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Research Article

Enhancing the performance of water-based PVT collectors with nano-PCM and twisted absorber tubes

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Abstract. The study investigated the thermal performance of a photovoltaic thermal (PVT) collector with a twisted absorber tube and nanoparticle-enhanced phase change material (nano-PCM). The PVT collector consisted of twisted absorber tubes, a container filled with nano-PCM, and a photovoltaic (PV) panel. To assess its efficiency, five different configurations were tested using an indoor solar simulator. The configurations analyzed were as follows: (a) an unenhanced PV panel, (b) PVT with circular absorber tubes (C-PVT), (c) PVT with twisted absorber tubes (T-PVT), (d) C-PVT with nano-PCM (C-PVT-PCM), and (e) T-PVT with nano-PCM (T-PVT-PCM). The thermal, photovoltaic, and combined photovoltaic-thermal efficiencies were evaluated at varying mass flow rates (0.008-0.04kg/s) and a constant solar irradiance of 800W/m^2. Among the configurations tested, the T-PVT-PCM configuration demonstrated the highest performance. Specifically, at a mass flow rate of 0.04kg/s, solar irradiance of 800W/m^2, and an ambient temperature of 27°C, it achieved photovoltaic, thermal, and combined photovoltaic-thermal efficiencies of 9.46%, 79.40%, and 88.86%, respectively. The utilization of twisted absorber tubes in the design notably improved thermal efficiency by enhancing heat transmission between the liquid and the tube surface. Furthermore, the implementation of T-PVT-PCM led to a significant reduction in surface temperature. Compared to the unenhanced PV panel, it lowered the surface temperature by approximately 30°C, and when compared to C-PVT-PCM, it reduced it by around 10°C. Notably, T-PVT-PCM outperformed the unenhanced PV panel by exhibiting a 34.5% higher photovoltaic efficiency. Overall, the study highlights the performance of the PVT collector with twisted absorber tubes and nanoparticle-enhanced phase change material. The innovative design achieved remarkable thermal efficiency, reduced surface temperatures, and significantly enhanced photovoltaic efficiency compared to traditional configurations. These findings contribute to the development of more efficient and versatile solar energy systems with the potential for broader applications in renewable energy technology.

Keywords: PVT-PCM, Twisted absorber tube, Nano-PCM, Photovoltaic thermal efficiency, Primary Energy Saving efficiency

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1. Introduction

Renewable solar energy is an efficient and environmentally friendly power source (Zamen *et al.* 2022). PV panels typically exhibit an efficiency of 12–16% under standard test conditions (Siecker *et al.* 2017). However, as the temperature of the PV surface rises, the electrical voltage decreases due to increased internal resistance, leading to a decline in energy production (Sabry *et al.* 2021). Specifically, for every 1°C increase in PV surface temperature, photovoltaic efficiency is reduced by 0.45–0.50% (Siecker *et al.* 2017). Integrating thermal collectors with PV panels in photovoltaic thermal (PVT) designs enhances photovoltaic efficiency, generates thermal energy, and optimizes space utilization (Ibrahim *et al.* 2011). Over the years, there have been significant advancements in PVT design studies since the 1970s (Chow 2010, Tirupati Rao *et al.* 2021). Additionally, as the costs of PV panels decrease, PVT systems are becoming more affordable (Sopian *et al.* 2020).

Rejeb *et al.* (2020) proposed a PVT configuration with an absorber tube collector and a standard sheet. However, they found that the temperature distribution in the system would limit its photovoltaic and thermal efficiencies due to a small contact area between the PV panel and the tubes and an increase in thermal resistance. Touafek *et al.* (2014) studied a novel water-based PVT collector that utilized tube and sheet galvanized steel parallel absorber tubes. The authors investigated the temperature distribution in the collector both theoretically and experimentally. They compared the performance of this new PVT arrangement with that of a copper serpentine absorber tube explored in a previous study (Touafek *et al.* 2006). The sheet and tube PVT configuration exhibited an improved thermal efficiency of 70% compared to the serpentine collector, and both configurations achieved comparable output temperatures of 40°C for an inlet water temperature of 20°C. The highest PV panel temperature recorded in the new PVT collector was 47°C, and the tube and sheet design outperformed traditional collectors.

Lari *et al.* (2017) developed a PVT collector that uses Ag/nanofluids as a working fluid to supply the energy demands of a residential structure. The traditional rectangular tube cross-

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section was changed to a modified serpentine design for the absorbent tubes. The PVT collector outperforms traditional PV and water-based PVT in terms of electrical and thermal generation. The use of nanofluids increases solar efficiency by 8.5% and thermal efficiency by 13%. An economic study suggests a considerable reduction in energy expenditures, with the investment being returned within two years and a possible reduction in CO2 emissions.

Herrando *et al.* (2019) developed 3D numerical models to evaluate and compare 26 different designs for PVT collectors, aiming to enhance performance while reducing costs and weight. These designs included variants of traditional sheet and tube configurations as well as flat box arrangements constructed with various dimensions and materials. The sheet and tube designs used aluminium and copper materials, while the flat box designs employed aluminium, copper, and polymer components. The study found that flat box designs outperformed traditional PVT collectors, particularly those with a polymer architecture and 3 by 2mm rectangular channels. Optimizing the bond connection between the absorber tube and the PV panel was identified as crucial for achieving optimal thermal and electrical performance. The larger bond area in flat box designs resulted in a uniform temperature distribution of the PV panel. Moreover, flat box designs made of ready-to-use polymers without additives showed potential as alternatives to commercial collectors, offering higher performance, reduced investment costs (up to 22%), and decreased weight (up to 10%).

Zamen *et al.* (2022) designed a PVT system with a new cooling system architecture and investigated the impact of nanofluid concentration and flow rate on thermal and photovoltaic efficiency. The study revealed photovoltaic thermal efficiencies of 11.63%, 82.26%, and 93.73% for different nanofluid concentrations. Nanofluids at any concentration improved the electrical performance of the PVT system by 0.53-7.38%. Menon et al. (Menon *et al.* 2022) assessed the electrical and thermal performance of an integrated unglazed PVT system using nanofluids and water. The study found that nanofluids increased the system's thermal efficiency from 58.77% to 71.17%.

