SCIENCE CHINA
Technological Sciences

• REVIEW •
Special Topic: Clean and Efficient Heating Technology

June 2025, Vol. 68, Iss. 6, 1600101:1–1600101:13
https://doi.org/10.1007/s11431-024-2814-4

Hybrid solar photovoltaic/thermal module based on various nanofluid applications: A state-of-art review

Shuangqing TIAN & Yuanlong CUI*

School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan 250101, China

Received May 22, 2024; accepted October 21, 2024; published online April 24, 2025

Abstract Solar energy is one of the most extensively utilized sustainable energy resources. It can effectively reduce greenhouse gas emissions and achieve energy savings. Photovoltaic/thermal (PV/T) modules are typically used to achieve photo-to-electricity and photo-to-thermal energy conversions. Various nanofluids have been adopted as thermal fluids to improve the heat exchange performance of PV/T modules. Consequently, this paper reviews and investigates the latest progress in PV/T module applications integrated with different types of nanomaterials, including metal and metal oxides, non-metallic materials, magnetic fluids, and nano-reinforced phase change materials (NePCMs), and thermal pipe structures such as twisted tubes, bionic tubes, serpentine tubes, and microchannels. The influences of different parameters, including dimensions, concentration, stability, and nanomaterial base-fluid choices, on the overall energy conversion efficiency are also discussed. Furthermore, the effect of an external magnetic field on the PV/T system performance is analyzed. The results demonstrated that the entire system efficiency could be achieved in the 85%–90% range by optimizing the PV/T pipe structure arrangements and introducing various nanofluids compared with conventional PV/T modules.

Keywords renewable energy, photovoltaic/thermal, energy performance enhancement, thermal pipe structures, stability of nanofluids

Citation: Tian S Q, Cui Y L. Hybrid solar photovoltaic/thermal module based on various nanofluid applications: A state-of-art review. Sci China Tech Sci, 2025, 68(6): 1600101, https://doi.org/10.1007/s11431-024-2814-4

1 Introduction

Greenhouse gas emissions have drawn worldwide attention to sustainability owing to climate change and human activities. Traditional non-renewable energy is the primary source of carbon dioxide (CO_2) [1]. Therefore, various renewable energy resources, such as bioenergy, wind, hydro, and solar, have been utilized to combat climate risks [2]. Solar power is one of the renewable energy sources because of its inexhaustible supply and cost-effectiveness. Its primary applications include solar power and thermal generation, which are integrated for efficiency improvement. To be more specific, Wolf [3] first integrated the photovoltaic (PV) module with a heat exchanger as a single module to capture excess heat and improve the problem of PV cell overheating. Sarhaddi et al. [4] optimized the numerical photovoltaic/thermal (PV/T) model with air-cooled systems. They found that the system total efficiency could achieve 70%, much higher than that of PV or solar thermal collectors alone. Modjinou et al. [5] explored energy conversion efficiencies of PV/T systems with an encapsulated phase-change material (PCM), PV/T with a microchannel, and conventional PV/T systems. It is demonstrated that the average system efficiency can reach 36.71% for the PV/T system integrated with an encapsulated PCM, 35.53% for the PV/T with the microchannel system, and 31.78% for the conventional PV/T system. However, there are still some limitations, such as uniform temperature distribution, low thermal conductivity of working fluids, limited cooling effect, and high capital investment [6], making the current contribution of solar energy to global electricity production only 3.6% [7]. Consequently, many techniques for heat transfer improvement have been widely investigated by modifying thermal pipe structures involving

* Corresponding author (cuiyuanlong22@sdjzu.edu.cn)

bionic, microchannel, and serpentine pipe structures, as well as using nanomaterials as working fluids, including copper oxide (CuO), silicon carbide (SiC), multi-walled carbon nanotubes (MWCNT), and single-walled carbon nanotubes (SWCNT). Nanofluids are regarded as suspensions of nanoparticles doped into a base fluid, with better heat exchange efficiency and heat conductivity compared to a single base fluid, such as water [8]. The different nanomaterials used in PV/T systems are illustrated in Figure 1 [9].

Specifically, Emmanuel et al. [10] summarized the latest developments in PV/T. They found that a mixture of nanofluids and PCMs increases the availability of heat energy and exhibits better efficiency when solar radiation was unavailable or weak. Sohani et al. [11] utilized zinc oxide (ZnO), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3) as thermal fluids in a PV/T system and demonstrated that the ZnO nanofluid had the maximum system thermal and electrical conversion efficiencies of 47.63% and 14.65%, respectively. Abdallah et al. [12] tested the impact of the MWCNT nanofluid concentration on the PV electrical efficiency and surface temperature. It is demonstrated that the PV surface temperature could be eliminated by 10.3°C, leading to a 61.23% rise in overall system efficiency at 0.075 vol%. Rajamony et al. [13] incorporated graphene nanoparticles (GNP) into paraffin wax with the aim of enhancing the thermal conductivity of the thermal fluid within a PV/T module. It is revealed that the heat transfer coefficient could be increased by 75.09% compared with that of traditional PV/T systems.

Although solar PV/T modules can provide both electrical and thermal energy outputs concurrently, many aspects, including the low thermal conductivity and heat exchange rate of the carrier fluids, still need to be investigated for energy and efficiency improvements. Kalsi et al. [14] summarized the utilizations of nanofluids in heat transfer. They revealed that using nanofluids within PV/T modules is becoming an increasingly attractive area of research. Umam et al. [15] compared the effect of traditional nanofluids, such as metal- and carbon-based nanoparticles, on the system efficiency and concluded that metal-based nanofluids have satisfactory results. However, new composite nanomaterial modifications of the internal structures and pipe arrangements have not been mentioned. This study aims to bridge this knowledge gap by summarizing the applications of nanofluids in PV/T modules. The obstacles, foundational concepts of PV/T modules integrated with nanomaterials, and different pipe structures are given in Section 1; the structure and classification of PV/T systems are described in Section 2; the progress of thermal pipe structural modification and integration of nanofluids into PV/T modules as the core contents are illustrated in Sections 3 and 4; an economic and environmental assessment is presented in Section 5; and the limitations, challenges, and upcoming technological advancements are elaborated in Section 6. Eventually, the key outcomes are presented in Section 7.

2 PV/T system structure and performance

A typical PV/T system primarily is composed of a glass cover, a PV panel, a thermal collector, a working fluid, and an insulation layer, as shown in Figure 2(a). During operation, the PV module absorbs solar radiation to obtain electrical power, which captures the heat energy transferred via the working fluid and is utilized for space heating and hot water applications. Typically, PV/T modules can be divided into two main categories: flat-plate (PV/T) and concentrating type (CPV/T), which can be cooled using air, liquid, and two fluids, as illustrated in Figure 2(b). Compared with PV/T modules, CPV/T modules require more robust cooling methods because of the higher temperatures generated by light concentration.

3 Solar PV/T module with various pipe structures

To harvest more solar energy, some researchers have numerically and experimentally investigated the module structure, and improved the contact area and the number of cooling channels. Hence, some novel categories of PV/T modules are discussed in this section, including twisted tubes, bionics, new serpentine pipes, and microchannel pipe structures.

3.1 PV/T with twisted tube structure

PV/T modules with twisted tube structures can increase the heat transfer coefficient and heat transfer capacity because of

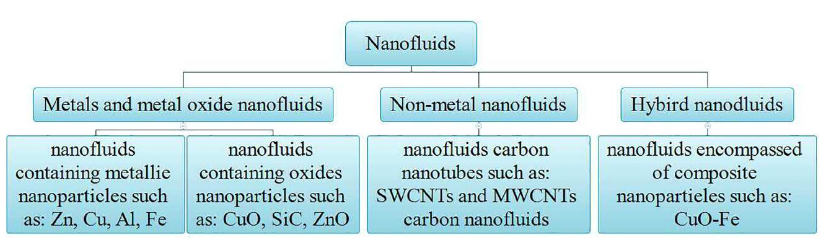

Figure 1 (Color online) Different kinds of nanoparticles applied into PV/T module [9].

the bonds, fins, and vanes of the twisted tube structures. However, limitations include pressure drop rise and temperature distribution inhomogeneity along the PV/T module [16]. Specifically, Tahmasebi et al. [17] explored PV/T modules with twisted tube structures to investigate the effect of twisted tape on thermohydraulic performance, as displayed in Figure 3(a). It is found that the presence of the bond could contribute to the improvement in thermal energy conversion performance. The performance evaluation coefficient (PEC) was approximately 27% when the pitch ratio was 0.75.

Elmasry et al. [18] explored a novel heat collector with a V-cut twisted-band turbulator to analyze the influence of the pitch and Reynolds number (*Re*) on the system efficiency, as depicted in Figure 3(b). It is concluded that, compared with the ordinary PV/T system, the total energy and exergy e fficiencies can increase by 7.70% and 13.08%, respectively, at *Re*=2000. Maadi et al. [19] integrated a tapered blade tip into a PV/T system, as shown in Figure 3(c). The total efficiency was the highest (up to 89%) at a blade angle of 360°, 11.9% higher than that of ordinary tubes. Ghasemian et al. [20] compared the impacts of different pipe shapes, including triangular, circular, and square pipes, on the pipe flow and system efficiency, as illustrated in Figure 3(d). This study revealed that the PV/T with a circular pipe exhibited the highest efficiency, reaching 13.01% among these pipe structures. In the meantime, the electrical efficiency could reach the maximum value of 7.2% resulting in a reduction of surface temperature by 17.55°C compared to the PV alone.

