Enhancing the Performance of Photovoltaic Thermal Solar Collectors using Twisted Absorber Tubes and Nanofluids with Optimal Design Parameters

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Abstract- A Photovoltaic Thermal Solar Collector (PVT) is a technology that combines the benefits of photovoltaic panels (PV) and solar thermal collectors. This study introduces a novel approach by incorporating twisted absorber tubes and nanofluids as working fluids into the PVT system. This innovative design aims to enhance the efficiency of the PV modules while simultaneously generating hot water. Computational Fluid Dynamics (CFD) simulations were used to determine the optimal header tube diameter and the number of absorber riser tubes. Increasing the number of riser tubes from 7 to 11 resulted in a decrease in the PV panel temperature from 73.41°C to 65.5°C, with a minimal further decrease observed at 13 tubes (64.6°C). The optimal values determined were a header tube diameter of 51mm and 11 absorber riser tubes. The implementation of twisted tubes resulted in significant improvements in the photovoltaic, thermal, and combined photovoltaic-thermal efficiencies. Specifically, the combined photovoltaic-thermal efficiency increased from 61.2% to 84.6% at a mass-flow rate of 0.04kg/s and a solar irradiance level of 800W/m^2. Furthermore, by employing nanofluids, we observed even more significant gains in the combined photovoltaic-thermal efficiency, which further increased from 84.6% to 88.2%. These findings provide valuable insights into the design of high-performance fluid-based PVT systems and, furthermore, highlight the exceptional potential of twisted tubes combined with nanofluids for enhancing overall system performance. The integration of these innovative elements showcases a significant advancement in PVT technology, offering promising opportunities for sustainable energy generation.

Keywords PVT, Optimization, Parallel absorber tubes, Twisted tube, Nanofluid.

1. Introduction

Photovoltaic Thermal Solar Collector (PVT) configurations combine photovoltaic panels (PV) and solar thermal collectors (STC) [1, 2]. These systems consist of PV panels and absorption tubes, which are crucial components in water-based PVT configurations [3, 4]. However, the efficiency of PV panels decreases as their surface temperature increases. For each 1°C increase in surface temperature, the photovoltaic efficiency decreases by approximately 0.45%-to-0.50% [5, 6]. To overcome this limitation, PVT systems have been developed to reduce the surface temperature of PV panels, resulting in improved electrical and thermal energy output [7]. The performance of a PVT configuration heavily relies on the design of the absorber tubes, which facilitate heat transfer to the working fluid [8]. In addition to providing household hot water and electrical energy, PVT configurations offer advantageous thermal and energy outputs in specific locations [9, 10].

The design of the absorber tube significantly impacts the combined photovoltaic thermal efficiency of a PVT system. Parallel absorber tubes, known for their uniform temperature distribution on the absorber surface and reduced water resistance, are a popular choice [8]. Several investigations have explored the effectiveness of water-based PVT configurations [11]. For example, Mihai et al. [12] proposed a PVT system utilizing water-based absorber tubes along with a water heat pump and hot water storage, resulting in up to a 45% enhancement in PVT efficiency compared to using PV and STC separately. Kazem et al. [13] evaluated three water-based PVT configurations and a standard PV panel. The absorber tube designs used were parallel, spiral, and web configurations. The web, parallel, and spiral PVT systems achieved photovoltaic efficiencies of 16.9%, 27.9%, and 35.1%, respectively, compared to conventional PV panels. The numerical study indicated that the highest temperature reached was 68°C for the PVT with web absorber tubes, while the lowest temperature achieved was approximately 45.2°C for the PVT with parallel absorber tubes. Yu et al. [14] analyzed the performance of a water-based PVT collector using aluminum roll-bond parallel absorber tubes, achieving a thermal efficiency of 85% on sunny summer days and a photovoltaic efficiency of 15.6% around the spring and fall equinoxes.

