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U-turn Shape Effect on Effective Thermal Conductivity of Double Pass Photovoltaic Thermal (PVT) Systems Configuration

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ABSTRACT

This study explores the thermal performance of double-pass photovoltaic thermal (PVT) systems by investigating the influence of turn shape on heat transfer characteristics using computational fluid dynamics (CFD) simulations. The aim is to evaluate various turn shapes, including half-circle, triangle, half-hexagon, half-octagon, and box, to determine their impact on turbulent intensity, effective thermal conductivity, and outlet temperature in PVT systems. The investigation reveals significant variations in heat transfer efficiency among the different turn shapes, with the triangle-shaped turn demonstrating superior performance across multiple parameters. The findings highlight that the triangle-shaped turn exhibits enhanced turbulence generation and heat exchange efficiency compared to other shapes. Specifically, the triangle-shaped turn achieves a maximum turbulent intensity of approximately 70%, surpassing other shapes which achieve around 60%. Moreover, the triangle-shaped turn displays a longer and more substantial area of high heat exchange, resulting in an effective thermal conductivity improvement of up to 20% compared to alternative shapes. Furthermore, the analysis indicates that the triangle-shaped turn exhibits a faster increase in outlet temperature, reaching steady-state conditions within 15 seconds, while other shapes require up to 19 seconds. These results underscore the significance of turn shape in optimizing the thermal efficiency of PVT systems.

1. Introduction

The depletion of fossil fuel supplies has become the next major global issue, after the increased need for energy. One strategy to lessen the effects of the global energy crisis is to employ renewable energy sources and create pertinent technologies [1]. One sustainable and eco-friendly renewable

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energy source is solar energy [2]. Because solar cells can directly convert solar energy into electrical energy, solar energy can be used to generate electricity [3]. Additionally, PV technology is the most reliable energy source and is suited for commercialization, claim [4]. Nevertheless, because PV technology's efficiency drops as operating temperature rises, [5] argue that the technology's possible application in hot climates cannot be maximized [6]. As a result, numerous researchers are attempting to cool solar panels using various efficient methods [7].

Studies on photovoltaic thermal (PVT) have been conducted since the 1970s [8]. In order to generate heat energy and electrical energy simultaneously [9, 10], this system blends a thermal collector with a PV panel. The installation rate is lowered from two to one when comparing self-deployed PV and PV-T systems, greatly lowering expenses [11]. Furthermore, PVT systems becoming more economical when PV panel costs decline [12].

To determine the efficiency and characteristics of PVT, researchers have carried out simulation tests on a laboratory scale and directly in real-world conditions. Hasan *et al.,* [13] used CFD to analyze the impact of using nanofluid concentration photovoltaic thermal (CPVT). CFD can also be used to validate experimental results [14]. Zohri *et al.,* [15] This research applies an experimental approach in the laboratory and outdoors. The higher the mass flow rate used, the higher the sustainability index. Mustafa *et al.,* [16] conducted tests with the help of a solar simulator and found that the use of fiberglass collectors could produce a total PVT efficiency of 82.68%. Muna Ali Talib *et al.,* [17] discovered that the efficiency of the current panel under investigation dramatically increased in a simulation utilizing water fluid.

Researchers are still working to improve the PVT system to boost its effectiveness. Making the design novel, including the collector design [18-20], was one of the actions carried out that also investigated the influence of each PVT component on its efficiency [21]. Numerous collector types have seen innovation as a result of collector design optimization, including the groove collector [22, 23] and the compound parabolic collector (CPC) [24]. In addition to collectors, researchers started experimenting with different fluids. Initially, water [25, 26] and air [27] were the fluids employed in PV systems. Furthermore, the use of phase change materials (PCM) is increasingly in demand, and research on mathematical models to assess the transient processes of a hybrid photovoltaic thermal solar system with phase change materials in comparison to a conventional photovoltaic panel was carried out [28]. Next, testing PCM capsules and water were combined by Hamada *et al.,* [29], yielding the greatest PVT system effectiveness of 74.1%. Additionally, Diwania *et al.,* [30] research demonstrated how various nanoparticles affect PVT systems, while other research also discusses using MWCNT/water nanofluids [31].

This type of bifacial PV, which has the advantage of being able to produce electricity from the back side, is also being researched for its use in PVT systems. Ishak *et al.,* [32] tested several bifacial PV facing factors on a PEVT system, and they produced the highest efficiency of 72.35% at a facing factor of 0.66. The performance of thermal photovoltaic (PV/T) type solar collectors can be optimized by using bifacial photovoltaic panels because they can utilize solar radiation absorbed from the front and back surfaces. To increase efficiency, it is necessary to increase the reflection of solar radiation on the back surface of the panel. Therefore, for PVT systems with bifacial panels, it is more appropriate to use a double-pass system [33]. Saberi *et al.,* [34] obtained the results that the optimum mass flow rate of a bifacial PV/T collector with CPC and mirror reflector was found to be 0.0589 kg/s, so that it could achieve a temperature output as high as 51 °C.

