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Evaluation of different methods to ameliorate the performance of PV/T systems using hybrid nanofluids and PCM in a spiral tube with different cross sections

Dheyaa J. Jasim [a], Hasan A Al-Asadi [b], As'ad Alizadeh [c], Hossein Nabi [d], Talib M. Albayati [e,**], Issam K. Salih [f], Pooya Pasha [d,*], Davood Domiri Ganji [g]

[a] Department of Petroleum Engineering, Al-Amarah University College, Maysan, Iraq
[b] Air Conditioning Engineering Department, Faculty of Engineering, Warith Al-Anbiyaa University, Iraq
[c] Department of Civil Engineering, College of Engineering, Cihan University-Erbil, Erbil, Iraq
[d] Department of Mechanical Engineering, Mazandaran University of Science and Technology, P.O. Box47166-85635, Babol, Iran
[e] Department of Chemical Engineering, University of Technology- Iraq, 52 Alsinaa St., PO Box, 35010, Baghdad, Iraq
[f] Department of Chemical Engineering and Petroleum Industries, Al-Mustaqbal University, Babylon, 51001, Iraq
[g] Department of Mechanical Engineering Babol Noshirvani University of Technology, P.O. Box47166-85635, Babol, Iran

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ABSTRACT

This study proposes a novel design for a serpentine tube to develop an efficient photovoltaic-thermal (PV/T) system. For this purpose, three different hybrid nanofluids and two types of PCM were numerically investigated in a novel serpentine tube with different cross-sectional shapes (rectangular, circular, and triangular). The electrical, thermal, and exergy efficiencies of the PV/T system are evaluated to ascertain the feasibility of the proposed configuration and working fluid. The results showed that using PCM composite and a rectangular cross-section increased thermal and electrical efficiency by 31.1 % and 5.4 %, respectively, compared to the state without PCM and the circular cross-section.For a more comprehensive assessment, the effect of three hybrid nanofluids with a volume concentration of 1.5 % is studied to determine which nanofluid improves heat transfer. Fe3O4-MWCNT demonstrates the most effective nanofluid for cooling down the PV cell temperature. It is used with a volume concentration of up to 4.5 % to investigate how increasing the concentration of hybrid nanofluid can affect important parameters such as cell temperature, fluid outlet temperature, electrical, and thermal efficiency.Moreover, using Fe3O4-MWCNT (4.5 %) along with PCM and PCM composite increases the exergy efficiency by 13.3 % and 16.2 %.

1. Introduction

Scientists are compelled to seek substitute fuels due to two main factors: firstly, the limitations of fossil fuels, and secondly, the ecological problems that arise from their combustion. Solar energy has garnered the most attention among renewable fuels for various reasons, including easy installation, repair, maintenance, global availability, and environmental compatibility. In many countries, plans have been formulated to make solar energy the primary source of energy supply by 2030. Photovoltaic cells are highly temperature-dependent, and lowering their temperature enhances their performance [1–5]. While numerous studies have been conducted on solar cells, the evident need for further research persists. To enhance the utilization of photovoltaic cells, a substantial increase in their efficiency is imperative for economic feasibility. For instance, typical photovoltaic cells, which directly convert sunlight into electrical energy, demonstrate an efficiency range of 9–20 %, varying based on the specific type of cell [6–8]. Much of the sunlight is either reflected or converted into heat. This heat leads to thermal degradation, altering the physical construction of the photovoltaic cell. Simultaneously, it raises the temperature of the photovoltaic cell, which exhibits an inverse relationship with the electrical efficiency of the cell [9–11]. Kasaeian et al. [12] investigated the impact of sheet temperature on amorphous silicon and polycrystalline silicon in photovoltaic cells. They concluded that a 1-degree increase in surface temperature reduces efficiency by 0.25 % and 0.45 %. The utilization of a photovoltaic/thermal

* Corresponding author.
** Corresponding author.
E-mail addresses: Talib.M.Naieff@uotechnology.edu.iq (T. M. Albayati), Pasha.pooya@yahoo.com (P. Pasha).