3.2 PV/T with bionic pipe structure

Considering the optimization process concerning thermal pipe structures, it has been found that the characteristics of nature inspire many promising structures. Bionic structures have proven to be effective for improving the performance of PV/T channels. Specifically, Wang et al. [21] developed a bionic microchannel heat sink based on the branch morphology to address the issue of nonuniform heat transfer within the pipe, as shown in Figure 4(a). Compared with a rectangular channel structure, the system exhibited a 30% reduction in the friction coefficient and a 45% increase in the thermal enhancement coefficient. Similarly, Zareie et al. [22] analyzed the effect of three variables, including space between branches (s), angle of branches (θ), and length of branches (L), PV/T with roll-bond collector structure as displayed in Figure 4(b). Results illustrated that the entire system efficiency could reach the maximum value of 75.56% when θ, s, and l were set as 96.7°, 19 mm, and 13 mm, respectively. Liang et al. [23] developed a novel thermal pipe insert to enhance the laminar convection from the perspective of bionics based on the motion of the cuttlefish shape, as shown in Figure 4(c). When the amplitude and *Re* were de-

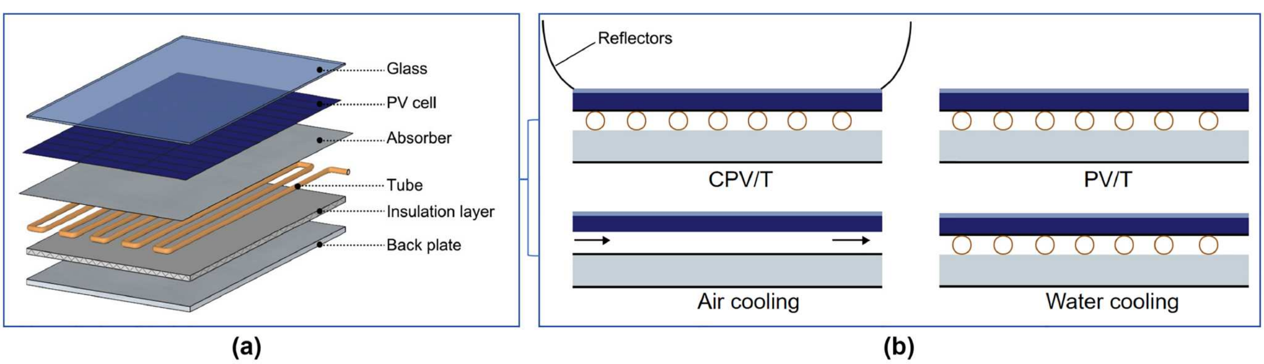

Figure 2 (Color online) (a) PV/T structure; (b) PV/T classification.

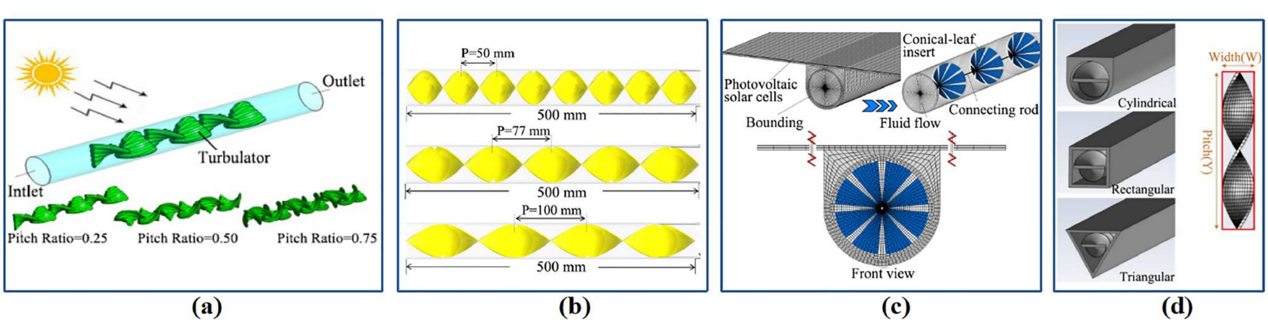

Figure 3 (Color online) Insert pipe styles. (a) Twisted tape [17]; (b) V-cut twisted-band [18]; (c) conical-leaf [19]; (d) pipe shapes [20].

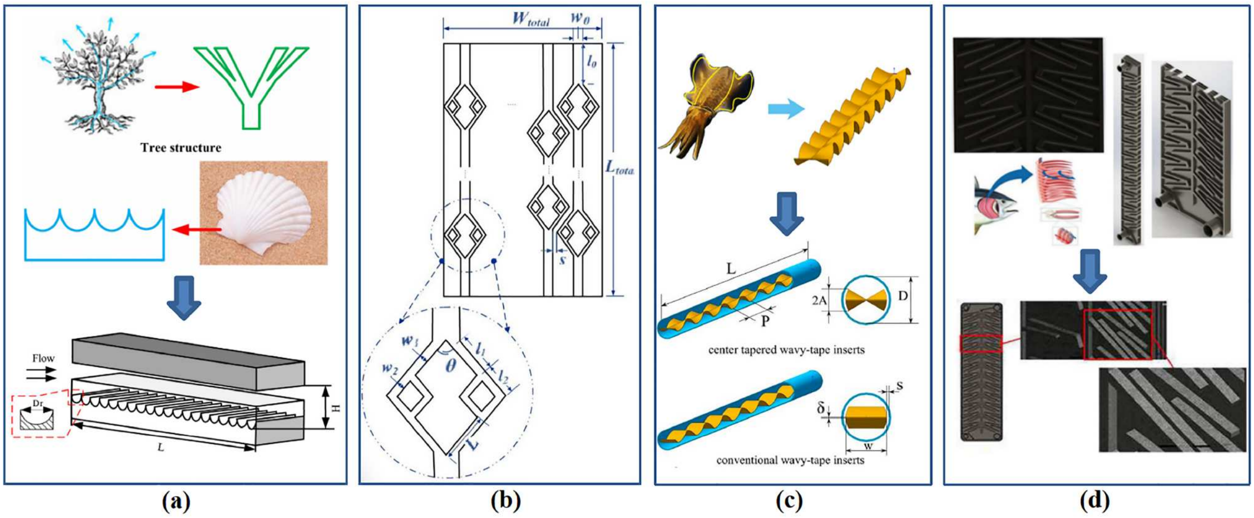

Figure 4 (Color online) Bionic pipe types. (a) Tree-like and shells bionic structure [21]; (b) branch morphology [22]; (c) cuttlefish-shaped inserts [23]; (d) gill-shaped fins [24].

fined as 5.4 mm and 1800, the optimal PEC value could reach 2.42, while the optimal PEC value for conventional wave-type inserts was 1.98. The system's thermal performance could be increased by 22%. Göltaş et al. [24] were inspired by the "gills" in nature to increase the fluid heat transfer area through narrow channels, as presented in Figure 4(d). Compared with a normal V-shaped corner heat exchanger, the system thermal efficiency enhanced by 17.5% when water was used as the working fluid, and the thermal uniformity was superior owing to the presence of micro-shaped channels.

3.3 PV/T with microchannel pipe structure

The advantages of using microchannel structures as heat exchangers include fast flow rates and large heat transfer areas, which can assist in performing more heat exchange than conventional hot plates under the same conditions [25]. For example, Zhou et al. [26] introduced an innovative PV/T design with microchannels as heat exchangers, which consisted of an aluminum plate with dimensions of 1950 mm × 950 mm × 0.4 mm connected to the heat exchanger by a thermally conductive adhesive. The thermal and electrical efficiencies of the experimental modules were 48.0% and 12.6%, respectively, under typical summer day conditions. Khan et al. [27] conducted a numerical analysis of a PV/T using three categories of microchannel heat exchangers: double corrugation, single corrugation, and straight grooves. It is demonstrated that the Nusselt number of the double-corrugated structure can increase by more than 50% compared with that of the flat groove structure. Moreover, the double corrugated channel exhibits an average maximum temperature drop of 10°C. In comparison, the flat-bottom channel shows a drop of 9°C at the same concentration. Li et al. [28] performed a numerical assessment of a PV/T with microchannels to investigate the influence of the microchannel quantity and width on the system performance. The thermal efficiency of the system could be enhanced by 2.71% when the number of microchannels increased from 12 to 20. In contrast, the thermal efficiency increased by 4.3% when the width varied from 40 to 80 mm. Shahsavar et al. [29] examined a PV/T combined with three types of gyratory groove microchannel modules: smooth, symmetric, and staggered grooves for internal piping. It is concluded that the PV/T with staggered grooves demonstrates superior performance, with an entire efficiency of 86.47%, whereas the smooth and symmetrical groove types have overall efficiencies of only 69.42% and 79.51%, respectively.

