q criterion and vorticity distributions suggest that the number of vortical structures remains greater at higher Reynolds numbers, but their role for effective wall heat transfer becomes increasingly smaller. However, in spite of the continued increase in flow velocity, the rate of increase in Nusselt number slows down. This behaviour accounts for the fact that the thermal performance improvements reduce at Reynolds numbers above about 8500, where the heat transfer enhancement is small, but the hydraulic penalty continues to increase.

The PV temperature contours, as shown in Fig. 10, clearly indicate the interaction of jet-induced convection and spatial variation of

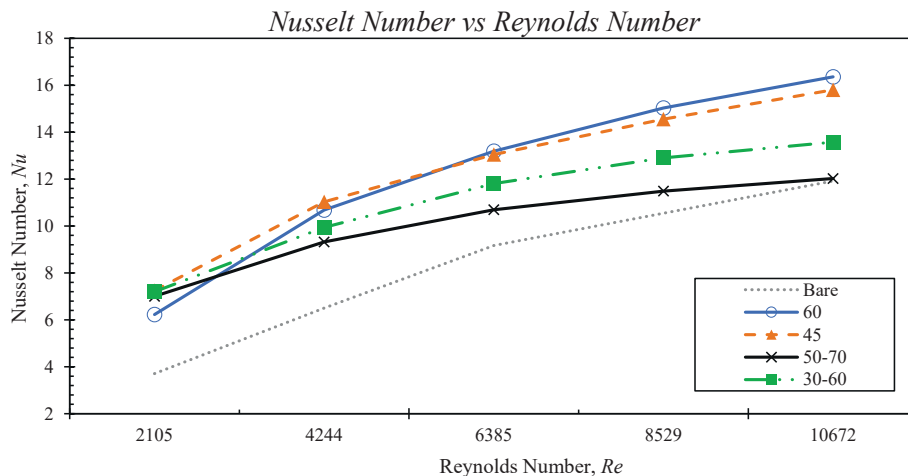


Fig. 9. Nusselt number vs Reynolds number of (a) Design 1: 60 deg equilateral wavy jet plate, (b) Design 2: 45 deg isosceles wavy jet plate, (c) Design 3: 50–70 deg scalene wavy jet plate, and (d) Design 4: 30–60 deg wavy right angle at 1000 W/m².

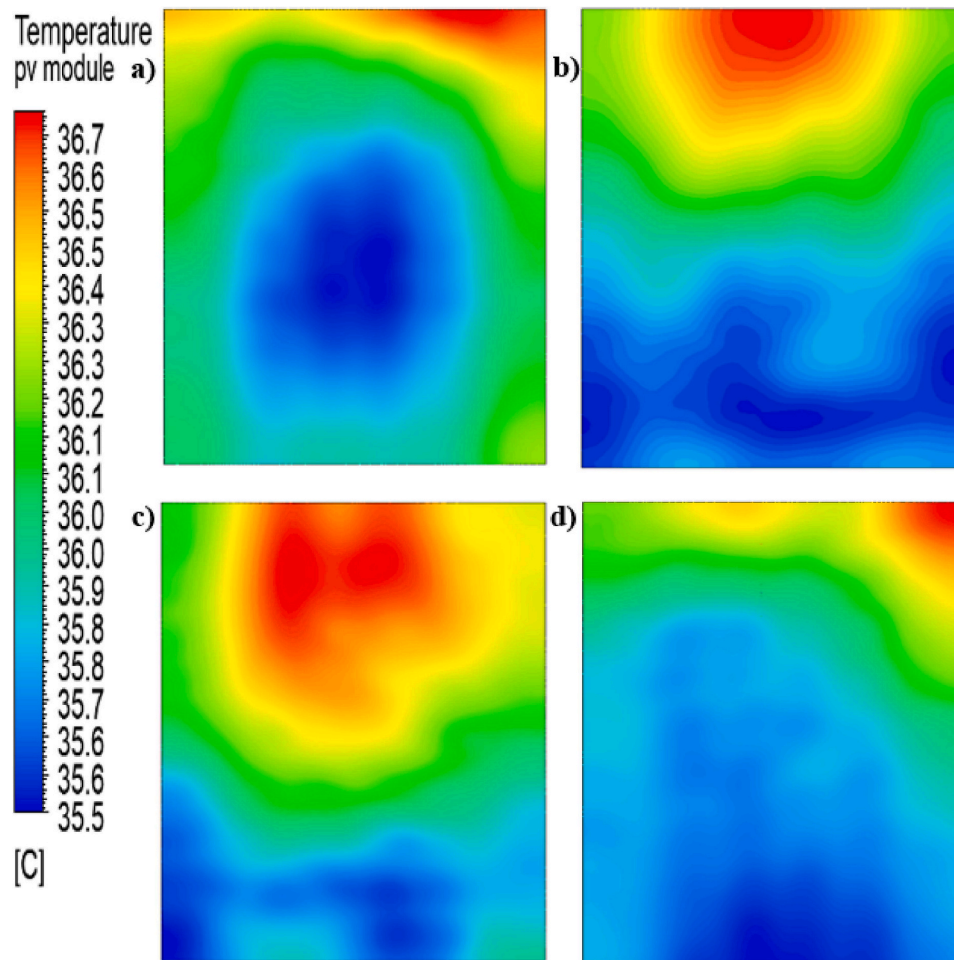


Fig. 10. PV temperature contour of (a) Design 1: 60 deg equilateral wavy jet plate, (b) Design 2: 45 deg isosceles wavy jet plate, (c) Design 3: 50–70 deg scalene wavy jet plate, and (d) Design 4: 30–60 deg wavy right angle at 1000 W/m^2 .