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Nomenclature

A	Area (m^2)
α	Absorviptivity
Bf	Base fluid
K_B	Boltzmann constant
d	Diameter (m)
ρ	Density (kg/ m^3)
μ	Dynamic viscosity (kg/ $m.s$)
El	Electrical
η	Energy efficiency (%)
L	Latent heat (J/kg)
β	Liquid fraction
C	Mushy zone constant(kg/ $m^3.s$)
$\dot{m}$	Mass flow rate (kg/s)
Nf	Nanofluid
φ	Nanoparticles volume fraction
Out	Outlet
$\dot{E}$	Power (W)
P	Pressure (Pa)
h	Specific enthalpy (J/kg)
T	Temperature (K)
Th	Thermal
K	Thermal conductivity (W/m.k)
V	Velocity (m/s)

system, initially proposed by Kern in 1970, allows the beneficial use of heat absorbed in the solar collector, thereby reducing the panel temperature [13,14]. Touti et al. [15], through simulations involving various geometries for the photovoltaic thermal system, observed a cell temperature change from 53.37 to 42.5 and an efficiency increase of 58.48 %. Various methods can be employed to induce more significant temperature changes and enhance system efficiency. Heat transfer can be augmented in systems through both active and passive methods. Nowadays, using phase change materials and nanoparticles is a pioneer in improving heat transfer in solar systems, and researchers are investigating various methods and materials to find the most efficient ones to speed up the commercialization of solar cells [16,17].

PCMs are widely recognized as the most suitable material for storing thermal energy due to their versatility and applicability across various temperatures. These materials are acknowledged for their role as heat storage agents and have been extensively employed to enhance the capacity for energy storage in different thermal energy storage systems. The effectiveness of a solar thermal storage system is heavily contingent on the phase change materials (PCMs) employed within the system. These materials play a pivotal role in energy storage, particularly as the temperature of the heat source rises. PCMs undergo a chemical transformation, commonly transitioning from a solid to a liquid state, as they absorb additional energy entered into the system. The energy stored in PCMs can be released into the pre-designed system when needed [18,19]. The solar thermal water heating system is the most beneficial device developed to harness this advantage. This system incorporates PCMs as a crucial component to capture heat from the source and effectively store the energy. PCMs can be split into eutectic, inorganic, and organic. Research has confirmed that the most optimal PCMs for solar thermal water heating systems are combinations of fatty acids, followed by paraffin wax as the second most commonly used PCM. Their elevated ranking is attributed to their favorable characteristics, including non-toxicity, good chemical stability, and melting points well-suited for solar heating applications [20,21]. The concept of nanofluids encompasses suspensions containing nanoparticles, metallic and non-metallic. Hybrid nanofluids, a subset of nanofluids, are considered promising fluids due to their enhanced thermal performance and improved thermophysical properties compared to common heat transfer fluids such as water, ethylene glycol, and mineral oils, as well as nanofluids containing only one type of nanoparticle. A hybrid nanofluid is a novel fluid created by dispersing two distinct types of nanoparticles within a base fluid to augment its heat transfer capabilities [22–24]. Nanoparticles exhibit high thermal conductivity, and when dispersed within a base fluid, they elevate the thermal conductivity coefficient of the fluid. This is a crucial factor contributing to the enhancement of thermal processes. Hybrid nanofluids outperform regular nanofluids in photovoltaic-thermal systems [25–27].

Here are some previous studies that examined using PCM and nanoparticles in PVT systems.

Khanjari et al. [28] numerically assessed the impact of using two different nanofluids in PV/T systems. They found that utilizing alumina water at a concentration of 5 % can increase the heat transfer coefficient by 8–10 % compared to pure water. In contrast, using Ag-water nanofluid at the same concentration increases it by 28 %–45 %. Sardarabadi et al. [29] experimentally evaluated the effect of using paraffin wax and ZnO/water nanofluid (0.2 wt%) in PV/T systems and observed that their use increases the overall exergy by up to 23 %. Bhattacharjee et al. [30] conducted an experimental evaluation of the effect of channel shape in PV/T systems. By examining three shapes (circular spiral semi-flattened, circular spiral, and semi-oval serpentine), they found that using circular spiral semi-flattened increases efficiency by 4.32 % more than the other cases. Cui et al. [31] assessed a photovoltaic thermal system's environmental, energy, and economic performance utilizing PCM. They concluded that using this composite can increase the system's thermal efficiency by at least 20 to 30%. In another study, Kazemian et al. [32] examined various hybrid nanofluids in a photovoltaic system and concluded that using carbon-based nanofluids with thermal and electrical efficiencies of 13.85 % and 56.55 %, respectively, outperforms other hybrid nanofluids, resulting in a significant improvement in overall efficiency.Yousuf Bhat et al. [33] studied the effect of CuO, MWCNT, and CuO/MWCNT hybrid nanofluid with volume concentration 3 % in PV/T system with innovative tube design. The CuO/MWCNT hybrid nanofluid outperforms the mono nanofluids by demonstrating an improvement of 9.01 % and 6.5 % in overall effective and electrical efficiency, respectively. Yousuf Bhat et al. [34] evaluated how using innovative tube change the efficiency of PV/T systems. The results of their study showed using optimized hybrid tube with phase-change material slurries can improve thermohydraulic and exergy efficiencies 20 % and 1.1 %, respectively.