Based on literature studies, no one has discussed in detail the type of u-turn that is suitable for use in double-pass PVT systems. In general, the type of u-turn chosen is box [35]. Furthermore, based on the problems described previously, this research will investigate the relationship between the u-turn and the thermal conductivity focused on the bottom surface of the solar panel. This is in line with the findings in the reference, which explain that there have been an increasing number of studies using bifacial PV panels in PVT systems, hereinafter called bifacial photovoltaic thermal (B-PVT). In this research, it is hoped that we can find out the type of u-turn that is most responsive in heat transfer and reaches a steady point the fastest as a function of time. In this study, computational fluid dynamics (CFD) will be employed to analyze the thermal conductivity and heat transfer performance of different types of u-turns in double-pass PVT systems. This approach will provide detailed insights into the thermal behavior of the u-turns and help identify the most efficient design for maximizing heat transfer in B-PVT systems.

2. Methodology

2.1 Description of the CFD Model

The proposed CFD model is 2D, as this research is only interested in the effect of the shape of the turn of the double pass on heat transfer. The lower and upper passages are kept at the same height. The PV is modeled as a very thin void with a constant temperature, as the research only focuses on the turn geometry effect on the heat transfer phenomenon. The investigated shapes are selected based on their side amounts. The sides are equal, and the gap between the furthest point of the shape and the PV is kept equal. The furthest point is equal to the lower and upper passages, so there would be no continuity difference resulting from the turn, and the result would only be influenced by the geometric characteristics. The side length for each shape is also equal. The shape is shown in Figure 1 below.

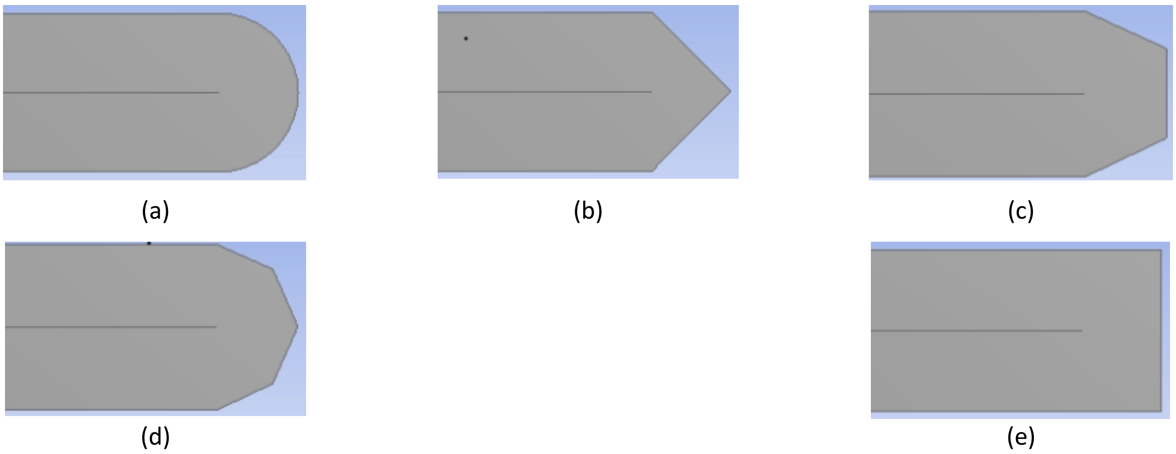

Fig. 1. Geometry variation illustration (a) Half-Circle, (b) Triangle, (c) Half-Hexagon, (d) Half-Octagon (e) Box

Figure 1 shows a geometry variation illustration, where there are five shapes to be discussed in this research. Figure 1(a) shows a half-circle with an infinite number of equal sides; Figure 1(b) triangle with 2 equal sides; Figure 1(c) half-hexagon with 3 equal sides; Figure 1(d) half-octagon with 4 equal sides; and finally Figure 1(e) box. form Figure 1(e) box, which is commonly used by previous researchers. The shapes are shown below. In the CFD model, gravity is taken into account, the air is viscous and incompressible, and the wall is a no-slip wall. So, there is turbulent flow and heat convection happening between the wall and the flow.

In a double-pass PVT system, the direction of fluid flow starts from the top through the bend towards the bottom. By flowing fluid through two passes, a double-pass system allows heat to be absorbed more efficiently by the solar panels, improving the overall performance of the PVT system.

The flow direction scheme that will be tested in the research by testing each type of bend shape variation is shown in Figure 2 below.