Kallio et al. [15] utilized MATLAB/Simulink to investigate the performance of a water-based PVT collector with a parallel absorber tube design. The collector consisted of a glass cover, an air gap, a PV panel, an absorber plate with water tubes, insulation, and a working fluid (water). The selection of a water-based PVT collector was based on its higher efficiency compared to collectors that use air. The findings revealed a 7.7% increase in energy production and a 72.9% increase in thermal exergy generation. Pang et al. [16] investigated PVT configurations with different absorber tube designs. The riser tubes of the absorber tubes utilized various cross-sectional areas, including circular, rectangular, and arch shapes, which were coupled along the long and short side dimensions of the PV panel. PVT systems with arch and rectangular cross-section area absorber tubes achieved daily thermal efficiencies of 39.81% and 35.39%, respectively. Furthermore, the experimental findings demonstrated higher photovoltaic and thermal efficiency of 16.98% and 67.12%, respectively, for the PVT system with arch cross-section area absorber tubes.

Simms and Dorville [17] developed a modified absorber tube design for a PVT collector, enhancing heat transfer. The hybrid collector successfully heated 7.5 liters of water from 26.4°C to 45°C in approximately 5.5 hours. In comparison, the solar water heater achieved the same temperature rise from 28.4°C to 47.6°C in around 4.5 hours. Notably, the PVT collector operated at an average temperature of 51.6°C, which was 5.5°C cooler than the PV panel's operating temperature of 57.1°C. The lower operating temperature of the PVT collector holds potential advantages, including a longer lifespan and a theoretical 2.5% increase in electrical output from the PV cells.

The uniform flow of the working fluid in parallel absorber tubes is essential for achieving optimal performance, and this can be accomplished by designing the internal structure of the absorber system. García-Guendulain [18] conducted a study investigating the impact of distribution plates on the design of parallel absorber tubes in header tubes. Four different distribution plate designs were evaluated, and the inclusion of two distribution plates in each header tube resulted in a significant improvement in flow uniformity, up to 40%. While there was a slight increase in total pressure loss, it remained minimal for the typical tilt angles utilized in solar thermal collectors (STC). The thermal efficiency was enhanced by implementing closed-end distribution plates in the header tubes. This approach effectively minimized temperature gradients in the absorber plate, leading to improved system efficiency and durability without necessitating changes to the header tube design.

In addition to optimizing the absorber tube design, thermal regulation methods play a crucial role in maintaining optimal operating conditions for PVT systems and enhancing overall system performance [19]. Passive methods, such as the use of nanofluids and modifying the cross-sectional area of absorber tubes, have been explored to improve heat transfer within fluid-based PVT systems. Nanofluids, for example, enhance the thermal properties of the working fluid, resulting in improved heat transfer efficiency [20]. Similarly, modifying the cross-sectional area of the absorber tube induces vortices and turbulence, enhancing heat transfer through improved fluid mixing and convective heat transfer within the tube [21].

Recent studies have explored alternative designs to circular tubes and highlighted their impact on PVT efficiency. Shahsavar et al. [22] investigated nanofluid-based PVT designs with triangular, circular, and rectangular serpentine absorber tubes, revealing varying effects on photovoltaic efficiency. Additionally, the use of eight-fin tubes in a sheet and tube nanofluid-based PVT achieved the highest combined photovoltaic thermal efficiency of 84.13% [23]. Another investigation by Shahsavar et al. [24] compared circular tubes with rifled tubes featuring three or six ribs, demonstrating the superiority of the six-ribbed rifled tube with a maximum combined photovoltaic thermal efficiency of 22.5%. Furthermore, Bassam et al. [25] studied a nanofluid-based PVT collector with an absorber tube incorporating inner micro fins and nano-PCM, achieving exceptional photovoltaic thermal efficiency of 86.78% by utilizing SiC nanoparticles. These studies collectively illustrate the potential for alternative absorber tube designs to improve PVT efficiency [22-25].

This study aims to improve the thermal performance of a nanofluid-based PVT collector by introducing a novel approach: employing twisted absorber tubes. Through simulations using COMSOL software, the optimal diameter of the headers and the number of riser absorber tubes using circular tubes will be determined. Experimental verification will be conducted under laboratory conditions to validate the findings. Finally, the effectiveness of the PVT configuration utilizing twisted tubes and nanofluid will be evaluated using the optimized parameters in the same laboratory setting.