One of the main disadvantages of nanofluids is their high cost and environmental toxicity. Another critical issue related to nanofluids is the long-term stability of nanoparticles. Metal-based nanofluids, in particular, face challenges due to the significant difference in density between the nanoparticles and the base fluid, resulting in the least stability [35,36]. As nanoparticles have a limited lifespan and must eventually be disposed of, it becomes essential to choose a nanoparticle that can provide economically and environmentally suitable conditions. When selecting the appropriate PCM for solar systems, the following factors should be considered [37,38]:

- Economic properties: reasonable price, availability, recyclability
- Physical properties: low volume change, desirable phase equilibrium, high density, low vapor pressure
- Thermal properties: high heat transfer, suitable phase change temperature, high latent heat

To enhance PCM's melting/solidification process, it is possible to incorporate it within a conductive foam, such as carbon or metal foam.

Previous research has shown that metal foams can decrease the PCM's melting time. This study specifically focuses on enhancing the thermophysical characteristics of PCM by embedding it within a heat-conductive foam known as PS-CNT foam, which acts as a thermal spreader [39–45].

Previous studies evaluated the impact of various methods to improve performance in PV and PV/T systems. This paper innovatively assesses the effects of using rectangular, circular, and triangular ducts in a novel serpentine tube, as well as paraffin (an organic phase change material) and PCM composite, along with three hybrid nanofluids at different concentrations in the PVT system using Ansys software. The study includes an examination of thermal and electrical efficiency, exergy, and their impact on outlet fluid temperature and cell surface temperature. The results are presented and compared in different graphs to identify the case with the highest efficiency in economics and heat transfer. These findings offer valuable insights for further studies in this field. The novelty of this paper is an innovative serpentine tube was used for the first time in the PV/T system, and Three different cross-section shapes along with three types of hybrid nanofluid and PCM and PCM composite were used to improve the system's performance. Also, exergy, electrical, and thermal efficiency were numerically investigated to the best result obtained from the simulation should be presented for experimental work.

2. Materials and methods

This paper introduced a physical model to examine the thermal-electrical performance of a PV/T system with three different cross-sections of serpentine tubes in the presence of a nanofluid and PCM (Fig. 1). Triangular and rectangular ducts are considered with dimensions that their hydraulic diameter is equal to that of a circular duct. The three-dimensional physical model is drawn in CATIA-V5 software, and the proposed geometry components, including glass, vanillin, Photovoltaic (PV), Ethylene-vinyl acetate (EVA), Tedlar, absorber tube, insulation, and PCM are arranged(Fig. 2).

The heat transfer fluids in this study are hybrid nanofluids with various concentrations. The designed model comprises a single-crystal silicon W40 photovoltaic module made by Suntech (China). The dimensions of the PV-thermal system are 630*540 mm, and the absorber tube material is copper due to its stability in various factors like corrosion, high voltage environments, and dielectric fluids. The important thermophysical properties of various system components are reported in (Table 1).

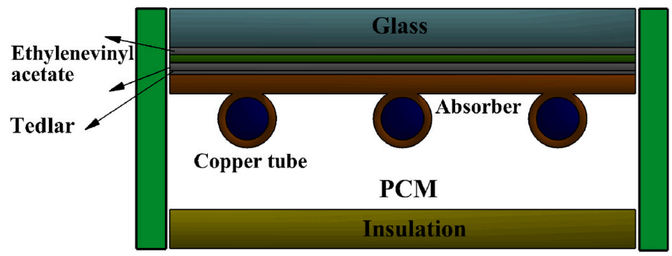

Fig. 2. Structure of the studied PVT system.

The simulation can be generally described as follows: Analyzing three cross-sections (rectangle, triangle, and circle) in a specific serpentine tube to understand the effect of cross-section geometry on heat transfer between the structure and the fluid. The study evaluates thermal and electrical efficiencies, outlet liquid temperature, cell temperature, and exergy of the proposed designs with two types of PCMs and three different types of hybrid nanofluids at various concentrations (φ = 1.5, 2.5, 4.5). The thermos-physical properties of the nanofluids and PCMs are shown in Tables (2–6), [46–48].

Table 1
Properties of different components of PV/T system.