3.4 PV/T with serpentine thermal pipe structure

PV/Ts with a serpentine-tube collector have been extensively utilized because of their serpentine-shaped flow path. Several approaches have been adopted, including the addition of fins and grooves. More specifically, Ali et al. [30] contrasted the efficiency of a single serpentine channel and a double serpentine channel with Al_2O_3-Cu hybrid nanofluids as the working fluid, as shown in Figure 5(a). It is found that the double serpentine channel has a larger heat-transfer area than the single channel based on identical circumstances. Meanwhile, the efficiency of the PV/T with a double serpentine channel was 90.47%, whereas that of the single serpentine channel is 84.3% at Re=1000 and a nanofluid concentration of 1 wt%. Shahsavar et al. [31] developed the solar PV/T system performance of a new plate-grooved serpentine tube by adding groove spacings of 8 and 5.4 mm, respectively, as

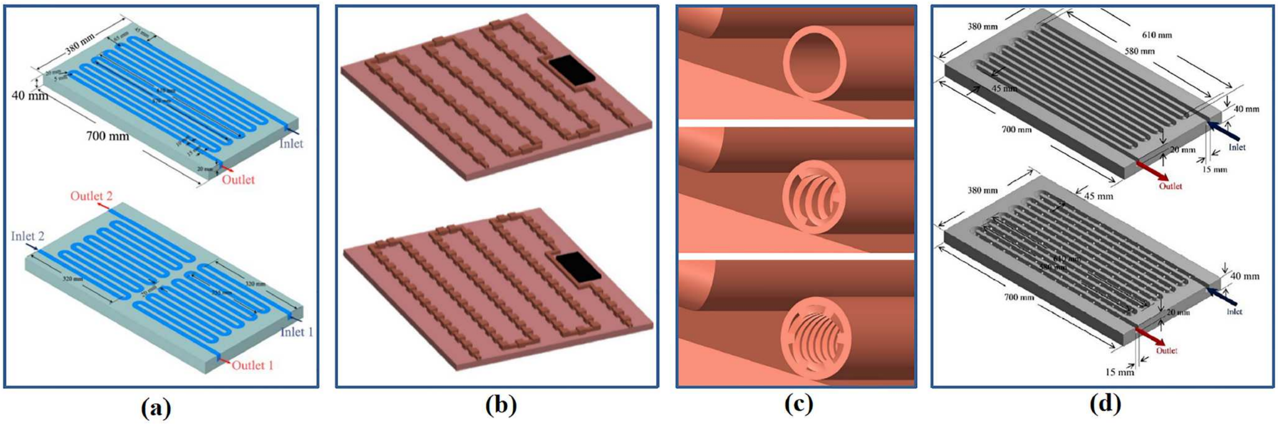

Figure 5 (Color online) Serpentine tube types. (a) Double channel [30]; (b) plate-grooved tube [31]; (c) threaded pipe [32]; (d) thread and fin tubes [33].

shown in Figure 5(b). It is found that the total efficiency of the serpentine tube with a spacing of 5.4 mm grooves could reach a maximum value of 83.47%, which is an improvement of 15% compared to the plain serpentine tube. In addition, a thermal pipe with a threaded structure was employed instead of the conventional pipe applied to the PV/T module, as depicted in Figure 5(c), and it is found that the total efficiency of the 6-wire threaded PV/T module could reach up to 95.58%, which is 22.5% and 3.8% higher than those of the original and 3-wire threaded PV/T modules, respectively [32]. Si et al. [33] designed a serpentine-channel PV/T module with pin fins and a heat-exchanger structure, as depicted in Figure 5(d). The results illustrated that the serpentine channel with needle fins had a more uniform thermal distribution than the flat serpentine channel. The thermal efficiency increased by 8.35%, while the electrical efficiency raised by 0.18%.

Optimizing the pipeline configuration improves the photothermal conversion efficiency of PV/T modules. Notably, the thermal efficiency of PV/T with serpentine pipes can be increased by 8%–15%, and it was widely utilized in various industrial and commercial fields. Moreover, the PV/T with microchannel modules exhibited the best efficiency, reaching 86.47%. Moreover, the system efficiency can be improved by augmenting the number of additives, including threads, needles, and fish scale-like objects. Meanwhile, it is demonstrated that the pipe arrangement with a staggered distribution displays a more effective energy conversion than that with a symmetrical distribution.

4 Effect of the nanomaterials on PV/T system performance

4.1 Nanofluids stability analysis

The stability of nanofluids has the most significant influence on the functionality of the PV/T module and its actual applications, which are primarily controlled by the pH [34], concentration [35,36], surfactant [37,38], and ultrasonic mixing time. For instance, Zhang et al. [39] discovered that the stability of nanofluids has a positive effect on heat transfer efficiency and demonstrated that the TiO_2 nanofluid exhibited high stability when the PH values were 2 and 12. Huq et al. [35] reviewed the applications of GNP nanofluids and demonstrated that their stability increased as the particle dimensions decreased. Al-Waeli et al. [40] found that adding surfactants such as cetyltrimethylammonium bromide (CTAB) to SiC nanofluids contributed to the amelioration of stability over a long-term period. Qi et al. [41] found that SiO_2 and TiO_2 nanofluids exhibited optimum stabilization when sodium hexametaphosphate (SHMP) with an optimal mass ratio of 1:1 was employed as a dispersant in the nanofluid. Similarly, Mostafizur et al. [37] compared the effects of CTAB, sodium dodecyl sulfate (SDS), and Arabic gum (AG) on the stability and thermal properties of Al_2O_3-methanol nanofluid. They clarified that the Al_2O_3-methanol nanofluid with the CTAB dispersant was more stable than the other two dispersants after six months of observation. Ji et al. [42] also demonstrated that the γ-Al_2O_3 nanoparticles with the addition of cationic surfactant CTAB are less agglomerated compared to introduction of SDBS and Tween 60.

4.2 Types of nanofluids

The application of nanofluids is key to improving the efficiency of PV/T modules. Some nanofluids can be utilized in PV/T modules, including metal nanofluids, magnetic nanofluids, carbon-based nanofluids, and other composite nanofluids, for instance, nano-enhanced phase change materials (NePCMs).

4.2.1 Metal and metal oxide nanofluids

Metal and metal oxide nanofluids have emerged as breakthrough solutions for enhancing module performance and energy efficiency. Salehi et al. [43] investigated the effect of Al_2O_3 nanoparticles at a concentration of 2 vol% on the cooling effect and efficiency of a solar panel. It is found that the overall efficiency can be increased by 13.5%, and the average surface temperature could be reduced by 13°C, in contrast to water-cooled solar panels. Menon et al. [44] tested the efficiency of a glassless PV/T system with CuO nanofluids at a concentration of 0.05%. They concluded that the electrical and thermal efficiencies were 14.58% and 58.77% for water-based and, 17.61% and 71.11% for nanofluid-based systems, respectively. Diniz et al. [45] conducted a numerical investigation on the performance of a PV/T module by adding a gold nanofluid as the working carrier. The result demonstrated that the maximum efficiency of the PV/T module reached 52.45% at an optimal concentration of 9×10^{-6} vol%, which was 21% higher than that of a single PV module. Alktranee et al. [46] compared the effects of tungsten trioxide (WO_3)/deionized (DI) water nanofluids with different volumetric concentrations ranging from 0.5% to 1% on PV/T module performance. The electrical and thermal efficiencies of the WO_3 nanofluid at a concentration of 1 vol% increased by 58.3% and 24.7%, respectively, as compared to the PV/T module utilizing deionized (DI) water.

4.2.2 *Magnetic nanofluids*

Magnetic nanomaterials are typically classified into magnetite and ferrite nanoparticles, which can respond to external magnetic fields and enhance heat transfer efficiency. Zheng et al. [47] dispersed spherical ferric oxide (Fe_3O_4) particles in DI water to form a ferromagnetic nanofluid that possessed a concentration of 0.1 vol%. This indicated that the *Re* of Fe_3O_4 nanofluids without a magnetic nanofluid only increased by 0.22%. In contrast, *Re* was enhanced by 28.2% when the magnetic field was introduced. Bhattacharyya et al. [48] numerically investigated the effects of magnetic fields on the heat transfer performance of hybrid magnetic nanofluids. The results revealed that the applied magnetic field improved the heat-transfer rate, and the maximum Nusselt number could be increased by 230%. Ghadiri et al. [49] performed an experimental assessment of the forced convective heat transfer of Fe_3O_4 nanofluids, utilizing a concentration of 3 wt%, under the action of constant and alternating magnetic fields. It is demonstrated that a constant magnetic field has little impact on the system efficiency. Almarashi et al. [50] evaluated the influence of introducing a vertical magnetic field on the efficiency of a PV/T module with Fe_3O_4 nanofluids, revealing that the thermal and electrical efficiencies of the system could be increased by 59.48% and 8.23%, respectively, when the Hartmann number was 120.