thermal boundary layer formation. The 60° equilateral has a fairly symmetrical cooling surface area with a noticeably low temperature core at the center point, indicated by the blue region. Effective jet impingement and localized thermal boundary layer deformation occur at the center of the PV module. However, the peripheral regions remain warmer, implying weaker lateral heat dispersion. The 45° isosceles has a

higher temperature gradient concentrated at the air outlet region. This results in a localized hot spot, but a higher outlet temperature can contribute to a more effective thermal efficiency. The $30\text{--}60^\circ$ right-angle design produces a more diffused contour with broader moderate temperature zones. Mixing and lateral heat distribution increase, but also significantly weaken regional cooling intensity due to distributed jet

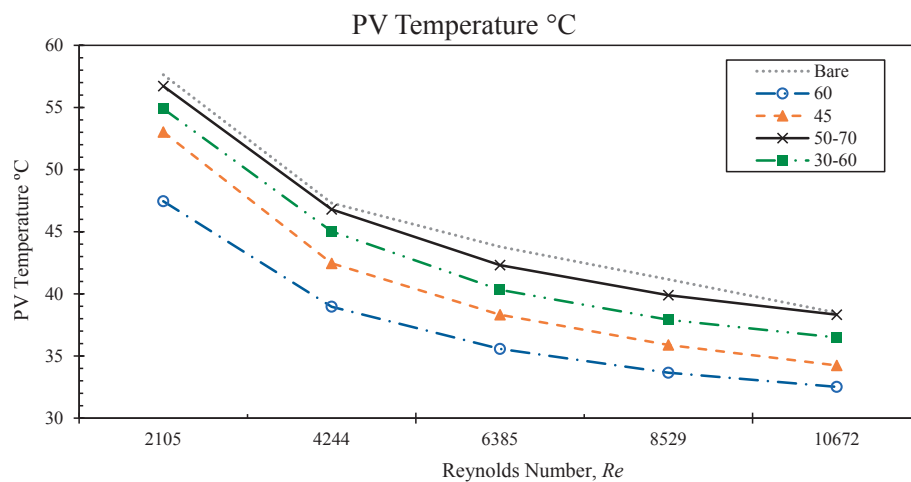


Fig. 11. PV Temperature vs Re of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m^2 .

motion. The most noticeable temperature gradient is observed by the 50-70° scalene design, where a large area of the PV module is covered by warmer temperatures. This leads to a higher operating temperature, thus reducing the efficiency of the PV. Overall, the PV temperature gradient is determined by the interaction of turbulent mixing and local Nusselt number enhancement.

3.2. Phase 2: Indoor experiment

3.2.1. Energy performance

The correlation of PV temperature with Reynolds number, shown in Fig. 11, displays a strong inverse correlation for all four wavy jet plate configurations. As the Reynolds number increases from 2105 to 10672, the PV temperature gradually drops for every design configuration. This is due to improved jet impingement effects and increased turbulent flow in the PVT system. Higher Reynolds numbers increase the jet impingement momentum and prevent the formation of a thermal boundary layer. The convective heat transfer coefficient helps to extract more heat from the PV module. Design 1, a 60° equilateral wavy jet plate, produces the lowest PV temperature compared to the other designs for the entire Reynolds number range. The highest temperature recorded by the 60° equilateral was peaking at 32-33°C. The high heat management performance is most likely due to its geometrical symmetry, which promotes an equal jet distribution and balanced air flow pattern. In contrast, design 3, 50-70° scalene wavy jet produces the highest temperature, which shows an ineffective flow homogeneity and weak impingement. This results in localized stagnation zones and lower heat transfer efficiency. Designs 2 and 4 show a recorded more intermediate PV temperature, which indicates some improvement in flow mixing, but not as optimized as design 1. From the graph shown in Fig. 11, it can be observed that the temperature decreases as the Reynolds number increases. This means that the turbulent state has attained thermal stability to a point where further turbulence generation makes no substantial difference. This phenomenon is prevalent in a case where there is a jet impingement, which involves thermal boundary layer disruption. On the whole, these findings show how the geometry of the wavy jet plate is very important at moderate Reynolds numbers. On the other hand, high flow rate leads to dominance of turbulence convection in the fluid system.

The PV efficiency trend for all wavy jet plate geometries shows a positive relationship with the Reynolds number, as shown in Fig. 12. As the Reynold number increases, the efficiency continuously improves from 12.4% to 13.00% at low Reynolds and ranges between 13.6% and 14.00% at higher Reynolds numbers. This improvement is primarily

driven by the reduction in PV temperature as indicated in Fig. 11. Reducing the operating temperature mitigates thermal-induced bandgap and reduces intrinsic semiconductor losses. In PV systems, lowering the operating temperature can yield considerable efficiency gains, typically ranging from -0.3% to -0.5% per Celsius. The PV efficiency is closely related to the PV temperature. Based on the PV temperature, design 1 yields the lowest PV temperature. Thus, as evidenced in Fig. 12, design 1 produces the highest PV efficiency compared to the other geometric designs. The uniform jet impingement and well-balanced vortical structure created by the 60° equilateral wavy design contribute to a homogenous temperature distribution over the PV surface. Local hotspot which can adversely reduce performance are reduced by this design. Design 3, on the other hand, consistently recorded the lowest efficiency values due to its high thermal resistance and less effective flow distribution. In addition, resulting in the weakest heat transfer rate and the highest recombination losses. Interestingly, the efficiency curves exhibit a narrowing gradient at higher Reynolds numbers and diminishing electrical efficiency improvement. This implies that the PV module approaches a thermal equilibrium at a certain threshold. Thereby, enhancing convective heat transfer provides no extra benefits. Overall, the findings significantly support the efficiency of wavy jet plate geometry optimization in improving jet impingement PVT system performance.

Meanwhile, the outline temperature declines monotonically as the Reynolds number increases for all configurations, as demonstrated in Fig. 13. Convective heat transfer increases due to stronger impinging effects and deformation of the thermal boundary layer. At Reynolds number 2100, design 1 recorded the highest outlet temperature due to weaker mixing and low turbulence at the impinging surface target. However, for the remaining designs, 2, 3, and 4 show an identical outlet temperature. Asymmetrical geometries and sharper angle fluctuations encourage faster transition to turbulence and stronger jet disintegration. As Re approaches 6400, the temperature gap narrows, implying that inertial force begins to dominate over geometric effects. However, design 1 outperforms compared to the other design due to its uniform wave structure and angle design, which causes less flow redirection and weaker vortices. Overall, the findings suggest that incorporating geometric non-uniformity in the wavy jet plate is advantageous at low to moderate Reynolds numbers. However, at a higher Reynolds number, the system becomes hydrodynamically dominated.