PV cells	EVA	PV cells	TPT
Type	Monocrystalline silicone	serpentine	–
Thermal conductivity/W $m^{-1}K^{-1}$	148	386.6	0.35
C_p/J $Kg^{-1}K^{-1}$	700	385	2090
Density/Kg m^{-3}	2330	8920	960

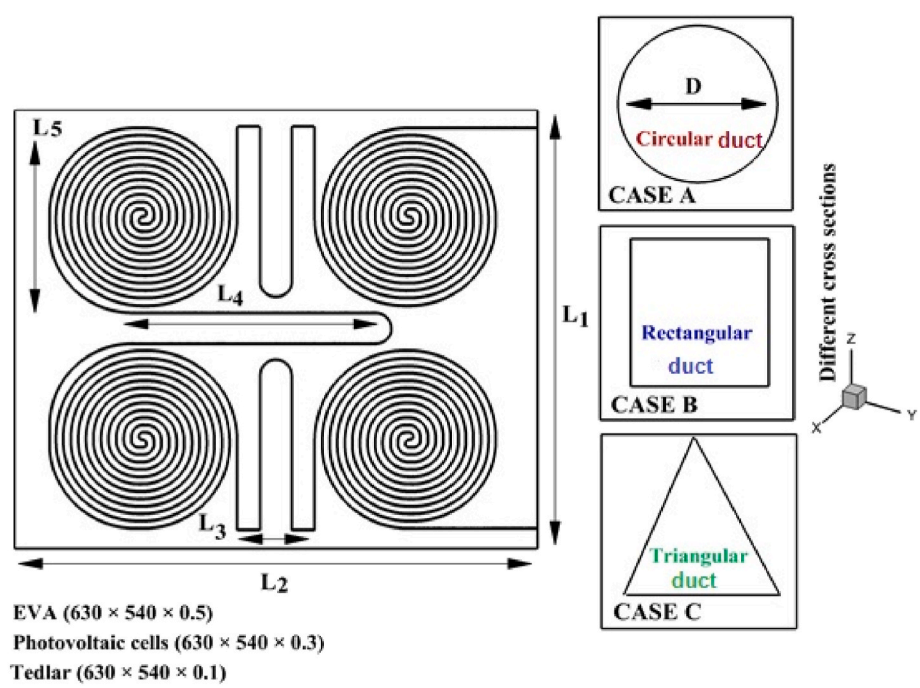

Fig. 1. Geometries of three different cross sections of serpentine tubes. L1:540 mm, L2:630 mm, L3:91 mm, L4:367 mm, L5:225 mm, D: 8 mm.

Table 2
Thermo-physical properties of nanofluids.

Property	Water	Cu	CuO	Al_2O_3	TiO_2	Fe_3O_4	MWCNT
Density (kg/m^3)	998.2	8933	6510	3880	4175	5180	1600
Specific Heat Capacity (J/kg.K)	4182	385	540	792	692	670	796
Thermal Conductivity (W/m.K)	0.6	401	18	42.34	8.4	9.7	3000
Viscosity (Pas)	0.001003	–	–	–	–	–	–

Table 3
Equations for obtaining the properties of hybrid nanofluids.

Properties	Hybrid Nano fluid
Viscosity	$\mu_{hnf} = \frac{\mu_f}{(1-\varphi_1)^{2.5}(1-\varphi_2)^{2.5}}$
Density	$\rho_{hnf} = \rho_f(1-\varphi_2)\left((1-\varphi_1)+\varphi_1\left(\frac{\rho_{s1}}{\rho_f}\right)\right)+\varphi_2\rho_{s2}$
Heat capacity	$(\rho c_p)_{hnf} = (\rho c_p)_f(1-\varphi_2)\left((1-\varphi_1)+\varphi_1\frac{(\rho c_p)_{s1}}{(\rho c_p)_f}\right)+\varphi_2(\rho c_p)_{s2}$
Thermal conductivity	$\frac{k_{hnf}}{k_{bf}} = \frac{k_{s2}+(s-1)k_{bf}-(s-1)\varphi_2(k_{bf}-k_{s2})}{k_{s2}+(s-1)k_{bf}+\varphi_2(k_{bf}-k_{s2})}$, Where $\frac{k_{bf}}{k_f} = \frac{k_{s1}+(s-1)k_f-(s-1)\varphi_1(k_f-k_{s1})}{k_{s1}+(s-1)k_f+\varphi_1(k_f-k_{s1})}$

2.1. Initial and boundary conditions

The turbulent flow conditions and single-phase model are utilized in conducting the CFD simulation using ANSYS Fluent 18.2. Solar radiation with uniform heat flux (1000 W/) is applied to the upper wall of the system. Four circular-shaped copper loops are located on the PVT-PCM surface, which provides conductive heat transfer with the walls and convective heat transfer with the hybrid nanofluids. The input temperature for the fluid is 303.15 K, which enters the copper tube under the boundary conditions of a constant mass flow rate of 30 kg/s and exits at a relative pressure of zero designated as a pressure outlet. The ambient temperature is assumed to be 308 K, and the wind speed is one m/s. Under the first law of thermodynamics, the total input energy to PV/T-PCM is equal to the incident irradiation (340.2 W), and the output energies include Electrical energy (45 W), Thermal energy (143 W), convection losses (58 W), and Radiation losses (93 W). There is a small mistake of only 0.36 % in these calculations. Additionally, there is a difference of 1.2 W between the amount of energy that goes into the system and the amount that comes out. In this simulation, the adoption of no-slip and adiabatic boundary conditions has been employed for all external walls. This article has solved a transient model, and time variations have been applied to it. Natural convection through PCM, gravity, and the adhesive layer thickness between the panel and the absorber has been neglected.