4.2.3 *Non-metallic nanofluids*

Non-metallic nanomaterials mainly include carbon-based and many composite nanomaterials, such as MXene (Ti_2C_3), and their thermal physical properties and energy conversion efficiencies are superior to those of traditional thermal fluids. Specifically, Sreekumar et al. [51] performed a numerical investigation of PV/T modules integrated with MXene nanofluid. The results showed that, at a concentration of 0.2 wt%, the thermal and electrical efficiency were individually increased by 3.5% and 17%, respectively, in comparison to water. Kazem et al. [52] performed an experimental evaluation of the performance of a PV/T system combined with a SiC nanofluid as the heat transfer medium. They found that the electrical efficiency of the system using SiC nanofluid and water could be improved by 20.21% and 8.56%, respectively. Gelis et al. [53] formulated a numerical framework for a PV/T system with a SiC nanofluid based on the response surface methodology to determine the energy output at various concentrations (0.1 vol%, 0.2 vol%, 0.3 vol %). They concluded that the thermal efficiency ranged spanning from 47.08% to 59.12%. In contrast, the electrical efficiency varied from 17.31% to 19.8% when subjected to solar irradiance level of 600 W/m^2. Venkatesh et al. [54] experimentally explored the efficiency of a PV/T system integrated with a GNP-based nanofluid to assess the effect of various concentrations (0.1 vol%, 0.2 vol%, 0.3 vol%) and distinct flow rates on thermal and electrical efficiency. It is confirmed that the highest thermal and electrical efficiencies could attain 85% and 16%, respectively, at the concentration of 0.3 vol% and mass flow rate of 0.085 kg/s, resulting in PV surface temperature reduction by approximately 20°C. Hassan et al. [55] used GNP nanofluids as heat transfer medium in PV/T modules, with the objective of improving the total efficiency of the system. It is concluded that the overall efficiency reaches a maximum of 56.7% at a concentration of 0.1 vol%, representing an approximate 14.1% improvement in overall efficiency compared to PV/T with pure water. Büyükalaca et al. [56] numerically investigated the performance of a PV/T system with a hexagonal boron nitride (hBN)/water nanofluid using an artificial neural network model. They indicated that the electrical, thermal, and energy efficiencies of the system increased by 0.7%, 3.01%, and 1.80%, respectively, compared to the PV/T system using water.

4.2.4 *Hybrid nanofluids*

It has been demonstrated that composite nanofluids with a combination of two or more types of nanoparticles are conducive to ameliorating thermal physical properties. The type and size of the nanoparticles and their mixing ratio are key factors for the effectiveness of composite nanofluids [57]. For example, Alktranee et al. [58] added a composite TiO_2-CuO nanofluid into a PV/T system as the working fluid. They found that when the concentration was 0.2 vol%, the electrical and thermal efficiencies were increased by 10.7% and

50.2%, respectively. Karaaslan and Menlik [59] conducted a numerical assessment of the thermal harvesting influence of PV/T with a composite CuO-Fe nanofluid (50:50). The electrical and thermal efficiencies could be boosted by 2.14% and 5.4%, respectively. In contrast, the PV/T with the CuO nanofluid was improved by only 1.32% and 3.33%, respectively. Khan et al. [60] experimentally investigated the effect of a composite Fe_3O_4-SiO_2 nanofluid on the PV/T electrical energy output when the concentration was set to 3 wt%. The average electrical efficiencies were 13.85%, 13.15%, and 12.5% for PV/T with Fe_3O_4-SiO_2, SiO_2 and Fe_3O_4 nanofluids, respectively. Alktranee et al. [61] explored the effect of a hybrid TiO_2-Fe_2O_3 nanofluid on the PV/T system performance at a concentration of 0.3 vol%. The results demonstrated that the electrical and thermal efficiencies were increased by 38.36% and 35.15%, respectively, compared to PV/T with water. Murtadha [62] demonstrated that the power output of a PV/T module with a mixed Al_2O_3-TiO_2 nanofluid surpassed that of a single PV cell by 11.1%. In contrast, the enhancement with a single Al_2O_3 nanofluid reached 12.3%. Vaka et al. [63] emphasized the excellent application effects of hybrid nanofluids and nanofluids. They found that combining two-dimensional nanoparticles with metal oxides can achieve more effective performance.

4.2.5 *Comparison of different nanofluids*

In summary, there has been much research on the effect of different types of nanofluids on PV/T module efficiency enhancement under various conditions. Specifically, Diwania et al. [64] confirmed that the PV/T of CuO nanofluids has a better thermoelectric conversion performance than that of TiO_2 and Al_2O_3 nanofluids. Likewise, Lee et al. [65] found that PV/T with CuO and Al_2O_3 nanofluids could increase thermal efficiency by 21.3% and 15.14%, respectively, compared to water. In contrast, both nanofluids had very little effect on the electrical efficiency, achieving a maximum value of only 0.07%. Hooshmandzade et al. [66] reported that PV/T with an Al_2O_3 nanofluid could increase thermal and electrical efficiencies by 9.98% and 1.84%, respectively, slightly higher than SiO_2. However, the composite SiO_2-Al_2O_3 nanofluid presents the highest thermal and electrical efficiencies of 14.33% and 2.32%, respectively. Similarly, Basalike et al. [67] found that a PV/T with silver (Ag) nanofluid obtained a coefficient of performance of approximately 3, which was higher than that of the Al_2O_3 nanofluid owing to the high thermal conductivity of the Ag particles. Abesh Ahmadlou et al. [68] conducted a long-term experimental analysis to determine the efficiency of a PV/T module by adding MWCNT/water and SWCNT/water composites. The system efficiency of the PV/T with SWCNT/water reached 44.94%; in comparison, that of MWCNT/water only increased by 21.77%. This resulted in 47.28% and 30.55% PV surface temperature reductions for the two operating fluids. Furthermore, Ahmadinejad and Moosavi [69] found that PV/T with CNT and CuO nanofluids could increase the thermal efficiency by 9.46% and 14%, respectively. Alous et al. [70] contrasted the thermal efficiency of PV/T combined with three categories of nanofluids involving MWCNT, GNP, and pure water. The thermal efficiencies were 53.4%, 57.2%, and 63.1% for pure water, MWCNTs, and GNP, respectively.

Therefore, the stability of nanofluids is a crucial factor that influences their application. Introducing surfactants is the most commonly used method to obtain nanofluid stability; however, sometimes, it may negatively impact the thermophysical properties. Additionally, previous research has demonstrated that PV/T with CuO nanofluids is more efficient than Al_2O_3, TiO_2, and other nanofluids in metals and metal oxides under the same conditions. The latest research on PV/T includes two-dimensional nanofluids such as MXene, as discussed by Sreekumar et al. [51] and Das et al. [71].

4.3 Nanocomposite phase change materials

4.3.1 *NePCM thermophysical properties analysis*

To avoid the agglomeration of NePCMs, it is necessary to increase the dispersion uniformity with various solutions involving increasing the use of surfactants [72], adjusting the pH [73], and controlling the preparation temperature, similar to nanofluids. However, most studies have indicated that time has little impact on material properties [74]; meanwhile, most materials remain stable after more than 500 heat absorption and release cycles. Moreover, the selection of the PCM depends more on the phase transition temperature and latent heat capacity.

A common problem with PCM is their low thermal conductivity, which affects their energy absorption and release. By combining various nanomaterials with PCM to form NePCMs, the thermal conductivity of organic PCM can be increased by 55%–60% [75]. This is an effective approach to regulating the temperature of PV systems and prolonging the operational lifespan of the PV cells. In addition, other properties such as undercooling, latent heat capacity, phase transition temperature and density are also impacted by nanoparticles. Bhutto et al. [76] added a mixture of Ag and GNP nanoparticles to TEG. They observed that the thermal conductivity of the composite material increased by 57%. The latent heat increased by 8%. Khodadadi and Sheikholeslami [77] found that a 4% concentration of Cu-NePCM increased the energy storage capacity by 1.02% compared to a single PCM. Yang et al. [78] incorporated CuO and ZnO nanoparticles into paraffin. They found that ZnO and CuO enhanced the thermal conductivity by 5.87% and 13.12%, respectively.