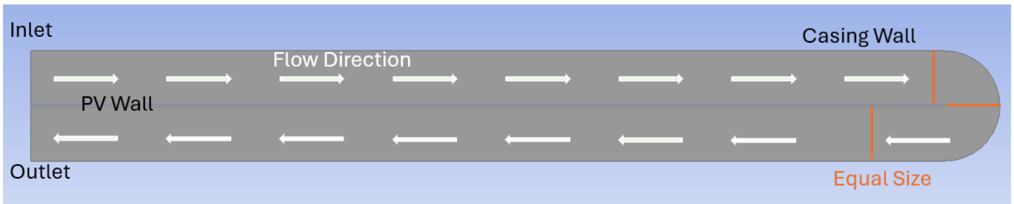

Fig. 2. PVT flow direction schema

The design size is based on the type of bifacial photovoltaic thermal (BPV) available in Indonesia. From the BPV size, it will be reduced to the size of the entire B-PVT system. The detailed specification of the domain is shown in Table 1 below.

Table 1
Parameter of B-PVT

Parameter	Value
The B-PV length	2.2400 m
The box length	2.3725 m
The PV and furthest U-Turn distance	0.1325 m
The passage height	0.1325 m

2.2 Computational Domain and Boundary Conditions

The computational domain is discretized with structured grid method. This would enhance the computational efficiency for the simulation. This would ensure a lower residual result that implies more accurate computation result. The structured grid is shown below.

Figure 3 shows the overall domain computation. These images are also made for each type of shape. Next, Figure 4 shows details of the cases per case that will be investigated in this study. The image explains the computation domain variation illustration. Half-Circle, Triangle, Half-Hexagon, Half-Octagon, and Box.

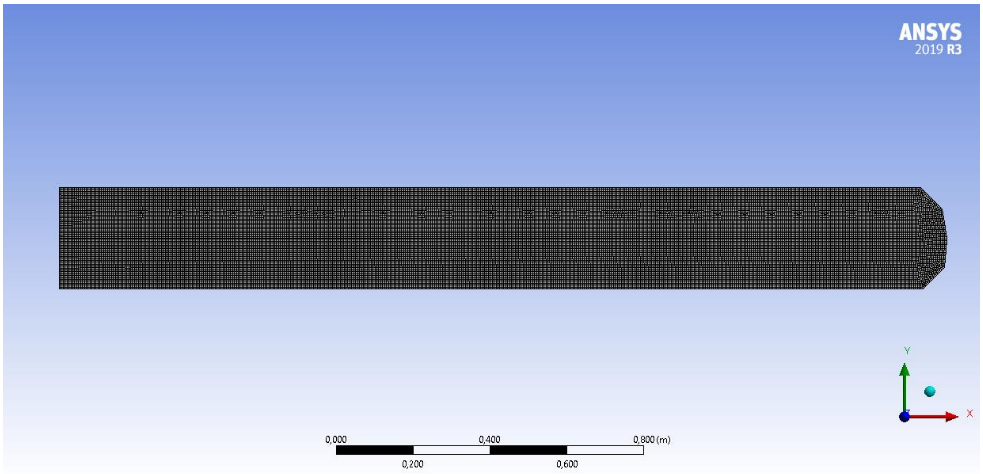

Fig. 3. Computation domain

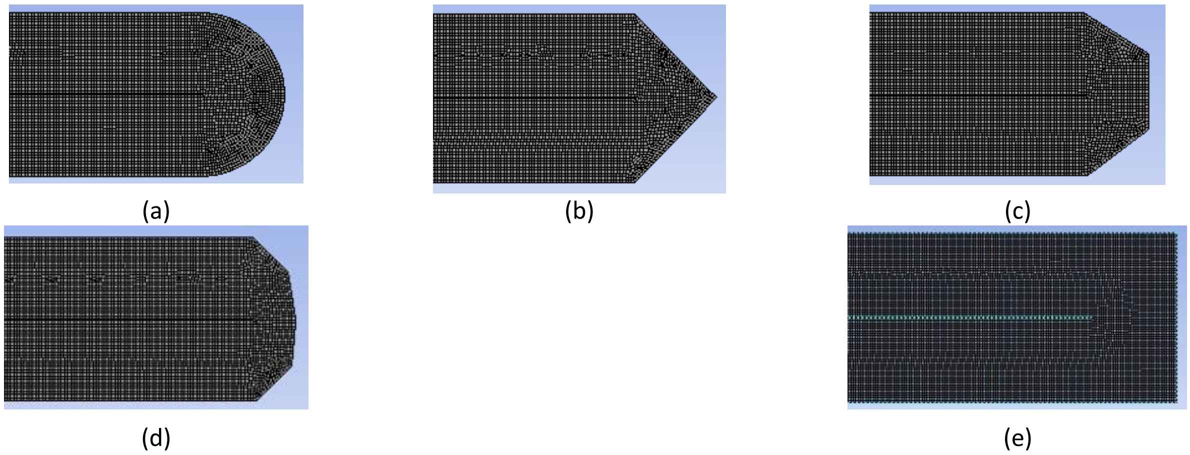

Fig. 4. Computation domain variation illustration (a) Half-Circle, (b) Triangle, (c) Half-Hexagon, (d) Half-Octagon and (e) Box