Table 6
Thermo-physical properties of PCM and PCM-composite.

Property	PCM	PCM composite
Thermal conductivity (W m^{-1} K^{-1})	0.22	0.40
Solidification temperature point (k)	309–317	309–319
Melting temperature point (k)	313–322	311–320
Melting enthalpy (kJ kg^{-1})	136.6	124.9

2.2. Governing equations

The 3D simulation used the ANSYS-Fluent software, employing the finite volume method (FVM). The simulation involved solving the stable, Newtonian, and viscous incompressible fluid flow using the Navier-Stokes equations. Additionally, the temperature distribution was determined by solving the thermal energy equation. Momentum, energy, and continuity equations are applied according to research [49].

$$\text{Continuity}: \frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{V}\right) = 0 \quad (1)$$

$$\text{Energy}: \frac{\partial(\rho h)}{\partial t} + \nabla.\left(\rho \vec{V} h\right) = \nabla.(k\nabla T) \quad (2)$$

$$\text{Momentum}: \frac{\partial \rho \vec{V}}{\partial t} + \nabla.\left(\rho \vec{V}\vec{V}\right) = -\nabla P + \nabla\left(\mu \nabla \vec{V}\right) + \rho g + S \quad (3)$$

where $\vec{V}$ and P are velocity vector and pressure, respectively.

The PCM in this study is paraffin, which is low price, safe, resistant, and non-corrosive. The porous enthalpy method simulates the phase transition phenomenon in PV/T-PCM. In this approach, the liquid fraction is set to 1 when the phase change material is fully melted, and it is set to 0 when the material is completely solidified. The porous parameter S is utilized in the momentum equation to define the interface between the liquid and solid phases in the aforementioned equation [50, 51].:

$$S = \left(\frac{(1-\beta)^2}{(\beta^2+\varepsilon)}\right) C \vec{V} \quad (4)$$

The constant C, which varies between 10^4 and 10^7, represents the

Table 4
Properties of the studied hybrid nanofluids at $\varphi = 0.015$.

Property	TiO_2–Cu (50:50 vol %)/Water	Al_2O_3–CuO (50:50 vol %)/Water	Fe_3O_4-MWCNT (50:50 vol %)/Water
Density (kg/m^3)	1164.159	1123.455	1069.818
Specific Heat Capacity (J/kg.K)	3515.725	3645.520	3803.443
Thermal Conductivity (W/m.K)	0.650	0.652	0.653
Viscosity (Pas)	0.00108	0.00108	0.00108

Table 5
Thermo-physical properties of hybrid nanofluid at different concentrations.

Property	Fe_3O_4-MWCNT (50:50 vol %)/Water $\varphi = 0.03$	Fe_3O_4-MWCNT (50:50 vol %)/Water $\varphi = 0.045$
Density (kg/m^3)	1141.166	1212.2434
Specific Heat Capacity (J/kg.K)	3474.360	3185.793
Thermal Conductivity (W/m.K)	0.656	0.685
Viscosity (Pas)	0.00116	0.00126

reflection of the mushy zone morphology. The mushy zone refers to the region where the liquid fraction β ranges between 0 and 1. In particular, a value of 10^5 is chosen as the constant for the study. To avoid division by zero, the parameter ε is assigned a numerical value of 0.001 in this study.

$$\beta=\begin{cases} 0 & \text{if } T < T_s \\ 1 & \text{if } T > T_l \\ \frac{T-T_s}{T_l-T_s} & \text{if } T_s < T < T_l \end{cases} \tag{5}$$

Equations (6) and (7) define the total enthalpy, denoted as h, which is the combined value of latent enthalpy (h_{le}) and sensible enthalpy (h_{se}).

In equations (6) and (7) h is total enthalpy which is the sum of ensible enthalpy (h_{se}) and latent enthalpy (h_{le}).

$$h_{se} = h_{ref} + \int_{T_{ref}}^{T} C_p dT \tag{6}$$

$$h_{le} = \beta L \tag{7}$$

where h_{ref} is the reference enthalpy at temperature ($T_{ref} = 298.15k$). To handle the presence of distinct, unmixed fluids within the system, the Volume of Fluid (VOF) model is utilized. This model characterizes the volume fraction of each fluid within a computational cell using the following equation:

$$\frac{\partial \alpha_n}{\partial t} + \nabla\left(\alpha_n . \vec{V}\right) = 0 \tag{8}$$

The value of the volume fraction parameter ' α_n' within a computational cell denotes the fraction of the 'n' fluid present in it. This value ranges from 0 when the cell does not contain the fluid to 1 when it is filled.