4.3.2 PV/T with NePCM

Currently, more organic paraffin wax is used, which has a low price and good thermal stability, making it suitable for low-temperature household water use. Preet et al. [79] studied the influence of PCM on the performance of a PV/T system, and the findings revealed that the maximum temperature was reduced by 53% compared with a conventional water-cooled. The average daily electricity energy output was increased by 300%. This is because PCM can release or absorb energy during the gas-liquid-solid physical phase change and maintain a constant temperature during the phase transition [80]. Bassam et al. [81] incorporated 1 vol% SiC nanoparticles into a PCM to form a NePCM and applied it to PV/T modules. The results illustrated that the electrical efficiency of the PV/T module with NePCM was 8.9%, whereas that of the PV/T module integrated with water was only 6%. Moein-Jahromi et al. [82] evaluated the performance of adding GNP-CuO and NePCM to PV/T modules. The results indicated that the surface temperature of the NePCM system is reduced by 6.6°C, resulting in about 3% power energy output enhancement compared with the system with pure PCM. Fu et al. [83] combined expanded GNP with paraffin wax to create a NePCM, increasing 24.3% and 0.9% in the average thermal and electrical efficiencies at a mass fraction of 15%. Furthermore, they utilized a PCM material (MPCM) in the cooling working fluid at a concentration of 5%, leading to enhancements of 0.8% and 13.5% in the average electrical efficiency and maximum thermal efficiency for the MPCM-based PV/T system, respectively. In outdoor testing, the electrical efficiency of the MPCM PV/T system was found to be 0.1% lower than that of a pure water system, owing to its lower phase transition point [84]. The application of inorganic PCM, such as hydrated salts, in PV/T systems is limited. This was important because of their corrosiveness and propensity to react with metals. Additionally, the difference between the solid-liquid densities of salts requires PCM encapsulation units to prevent salt corrosion and provide sufficient space for salt volume expansion [85]. Abdelrazik et al. [86] incorporated four nanoparticles (GNP, MWCNT, CuO, and diamond) into inorganic calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) to investigate the impact of the loading on the efficiency. It is concluded that the PV/T with multi-carbon nanotubes could increase the thermal and electrical efficiencies of the system by 9.3% and 18%, respectively, compared with PCM alone.

In conclusion, nanofluids and NePCM positively affected the thermal and electrical energy conversion of a PV/T system. Efficiency comparisons of typical nanofluids and NePCMs applied in PV/T systems are depicted in Figure 6. Specifically, the PV/T system with CuO in the metal and metal oxides achieved a maximum total efficiency of 88.7%, exhibiting the highest performance among all cases. Meanwhile, the PV/T module with carbon-based nanofluids, such as GNP and MXene, could achieve efficiencies of over 80%, which was moderate to above average. The advantages of magnetic nanofluids depend on adding an external magnetic field that can achieve a thermal efficiency of approximately 70%. Furthermore, it is demonstrated that PV/T with the NePCM significantly can improve the thermal efficiency by 24.3%, attributed to the efficient heat transfer of nanoparticles. Table 1 outlines the details and critical findings of various nanofluids applied to PV/T modules.

5 Economic and environmental assessments

The economic assessment of the PV/T system included initial investment, installation costs, operation and maintenance costs, auxiliary equipment, energy prices, government subsidies, and other relevant parameters. Currently, PV/T systems based on nanofluids show better efficiency, which, to some extent, represents the potential for reducing the com-

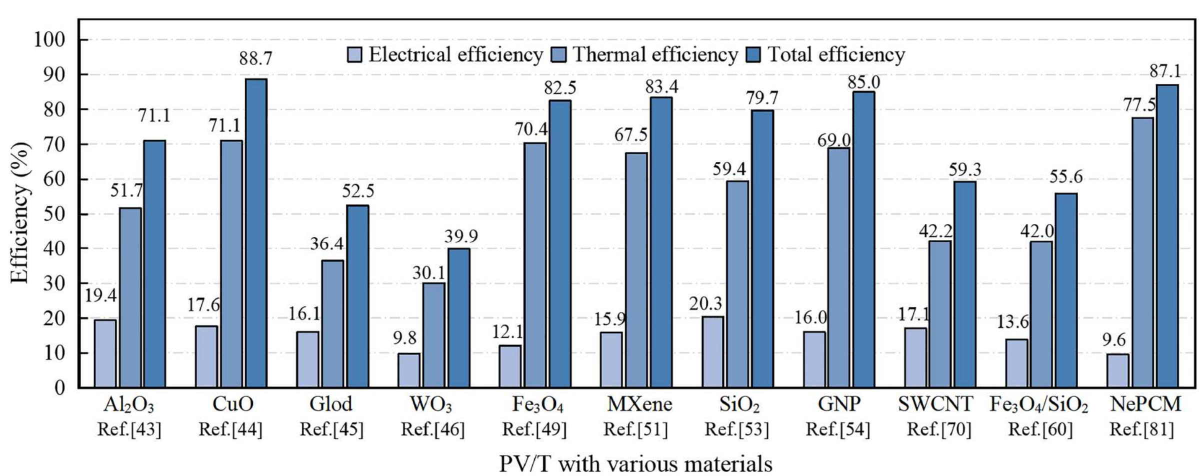

Figure 6 (Color online) Efficiency comparisons among PV/T modules with different materials.

Table 1 Summary of PV/T systems employing different nanofluids

Ref.	Method	Type of nanoparticles	Concentration	Flow rate	Key findings
Salehi et al. [43]	Experimental analysis	Al_2O_3	2 vol%	–	The overall efficiency of the PV/T with nanofluid is increased by 13.5%, leading to a reduction in the surface temperature of the PV panels by 13°C, compared to PV/T with water.
Khelifa et al. [87]	Numerical analysis	Al_2O_3	0.0–1%	–	The thermal efficiency of the PV/T with nanofluid is increased by 1% compared to PV/T with water.
Madas et al. [88]	Numerical analysis	CuO	0.1 vol%–0.5 vol%	60–120 kg/h	The optimum conditions are 0.1 vol% and 80 kg/h, with a final electrical efficiency of 15.12%.
Menon et al. [44]	Experimental analysis	CuO	0.05%	–	The thermal efficiencies of the PV/T with water and CuO nanofluids are 58.77% and 71.77%, respectively.
Diniz et al. [45]	Numerical analysis	Ag and gold	0–1 vol%	0–0.02 kg/s	The optimal concentration is 9×10^{-6} vol%. The overall PV/T energy efficiency is 52.45%, 21% higher than the PV module alone.
Alktranee et al. [46]	Experimental analysis	WO_3	0.5 vol%–1 vol%	–	The system thermal efficiency of WO_3 nanofluid at 1 vol% exhibits an increase of 24.7% in comparison with DI water.
Zheng et al. [47]	Experimental analysis	Fe_3O_4	0.1 vol%	–	The Nusselt number of PV/T with magnetic nanofluid is improved by 28.2%, while the Nusselt number without magnetic nanofluid is only 0.22%.
Bhattacharyya et al. [48]	Numerical analysis	Fe_3O_4–TiO_2	–	–	The magnetic field contributes to ameliorating the heat transfer rate. The maximum Nusselt number could be increased by 230%.
Ghadiri et al. [49]	Experimental analysis	Fe_3O_4	1 wt%, 3 wt%	–	The overall efficiency of the system using 3 wt% Fe_3O_4 nanofluids reaches about 75% under an alternating magnetic field at 50 HZ.
Almarashi et al. [50]	Numerical analysis	Fe_3O_4	0.037 vol%	0.07–0.14 m/s	The system's thermal and electrical efficiency could be increased by 59.48% and 8.23%, respectively.
Sreekumar et al. [51]	Numerical analysis	MXene	0.01 wt%–0.2 wt%	–	When the nanofluid concentration is 0.2 wt%, the thermal and electric efficiencies increase by 17% and 3.5%, respectively.
Kazem et al. [52]	Experimental and Numerical analysis	SiC	0.1 wt%, 0.5 wt%, 1 wt%, 2 wt%, 3 wt% and 4 wt%	–	The system's thermal efficiencies using water and SiC/water are improved by 29.0% and 43.3%, respectively. The electrical efficiency is improved by 8.56%.
Gelis et al. [53]	Numerical analysis	SiO_2	0.1 vol%–0.3 vol%	–	At a solar irradiance level of 600 W/m^2, the electrical efficiency varies from 17.31% to 19.8%.
Venkatesh et al. [54]	Experimental analysis	GNP	0.1 vol%–0.3 vol%	0.085, 0.075, 0.065 kg/s	The highest thermal and electric efficiencies are 85% and 16% when the concentration and mass flow rate are 0.3 vol% and 0.085 kg/s, respectively.
Alktranee et al. [58]	Experimental analysis	50%:50% TiO_2-CuO	0.2 vol%, 0.3 vol%	–	When the concentration is defined as 0.2 vol%, the thermal and electrical efficiency increases by 50.2% and 10.7%, respectively.
Karaaslan and Menlik [59]	Numerical analysis	CuO-Fe	0.5 vol%–2 vol%	0.02–0.08 m/s	When using CuO-Fe nanofluid, the electrical and thermal efficiencies can be increased by 2.14% and 5.4%, respectively, compared to water cooling.
Murtadha [62]	Experimental and Numerical analysis	Al_2O_3-TiO_2	2 wt%	0.5–3 L/min	Compared to PV panels alone, the surface temperature of PV panels is reduced by 20.9%.
Khan et al. [60]	Experimental analysis	Fe_3O_4-SiO_2	0.3 wt%	20–40 L/min	The average electrical efficiencies could achieve 13.85%, 13.15%, and 12.5% for PV/T with Fe_3O_4-SiO_2, SiO_2 and Fe_3O_4 nanofluids, respectively.
Bassam et al. [81]	Experimental analysis	SiC	1 vol%	–	The electrical efficiency of the PV/T with NePCM is 8.9%, while the electrical efficiency of the PV/T module integrated with water is merely 6%.
Moein-Jahromi et al. [82]	Experimental analysis	GNP-CuO	3 wt%	–	The surface temperature of the NePCM system is reduced by 6.6°C, resulting in approximately 3% power energy output enhancement compared to pure PCM.