Shahsavar *et al.* (2020) conducted a study on PVT designs featuring triangular, circular, and rectangular serpentine absorber tubes. The research revealed that triangular tubes decreased photovoltaic efficiency by 3%, while rectangular tubes improved it by 2%. The photovoltaic thermal efficiencies of circular, triangular, and rectangular PVT configurations were measured at 13.54%, 13.19%, and 13.73%, respectively. Additionally, the performance of a sheet and tube PVT system with circular tubes and four- and eight-fin tubes was examined. (Shahsavar *et al.* 2021b). The combined photovoltaic thermal efficiency was for the PVT, with the eight-fin tubes reaching 84.13%, demonstrating that the eight-fin tubes achieved the highest efficiency. In another investigation by Shahsavar *et al.* (2021a), the effects of rifled tubes with three or six ribs were compared to those of circular tubes. The research showed that the rifled tube with six ribs exhibited a maximum combined photovoltaic thermal efficiency of 22.5%, which was 3.8% higher than the circular and three-ribbed rifled tubes. These investigations collectively concluded that alternatives to the circular tube design led to improvements in PVT efficiency.

Missoum *et al.* (2021) conducted a study to assess the effectiveness of multigenerational solar technology. This system integrates water-based photovoltaic-thermal (PVT) collectors with various components, including three storage tanks, five pumps, a water-based adsorption chiller, a heat pump, an auxiliary heater, as well as secondary elements like pipelines, valves, and diverters. The system's performance was analyzed using numerical simulation models and compared to a traditional power system. According to the findings, the water-based PVT collectors in the multigenerational system could meet more than 56% of the annual heat demand and 72% of the annual power demand indicating a significant contribution to the overall energy requirements of the building. Moreover, the system achieved primary energy savings of 37.1 MWh/year, corresponding to a 39% reduction compared to the traditional system. However, despite its favorable performance, the system's economic viability was deemed impractical due to the high initial cost of the solar collectors. The payback time was estimated to be 55.40 years, which poses a significant financial challenge for implementation. Various factors, including the size of the PVT collectors, the overall cost of the system, and the unitary price of energy, influence economic feasibility. Nonetheless, the system demonstrated its potential as an effective solution, particularly in hot climate zones characterized by high cooling energy demands and abundant solar radiation. In such regions, integrating water-based PVT collectors can offer substantial benefits in meeting energy needs and reducing reliance on traditional power systems.

Incorporating PCM containers has enhanced the combined photovoltaic thermal efficiency of PVT systems. Sardarabadi *et al.* (2017) evaluated the impacts of ZnO-nanofluid and a PCM (paraffin wax) in a PVT. Nanofluid PVT-PCM configuration enhanced average photovoltaic production by more than 13% and average thermal generation by over 9% without using any more energy, compared to a standard PV panel. The PVT's total exergy efficiency is increased by more than 23% compared to a standard PV panel, suggesting the potential of PCM and nanofluid integration for greater cooling in PV systems.

Phase change materials (PCM) have been enhanced using nanoparticles to improve their performance and thermal characteristics. Nanoparticles and PCM are combined to form a material known as nano-PCM. This change has noticeable advantages, including higher thermal conductivity, more effective heat transfer characteristics, increased energy storage capacity, temperature regulation and stability, and modified thermal properties (Nazir *et al.* 2019). Additionally, it improves thermal energy absorption and storage, allowing more energy storage in a smaller space. These advancements have potential uses in solar thermal systems such as solar collectors or PVT setups. Overall, integrating nanoparticles into PCM offers significant improvements in thermal performance and opens up new possibilities for efficient energy storage and utilization. Ongoing research and development in this field aim to optimize nanoparticle selection, concentration, and dispersion techniques to maximize the benefits of nano-PCM in various applications (Alam *et al.* 2021).

Al-Waeli et al. (2017c, 2019a) developed a mathematical model and conducted experimental testing to examine a nanofluid/nano-PCM-PVT configuration. Their findings revealed notable enhancements in thermal and photovoltaic efficiencies, achieving 72% and 13.7%, respectively. Incorporating nanoparticles into PCM offers advantages such as enhanced thermal conductivity and heat transfer, improving overall system performance. In another study, Al-Waeli et al. (2018, 2019b) evaluated the techno-economic performance of PVT configuration with nanofluid. The research analyzed productivity, utilization, cost of energy, and payback period. Results showed improved PV technical and economic performance, with an annual yield factor of (128.34–183.75) kWh/kWp, CF of (17.82–25.52)%, energy cost of 0.196 USD/kWh, payback period of 7–8 years, and efficiency of 9.1%.

In addition to nanoparticle-enhanced PCM, PCM has been proposed to optimize PVT systems. Carmona *et al.* (2021) suggested incorporating PCM into PVT systems to reduce the operating temperature and stabilize the mean surface temperature of photovoltaic (PV) panels. This modification resulted in a significant increase in daily photovoltaic efficiency by 7.43%. The addition of PCM acts as a thermal buffer, absorbing excess heat during peak solar irradiance and releasing it when solar input decreases, thus mitigating temperature fluctuations and improving the overall energy conversion efficiency of the PV panel.

While the design of the absorber tube is known to influence the photovoltaic-thermal efficiency of PVT systems primarily, there has been a growing interest in studying the impact of the thermal collector's cross-sectional geometry on thermal efficiency and operating temperature. Studies conducted by Barbosa *et al.* (2019) have explored the effects of varying cross-sectional geometries on thermal system performance. These investigations contribute to a comprehensive understanding of the interplay between design parameters, thermal efficiency, and operating conditions in thermal systems.