The following equations are employed to evaluate the electrical and thermal efficiency of the system [52–54]:

$$\text{Electrical efficiency}: \eta_{el} = \frac{E_{el}}{E_{sun}} = \eta_r . [1\text{-}0.0045. (T_{cell} - 298.15)] \tag{9}$$

where T_{cell} represents the PV cell temperature and η_r represents the PV module temperature at the modulus condition.

$$\text{Thermal efficiency}: \eta_{th} = \frac{E_{el}}{E_{sun}} = \frac{m_{nf}.C_{p,nf}.\left(T_{nf,out}\text{-}T_{nf,in}\right)}{G.A_c.\tau_c.\ \alpha_{cell}} \tag{10}$$

Additionally, the thermal exergy of the current model can be expressed as following:

$$\text{Thermal exergy}: mC_{p,nf}\left[(T_{out}) - (T_{in}) - T_0 \ln\frac{T_{out}}{T_{in}}\right] \tag{11}$$

in this simulation, k-epsilon turbulent model was used in ANSYS-FLUENT commercial software. The QUICK method was employed to determine turbulent kinetic energy, while the PRESTO method was utilized for pressure equations. The SIMPLE approach demonstrated the connection between pressure and velocity in a model. The convective components of the momentum and energy equations utilized a specialized technique known as a second-order upwind scheme, which was applied when organizing the data into distinct parts. However, the specific dissipation rate term was interpolated using a first-order upwind scheme. The convective terms in the energy and momentum equations were discretized using a second-order upwind scheme. Convergence criteria for residuals in all equations were set to be under 10^{-6}, and under 10^{-8} for the energy equation. The simulation time for PCM is 1 h.

By observing Fig. 3, it is evident that when the mesh size is increased, the average surface temperatures become more similar. Specifically, the temperature difference for the PV cell between 3.73*10^6 and 5.01*10^6 elements is 0.64 %. On the other hand, when comparing 1.52*$10^{\hat{}6}$ and 3.73*10^6 elements, the temperature difference is 5.9 %.

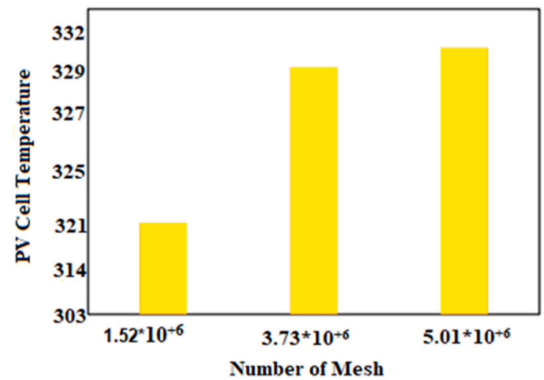

Fig. 3. Mesh indecency.

2.3. Validation and mesh independence

The CFD quandary-solving approach should be designed so that the changes in the results become insignificant as the mesh is refined—the grid distribution for the PV/T systems generated by ANSYS Workbench 18.2 software. Moreover, the meshing strategy should prioritize placing the highest density of cells near the solid walls, as depicted in Fig. (4). By comparing the data of this article with the [55] for Case A and no PCM, it can be concluded that by changing the number of meshes from 1552000 to 5014000, the optimal number of meshes is 3730000, which has both good accuracy and can reduce simulation cost and time. (See Table 7). To check if this paper is correct, we will compare its results with the experiments done by Shahsavar et al. [56] and Irem Karaaslan et al. [57]., and its results include PV cell temperature and electrical efficiency show good agreement. The maximum error is less than 3.3 % (Fig. 5).

3. Results

This article examines the impact of using PCM and PCM composites in a thermal photovoltaic system that consists of three different flow paths and various mixtures of hybrid nanofluids. The study was conducted using numerical data and calculations. The main goal in the PV/T system simulations is to reduce the surface temperature of the cell and increase the outlet fluid temperature, which can be used for various purposes. In the first part, the impact of using two types of PCMs in different geometries was compared with the state without PCM, and the