The boundary condition is shown in Table 2 below. The boundary conditions are created so that they only focus on the heat transfer phenomenon from the PV wall to the flow. Therefore, every wall except for the PV wall has the same temperature as the inlet temperature. The inlet velocity is the only parameter to be varied so that the behavior of the heat transfer can be seen across multiple Reynolds numbers. The flow is assumed to be a fully developed turbulent flow with 10% turbulent intensity at the inlet [36].

Table 2
The boundary condition

Name	Momentum	Thermal
Inlet	0.4 m/s < x>1.2 m/s	300 K
Pv wall	-	333.15 K
Casing wall	-	300 K
Outlet	Calculated	Calculated

2.3 Governing Equation

The governing equations for a viscous flow that include heat transfer consist of 3 Navier Stokes equations, Continuity, momentum, and energy equation. For this case, the domain only 2D therefore the equation only consists of 2 axes, x and y. To capture the cooling process from the flow, the case is time dependent or transient. To apply the transient case, the unsteady factor $\frac{\partial u}{\partial t}$ on the Navier-Stokes Equation is kept for the equations. The equations are written below [37, 38].

Continuity Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left\{\frac{\partial}{\partial x}\left(u\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(u\frac{\partial u}{\partial y}\right)\right\} - g\beta_f \cos\alpha \tag{2}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left\{\frac{\partial}{\partial x}\left(v\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(v\frac{\partial u}{\partial y}\right)\right\} - g\beta_f \cos\alpha \quad (3)$$

Energy Equation:

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\lambda_f}{\rho_f C_{pf}}\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right] \quad (4)$$

2.4 Time Discretization

For the time discretization, the stability criterion that used in the CFD simulation is CFL (Courant-Friedrich-Lewy) number. The formula for CFL calculation as follows [39].

$$CFL = \frac{u\Delta t}{\Delta x} \quad (5)$$

The formula consists of three factors, flow velocity, the time step interval and mesh sizes. These factors are crucial in determining the convergence and accuracy of the simulation. Identical CFL value for each geometry is applied for every simulation that conducted in this research. This would ensure that the effect of different grid total that naturally occurs between different geometry is kept at minimal. This would also keep the effect of different Reynolds number to the numerical error are minimal because the time discretization is adaptive to the change of Reynolds number inside the flow.

In summary, the CFL criterion is used to determine the adaptive time discretization so that the effect of different grid total and Reynolds number in the simulation are kept at minimum and enhance the validity of the simulation results [40, 41].

2.5 Validation

The validation of the simulation conducted for this research is the grid independence test. In other studies, independent grid analysis was also carried out to determine the ideal mesh [17]. This method was selected because there is no experimental data available to cross-reference this simulation. The grid independence test is done by varying the grid sizes for the same geometry and comparing each result to ensure that the result is not affected by the grid sizes. The test was conducted using five different grid sizes. It ranges from a 10mm grid to a 3mm grid. The comparison parameter selected is outlet temperature. The results are shown in Table 3 below.

Table 3
The grid independence test

Grid Type	Grid Size (mm)	Outlet Temperature (K)
Very coarse	10	307.57
Coarse	7.5	307.75
Standard	5	308.12
Fine	4	307.82
Very fine	3	307.90

For a more intuitive impression, the results and the total number of grid nodes are graphically shown in Figure 5 below. From the graph, it can be concluded that after 40000 node counts, the result is saturated because there is no significant difference in the result after that point. Therefore, for this research, all of the geometry uses fine discretization with 4mm grid sizes. This would ensure grid-independent value, resulting in excessive computational time costs.

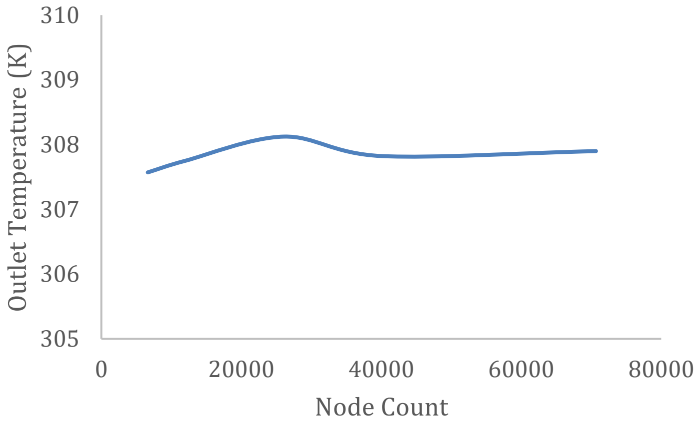

Fig. 5. Grid independence test result

2.6 Selection of the CFD Model

The numerical simulation type is transient type as the turn shape effect would be more significant on the cooling process rather than only the end result. The simulation is done using adaptive time stepping govern by CFL criterion [39]. In total, the simulation would run for 25 seconds flow time. This flow time is enough to capture the transient process until the steady state of the flow.