2. Methodology

The methodology consisted of four segments. Firstly, a Computational Fluid Dynamics (CFD) simulation was conducted to determine the optimal design of the PVT configuration using a circular absorber tube, including the number of riser absorber tubes and the diameter of the header tubes. Secondly, an experimental setup was established to validate the accuracy of the simulation results. Thirdly, the PVT configuration was evaluated by utilizing twisted tubes as riser absorber tubes. Finally, the performance of the PVT system was assessed by incorporating nanofluid as the working fluid.

2.1. Simulation analysis

A simulation analysis was conducted to investigate a water-based PVT system with parallel circular absorber tubes, aiming to optimize the number of riser tubes and the diameter of the header tubes. The system's design, illustrated in Figure 1, consists of a PV panel and absorber tubes (headers and risers). The PV panel is composed of glass, EVA (ethylene vinyl acetate) sheets, silicon PV cells, and protective Tedlar. The absorber riser tubes are copper tubes attached to the rear of the PV panel, while the header tubes are made of acrylonitrile butadiene styrene (ABS). The PV panel dimensions are 64*30 cm, with an electrical reference efficiency of approximately 15% at 1000 W/m^2 and 25°C PV surface temperature. The header diameter (D_h) varies from 15 mm, 25 mm, 38 mm, 51 mm, 64 mm, and 76 mm. The circular riser tubes have a diameter of 15 mm, and the tube numbers (N) range from 7, 9, 11, and 13.

CFD simulations using COMSOL software were performed to obtain a 3D numerical solution for fluid flow and temperature distribution in a nonisothermal PVT system. The simulations were conducted under stationary conditions, assuming 100% transmissivity of EVA, no dust on the PV surface, laminar and incompressible flow, and constant thermal-physical parameters. The governing equations included the Navier-Stokes equations for laminar flow, comprising continuity and momentum equations for the fluid layer, as well as thermal energy equations for both the fluid and solid layers [26, 27].

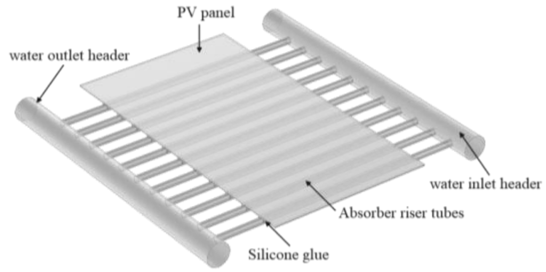


Fig. 1. PVT system parallel absorber tubes

Equation (1) represents the continuity equation for fluid layer:

$$\rho\nabla\cdot u = 0$$
(1)

Equation (2) represents the momentum equation for fluid layer:

$$\rho(u\cdot\nabla)u = \nabla\cdot[-p + \mu(\nabla u + (\nabla u)^T)]$$
(2)

Equation (3) represents the Energy equation for fluid and solid layers:

$$\rho C_p u\cdot\nabla T + \nabla\cdot(-k\nabla T) = 0$$
(3)

u is a velocity vector, *p* is a pressure, *T* is a temperature of solid layers and fluid layer, *ρ* is a density, C_p is a specific-heat-capacity at constant pressure, and *k* is a thermal-conductivity.

The boundary conditions for the simulation include an inward heat flow of 800 W/m2 at the top surface of the PVT. Convection and radiation losses on the top surface are also considered, with an ambient temperature of 25°C. Convection losses are induced at the backside of the PVT at the same ambient temperature. Thermal insulation is applied to the header tubes. The water inlet has a mass flow rate ranging from 0.008 kg/s to 0.04 kg/s and an inlet temperature of 20°C. The water outflow is adjusted at a pressure of 0 Pa.