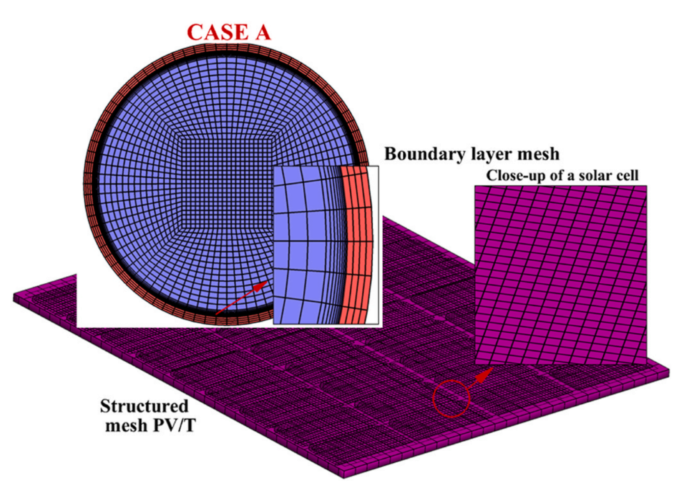

Fig. 4. Mesh elements of the PVT system.

Table 7
Grid independence study.

Test specifications	CASE A and NO-PCM				
Mesh number (10^{+6})	1.552	2.681	**3.733**	4.610	5.014
PV cells temperature	321.596	325.9435	**329.9710**	331.8840	332.3694
Outlet temperature	302.1138	305.7550	**307.5091**	308.2234	308.6437

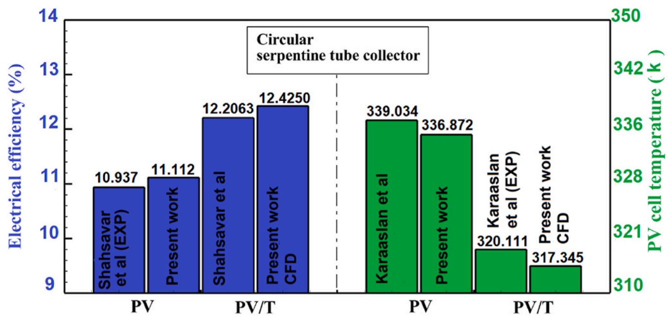

Fig. 5. The comparison of cell temperature and electrical efficiency of the present paper and [56,57].

results, including the outlet fluid temperature, cell surface temperature, and thermal and electrical efficiency, were investigated. In the next step, the impact of different types and concentrations of various hybrid nanofluids was studied in the geometry with the best performance (Case B).

3.1. Fluid outlet temperature and cell surface temperature

One of the primary factors that should be presumed in designing PVT systems, especially in areas with very hot climates, is the cell surface temperature. Because increasing temperature causes thermal degradation, the increase in the cell surface temperature is inverse to the solar system's efficiency. To examine the impact of PCM on the cell temperature, two different PCMs were used in various geometries, and their results were compared with the No PCM state. Fig. (6) illustrates that the utilization of PCMs leads to a substantial reduction in the surface temperature of the PV cell. This reduction helps mitigate the disadvantages associated with high surface temperatures. Due to the geometry that causes more heat transfer, Case B has lower temperatures than Case A and Case C in all the investigated states. In such a way, using PCM and PCM composite in Case B leads to a 1.8 and 3.1 % decrease in cell surface temperature compared to the no PCM state. The PCM absorbs the extra heat from the PVT surface and reduces the cell surface temperature. By comparing PCM and PCM composite, it can be seen that PCM composite has a better performance in cell surface temperature. Physically, it is advantageous for the melting point of the phase change materials to be within the working temperature range of the system. This alignment ensures better efficiency and performance of the system so that both hidden and sensible thermal energy storage models can be used simultaneously.

The outlet temperature of the fluid is a crucial parameter in the design of PV/T systems as it greatly influences the overall system efficiency. Fig. (7) shows that Case B has the hottest output temperature, followed by Case A and then Case C. Using PCMs has caused the fluid in the system to become hotter. Using PCM and PCM composite, the temperature of the fluid at the outlet has increased by 0.25 % and 0.39 %, respectively, compared to not using PCMs in Case B. The use of PCM COMPOSIT has better performance in the outlet temperature of the fluid in all the cases studied compared to the PCM case. After absorbing heat by the PVT system, the PCMs in the walls also begin to absorb heat and reach their melting point. From this point on, PCM continues to absorb thermal energy from the photovoltaic system but resists the increase in ambient temperature and maintains its temperature at its melting point. So, PCM and PCM COMPOSIT keep their temperature and the surrounding temperature steady at 313 k and 311 k throughout the melting process. Hence, the better performance of PCM Composit in increasing the fluid's outlet temperature and reducing the solar cell's surface temperature is justifiable.