For the turbulent model, the case is handled using URANS (Unsteady Reynolds Averaged Navier Stokes). It is a method that solves the Navier Stokes equations in a time-dependent manner, allowing for some unsteady effects to be captured [42]. The turbulence model that used for the URANS is SST (Shear Stress Transport) k-ω. The model is suitable for both the wall effected flow and the freestream flow that occurs on the double pass configuration [43]. This is consistent with studies by N Kaewchoothong, *et al.,* [44], who examined the parameters of flow and heat transfer in a ribbed parallel channel in order to assess thermal performance using a photovoltaic/thermal (PV/T) collector.

3. Results and Discussions

3.1 Turbulent Intensity

To investigate the effect of the geometry investigated in this research, turbulent intensity will be measured. Turbulent intensity can be seen as having a relationship with heat transfer. Highly turbulent flow would contribute to better heat transfer. Figure 6 below shows the turbulent intensity on the geometry after the turn for each shape after 25 seconds of flow time and reaching the steady-state solution. The data point used for the illustration is the 1.2 m/s inlet velocity. The high velocity would accentuate the difference between each shape, therefore making it easier to observe and analyze.

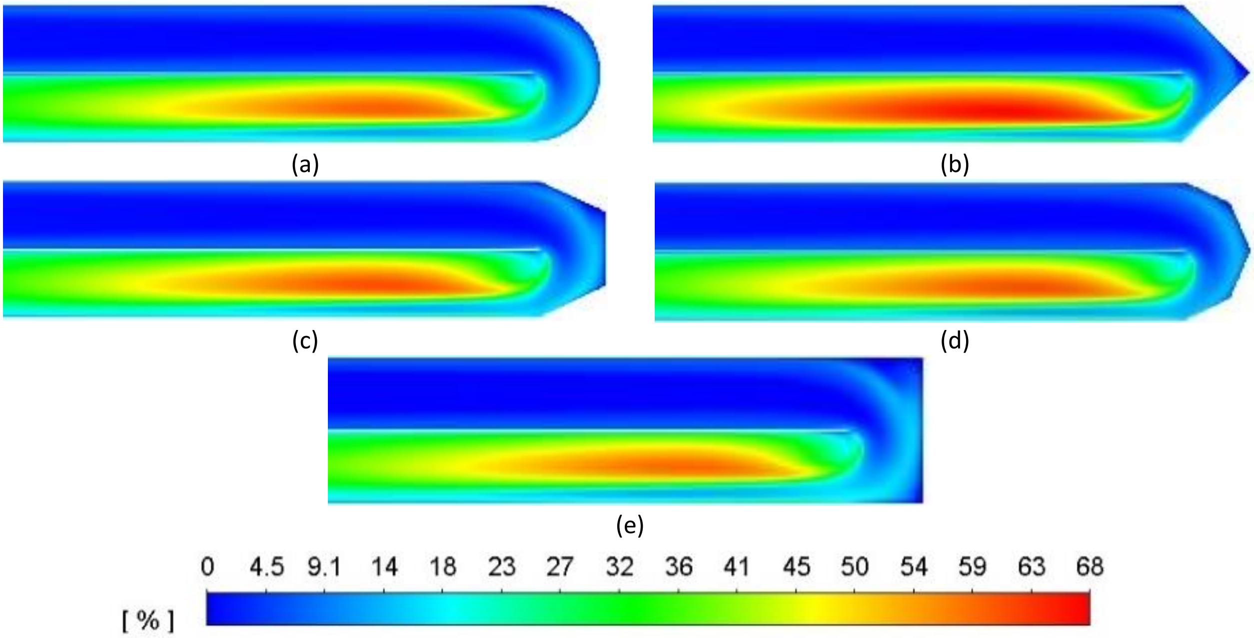

Fig. 6. Turbulent intensity contours (a) Half Circle, (b) Triangle, (c) Half Hexagon, (d) Half Octagon, and (e) Box

From Figure 6, turbulent contour comparisons can be carried out. From these five images, it can be seen that the triangle shape has a redder area than the other shape. This implies that the triangle geometry is able to produce turbulence significantly better than the other shapes. while The half circle has the least orange area of the other shapes. This implies that this particular shape is good at keeping the turbulence at a minimum.

The parametric analysis was also conducted to compare the shape performance across different flow velocities. The comparison parameter is the maximum turbulent intensity. The results are shown in Figure 7 below.