From the data depicted in Fig. 14, it is evident that there is a strong positive influence of thermal efficiency on Reynolds number in all cases. For example, in Design 1 (60° equilateral), efficiency is the lowest at about 38% and at a low Reynolds number of about 2100. There is poor

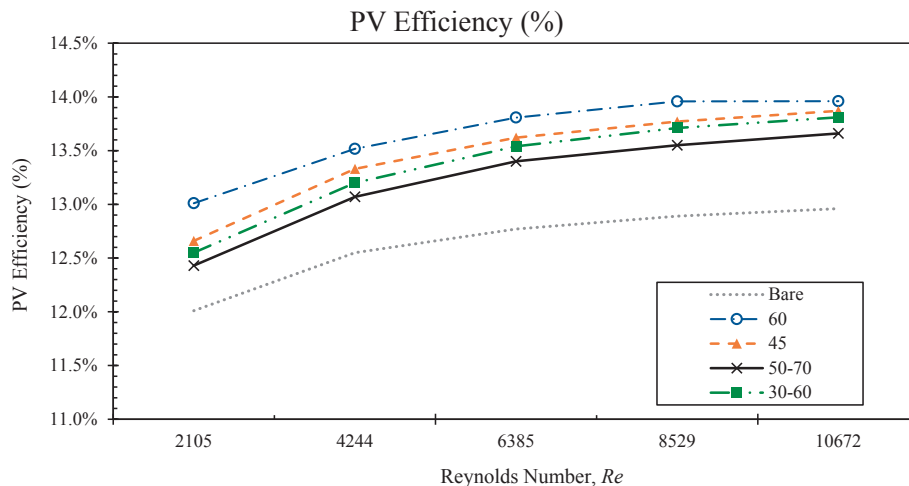


Fig. 12. PV efficiency vs Re of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50-70 deg scalene wavy jet plate, and Design 4: 30-60 deg wavy right angle at 1000 W/m².

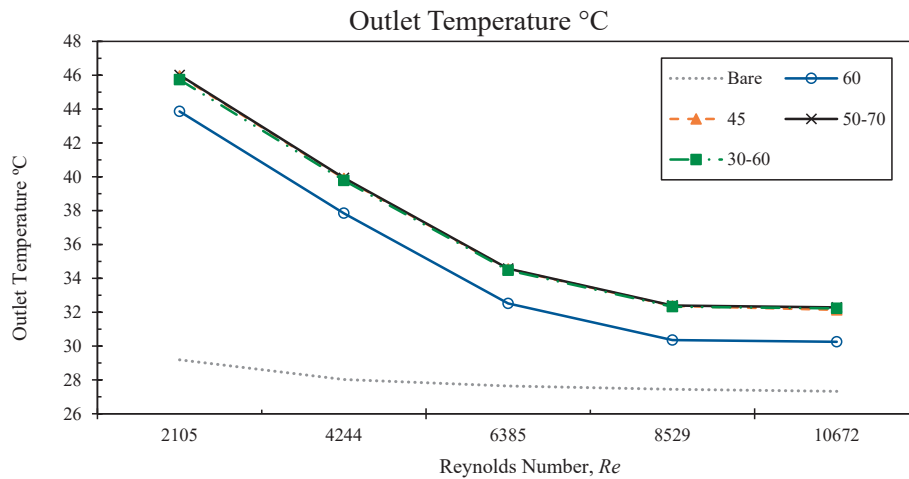


Fig. 13. Outlet temp vs Re of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m^2 .

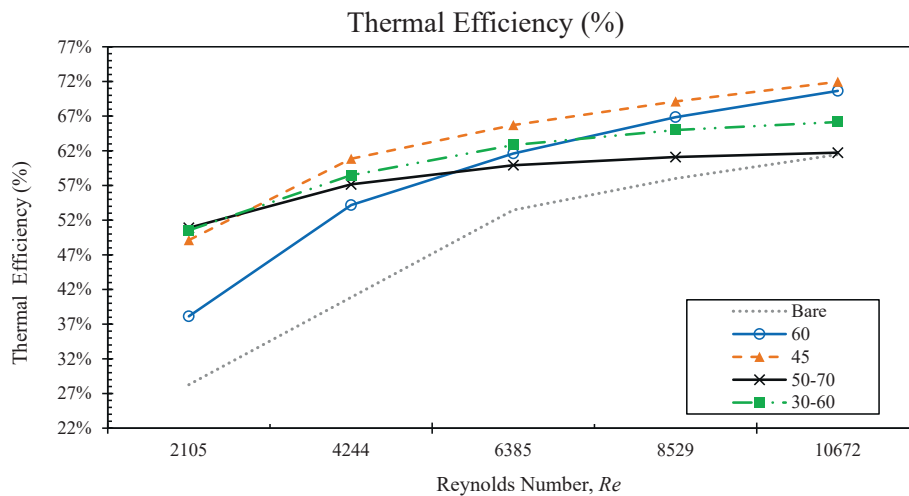


Fig. 14. Thermal efficiency vs Re of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m^2 .

development of turbulence as well as poor jet surface interaction leading to thermal boundary layer formation and heat extraction. On the other hand, at the same Reynolds number 2100, the thermal efficiency in designs 2, 3, and 4 are almost 50%. Therefore, it is evident that asymmetric and irregular geometrical forms promote instabilities in the flows, improving heat transfer and air flow mixing. In addition, Reynolds numbers increasing from 4200 to 6400 enhance inertia effects promoting jet core penetration, wall shear stress and boundary layer deformations. These results lead to a marked increase in thermal efficiencies across all geometrical forms. Specifically, design 2 with 45° isosceles has higher efficiency than other forms at Reynolds 6400 reaching about 66%. This is attributed to a favorable compromise between flow redirection and pressure losses in 45 isosceles geometries that probably create vortices that maintain thermal efficiency without energy losses. However, Reynolds above 8500 exhibit no additional gains in thermal efficiency for Designs 3 and 4, implying less turbulent behavior. This leads to saturation in turbulence intensity and thermal boundary layer destruction. Scalene design 3 performs poorly since flow segregations occur. Overall, the findings show that higher Reynolds numbers benefit all designs, particularly moderate asymmetry. Geometrical optimization is critical for improving thermal efficiency in the transitional flow regime.