This study aims to assess the performance of a PVT collector incorporating twisted absorber tubes and phase change material (PCM) containers to enhance its overall efficiency. The utilization of twisted absorber tubes is expected to facilitate improved heat transfer between the liquid and tube surface, resulting in enhanced thermal performance. Four different PVT designs were tested and compared against an unenhanced PV panel. The indoor solar simulator was employed to simulate solar irradiation and determine the photovoltaic, thermal, and combined photovoltaic-thermal collector efficiencies. The comparative analysis conducted in this study offers valuable insights into the effectiveness of the twisted absorber tube design and the influence of PCM containers on the overall performance of the PVT collector. This study contributes to the existing knowledge base on PVT systems by evaluating and comparing these different configurations.

2. Methodology

2.1 The PVT collector design

The performance evaluation of the PVT collector was carried out using parallel absorber tubes, including both twisted and circular tube cross-section areas. To ensure a uniform distribution of water flow, the absorber tubes were connected between two larger tubes known as the header and riser absorber tubes system. Additionally, to enable effective heat conduction between the tubes and the PV panel, a high thermal conductivity silicon glue was used to securely attach the absorber tubes to the bottom of the panel. The attachment of the absorber tubes using high thermal conductivity silicon glue facilitated optimal heat transfer from the tubes to the PV panel, enhancing overall thermal performance (Herrando *et al.* 2019).

Moreover, the impact of incorporating nanoparticle-enhanced phase change material (nano-PCM) into the PVT system was also investigated. Nano-PCM has the ability to store and release thermal energy during phase transitions, which can further enhance the thermal performance of the PVT collector. Evaluating the addition of PCM, the study aimed to assess its potential benefits in terms of utilization within the PVT system.

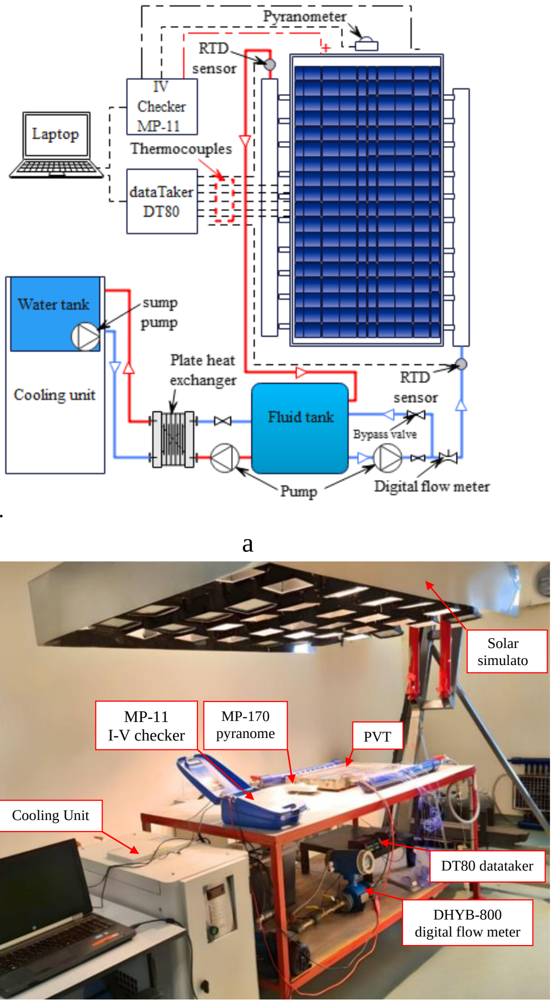
Fig 1 illustrates the nano-PCM container of the PVT configuration with circular absorber tubes and twisted absorber tubes. It visually represents the design of the PVT collector and how the absorber tubes are arranged. There are a total of 11 absorber tubes in the design. Among them, the circular tube has an inner diameter of 15mm, while the twisted tube was chosen to have an equivalent hydraulic diameter to ensure a fair comparison between the two configurations. The header tubes, which serve as inlet and outlet channels, have a diameter of 51mm. The PCM container's thickness is 5 cm.

Fig 1 The nano-PCM container with of PVT configuration with; a) circular absorber tubes, and b) twisted absorber tubes.

2.2 Experimental setup

The experiment utilized a specific PV panel model, namely the Bright-Sun BS-30P, with a maximum power rating of 30W and dimensions of 64*36cm (Bassam *et al.* 2023). Fig 2 visually depicts the experimental setup, providing a clear illustration of the arrangement and configuration of the components. Furthermore, Table 1 presents the measuring equipment employed during the experimental procedure.

This study's absorber tubes employed in the setup featured a twisted tube geometry. The twisted tube design was chosen due to its ability to create vortices within the tube, facilitating efficient heat transfer from the tube's surface to the fluid. The twisting of the tubes induces a rotational flow pattern, promoting fluid mixing and enhancing convective heat transfer. As a result, the overall thermal performance of the collector is improved (Khoshvaght-Aliabadi *et al.* 2016).



a

b

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

To conduct the experimental investigations, an indoor solar simulator was utilized. This simulator provides a controlled environment miming solar radiation conditions, allowing for accurate measurements and evaluations of the PVT collector's performance under standardized test conditions. The indoor solar simulator enables consistent and repeatable experiments, ensuring reliable data collection and analysis. The PVT setup included essential components such as the SPH20 cooling unit, fluid tank, and plate heat exchanger. Accurate measurements and data acquisition were ensured through the use of various instruments. The DHYB-800 flow meter accurately measured flow rates, while the DT80 DataTaker data logger provided versatile temperature measurements using thermocouples and RTD sensors. The MP-11 I-V Checker and the integrated MP-170 pyranometer evaluated electrical characteristics and solar irradiance, offering insights into cell performance and PVT system efficiency. These measurement devices played crucial roles in data collection and analysis, enabling a comprehensive understanding of the PVT system's operation and performance.