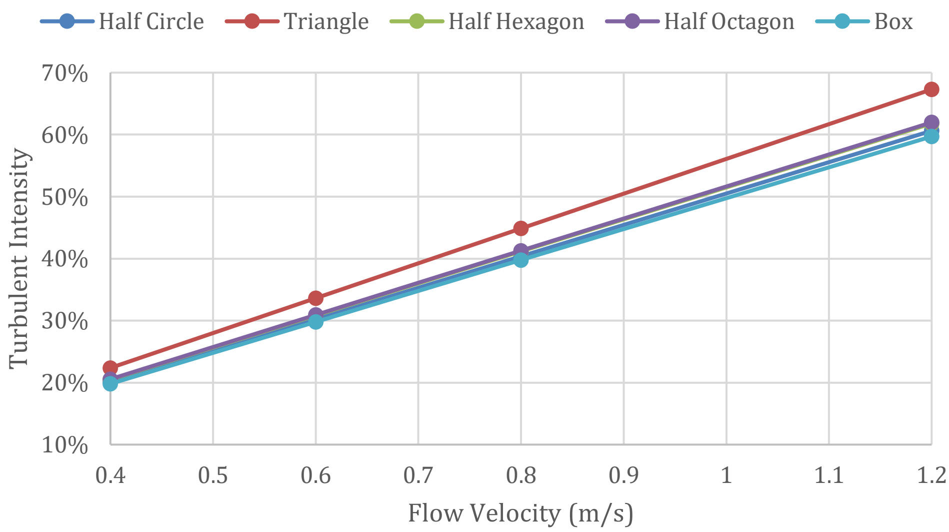

Fig. 7. The parametric analysis on turbulent intensity with radius axis turbulent intensity and the perimeters axis flow velocity

From Figure 7, it can be seen that increasing flow velocity results in an increase in turbulent intensity for all shapes of the turn offered. Furthermore, from the graph, it can also be seen that the triangle-shaped turn is indeed superior in producing turbulence. The turbulence value produced when the flow velocity is 1.2 m/s is close to 70%, while for other shapes it is only around 60%. From the graph, it can also be seen that the type of box that has often been used by researchers has the lowest value.

3.2 Effective Thermal Conductivity

The next analysis carried out is on effective thermal conductivity. This analysis aims to determine the influence of the turbulent intensity on the heat transfer from the PV. Theoretically, higher turbulent flow should increase the efficiency of heat transfer in the flow. Figure 8 shows the effective thermal conductivity contours to compare each turn shape. The data points used for the illustration are the same as in the in the previous analysis.

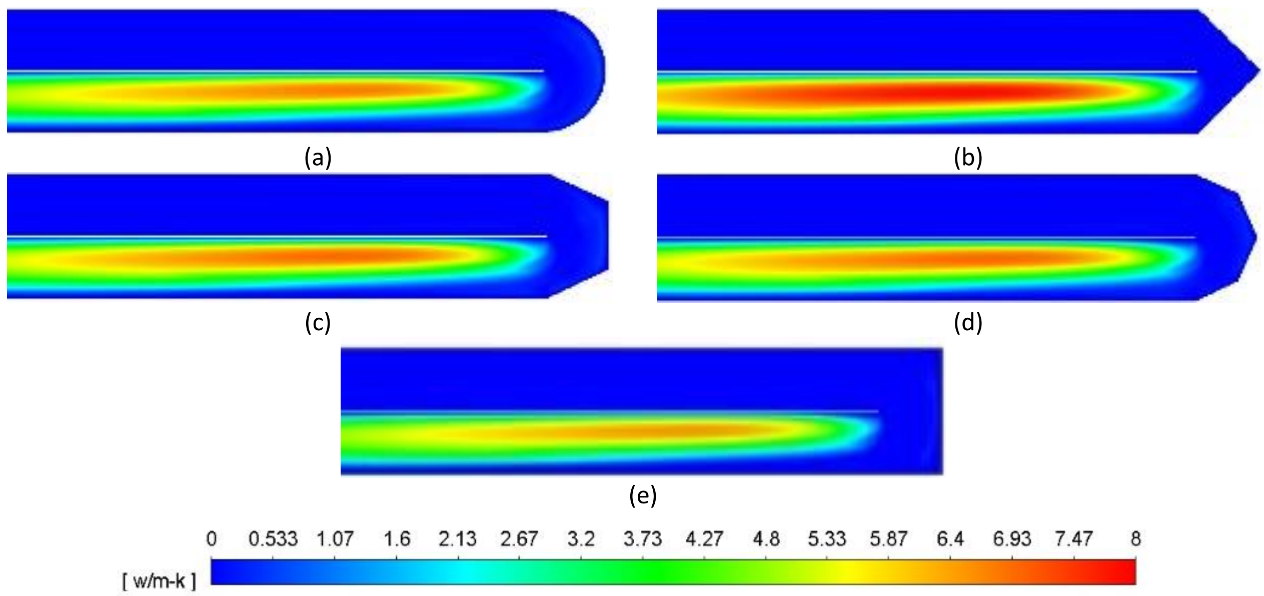

Fig. 8. Effective thermal conductivity contours (a) Half Circle, (b) Triangle, (c) Half Hexagon, (d) Half Octagon, and (e) Box

From the five images presented in Figure 8. From the contours, it can be seen that, again, the triangle-shaped turn does have a bigger and longer red area. This means that a longer area of high heat exchange from the PV to the flow happened. This is consistent with previous analyses of turbulent intensity.