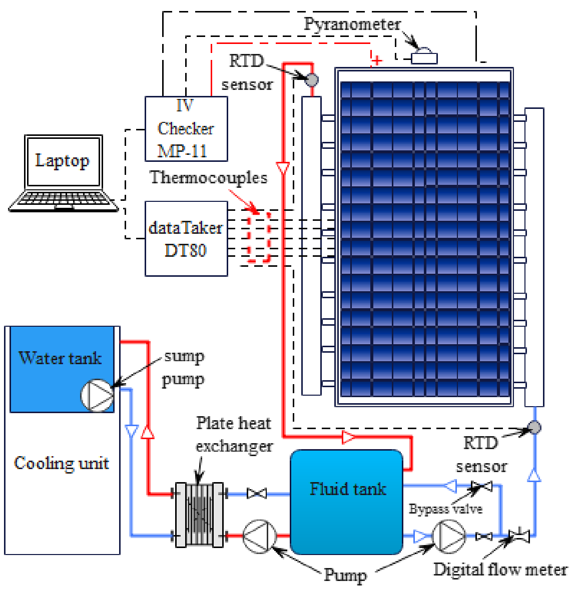
The COMSOL software assesses various PVT configurations with separate mesh independence tests. A heat flux of 800 W/m2 and a mass flow rate of 0.008 kg/s are used with PV surface temperature as the control parameter. All configurations are meshed using auto-mesh features with options of extra coarse, coarse, normal, fine, and finer mesh sizes. Results indicate that a normal mesh is suitable for numerical analysis in all configurations. The impact of mesh element numbers on finite element method numerical solutions was also investigated.

2.2. Experimental Setup

The experiment utilized a Bright-Sun PV panel with a maximum power rating of 30W and dimensions of 64*36cm [25]. Figure 2 illustrates the experimental setup, which included measuring equipment such as the Flow meter DHYB-800, Pyranometer MP-170, and IV Checker MP-11. The experiments were conducted in an indoor solar simulator, and two PVT configurations were evaluated: one with circular absorber tubes (C-PVT) and one with twisted absorber tubes (T-PVT). The twisted tube was selected to have the same hydraulic diameter as the circular tube, and its number was determined as the optimal value based on an analysis of the findings obtained from the circular tube. In addition, the T-PVT configuration was tested with a nanofluid comprising SiC nanoparticles (45-65nm) and water (0.6% volume fraction), which was mixed using a two-step method [28].

In order to ensure the accuracy of the results, it is essential to evaluate the uncertainties associated with the independent variables and their impact on the dependent variable [24]. The experiment was conducted with a high level of precision, as indicated by an uncertainty value of 1.86, representing a margin of error of less than 2% for the measurements taken using the provided equipment. Hence, the obtained results from these measurements can be considered reliable and acceptable.

a



b

Fig. 2. The experimental setups of the PVT (a) actual (b) schematic diagram.

3. Results and Discussions

The optimal design of the PVT configuration based on parallel circular absorber tubes was determined numerically. The influence of varying the diameter of the headers and the number of absorber tubes on the system was evaluated. Then, the efficiencies of the PVT configuration were evaluated through experimental investigation. Circular tubes were initially used as absorber tubes for the evaluation. The performance of the PVT was further examined by replacing the circular tubes with twisted tubes using the optimal parameters obtained from the initial evaluation. The PVT with twisted tubes was evaluated with water and nanofluid as working fluids.

3.1. Simulation-results

3.1.1. The Impact of Header Diameter on Flow Distribution within Riser Tubes in the PVT configuration

The influence of header diameter on flow distribution in the riser tubes of a PVT configuration was assessed by varying the header diameters (D_h) from 17mm to 76mm, the number of riser tubes (N) from 7 to 9, and the mass flow rates (m^o) from 0.008kg/s to 0.04kg/s. The first parameter examined was ßi, which represents the flow distribution within all riser tubes and can be calculated as the ratio of the average flow rate of a single riser tube to the total flow rate across all risers [18].

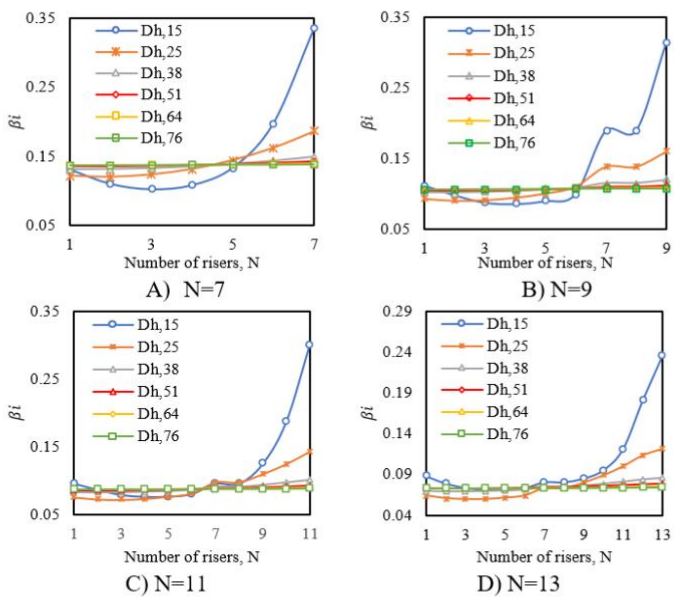


Fig. 3. The parameter $ß_i$ for each riser tube with varying header diameters (D_h) and varying number-of-riser-tubes (N)