The experimental evaluation encompassed five water-based PVT configurations with unique characteristics and components. These configurations, shown in Fig 3, include:

a) Unenhanced PV panel: This configuration represents the baseline case, where the PV panels operate independently without additional thermal enhancement.
b) Circular absorber tubes with PVT (C-PVT): This configuration integrates circular absorber tubes within the PVT system, aiming to enhance thermal performance by utilizing the absorbed heat from the tubes.
c) Twisted absorber tubes with PVT (T-PVT): In this configuration, twisted absorber tubes maximize heat transfer efficiency through the induced rotational flow pattern.
d) Circular absorber tubes with PVT and nano-PCM (C-PVT-PCM): This configuration introduces the use of nano-enhanced phase change material (nano-PCM) in combination with circular absorber tubes, aiming to exploit the heat storage capacity of PCM to improve thermal performance further.
e) Twisted absorber tubes with PVT and nano-PCM (T-PVT-PCM): This configuration combines the benefits of both twisted absorber tubes and nano-PCM, aiming to achieve the highest possible thermal performance by leveraging enhanced heat transfer and PCM's heat storage capabilities.

By evaluating these different PVT configurations, the study aims to compare their performance and identify the most efficient and effective design for maximizing combined photovoltaic and thermal energy conversion.

Stringent measures were taken to ensure the accuracy and reliability of the experimental parameters. The mass flow rate of water was carefully controlled and stabilized before initiating the irradiation process to prevent any preheating of the systems that could affect the accuracy of the results. Monitoring the system until thermal equilibrium was reached ensured the stability of the data, with minimal changes observed after approximately 30 to 45 minutes, depending on the specific volume flow rates employed. To validate the consistency and reliability of the data, each experiment was conducted for one hour, during which data was collected using the DataTaker. The electrical performance was also assessed using the I-V Checker before turning off the solar simulator. This evaluation ensured the accuracy of the solar irradiance levels by taking multiple measurements with the pyranometer, enabling a comprehensive assessment of the system's performance throughout a complete cycle.

This approach minimized uncertainties and errors in the data. Multiple repetitions of the experiments were performed under the same set of parameters and working conditions until consistent and similar results were obtained. For instance, if data was collected under specific conditions, such as a mass flow rate of 0.008 and solar irradiance of 800 W/m2, multiple repetitions were carried out to confirm the stability of the system's performance and the reliability of the instrumentation and other components. Thorough checks and comparisons were conducted to identify and address any significant differences or errors in the data. Upon completion of each experiment, the system was carefully brought back to the ambient temperature, and the collected data was meticulously examined and compared to ensure the absence of any notable discrepancies or errors.

2.3. Uncertainty analysis

Regardless of the methods adopted, it is critical to check the data in order to prevent the addition of measurement errors in any experiment. These errors might arise either accidentally or as a result of the examiner's blunders. In certain circumstances,

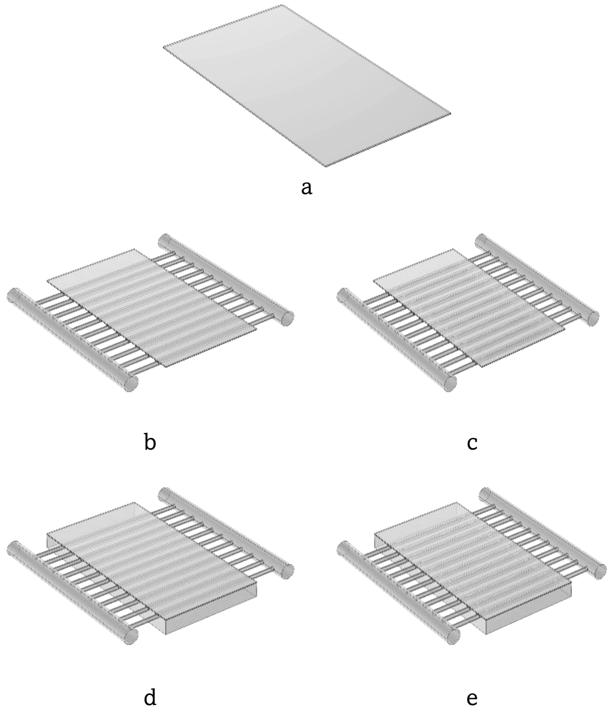


Fig 3 The configurations analyzed: a) Unenhanced PV panel, b) C-PVT, c) T-PVT, d) C-PVT-PCM, e) T-PVT-PCM).

obvious errors might assist in identifying and swiftly correcting data shortcomings. However, discarding data points randomly is inappropriate and may result in biased selection. The statistics may not match our expectations until the errors are addressed. Outliers beyond the range of projected random fluctuations can be identified and removed using reliable statistical data analysis. It is crucial to guarantee that subjective human assessments and prejudicial views do not impact the data analysis process, as suggested by the term 'should be' (Holman 2011).

The Kline and McClintock (1953) approach for determining test uncertainty was used to analyze various experimental measurement mistakes. To ensure the integrity and dependability of experimental results, it is essential to exhibit care and vigilance in data validation and analysis. Researchers may detect and rectify any issues by using proper procedures and statistical approaches, assuring the correctness and validity of the data. The amount of uncertainty in the obtained findings is determined using the following equation:

$$W_R = \left[\left(\frac{\partial R}{\partial \chi_1}\omega_1\right)^2 + \left(\frac{\partial R}{\partial \chi_2}\omega_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial \chi_n}\omega_n\right)^2\right]^{0.5} \qquad (1)$$

Uncertainty is represented by W_R. The uncertainties in the independent variables are denoted by $(\omega_1, \omega_2, \dots, \omega_n)$, whereas the dependent variable R is a known function of $(\chi_1, \chi_2, \dots, \chi_n)$. The experimental uncertainties were determined using the values in column four of Table 1. including the measurement equipment and their respective uncertainties. Moreover, Uniform conditions are assumed for all tests, but achieving uniform solar irradiance levels or mass flow rates can be challenging. To address this, the root mean square deviation (RMSD) is calculated to account for variations between actual experimental conditions and uniform conditions. This calculation helps quantify the uncertainty of the experiment. As a result, the practical experiences of this research are questionable in the following ways:

$$W_{R1} = [(0.1)^2 + (0.01)^2 + (0.5)^2 + (1.5)^2 + (2.91)^2 + (0.28)^2(1)^2 + (1.5)^2 + (2.91)^2]^{0.5} = 3.82\%$$

The overall uncertainty is less than 4%, indicating that the measurements are within acceptable limits and the findings are accurate.