ponent size and saving structural costs. Specifically, Amar et al. [89] demonstrated that PV/T with an SWCNT nanofluid saves 321.72 MJ of embodied energy. The investment payback period was approximately 2 years, which was 6.23% shorter than that of water cooling. Al-Waeli et al. [90] conducted an economic evaluation of PV/T systems using nanofluids (SiC/water) and PCM (SiC/paraffin). They found that the system had a payback period of 5–6 years. However, these performance-driven PV/T systems have not yet entered the market. This is partly owing to the additional costs incurred during production, including nanofluid preparation and material market costs, which limit commercial applications. Specifically, Praveenkumar et al. [91] illustrated that the PV/T system, incorporating a TEG/Al_2O_3 nanofluid, exhibited a levelized cost of energy (LCOE) ranging from 0.051 to 0.178 $/kWh, an energy payback time (EPBT) of 3.36 years, and an annual environmental impact equivalent to 2.07 tons/year. Compared with the PV/T with water, the LCOE, and EPBT of the PV/T with the TEG/nanofluid system were relatively higher. Tian et al. [92] evaluated the use of MgO nanofluids in PV/T systems under the climatic conditions of Guangxi, China, and found that the maintenance and initial costs were higher than those for PV systems. However, the investment payback period for PV systems is 6 years, whereas that for PV/T systems is 4 years. Abadeh et al. [93] conducted energy, economic, and environmental impact analyses on four metal oxide nanofluids used in flat-plate collectors with water. It is found that using ZnO in a PV/T system can reduce material usage by 33%. With a 75% energy subsidy from the Iranian government, the payback period is approximately 2.5 years. It is clear that government subsidies have a significant impact on the EPBT, and government policy guidance helps increase research and public attention, leading to an increase in material demand and contributing to a reduction in global trading prices.

The application of nanofluids in PV/T systems for reducing carbon emissions remains undisputed [56]. For example, Mustafa et al. [94] showed that the use of a mixed nanofluid (CuO-Al_2O_3) resulted in a reduction of 29.15 kg, 0.0149, and 0.0255 kg in the emissions of sulfur oxides, CO_2, and nitrogen oxides, respectively, compared to water. However, traditional nanofluid preparation processes involve chemical reactions that produce toxic byproducts with the potential to pollute the environment. Therefore, there is a need for further development of green nanofluids, primarily through extraction from natural plants. Kumar et al. [95] covalently functionalized graphene with gallic acid to prepare green GNP nanofluids. The findings indicated that the thermal efficiency of the nanofluids enhanced by 17.8% at a concentration of 0.1 wt%. Similarly, Alfellag et al. [96] utilized hydrogen peroxide to functionalize cloves on the surface of MWCNTS, resulting in a 20.5% reduction in collector dimensions. Currently, it is more complex to synthesize green and cost-effective nanofluids, which should be investigated further.

6 Recommendation and future work

Overall, adding nanomaterials to the PV/T module enhances the system performance. However, some challenges still hinder their practical applications, including limitations in commercial applications, high initial investment in synthesis, long-term stability, and operational issues. Moreover, various types of nanomaterials and pipe structures should be combined with PV/T systems for innovative applications. Some perspectives, challenges, and future research interests are as follows.

There are many possibilities for designing thermal pipe geometries. The influence of certain parameters, such as the working medium, flow rate, placement angle, and other geometric characteristics, on the system performance enhancement should be investigated to improve the heat exchange rate. Meanwhile, the modified thermal pipe structures enhanced the heat transfer area, dramatically increasing thermal efficiency. However, the economic assessment and material choice need to be further exploited.

Magnetic nanofluids, two-dimensional nanofluids, and composite nanofluids are new research directions; however, detailed information on various composite nanofluids, such as the mixing ratios and interactions between different types of nanofluids, requires further investigation. In addition, progress has been made in preparing green nanofluids based on natural extracts, effectively alleviating the environmental pressure on nanofluids and promoting their further applications.

Nanomaterials contribute to reducing structural size and saving costs and are more economically beneficial in the long operating period. However, the increased cost of nanomaterials is a fundamental factor affecting their short-term commercial applications. In the future, more attention should be paid to improving the heat exchange, reorganization of chemical bonds, long-term performance analysis, synthesis of ecological materials, and effective cost evaluation methods.

Most NePCMs disperse nanoparticles into paraffin, and there has been little research on inorganic PCM. Inorganic salt hydrates often have larger latent heat, but their drawbacks include undercooling and phase separation. Nanoparticles can improve the performance of the inorganic phase in terms of undercooling, phase-change temperature, and thermal stability.

7 Conclusions

This paper summarizes the latest technologies considering nanomaterial selection and modified thermal pipe structures within PV/T modules. Various nanofluids can be utilized in PV/T modules to enhance their energy conversion performance. Concurrently, configuring proper thermal pipe structures is conducive to optimizing the system performance and addressing obstacles. Consequently, the significant outcomes are as follows.

Modifications with different thermal pipe structures, including twisted and bionic pipes, have become the most effective and optimum structures for large contact areas, high heat transfer capabilities, and low thermal resistance rates, leading to electrical and thermal efficiency improvements ranging from 7% to 15% and 3% to 35%, respectively. It is concluded that optimizing the cavity structure and incorporating an external field could assist in boosting the passive heat transfer between the pipe wall and the working fluid.

The serpentine channel is mainly updated by changing the arrangement, cross-sectional size, and shape and adding microfins. Notably, the wavy shape is more effective than the linear shape owing to forming a secondary vortex at the bent part, which improves the convective heat transfer. Similarly, internal microfins and grooves like needles positively affect efficiency.

Nanofluids significantly improved the heat transfer efficiency of the coolant. It is confirmed that the thermal efficiency of PV/T integrated with CuO and GNP nanofluids could reach 21.3% and 63.1%, which reduces the surface temperature of PV by about 20°C. Additionally, introducing magnetic nanofluids and adding an external magnetic field increased *Re* by 25%, and the total system efficiency reached 75%.

The synthesis of the nanoparticles and PCM contributed to notable improvement in the thermal conductivity of the PCM by more than 90%, leading to improved heat transfer efficiency and surface temperature reduction. The thermal and electrical efficiencies of the PV/T with the NePCM module can be increased by 18% and 9.3%, respectively, compared to the PV/T with a pure PCM. Nevertheless, it is also found that thermal energy storage cannot be entirely released when a phase occurs in practical applications. Therefore, the choice of an appropriate PCM is critical.

Acknowledgements This work was supported by the Natural Science Foundation Project of Shandong Province (Grant No. ZR2023ME121), Taishan's Scholar Program of Shandong Province, China (Grant No. tsqn 202211183) and the Outstanding Youth Science Foundation Project of Shandong Province (Overseas) (Grant No. 2023HWYQ-076).

References

1 Igeland P, Schroeder L, Yahya M, et al. The energy transition: The behavior of renewable energy stock during the times of energy security uncertainty. Renew Energy, 2024, 221: 119746
2 Gao Y, Wu D, Dai Z, et al. A comprehensive review of the current status, developments, and outlooks of heat pipe photovoltaic and photovoltaic/thermal systems. Renew Energy, 2023, 207: 539–574
3 Wolf M. Performance analyses of combined heating and photovoltaic power systems for residences. Energy Convers, 1976, 16: 79–90
4 Sarhaddi F, Farahat S, Ajam H, et al. An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector. Appl Energy, 2010, 87: 2328–2339
5 Modjinou M, Ji J, Yuan W, et al. Performance comparison of encapsulated PCM PV/T, microchannel heat pipe PV/T and conventional PV/T systems. Energy, 2019, 166: 1249–1266
6 Erdiwansyah, Mahidin, Mamat R, et al. Target and demand for renewable energy across 10 ASEAN countries by 2040. Electricity J, 2019, 32: 106670
7 Pourasl H H, Barenji R V, Khojastehnezhad V M. Solar energy status in the world: A comprehensive review. Energy Rep, 2023, 10: 3474–3493
8 Herrando M, Wang K, Huang G, et al. A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems. Prog Energy Combust Sci, 2023, 97: 101072
9 Sheikholeslami M, Farshad S A, Ebrahimpour Z, et al. Recent progress on flat plate solar collectors and photovoltaic systems in the presence of nanofluid: A review. J Cleaner Product, 2021, 293: 126119
10 Emmanuel B, Yuan Y, maxime B, et al. A review on the influence of the components on the performance of PVT modules. Sol Energy, 2021, 226: 365–388
11 Sohani A, Shahverdian M H, Sayyaadi H, et al. Selecting the best nanofluid type for A photovoltaic thermal (PV/T) system based on reliability, efficiency, energy, economic, and environmental criteria. J Taiwan Inst Chem Eng, 2021, 124: 351–358
12 Abdallah S R, Saidani-Scott H, Abdellatif O E. Performance analysis for hybrid PV/T system using low concentration MWCNT (water-based) nanofluid. Sol Energy, 2019, 181: 108–115
13 Rajamony R K, Paw J K S, Pandey A K, et al. Energizing the thermophysical properties of phase change material using carbon-based nano additives for sustainable thermal energy storage application in photovoltaic thermal systems. Mater Today Sustainabil, 2024, 25: 100658
14 Kalsi S, Kumar S, Kumar A, et al. Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review. Arabian J Chem, 2023, 16: 105272
15 Umam M F, Hasanuzzaman M, Rahim N A. Global advancement of nanofluid-based sheet and tube collectors for a photovoltaic thermal system. Energies, 2022, 15: 5667
16 Chandrasekar M, Senthilkumar T. Five decades of evolution of solar photovoltaic thermal (PVT) technology—A critical insight on review articles. J Cleaner Product, 2021, 322: 128997
17 Tahmasebi A, Abed A M, Aghaei A, et al. Investigation into the effect of twisted tape on the thermo-hydraulic performance and entropy generation of turbulent flow of mono and hybrid magnetic nanofluids inside a parabolic solar collector absorber tube by applying two-phase analysis. Eng Anal Bound Elem, 2023, 150: 318–328
18 Elmasry Y, Chaturvedi R, Ali A, et al. Numerical analysis and RSM modeling of the effect of using a V-cut twisted tape turbulator in the absorber tube of a photovoltaic/thermal system on the energy and exergy performances of the system. Eng Anal Bound Elem, 2023, 155: 340–350
19 Maadi S R, Sabzali H, Kolahan A, et al. Improving the performance of PV/T systems by using conical-leaf inserts in the coolant tubes. Sol Energy, 2020, 212: 84–100
20 Ghasemian M, Sheikholeslami M, Dehghan M. Performance improvement of photovoltaic/thermal systems by using twisted tapes in the coolant tubes with different cross-section patterns. Energy, 2023, 279: 128016
21 Wang Y, Xia G, Yan Z, et al. Numerical study of bionic parallel minichannel heat sink applied to the cooling of a linear Fresnel photovoltaic system. Int J Heat Mass Transfer, 2022, 195: 123130
22 Zareie Z, Ahmadi R, Asadi M. A comprehensive numerical in-