The trend of the thermal efficiency also shows the competition

between the enhancement of heat transfer and the saturation of turbulence. For moderate Reynolds numbers, the coherent vortex structures created by the wavy geometries enhance the mixing between the fluid and increase the ability of the working fluid to carry thermal energy from the PV surface to the working fluid. The enhanced rate of heat extraction is directly contributing to the increase in thermal efficiency that has been observed. Once in the fully turbulent regime, however, the gains of adding more turbulence become increasingly smaller. The boundary layer is already highly disturbed, and further increases in flow intensity primarily result in higher losses, but not higher useful heat recovery. Despite the increased production of stronger vortices, the time of their existence in the vicinity of the heated surface is reduced due to the greater flow speed. Therefore, the interaction time for heat exchange is reduced. This decrease in the thermal contact time partly compensates for the improvement in mixing and results in the plateau behaviour for a number of configurations at high Reynolds numbers. Based on the results, it is concluded that balancing the generation of vortex and disruption of the boundary layer and residence time of fluid is necessary to achieve optimum performance, instead of optimizing them separately.

Although the Nusselt number (Nu), thermal efficiency, and PV efficiency are thermally coupled parameters, their optimal values do not necessarily occur under the same operating condition. The Nusselt

number is the intensity of convective heat transfer at the absorber-fluid interface, which is mainly dependent on the disruption of the boundary layer and the turbulence generation. A greater Nu means a better local heat transfer, but the heat transfer efficiency is determined by the total amount of useful heat recovered by the working fluid and not just the heat transfer coefficient locally. In the present study, those configurations of the wavy jet plates that produced strong turbulence and the highest Nu values were accomplished with strong mixing and impingement. However, if turbulent flow is excessive, it can also cause flow to recirculate, pressure losses, and flow non-uniformity that would affect the efficiency of heat removal from the entire absorber surface. Therefore, the maximum Nu may not necessarily be the most efficient thermal configuration. Heat transfer enhancement, flow distribution uniformity, residence time, and overall energy recovery, however, are instead combined to determine the thermal efficiency. Likewise, the average cell operating temperature has a major influence on PV efficiency. As the Nu increases, the cooling effect also increases, and the PV temperature decreases, but when there are some hot areas where the heat transfer is high, they do not always correspond to the lowest average PV temperature. Even if the peak Nu for a particular configuration is not as high as that of other configurations, the configuration that produces a more uniform distribution across the PV surface can make better electrical performance. Therefore, the optimum performance of the system is not achieved by maximizing Nu alone but is a compromise between the heat transfer enhancement, thermal energy recovery, and PV temperature regulation. Thus, the relationship

between Nu , thermal efficiency, and PV efficiency is not linear.

3.2.2. System evaluation

The relationship between thermal energy and Reynolds number in Fig. 15 shows how jet plate geometries enhance convective heat transfer in the jet impingement PVT system. At low Reynolds number, Design1 60° equilateral obtained the lowest thermal energy due to the relatively uniform and weak jet impinging effect. At this point, the turbulence is not fully developed, which limits turbulence intensity and near-wall mixing. However, as the Reynolds number increases, design 1 displays the steepest enhancement, which shows that its symmetric shape is effective in creating coherent jet formations and improved boundary layer breakdown at higher flow inertia. In the case of design 2 45° isosceles, the maximum value of thermal energy is achieved, outperforming others. It is explained by the presence of asymmetry that leads to a better generation of secondary flow structures. The design 4 30-60° right follows the same trend as design 2, however, with a bit lower efficiency level, probably due to poor flow distribution and uniformity of the impingement process. On the contrary, design 3 50-70° scalene exhibits the lowest thermal energy among all designs considered at any Reynolds number. Inappropriate geometry contributes to the separation of flow and early energy dissipation. The aforementioned behaviour is associated with the growing importance of the inertial force over the viscous one. It means more jet impinging effects, turbulence generation, and boundary layer breakdown. Thus, the overall combination of factors is such that design 2 can be regarded as the most