2.4. Nano-PCM preparation

The nano-phase change material (nano-PCM) was created using two-step methods. Paraffin wax was chosen as the PCM because it is easily accessible, inexpensive, and has a range of melting points to suit the intended use. Furthermore, it is noncorrosive, thermally stable, and has good chemical stability (Zalba *et al.* 2003). Due to its high latent heat content, paraffin wax is useful for solar system applications. Paraffin wax, which does not conduct heat well, is mixed with nanoparticles, which do conduct heat well (Kaviarasu *et al.* 2016). SiC nanoparticles between 45 and 65nm are used to create nano-PCM. SiC was chosen because previous research has shown that it makes PCM better at transferring heat (Al-Waeli *et al.* 2017a). Al-Waeli et al. (Al-Waeli *et al.* 2017c) selected a concentration of 1% nano-PCM due to its improved performance.

The procedure for producing nano-PCM is straightforward. The two-step method is the most cost-effective way to create nanofluids in large quantities, as well as a low-cost and commercial method. This method generates nanofluids by dispersing nanoparticles into the base liquid. This method can

Table 1
Details of the measurement equipment

Sensor/Instrument	Parameter	Experimental uncertainty (%)
Thermocouples (K-type)	Temperature	0.1 ℃
RTD sensor (PT100)	Temperature	0.01℃
Flow meter (DHYB-800)	Mass flow rate	∓0.5%
Pyranometer (MP-170)	Solar irradiance	∓1.5%
IV Checker (MP-11)	Voltage and current	∓1%
RMSD for determining solar irradiance level	Solar irradiance	∓2.91%
RMSD for determining the mass flow rate	Mass flow rate	∓0.28

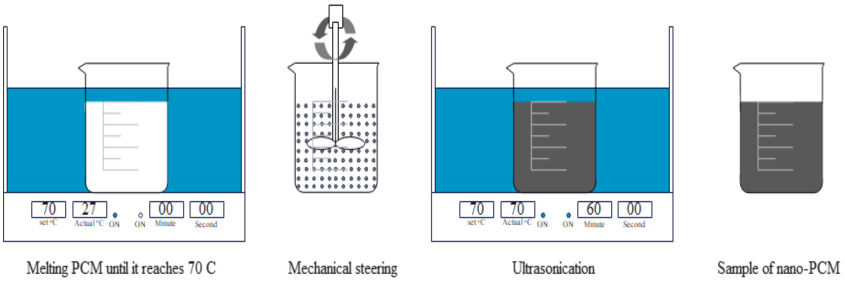


Fig 4 Process of nano-PCM preparation.

be used to produce nano-PCM. As shown in Fig 4, the procedure was as follows:

1) The PCM is melted in an ultrasonic water bath until it reaches 70°C.
2) Mechanical stirring disperses nanoparticles in melted PCM.
3) An ultrasonic water bath (XUELELILE PS-100A) with a vibration frequency of 40 kHz further enhances dispersible homogeneity.

2.5. Efficiencies analysis

The combination of photovoltaic efficiency η_{PV} and thermal efficiencyη_{th} , or the combined photovoltaic thermal efficacy η_{PVT} is as follows (Al-Waeli *et al.* 2017b, Abdallah *et al.* 2019, Kazem 2019):

$$\eta_{PVT} = \eta_{PV} + \eta_{th} \tag{2}$$

Comparing kWh of electricity to a kWh of heat makes the electrical power generated by a PVT system be regarded as a higher-grade type of energy versus the heat energy stored in water (Coventry *et al.* 2003). Thus, the Primary Energy Saving (PES) efficiency, η_{PES} is given as follows (Aste *et al.* 2014, Fudholi *et al.* 2014),

$$\eta_{PES} = \frac{\eta_{PV}}{\eta_P} + \eta_{th} \tag{3}$$

η_P is a typical power plant's electricity-generating efficiency, valued at 38%. (Fudholi *et al.* 2014, Liang *et al.* 2015, Sardarabadi *et al.* 2017).

Equation 7 could be used to determine the photovoltaic efficiency as follows (Lee *et al.* 2019),

$$\eta_{PV} = \frac{P_m}{I * A_{PV}} \tag{4}$$

P_m is the maximum power of the PVT, I is the irradiance on the PV plane, and A_{PV} is the area of the PVT.

Equations 8 and 9 can be used to determine the useful gain energy, Q_u , and the thermal efficiency, respectively (Yu *et al.* 2019).

$$Q_u = \dot{m} * c_p * (T_{out} - T_{in}) \tag{5}$$

$$\boldsymbol{\eta_{th}} = \frac{\boldsymbol{Q_u}}{\boldsymbol{I * A_{PV}}} \tag{6}$$

$\boldsymbol{\dot{m}}$ is the mass flow rate of fluid, $\boldsymbol{c_p}$ is the specific heat capacity of fluid (water/nanofluid), $\boldsymbol{T_{in}}$ and $\boldsymbol{T_{out}}$ is the inlet and outlet fluid temperature of the PVT, respectively.

3. Results and Observations

This study experimentally investigated the performance of five different configurations (unenhanced PV panel, C-PVT, T-PVT, C-PCT-PCM, and T-PVT-PCM). The configurations were evaluated using an indoor solar simulator, with a solar irradiance level of 800 W/m^2, and water was used as the working fluid with a mass flow rate ranging from 0.008 to 0.04 kg/s. The comparison between the PVT collectors focused on their photovoltaic and thermal efficiencies at the specified flow rates. The first subsection discusses the photovoltaic efficiency of both the unenhanced PV panel and the PVT collectors. The second subsection explains the thermal efficiency of the PVT collectors exclusively. Lastly, the study evaluates the photovoltaic thermal efficiency and the primary energy savings efficiency of the PVT collectors.