vestigation of a branch-inspired channel in roll-bond type PVT system using design of experiments approach. Energy, 2024, 286: 129452
23 Liang Y, Liu P, Zheng N, et al. Numerical investigation of heat transfer and flow characteristics of laminar flow in a tube with center-tapered wavy-tape insert. Appl Therm Eng, 2019, 148: 557–567
24 Göltaş M, Gürel B, Keçebaş A, et al. Thermo-hydraulic performance improvement with nanofluids of a fish-gill-inspired plate heat exchanger. Energy, 2022, 253: 124207
25 Siddiqui O K, Zubair S M. Efficient energy utilization through proper design of microchannel heat exchanger manifolds: A comprehensive review. Renew Sustain Energy Rev, 2017, 74: 969–1002
26 Zhou J, Zhao X, Yuan Y, et al. Mathematical and experimental evaluation of a mini-channel PV/T and thermal panel in summer mode. Sol Energy, 2021, 224: 401–410
27 Khan M Z U, Younis M Y, Akram N, et al. Investigation of heat transfer in wavy and dual wavy micro-channel heat sink using alumina nanoparticles. Case Studies Therm Eng, 2021, 28: 101515
28 Li R, Li J, Zhu J, et al. A numerical and experimental study on a novel micro heat pipe PV/T system. Energy, 2023, 282: 128746
29 Shahsavar A, Jha P, Baniasad Askari I. Experimental study of a nanofluid-based photovoltaic/thermal collector equipped with a grooved helical microchannel heat sink. Appl Therm Eng, 2022, 217: 119281
30 Ali A, Alhussein M, Aurangzeb K, et al. The numerical analysis of Al_2O_3Cu/water hybrid nanofluid flow inside the serpentine absorber channel of a PVT; the overall efficiency intelligent forecasting. Eng Anal Bound Elem, 2023, 157: 82–91
31 Shahsavar A, Jha P, Arıcı M, et al. Energetic and exergetic performances of a nanofluid-based photovoltaic/thermal system equipped with a sheet-and-grooved serpentine tube collector: Indoor experimental tests. Sol Energy, 2021, 225: 918–933
32 Shahsavar A, Jha P, Arıcı M, et al. Experimental investigation of the usability of the rifled serpentine tube to improve energy and exergy performances of a nanofluid-based photovoltaic/thermal system. Renew Energy, 2021, 170: 410–425
33 Si Y, Brumercik F, Yang C, et al. Prediction and evaluation of energy and exergy efficiencies of a nanofluid-based photovoltaic-thermal system with a needle finned serpentine channel using random forest machine learning approach. Eng Anal Bound Elem, 2023, 151: 328–343
34 Wang J, Yang X, Klemeš J J, et al. A review on nanofluid stability: Preparation and application. Renew Sustain Energy Rev, 2023, 188: 113854
35 Huq T, Ong H C, Chew B T, et al. Review on aqueous graphene nanoplatelet nanofluids: Preparation, stability, thermophysical properties, and applications in heat exchangers and solar thermal collectors. Appl Therm Eng, 2022, 210: 118342
36 Zhang T, Zou Q, Cheng Z, et al. Effect of particle concentration on the stability of water-based SiO_2 nanofluid. Powder Tech, 2021, 379: 457–465
37 Mostafizur R M, Rasul M G, Nabi M N. Effect of surfactant on stability, thermal conductivity, and viscosity of aluminium oxide–methanol nanofluids for heat transfer applications. Therm Sci Eng Prog, 2022, 31: 101302
38 Khairul M A, Shah K, Doroodchi E, et al. Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids. Int J Heat Mass Transfer, 2016, 98: 778–787
39 Zhang H, Qing S, Zhai Y, et al. The changes induced by pH in TiO_2/water nanofluids: Stability, thermophysical properties and thermal performance. Powder Tech, 2021, 377: 748–759
40 Al-Waeli A H A, Chaichan M T, Kazem H A, et al. Evaluation and analysis of nanofluid and surfactant impact on photovoltaic-thermal systems. Case Studies Therm Eng, 2019, 13: 100392
41 Qi Y, Liu Z, Shi Y, et al. Size optimization of nanoparticle and stability analysis of nanofluids for spectral beam splitting hybrid PV/T system. Mater Res Bull, 2023, 162: 112184
42 Ji J, Yao X, Gao J, et al. Effect of surfactants and pH values on stability of γ-Al_2O_3 nanofluids. Chem Phys Lett, 2021, 781: 138996
43 Salehi R, Jahanbakhshi A, Ooi J B, et al. Study on the performance of solar cells cooled with heatsink and nanofluid added with aluminum nanoparticle. Int J Thermofluids, 2023, 20: 100445
44 Menon G S, Murali S, Elias J, et al. Experimental investigations on unglazed photovoltaic-thermal (PVT) system using water and nanofluid cooling medium. Renew Energy, 2022, 188: 986–996
45 Diniz F L J, Vital C V P, Gómez-Malagón L A. Parametric analysis of energy and exergy efficiencies of a hybrid PV/T system containing metallic nanofluids. Renew Energy, 2022, 186: 51–65
46 Alktranee M, Shehab M A, Németh Z, et al. Energy and exergy assessment of photovoltaic-thermal system using tungsten trioxide nanofluid: An experimental study. Int J Thermofluids, 2022, 16: 100228
47 Zheng D, Yang J, Wang J, et al. Analyses of thermal performance and pressure drop in a plate heat exchanger filled with ferrofluids under a magnetic field. Fuel, 2021, 293: 120432
48 Bhattacharyya S, Jain N, Bhatt T, et al. Mini-channel cooling system for solar PV Panels with hybrid magnetic nanofluid and magnetic field. Results Eng, 2023, 20: 101473
49 Ghadiri M, Sardarabadi M, Pasandideh-fard M, et al. Experimental investigation of a PVT system performance using nano ferrofluids. Energy Convers Manage, 2015, 103: 468–476
50 Almarashi A, Alrahal D M, AL-bonsrulah H A Z, et al. Effect of loading Fe_3O_4 nanoparticles on electrical performance of solar panel utilizing numerical modeling. Case Studies Therm Eng, 2024, 55: 104165
51 Sreekumar S, Shah N, Mondol J D, et al. Numerical investigation and feasibility study on MXene/water nanofluid based photovoltaic/thermal system. Cleaner Energy Syst, 2022, 2: 100010
52 Kazem H A, Al-Waeli A H A, Chaichan M T, et al. Numerical and experimental evaluation of nanofluids based photovoltaic/thermal systems in Oman: Using silicone-carbide nanoparticles with water-ethylene glycol mixture. Case Studies Therm Eng, 2021, 26: 101009
53 Gelis K, Naci Celik A, Ozbek K, et al. Experimental investigation into efficiency of SiO_2/water-based nanofluids in photovoltaic thermal systems using response surface methodology. Sol Energy, 2022, 235: 229–241
54 Venkatesh T, Manikandan S, Selvam C, et al. Performance enhancement of hybrid solar PV/T system with graphene based nanofluids. Int Commun Heat Mass Transfer, 2022, 130: 105794
55 Hassan A, Wahab A, Qasim M A, et al. Thermal management and uniform temperature regulation of photovoltaic modules using hybrid phase change materials-nanofluids system. Renew Energy, 2020, 145: 282–293
56 Büyükalaca O, Kılıç H M, Olmuş U, et al. Numerical investigation and ANN modeling of performance for hexagonal boron nitride-water nanofluid PVT collectors. Thermal Sci Eng Prog, 2023, 43: 101997
57 Adun H, Kavaz D, Dagbasi M. Review of ternary hybrid nanofluid: Synthesis, stability, thermophysical properties, heat transfer applications, and environmental effects. J Cleaner Production, 2021, 328: 129525
58 Alktranee M, Ahmed Shehab M, Németh Z, et al. Experimental study for improving photovoltaic thermal system performance using hybrid titanium oxide-copper oxide nanofluid. Arabian J Chem, 2023, 16: 105102
59 Karaaslan I, Menlik T. Numerical study of a photovoltaic thermal (PV/T) system using mono and hybrid nanofluid. Sol Energy, 2021, 224: 1260–1270
60 Khan A A, Danish M, Rubaiee S, et al. Insight into the investigation of Fe_3O_4/SiO_2 nanoparticles suspended aqueous nanofluids in hybrid photovoltaic/thermal system. Cleaner Eng Tech, 2022, 11: 100572
61 Alktranee M, Shehab M A, Németh Z, et al. Thermodynamic analysis of mono and hybrid nanofluid effect on the photovoltaic-thermal system performance: A comparative study. Heliyon, 2023, 9: e22535
62 Murtadha T K. Effect of using Al_2O_3/TiO_2 hybrid nanofluids on improving the photovoltaic performance. Case Studies Therm Eng, 2023, 47: 103112
63 Vaka M, Walvekar R, Rasheed A K, et al. A review: Emphasizing the