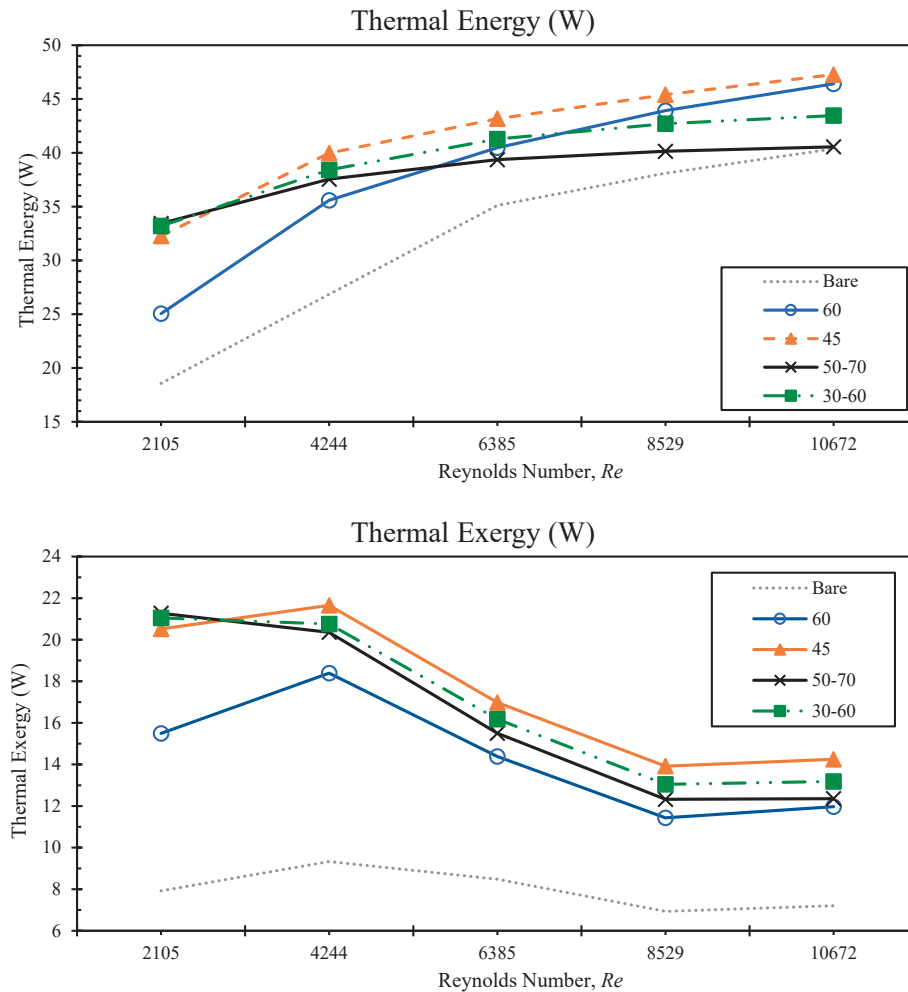


Fig. 15. Thermal energy and thermal exergy of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m².

efficient configuration concerning flow acceleration and turbulence production.

Furthermore, the dependence of thermal exergy on the Reynolds number is different among all configurations considered. Thermal exergy mainly depends on flow intensity and impingement characteristics. Configurations with the highest exergy are designs 2 and 4, with its values changing from 20.52 W to 22.45 W at the lowest value of the Reynolds number (2105). It suggests that effective thermal energy usage is ensured by efficient impinging and sufficient amount of heat transfer during the operation period. Design 1 demonstrates worse results, thus implying that the usage of 60° equilateral design could be rather ineffective. When the Reynolds number increases to 4242, then each design exhibits its maximum performance and reaches the peak of thermal exergy, and for design 2 45° isosceles it equals 21.65 W. That means that the combination of proper jet velocity and impingement process leads to high levels of turbulence and boundary layer breakdown enhancing convection and minimizing the influence of flow bypassing. For further increase in Reynolds number, all configurations exhibit a decreasing level of thermal exergy. Overall, designs 3 and 4 have a higher exergy than design 1 at higher Reynolds numbers, which proves that asymmetric and right-angle wave designs provide better mixing and prolonged impingement efficiency at higher flow circumstances. This pattern represents the conventional trade-off between convective improvement and thermal residence time. Higher Reynolds numbers

result in entropy creation and exergy destruction. Overall, design 2 outperforms most situations, proving that mild geometric asymmetry combined with controlled jet deflection can result in the most efficient thermodynamic configuration for PVT systems.

Meanwhile, the trend in electrical energy demonstrates a close correlation between hydrodynamic cooling and photovoltaic performance. As the Reynolds number grows from 2105 to 10672, the electrical output increases gradually for all configurations, as shown in Fig. 16. This indicates an improvement in the convective heat transfer at high flow rate. As the impinging effects become greater, the local heat transfer coefficient improves, resulting in a temperature reduction and reduced bandgap narrowing. This enhances the open circuit voltage and the efficiency of electricity. Design 1 achieves the highest electrical energy despite its lower thermal efficiency. This indicates that the equilateral 60° angle allows even distribution of cooling over the PV surface. Decreasing the hot spots improves electrical generation too. Designs 2 and 4 show similar levels of efficiency, but low electrical generation. Such results can be attributed to uneven flow distribution and pressure losses which inhibit even distribution of cooling on the PV surface. Another important finding is a staggered increase in electrical energy at high Reynolds numbers due to asymptotic properties. Further increases in flow intensity will not generate significant improvements in cooling because of turbulent flow and low thermal gradients. Beyond a certain point, increased energy input for cooling becomes greater than