3.1. Photovoltaic efficiency

First, the performance of the unenhanced PV panel was evaluated. The PV surface temperature reached 86.43°C, resulting in a photovoltaic efficiency of approximately 6.3%. Simultaneously, the short circuit current (Isc) was measured at 0.9 A, and the open circuit voltage (Voc) was recorded as 12.4 V.

Next, the PVT collectors were evaluated under identical conditions. Fig 5 displays the PV surface temperature. It can be observed that the surface temperature exhibited a slight decrease with an increase in the mass flow rate. Specifically, when the mass flow rate increased from 0.08 to 0.04 kg/s, the surface temperature decreased by approximately 3°C. This reduction can be attributed to the larger fluid passing through the absorber tubes at higher flow rates, resulting in enhanced convective cooling and faster heat transfer. Notably, the use of twisted absorber tubes led to a more pronounced decrease in the PV surface temperature compared to the collectors with circular tubes. For instance, the PV surface temperature for C-PVT was around 67°C, while T-PVT recorded a lower temperature of approximately 55°C. The advantage of twisted tubes lies in their ability to increase turbulence within the tubes, disrupting the boundary layer and promoting more efficient heat transfer between the tube and the fluid flowing through it.

Furthermore, incorporating nano-PCM in the PVT collectors contributed to a further reduction in the PV surface temperature. Specifically, the PV surface temperatures for C-PVT-PCM and T-PVT-PCM were measured at around 60°C and 54°C, respectively. This decrease can be attributed to the PCM's ability to absorb and store excess heat energy, preventing overheating and maintaining a lower surface temperature.

The photovoltaic efficiency of the PVT collectors is illustrated in Fig 6. The C-PVT configuration exhibited an efficiency of approximately 8.1%. However, the efficiency increased to around 8.9% when utilizing the T-PVT

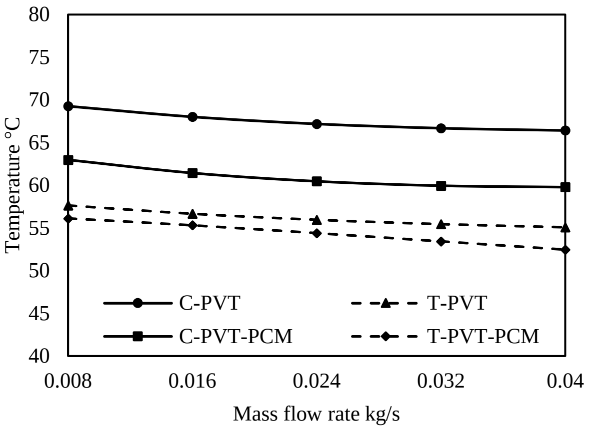


Fig 7 Mean PV surface temperature.

configuration. Incorporating PCM in the collectors resulted in further improvements, with C-PVT-PCM achieving an efficiency of about 9.3% and T-PVT-PCM reaching approximately 9.9%. It is important to note that the PV surface temperature influences photovoltaic efficiency. As the surface temperature decreases, the photovoltaic efficiency tends to increase. This relationship can be attributed to lower temperatures mitigating thermal losses and reducing the resistance of the semiconductor materials used in the PV cells. Consequently, a lower surface temperature enables a more efficient conversion of solar irradiance into electricity.

Fig 7 presents the IV curves for all the evaluated configurations. Notably, the Isc did not exhibit a significant variation with the PV surface temperature and remained around 0.95 A. It is important to highlight that Isc is primarily influenced by the solar irradiance level, which remained constant throughout this study. In contrast, the Voc demonstrated a clear relationship with temperature, increasing as the PV surface temperature decreased. This phenomenon can be attributed to the reduced losses associated with electron-hole recombination at lower temperatures, resulting in improved voltage output of the photovoltaic cell. Specifically, the unenhanced PV panel recorded a Voc of around 16.2 V, meanwhile the C-PVT, T-PVT, C-PCT-PCM, and T-PVT-PCM configurations achieved Voc values of approximately 18.8 V, 20 V, 19.7 V, and 21.2 V, respectively.

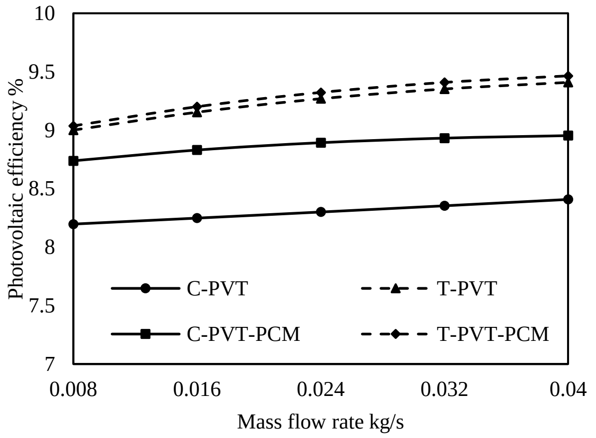


Fig 6 Photovoltaic efficiency.

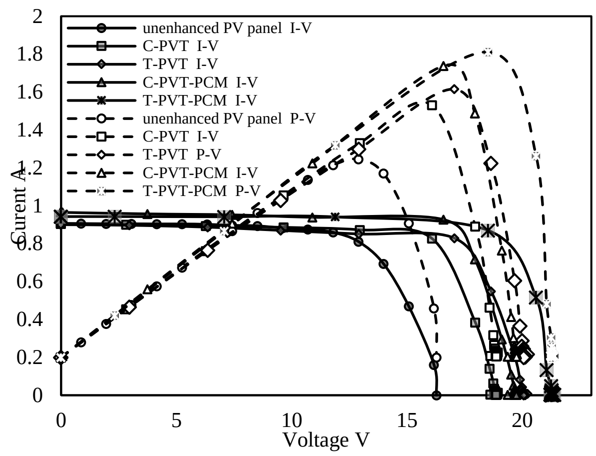


Fig 5 IV and PV curves.