The analysis of Figure 3 reveals that when smaller header diameters were employed, it resulted in a non-uniform flow distribution within the riser tubes. Conversely, the use of larger diameters, specifically those measuring 50mm or larger, led to a significantly improved and more uniform flow distribution throughout the system.

The nonuniformity parameter (Φ), which quantifies the deviation from uniform flow in the tubes [18], is depicted in Figure 4 for all PVT configurations across different mass flow rates. It is observed that Φ increases as the mass flow rates increase. However, larger header diameters contribute to an equal distribution of flow across the riser tubes, even at higher flow rates, owing to reduced pressure drop and a larger cross-sectional area for fluid flow. Consequently, the flow distribution over the risers becomes more uniform.

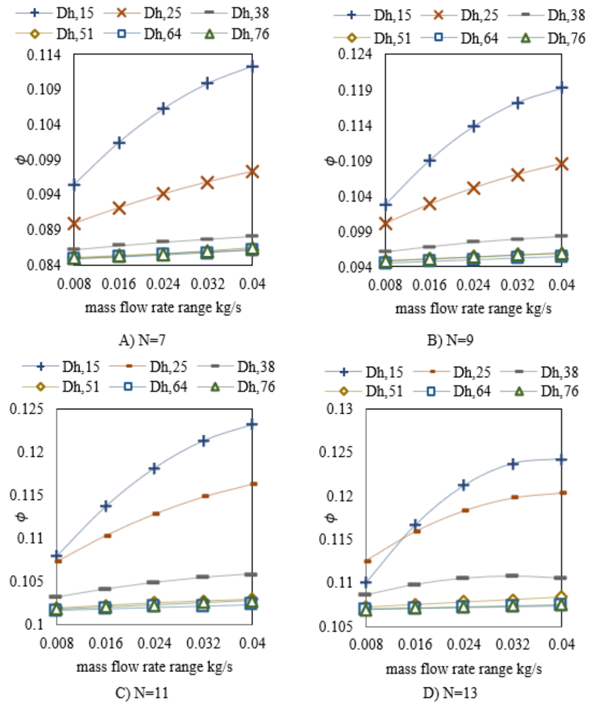


Fig. 4. The nonuniformity parameter (Φ) comparison for all configurations varies with number-of-riser-tubes (N) and mass-flow rate (m°).

3.1.2. The Impact of the Number of the-Riser-Tubes in the PVT configuration

Increasing the number of riser absorber tubes (N) in a PVT system with a 51mm header diameter (D_h) enhances heat transfer and improves photovoltaic and thermal efficiency. However, once a certain number of tubes is reached, the efficiency improvement becomes minimal compared to the increased cost.

Fig. 5. Thermal efficiency is based on the mass flow rate.

The thermal efficiency of the PVT configuration was determined using the equations presented in [29-31]. Figure 5 illustrates that the thermal efficiency increased from 34.1% (with 7 tubes) to 58.3% (with 13 tubes) at a mass flow rate (m°) of 0.04kg/s. Therefore, the optimal design for this PVT system consists of 11 absorption riser tubes with a 51mm header diameter.

3.2. Experimental results

The The results of the PVT system with circular absorber tubes obtained from CFD simulations were verified and compared with experimental data. The experiment also included the use of twisted tubes with water (T-PVT) and nanofluids (T-PVT-SiC). The number of twisted tubes and header tube diameter were determined based on the optimal values found in the previous subsection.