nanofluids use in PV/T systems. IEEE Access, 2020, 8: 58227–58249
64 Diwania S, Kumar R, Singh S K, et al. Performance assessment of a serpentine tube PVT system using Cu and TiO_2 nanofluids: An experimental study. J Braz Soc Mech Sci Eng, 2022, 44: 44–71
65 Lee J H, Hwang S G, Lee G H. Efficiency improvement of a photovoltaic thermal (PVT) system using nanofluids. Energies, 2019, 12: 3063
66 Hooshmandzade N, Motevali A, Reza Mousavi Seyedi S, et al. Influence of single and hybrid water-based nanofluids on performance of microgrid photovoltaic/thermal system. Appl Energy, 2021, 304: 117769
67 Basalike P, Peng W, Zhang J. Numerical study on the performance of photovoltaic thermal unit condenser with water/nanofluids as fluids medium. Renew Energy, 2022, 197: 606–616
68 Abesh Ahmadlou L, Najafi G, Loni R, et al. Experimental investigation of PV/T and thermoelectric systems using CNT/water nanofluids. Appl Therm Eng, 2023, 227: 120350
69 Ahmadinejad M, Moosavi R. Energy and exergy evaluation of a baffled-nanofluid-based photovoltaic thermal system (PVT). Int J Heat Mass Transfer, 2023, 203: 123775
70 Alous S, Kayfeci M, Uysal A. Experimental investigations of using MWCNTs and graphene nanoplatelets water-based nanofluids as coolants in PVT systems. Appl Therm Eng, 2019, 162: 114265
71 Das L, Habib K, Saidur R, et al. Improved thermophysical properties and energy efficiency of aqueous ionic liquid/MXene nanofluid in a hybrid PV/T solar system. Nanomaterials, 2020, 10: 1372
72 Agresti F, Fedele L, Rossi S, et al. Nano-encapsulated PCM emulsions prepared by a solvent-assisted method for solar applications. Sol Energy Mater Sol Cells, 2019, 194: 268–275
73 Velusamy P, Chia-Hung S, Shritama A, et al. Synthesis of oleic acid coated iron oxide nanoparticles and its role in anti-biofilm activity against clinical isolates of bacterial pathogens. J Taiwan Inst Chem Eng, 2016, 59: 450–456
74 Yang L, Huang J, Zhou F. Thermophysical properties and applications of nano-enhanced PCMs: An update review. Energy Convers Manage, 2020, 214: 112876
75 Zhong Y, Guo Q, Li S, et al. Heat transfer enhancement of paraffin wax using graphite foam for thermal energy storage. Sol Energy Mater Sol Cells, 2010, 94: 1011–1014
76 Bhutto Y A, Pandey A K, Saidur R, et al. Hybrid silver-graphene nanoparticles enhanced lauric acid phase change material for photovoltaic and thermoelectric generator applications: Experimental and simulation analysis. J Energy Storage, 2024, 93: 112320
77 Khodadadi M, Sheikholeslami M. Heat transfer efficiency and electrical performance evaluation of photovoltaic unit under influence of NEPCM. Int J Heat Mass Transfer, 2022, 183: 122232
78 Yang R, Li D, Salazar S L, et al. Photothermal properties and photothermal conversion performance of nano-enhanced paraffin as a phase change thermal energy storage material. Sol Energy Mater Sol Cells, 2021, 219: 110792
79 Preet S, Bhushan B, Mahajan T. Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM). Sol Energy, 2017, 155: 1104–1120
80 González-Peña D, Alonso-deMiguel I, Díez-Mediavilla M, et al. Experimental analysis of a novel PV/T panel with PCM and heat pipes. Sustainability, 2020, 12: 12051710
81 Bassam A M, Sopian K, Ibrahim A, et al. Experimental analysis for the photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube nanofluid. Case Studies Therm Eng, 2023, 41: 102579
82 Moein-Jahromi M, Rahmanian-Koushkaki H, Rahmanian S, et al. Evaluation of nanostructured GNP and CuO compositions in PCM-based heat sinks for photovoltaic systems. J Energy Storage, 2022, 53: 105240
83 Fu Z, Liang X, Li Y, et al. Performance improvement of a PVT system using a multilayer structural heat exchanger with PCMs. Renew Energy, 2021, 169: 308–317
84 Fu Z, Li Y, Liang X, et al. Experimental investigation on the enhanced performance of a solar PVT system using micro-encapsulated PCMs. Energy, 2021, 228: 120509
85 Junaid M F, Rehman Z, Čekon M, et al. Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications. Energy Buildings, 2021, 252: 111443
86 Abdelrazik A S, Saidur R, Al-Sulaiman F A. Thermal regulation and performance assessment of a hybrid photovoltaic/thermal system using different combinations of nano-enhanced phase change materials. Sol Energy Mater Sol Cells, 2020, 215: 110645
87 Khelifa A, Kabeel A E, Attia M E H, et al. 3D numerical analysis of a photovoltaic thermal using bi-fluid: Al_2O_3–water nanofluid at various concentrations. Int J Thermofluids, 2023, 20: 100523
88 Madas S R, Narayanan R, Gudimetla P. Numerical investigation on the optimum performance output of photovoltaic thermal (PVT) systems using nano-copper oxide (CuO) coolant. Sol Energy, 2023, 255: 222–235
89 Amar M, Akram N, Chaudhary G Q, et al. Energy, exergy and economic (3E) analysis of flat-plate solar collector using novel environmental friendly nanofluid. Sci Rep, 2023, 13: 411
90 Al-Waeli A H A, Kazem H A, Chaichan M T, et al. Experimental investigation of using nano-PCM/nanofluid on a photovoltaic thermal system (PVT): Technical and economic study. Therm Sci Eng Prog, 2019, 11: 213–230
91 Praveenkumar S, Agyekum E B, Kumar A, et al. Thermo-enviro-economic analysis of solar photovoltaic/thermal system incorporated with u-shaped grid copper pipe, thermal electric generators and nanofluids: An experimental investigation. J Energy Storage, 2023, 60: 106611
92 Tian M W, Khetib Y, Yan S R, et al. Energy, exergy and economics study of a solar/thermal panel cooled by nanofluid. Case Studies Therm Eng, 2021, 28: 101481
93 Abadeh A, Rejeb O, Sardarabadi M, et al. Economic and environmental analysis of using metal-oxides/water nanofluid in photovoltaic thermal systems (PVTs). Energy, 2018, 159: 1234–1243
94 Mustafa J, Alqaed S, Sharifpur M. Evaluation of energy efficiency, visualized energy, and production of environmental pollutants of a solar flat plate collector containing hybrid nanofluid. Sustain Energy Technol Assess, 2022, 53: 102399
95 Kumar L H, Kazi S N, Masjuki H H, et al. Energy, exergy and economic analysis of liquid flat-plate solar collector using green covalent functionalized graphene nanoplatelets. Appl Therm Eng, 2021, 192: 116916
96 Alfellag M A, Mohamed Kamar H, Abidin U, et al. Green synthesized clove-treated carbon nanotubes/titanium dioxide hybrid nanofluids for enhancing flat-plate solar collector performance. Appl Therm Eng, 2024, 246: 122982