3.2. Photovoltaic efficiency

Fig 8 illustrates the variation in the temperature difference between the outlet and inlet water of the PVT collector. It is observed that the temperature difference decreases as the mass flow rate increases. This phenomenon can be attributed to the shorter residence time of the fluid within the absorber tube at higher flow rates. Consequently, there is less time for heat absorption, leading to a reduced temperature difference between the fluid's inlet and outlet. In contrast, Fig 9 reveals that the thermal efficiency of the PVT collector increases with higher mass flow rates. This improvement in thermal efficiency can primarily be attributed to the enhanced heat transfer coefficient. Higher flow rates promote more efficient convective heat transfer between the absorber tube and the working fluid. As a result, there is more effective energy transfer from the collector to the fluid. Despite the decrease in temperature difference, this enhanced heat transfer compensates for the reduced temperature gradient, leading to an overall increase in thermal efficiency.

Furthermore, the T-PVT configuration exhibits higher thermal efficiency compared to C-PVT. The thermal efficiency of C-PVT ranges from 43.1% to 52.8%, whereas T-PVT achieves a higher range of 61.5% to 75.2%. This disparity can be attributed to the superior heat transfer coefficient in the twisted tube design, which enhances the collection of useful heat.

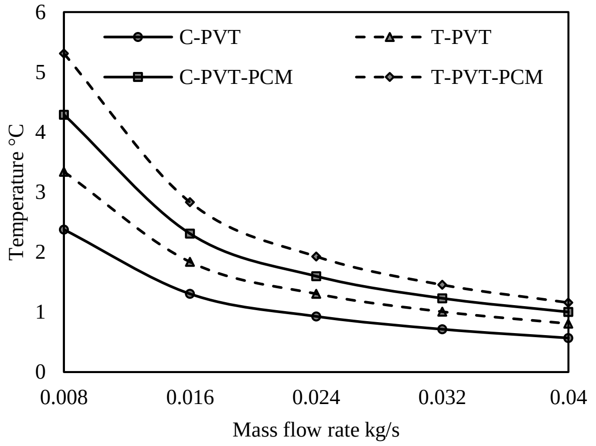


Fig 8 The temperature difference between the outlet and inlet water of the PVT collector

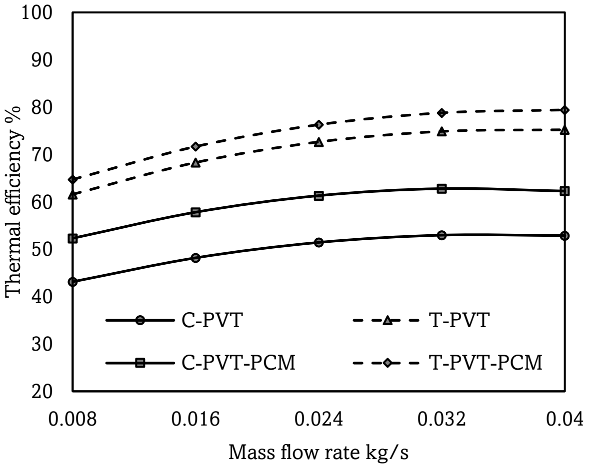


Fig 9 Thermal efficiency

Moreover, incorporating PCM in C-PVT-PCM and T-PVT-PCM configurations further improves thermal efficiency. In the case of C-PVT-PCM, the efficiency increases from 52.3% to 62.2%, while for T-PVT-PCM, it increases from 64.7% to 79.4%. The utilization of PCM enables the absorption and storage of excess heat energy. This thermal energy storage capability allows PCM to consistently release heat to the fluid. Consequently, it helps maintain a more constant and optimal temperature within the collector, leading to an overall increase in thermal efficiency.

3.3. Photovoltaic thermal efficiency and primary energy-saving efficiency

Fig 10 provides insights into the photovoltaic thermal efficiency and primary energy-saving efficiency of the PVT/PCM setups. The T-PVT-PCM combination demonstrated a remarkable maximum primary energy savings efficiency of 104.3% and a maximum photovoltaic thermal efficiency of 88.68%. These findings align with a previous study by Menon *et al.* (2022), which investigated the serpentine collector PVT configuration with water as the working fluid. Menon et al. reported photovoltaic thermal efficiency and primary energy saving efficiency values of 88.44% and 103.08%, respectively. This agreement between the results strengthens the reliability and consistency of the observed efficiencies.

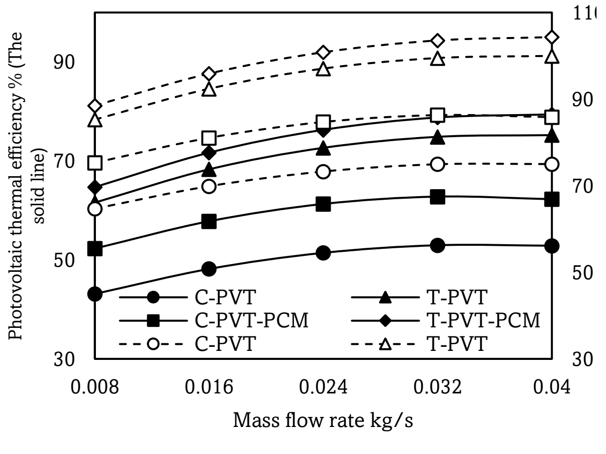


Fig 10 The photovoltaic thermal efficiency and the primary energy savings efficiency based on the mass flow rate.

Table 2
Summary of the Performances.

Configuration	η_{th}%	T$_{PV}$ °C	P_m W	η_{PV}%	FF
PV	-	86.43	10.09	6.3	0.68
C-PVT	52.86	66.41	12.86	8.4	0.75
T-PVT	75.21	55.08	13.40	9.4	0.74
C-PVT-PCM	62.27	59.78	13.15	8.9	0.74
T-PVT-PCM	79.40	52.46	14.16	9.4	0.77

The experimental results revealed that the utilization of the twisted tube in conjunction with PVT configurations resulted in a significant increase in the system's thermal efficiency when water was employed as the main fluid. This enhancement is summarized in Table 2, which presents the key findings derived from the experiments. Notably, both circular and twisted tube configurations improved performance when PCM was incorporated.