The simulation results of the PVT configuration with circular tubes showed good agreement with the experimental results, indicating a strong correlation between the two. Figure 6 illustrates a decrease in PV surface temperature from 65.5°C to 55°C when comparing the T-PVT system with the C-PVT system. This decrease led to an increase in photovoltaic efficiency from 8.3% to 9.4%, as shown in Figure 7. Furthermore, Figure 8 demonstrates an improvement in thermal efficiency from 56.2% to 75.2%. This improvement can be attributed to the use of twisted tubes, which enhance turbulence inside the tubes, resulting in better heat transfer from the tube surface to the fluid inside. However, it also has the disadvantage of increasing the pressure drop inside the tube, thus requiring more pumping power to circulate the fluid within the absorber tube [32].

Moreover, the utilization of nanofluids resulted in a further increase in thermal efficiency, with an improvement from 75.2% to 78.8%. However, there was no significant improvement in surface temperature, and consequently, no notable enhancement in photovoltaic efficiency, as the decrease in surface temperature was less than 2°C. These results indicate that the performance of the PVT configuration can be further enhanced by incorporating twisted tubes and utilizing nanofluids.

Fig. 6. PV surface temperature based on the mass flow rate (m°).

Fig. 7. Photovoltaic efficiency based on the mass flow rate (m^o).

Fig. 8. Thermal efficiency based on the mass flow rate (m^o).

The T-PVT system utilizing SiC nanofluid as the working fluid achieved the highest combined photovoltaic-thermal efficiency, reaching 88.2% according to Figure 9. The T-PVT system using water obtained the second-highest efficiency, with an efficiency of 84.6%. On the other hand, the C-PVT system using water exhibited the lowest efficiency among the evaluated systems, with an efficiency of 61.2%.

Fig. 9. Combined-Photovoltaic-Thermal efficiency based on the mass flow rate (m^o).

The experiment focused on evaluating the electrical characteristics of the PV panel and the thermal performance of the PVT system. The IV (current-voltage) and PV (power-voltage) curves, shown in Figure 7, provided insights into the panel's electrical performance and its suitability for various applications. Evaluating the electrical behavior of the PVT configurations under different operating conditions is crucial for optimizing efficiency while ensuring long-term reliability.

Fig. 10. Characteristic I-V-and-P-V curves of all PVT configurations

Figure 11 presents a comparison of photovoltaic thermal efficiency. Previous research has investigated the effectiveness of nanofluid-based PVT systems. PVT efficiency can be influenced by various factors, such as the technologies employed, the design of the absorber tubes, and the location of the experiment (outdoor or indoor). Consequently, accurately measuring thermal efficiency in relation to PV efficiency poses challenges. However, the twisted tube design has consistently outperformed other designs.

Fig. 11. Comparisons of PVT in the literature and the present work

4. Conclusion

The performance of a photovoltaic thermal (PVT) configuration was examined in terms of its photovoltaic and thermal effectiveness. Optimal design parameters were determined using circular tubes through numerical simulation. The surface temperature of the PV panel decreased from 73.41°C to 65.5°C when the number of tubes increased from 7 to 11, while further increasing the number of tubes to 13 only slightly reduced the temperature to 64.6°C. This resulted in an optimal header diameter of 51mm and 11 absorber riser tubes.

The photovoltaic thermal efficiency of the PVT system with circular absorber tubes was found to be 64.60% in the numerical simulation at a mass flow rate of 0.04kg/s and a solar irradiance level of 800W/m^2, which was 3.4% lower than the experimental results at the same conditions. Nonetheless, this correlation demonstrated a satisfactory level of agreement, confirming the accuracy and reliability of the models. Subsequently, replacing circular tubes with twisted tubes led to a significant increase in efficiency. The photovoltaic efficiency improved from 8.3% with circular tubes to 9.4% with twisted tubes, while the thermal efficiency improved from 56.2% to 75.2%.

Furthermore, the utilization of a 0.6% volume fraction of SiC nanofluid resulted in increased thermal efficiency from 75.2% to 78.8%, indicating the potential for enhancing PVT performance. However, no significant improvement in photovoltaic efficiency was observed when changing the working fluid from water to nanofluid. These findings have important implications for the design of high-performance fluid-based PVT configurations.

Future research should explore the impact of different twisted tube geometries on the performance of the PVT configuration and investigate alternative twisted tube designs to improve the convective heat transfer coefficient. Another approach to enhancing the PVT configuration's performance is to incorporate phase change materials (PCMs), including nanoparticles, in a container. This would result in more efficient heat transfer and higher overall system performance.

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