To see the effect of time on the effective thermal conductivity, the value is plotted along the flow time as shown in Figure 9. From the graph, there is a bulge in the first 3 seconds of the simulation, with the triangle-shaped turn having the highest value with the shortest duration. Octagon and hexagon had similar peak and duration of the bulge, with the half-circle-shaped turn having the lowest peak and duration of the bulge. This implies that the geometry affects the flow process under steady conditions. The graph also shows different steady values, with the triangle-shaped turn being the highest.

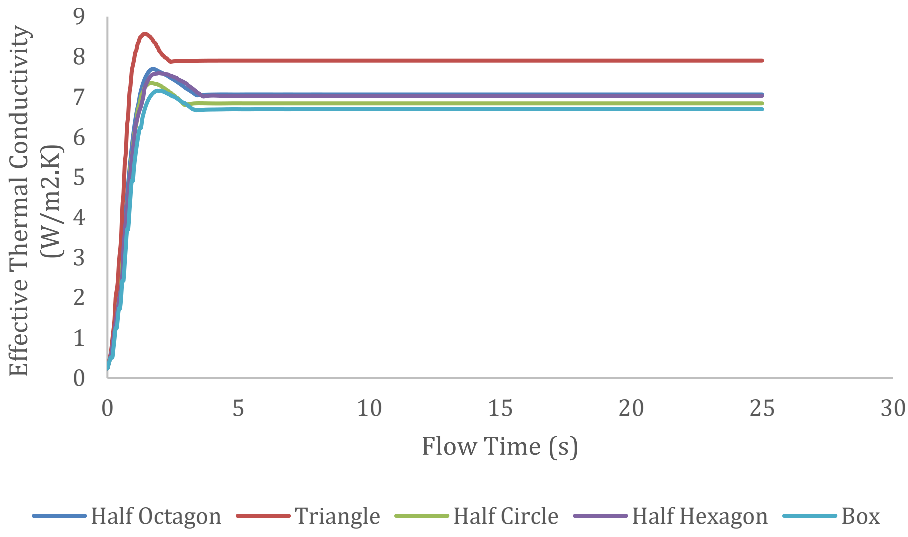

Fig. 9. Maximum effective thermal conductivity versus flow time

3.2 Outlet Temperature

Many air-based PVT systems are applied for drying, where the hot air produced by the system will flow into the drying room. For a system like this, a high air temperature is required at the outlet. For this reason, this chapter will discuss outlet air temperature. The turbulent intensity and effective thermal conductivity should contribute to the increase in flow temperature. In the BPV-T context, the higher the outlet temperature, the more effective the drying and cooling of the PV module, which prevents the PV from overheating and maintains its efficiency. The heating process of the outlet temperature is illustrated by plotting the outlet temperature with the flow time, as shown below. The data points used for this comparison are 0.4 m/s flow velocity, which has higher outlet temperatures, thus making it easier to observe the difference between shapes.