These findings highlight the effectiveness of the T-PVT-PCM combination in achieving high thermal efficiency and primary energy savings. The successful integration of PCM in the PVT system offers promising potential for improved energy utilization and management. Overall, the results emphasize the significance of the twisted tube design and the incorporation of PCM in enhancing the performance and efficiency of PVT systems, particularly in terms of thermal characteristics and energy savings.

Numerous previous studies have been conducted to assess and enhance PVT collectors' thermal energy and electrical power generation capacity and overall performance. Similarly, the present study aims to improve these aspects by replacing the conventional circular absorber tube with a novel twisted tube design. To our knowledge, the performance evaluation of PVT collectors utilizing a twisted absorber tube has not been previously explored. Therefore, previous works have primarily made comparisons among configurations employing water as the working fluid, with a specific focus on the absorber tubes. In previous studies, Sopian *et al.* (2016) employed a PVT collector with a rectangular absorber tube, while Al-Waeli et al. (2017b, 2020) used a circular absorber tube and further enhanced it by adding nano-PCM surrounding the absorber tube in a subsequent study. Shahsavar *et al.* (2020) utilized absorber tubes of circular, triangular, and rectangular shapes. Furthermore, Shahsavar *et al.* (2021b) investigated the performance of circular absorber tubes with four and eight inner fins, while Shahsavar *et al.* (2021a) explored circular absorber tubes with three and six rib fins. Zamen *et al.* (2022) employed a PVT collector with a half-circular absorber tube. Bassam *et al.* (2023) also incorporated inner micro fins in their absorber tubes. Fig 11 provides a comparative analysis of the thermal efficiency of the PVT collector investigated in the current study with those reported in previous works. However, it should be acknowledged that evaluating efficiency differences across studies is challenging due to variations in factors such as solar cell cooling techniques, absorber tube designs, experimental conditions (indoor or outdoor), and overall system configurations. Given the unique set of conditions and variables in each study, a comprehensive comparison becomes inherently complex. Nevertheless, the present study demonstrates that the twisted tube configuration outperforms other configurations in terms of thermal efficiency.

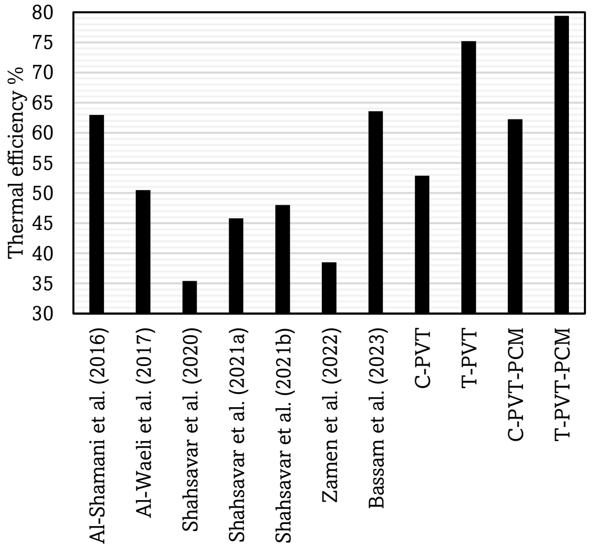


Fig 11 Comparisons of PVT and PVT-PCM in the literature and the present work

5. Conclusions

This study aimed to comprehensively evaluate the photovoltaic, thermal, and combined thermal efficiencies of four distinct configurations: C-PVT, T-PVT, C-PVT/PCM, and T-PVT/PCM. The performance of each configuration was compared to that of the unenhanced PV panel. The results obtained shed light on several key findings.

Firstly, all configurations exhibited a significant decrease in surface temperature compared to the unenhanced PV panel. The T-PVT-PCM configuration stood out with the most substantial temperature reduction, reaching approximately 30°C. This reduction in surface temperature is of great significance as it helps maintain optimal operating conditions for the PV panel, contributing to its overall efficiency and longevity.

Moreover, the T-PVT-PCM configuration achieved the highest photovoltaic thermal efficiency, reaching an impressive 88.86% when operated at a flow rate of 0.04 kg/s. This configuration demonstrated the seamless integration of photovoltaic and thermal energy, maximizing the system's overall energy output. On the other hand, the T-PVT configuration excelled in electric power enhancement, achieving a remarkable increase of 27.74% compared to the unenhanced PV panel.

In terms of primary energy savings, all configurations surpassed a minimum efficiency threshold of 74.99%. The T-PVT-PCM configuration exhibited the highest primary energy savings efficiency, surpassing expectations with a remarkable efficiency of 104.31%. These findings highlight the substantial energy-saving potential of the evaluated configurations, thereby emphasizing their relevance for sustainable energy applications.

Furthermore, the study unveiled the superiority of twisted tubes over circular tubes in terms of thermal efficiency within both PVT and PVT-PCM configurations. Twisted tubes demonstrated enhanced convective heat transfer characteristics, resulting in improved thermal performance. While the addition of PCM positively influenced the efficiency of circular tubes, its impact on twisted tubes was relatively minimal.

As a prospective avenue for future research, addressing the limitation of water's poor thermal conductivity could be explored by investigating the potential utilization of nanofluids. Incorporating nanofluids into PVT and PVT/PCM systems holds promise for further enhancing their efficiency and overall performance. Conducting research in this area could open up new opportunities for advancing the field and achieving even greater improvements in the efficiency of PVT and PVT/PCM systems. This study comprehensively assesses various configurations for PVT and PVT/PCM systems, elucidating their photovoltaic, thermal, and combined efficiency. The findings underscore the advantages of employing twisted tubes, the benefits of integrating PCM, and the potential for future nanofluids advancements.

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