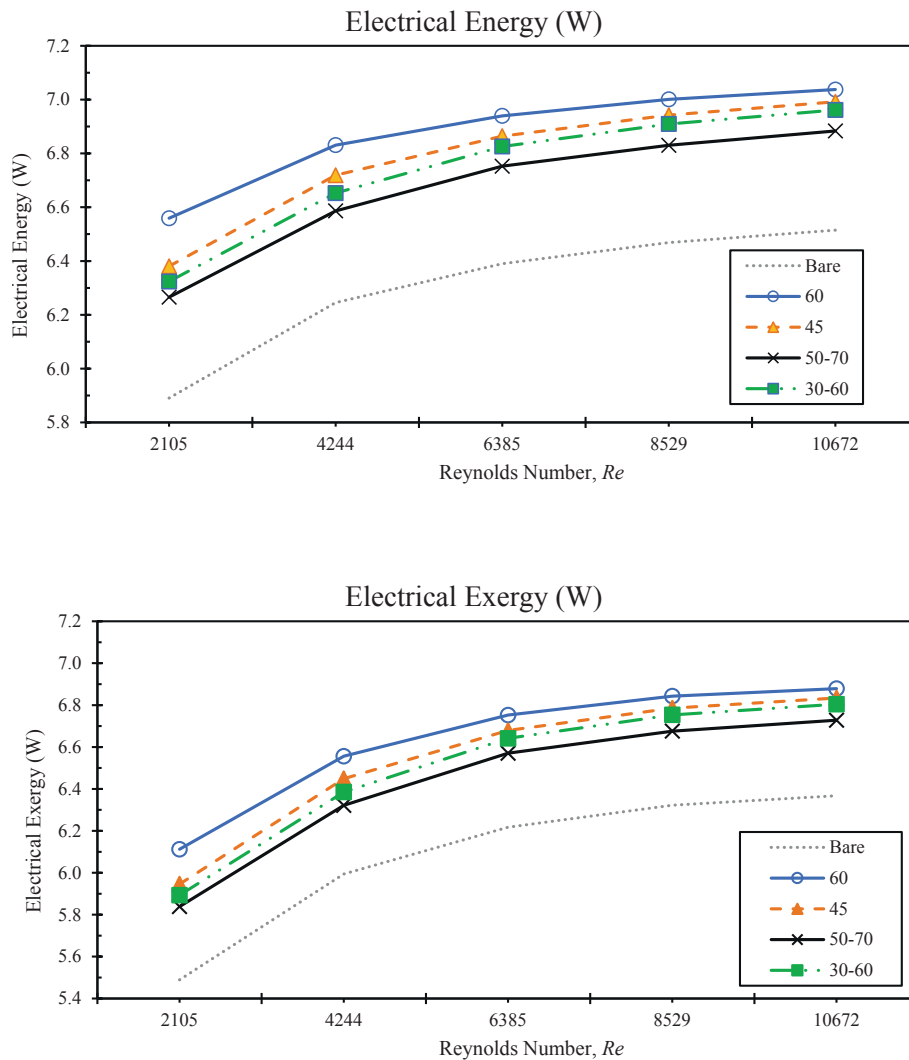


Fig. 16. Electrical energy and electrical exergy of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m².

accumulated electrical energy. Therefore, the conclusions made from such results indicate the need to optimize jet geometry for an even distribution of cooling over the PV surface in order to achieve improved electrical energy generation.

Electrical exergy demonstrates a similar pattern to that of electrical energy. Electrical exergy is the measure of energy produced, which can bring some useful work. According to the results, all designs achieve an increasing trend in electrical exergy, resulting from better geometries of jet plates as compared to the conventional flat jet plate design. Besides, the improvements of jet impingement cooling also contribute to a higher quality of electricity generated. Lower PV temperature will enhance voltage while reducing any waste. Design 1 yields the highest amount of electrical exergy compared to other designs, which means the 60° equilateral wavy jet plate ensures effective thermal control which leads to a higher level of electrical exergy. Even surface temperature and minimal entropy are necessary for ensuring a better quality of electrical exergy, since it is highly vulnerable to temperatures. The third design achieves low levels of electrical exergy. Poor distribution of flows and high heat gradients impair electricity generation. Like electrical energy, the rate of exergy increase slows down with the increase of the Reynolds number. In addition, excessive Reynolds numbers would result in larger pumping losses and minimal exergy gains. Overall, the findings show that good thermal management obtained by optimizing the jet geometry can improve the PVT system's beneficial electrical energy.

The variation of overall PVT efficiency with Reynolds number in Fig. 17 demonstrates a clear dependency on jet hydrodynamics and surface geometry induced by the wavy jet plate configurations. All design exhibits relatively modest efficiency at Reynolds number 2105. At low Reynolds number, design 1 60° equilateral) displayed the poorest PVT efficiency as decreased jet momentum and restricted turbulence formation limited convective heat transfer. As the Reynolds number increases, a notable improvement is found in all configurations. This is because the nature of the impinging flow becomes more turbulent, thus causing mixing and improving heat transfer with no boundary layer formation. Design 2 45° isosceles gives the highest and maximum efficiency level at a Reynolds number of about 10,672 when compared with other designs. It means that its geometry shape helps promote vortex creation, making the process of impinging flow improve heat transfer without losing good flow pattern. Design 4 30-60° right comes next by proving that the asymmetry of wave angles still creates effective secondary flow and turbulence generation. On the contrary, design 3 50-70° scalene becomes the poorest due to poor flow pattern and higher pressure losses created by irregular impinging flow pattern. The

efficiency of PVT efficiency at higher Reynolds number shows that the forces of inertia slowly overpower geometrical factors. With high efficiency, design 2 predicts a continued lead in maintaining the balance between turbulence generation and hydraulic friction. Therefore, from the results obtained, it has been found that optimizing wavy jet plate geometry has a major impact on the behavior of thermos fluid.

The variation of friction factor and pressure drop with respect to the Reynolds number for the plain channel as well as for all four wave jet plates is illustrated in Fig. 18. The performance of all the designs in terms of their hydraulic properties is plotted to facilitate comparison between pressure losses due to different geometries. Generally, all four designs show similar hydraulic behavior where the increase in Reynolds number results in decrease in friction factor and increase in pressure drop. The friction factor for the flow increases with the increase in Reynolds number from 1.23×10^{-2} at a Reynolds number of 2105 to 8.18×10^{-3} at a Reynolds number of 10672; the higher value of friction factor signifies increasing importance of inertia over viscosity in the flow field. With increase in Reynolds number, the significance of wall shear stress reduces as far as momentum equation is concerned, and hence smaller friction factor is observed despite higher velocities. Conversely, a significant increase in Reynolds number occurs with pressure drop from around 0.58 Pa at $Re = 2105$ to 9.65 Pa at $Re = 10672$. This trend is expected since inertia and pressure drop depend strongly on the flow velocity. The differences in friction factor and in pressure drop between the four geometries are relatively small, although the wavy jet plates increase the flow acceleration, the development of vortices, and flow recirculation in the vicinity of the jet plate. This is due to the fact that the overall dimensions, flow passage area, jet opening ratio, and the hydraulic diameter have the same value for all configurations, and only the wave angle is changed. The overall hydraulic resistance is therefore determined mostly by the local geometric changes and the bulk flow characteristics. The slight variations in the geometries that were observed are due to the variation in the intensity of the flow separation, vortex creation, and secondary flow structures created by each of the wave shapes. The effects, however, are confined to a small region and play an insignificant role in the overall pressure drop. The two curves of the friction factor and pressure drop almost overlap, suggesting that the change in wave angle has a small effect on the overall system hydraulic resistance.