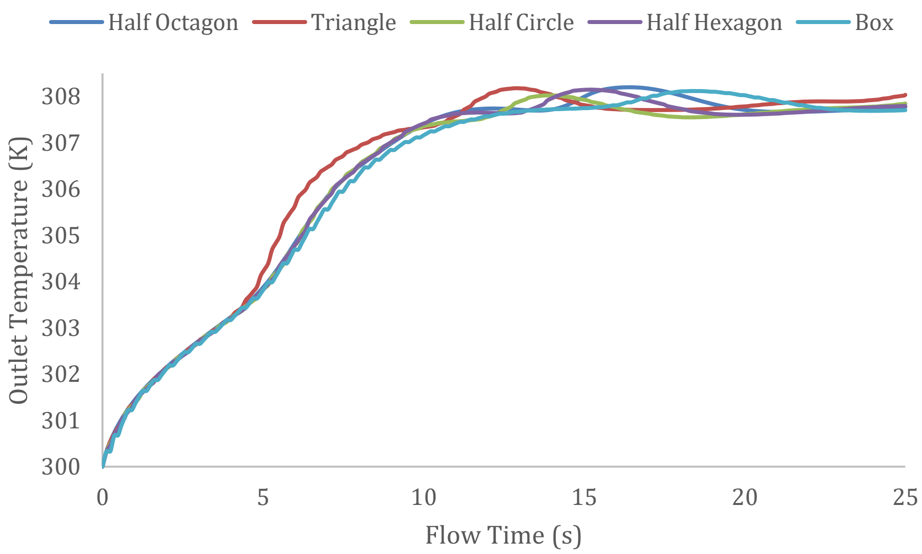

Fig. 10. Outlet temperatures versus flow time

Figure 10 explains the relationship between outlet temperatures and flow time. From the graphs, the triangle-shaped turn is particularly interesting, with it increasing outlet temperature earlier than other shapes. The triangle's graph has two bulges in the period of 5 to 10 seconds and 12 to 15 seconds before finally becoming steady. Other shapes are quite similar, with only one bulge in the period of 14 to 19 seconds before finally becoming steady. This implies that the triangle-shaped turn is able to provide faster and higher temperatures; therefore, it is the most responsive shape out of the others. Next The analysis was also conducted at various flow velocities with five different velocities: 0.4 m/s, 0.6 m/s, 0.8 m/s, and 1.2 m/s. The results are shown in Figure 11 below.

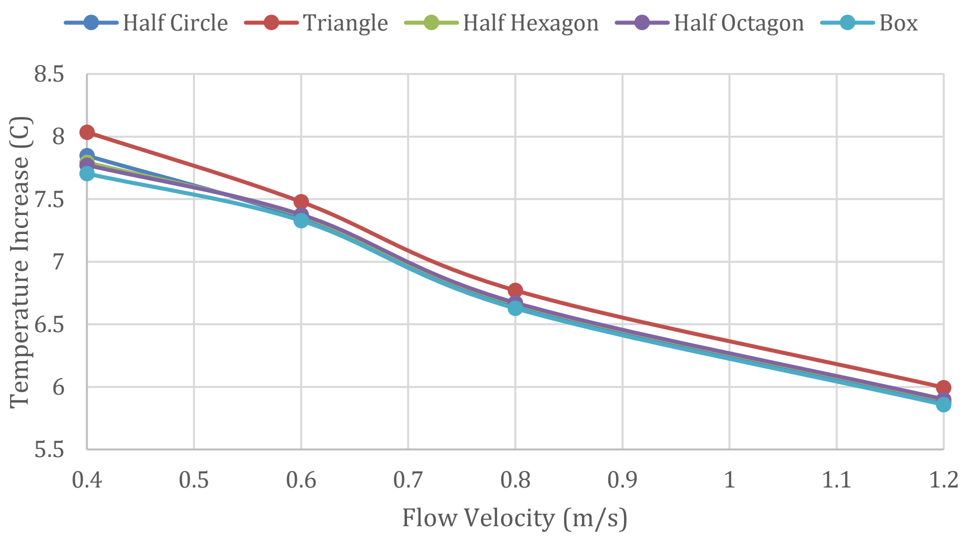

Fig. 11. The parametric analysis on outlet temperature with radius axis turbulent intensity and the perimeters axis flow velocity

Based on the parametric analysis of outlet temperature with the radius axis turbulent intensity and the perimeter axis flow velocity in Figure 10, the results are consistent with the triangle-shaped turn outlet temperature being superior across the flow velocities. The hexagon performed slightly better than the octagon, and the lowest outlet temperature is produced by a half-circle-shaped turn.

4. Conclusion and Recommendation

The study investigated the impact of different turn shapes in double-pass photovoltaic thermal (PVT) systems on heat transfer and thermal performance. Computational fluid dynamics (CFD) simulations were conducted to analyze turbulent intensity, effective thermal conductivity, and outlet temperature for various turn shapes, including half-circle, triangle, half-hexagon, half-octagon, and box. The results revealed significant variations in heat transfer characteristics among the different shapes, with the triangle-shaped turn demonstrating superior performance in generating turbulence and facilitating heat exchange. Specifically, the triangle-shaped turn exhibited a maximum turbulent intensity of approximately 70%, whereas other shapes achieved around 60%. Furthermore, the triangle-shaped turn displayed a longer and more substantial area of high heat exchange, resulting in enhanced effective thermal conductivity compared to other shapes. The triangle-shaped turn also exhibited a faster increase in outlet temperature, reaching steady-state conditions within 15 seconds, while other shapes required up to 19 seconds. Moreover, the triangle-shaped turn exhibited a faster increase in outlet temperature, reaching steady-state conditions earlier than other shapes. This finding suggests that the choice of turn shape can profoundly influence the thermal efficiency of PVT systems. Additionally, the study underscored the importance of considering geometric factors in optimizing PVT system design for enhanced heat transfer and overall performance.

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Author Contributions
All authors contributed equally as the main contributors to this paper. The final paper was read and approved by all authors.

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