Fig. 19 illustrates the PEC trend of design configuration that evaluates the thermohydraulic performance by considering heat transfer improvement and pressure drop penalty at the same time. It can be noted that the PEC value tends to decline along with Reynolds number in

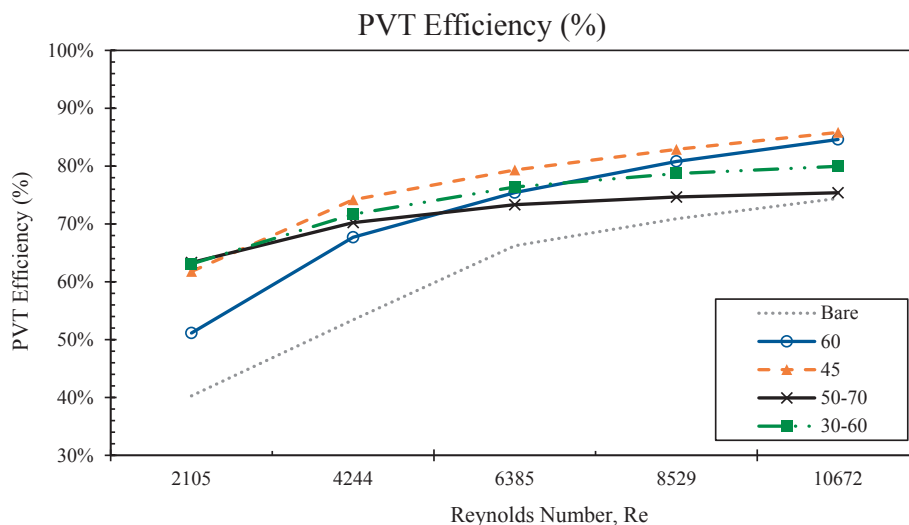


Fig. 17. Total PVT efficiency of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50-70 deg scalene wavy jet plate, and Design 4: 30-60 deg wavy right angle at 1000 W/m^2 .

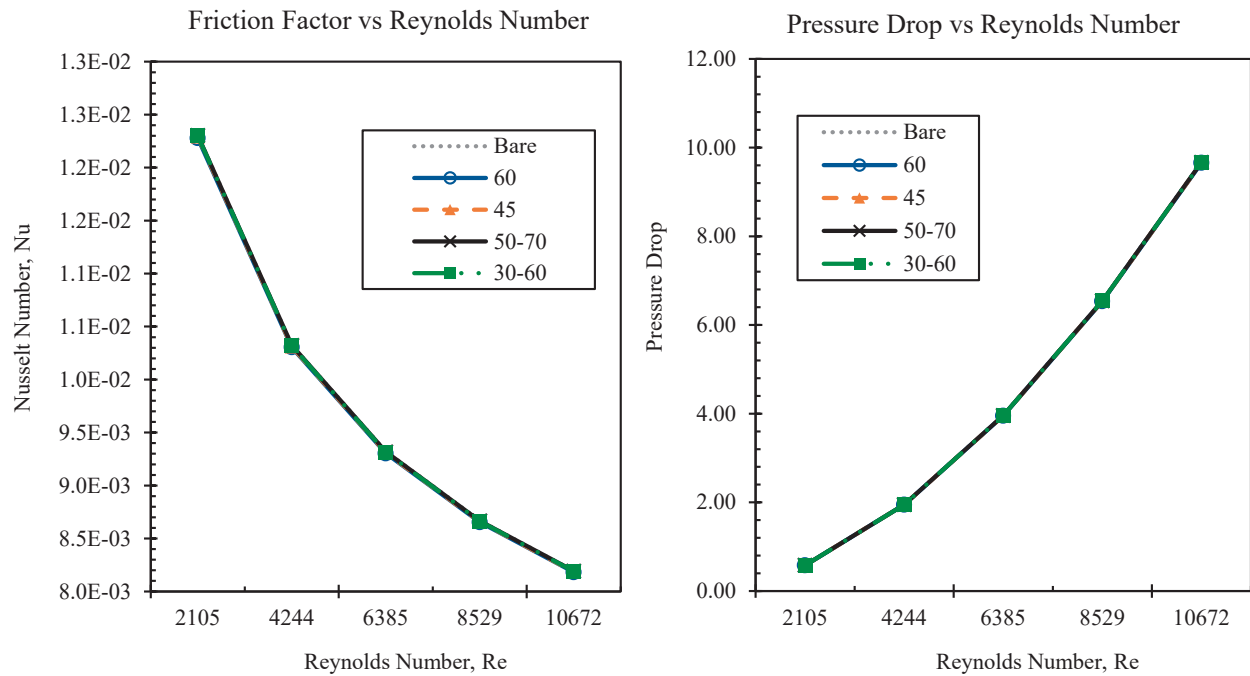


Fig. 18. Friction factor and pressure drop of wavy jet plate at 1000 W/m².

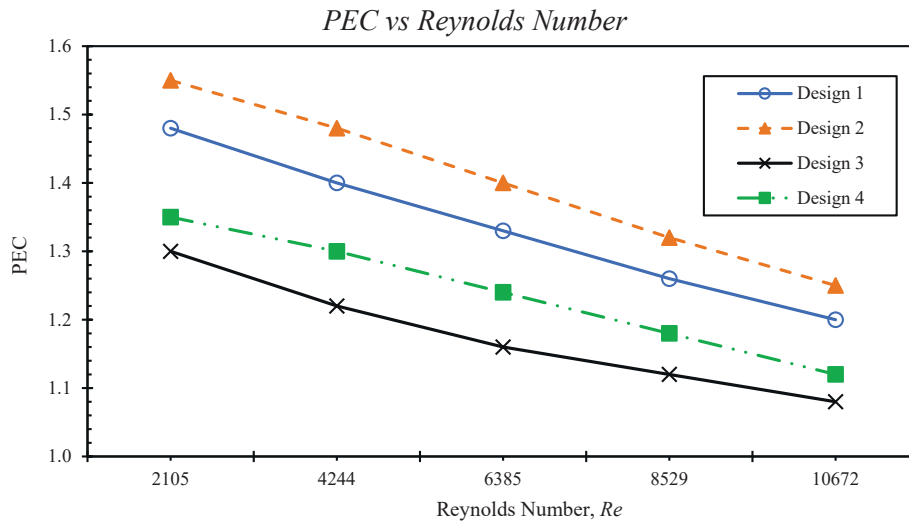


Fig. 19. PEC vs Re of Design 1: 60 deg equilateral wavy jet plate, Design 2: 45 deg isosceles wavy jet plate, Design 3: 50–70 deg scalene wavy jet plate, and Design 4: 30–60 deg wavy right angle at 1000 W/m².

every case. Since high Reynolds number increases heat transfer, friction factor will rise. Thus, the pumping power is crucial when evaluating PEC of heat exchanger. For Reynolds number of 2105, design 2 achieves the maximum value for PEC, i.e. 1.55. This value implies that there is an effective balance between induced turbulence and pressure drop. The vortex formation and jet impingement effects of design 2 are consistent while the flow resistance is minimal. The next configuration is design 1, which obtains the maximum benefit from the symmetric wave as it enhances mixing effect. However, designs 3 and 5 have low PEC because of inadequate turbulence development. More specifically, design 3 has minimum value of PEC since its angular shape causes additional pressure drop effect. Right angle variation of design 4 still provides moderate performance. Overall, design 2 dominates over the Reynolds range, showing that geometric uniformity combined with an ideal orientation angle improves boundary layer breakdown while limiting entropy formation owing to excessive pressure losses. In a nutshell, the findings

suggest that maximizing heat transfer is insufficient. An ideal trade-off between thermal augmentation and pumping power is required to ensure a practical and energy-efficient PVT system.

It should be noted that the present investigation was conducted under controlled indoor conditions to isolate the influence of wavy jet plate geometries on the thermo-fluid performance of the jet impingement PVT system. In real operating conditions, all the above factors are not constant, but variable, and may affect the thermal and electrical performance of the system when compared with outdoor conditions. However, the main goal of the indoor experimental rig was to have a repeatable comparison among the different jet plate configurations investigated and to have a consistent thermal boundary condition. The mechanisms of heat transfer found in this work, such as disruption of the boundary layer, increased turbulence production, creation of secondary flow, and increased convective heat transfer, are all of fundamental origin and independent of whether the system is installed indoors or

outdoors. Hence, the relative performance trends observed for the various wavy jet plate designs are likely also to be valid in practical operating conditions. The absolute values of the Nusselt number, thermal efficiency, and PV efficiency can change with the environmental changes under outdoor operation, but the excellent thermo-fluid performance of the optimized wavy jet plate configurations is expected to yield similar advantages. To validate the durability, thermal stability, and energy performance of the proposed design for year-round use, future studies should be directed towards long-term outdoor tests in different meteorological conditions.

4. Conclusion

The present research presents a comprehensive analysis of how the geometry angles of the wavy jet plate influence the thermos fluid performance of a jet impingement photovoltaic thermal (PVT) system. CFD simulation was used to simulate the flow behaviour and heat transfer with each of the geometries, while an indoor experiment was conducted to analyse the energy performance and system evaluation, including exergy performance, friction factor, pressure drop, and performance evaluation criteria. The findings support the assumption that altering the jet plate geometry, rather than a typical flat jet plate, can influence the flow behaviour, turbulence intensity, and heat transfer characteristics. The 45° isosceles wavy jet plate demonstrated the most balanced operating performance compared to the other design configuration, with an overall PVT efficiency of 86%. In contrast, the 60° equilateral design exhibits the highest electrical efficiency due to its uniform cooling distribution. Additionally, the findings reveal that a higher Reynolds number improves the system efficiency and convective heat transfer. However, at higher flow causes the turbulence starts saturating and the pumping penalties increase. The results also highlight how minimal geometry asymmetry promotes optimal boundary layer disturbance and vortex generation without producing excessive hydraulic losses. The novelty of this study emphasized jet plate geometries as a crucial design element. Previous study utilizes conventional flat jet plate, which has not taken into account the effects of the jet plate geometry, which could affect the jet impingement performance. This work demonstrates that the geometry of the jet plate can be modified to actively control jet formation and turbulence development, rather than focusing on the enhancement of the absorber surface or optimization of the operating parameters, which is the approach taken in previous PVT studies that investigated the jet impingement effect. This adds a new design routing to enhance thermo-fluid performance while maintaining the same absorber routing. This paper provides a fresh perspective on flow modification techniques for enhancing the PVT system using the jet impingement method. Overall, the study offers a useful insight into jet impingement jet plate geometries for achieving the optimum and balanced performance between pressure drop and heat transfer. The main findings can be summarized as follows:

- The wavy jet plate geometry significantly influences turbulence, flow distribution, and heat transfer performance.
- 45° isosceles design achieved the highest overall PVT efficiency of 86% due to an optimal balance between turbulence intensity and air flow.
- 60° equilateral design provides the electrical performance due to uniform cooling and minimized thermal gradient.
- Thermal and electrical performance improved with higher Reynolds number but plateaued at higher values.
- Excessive geometries, such as 50–70° Scalene design, reduced overall performance due to flow instability and non-uniform jet impingement.
- Wavy jet plate geometry helps to alter jet coherence, vortex formation, and prevent boundary layer formation.

CRediT authorship contribution statement

Muhammad Amir Aziat Ishak: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adnan Ibrahim:** Supervision, Project administration, Funding acquisition, Conceptualization. **Khaled M. Al-Arabe:** Writing – review & editing, Methodology, Conceptualization. **Zikrul Hakiem:** Writing – review & editing, Validation, Data curation. **Muhammad Aqil Afham Rahmat:** Validation, Methodology, Formal analysis. **Yassine El Alami:** Writing – review & editing, Validation, Data curation. **Ahmad Fazlizan:** Validation, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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