3.2. The effect of hybrid nanofluids on T_{out} and T_{cell}

The application of nanofluids in heat transfer has become very popular, and their use can significantly improve the performance of thermal systems. Fig. (8) shows the changes in cell surface temperature in the NO PCM, PCM, and PCM COMPOSITE photovoltaic thermal system in four different fluids for CASE B, which had the best performance in the previous section. The figures show that using pure water cannot cool the surface temperature of the cell very well in comparison to using different hybrid nanofluids at a concentration of 1.5 %. Physically, using hybrid nanoparticles increases thermal conductivity and heat absorption capacity. Parameters such as Brownian diffusion, thermophoresis, and irregular movements of nanoparticles result in an enhanced energy exchange rate, leading to an increased temperature gradient between the structure and fluid. As can be seen in the figure, the use of hybrid

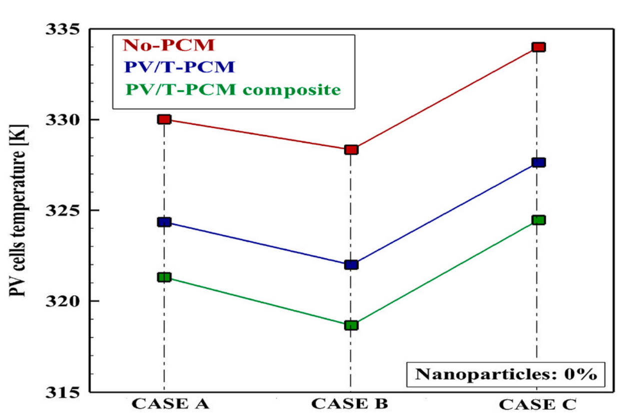

Fig. 6. PVT cell temperature in different geometries with PCMs and without PCM.

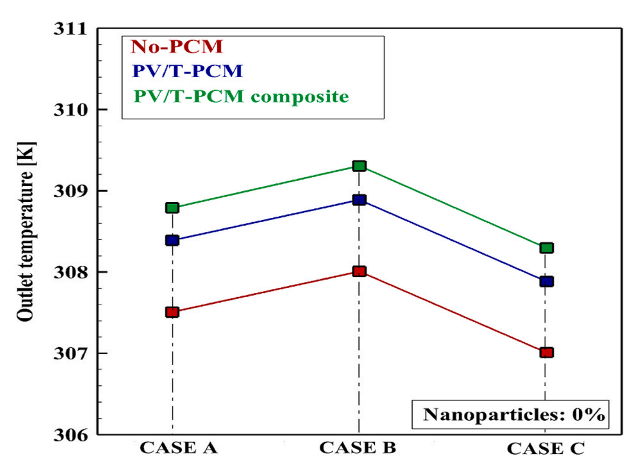

Fig. 7. Fluid outlet temperature in the various cases.

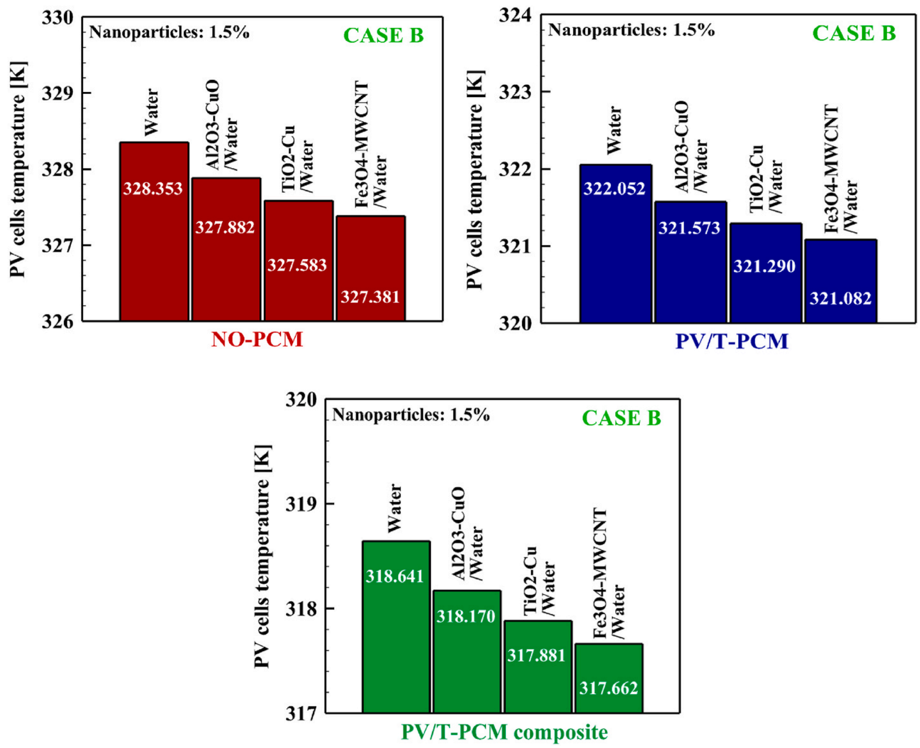

Fig. 8. PV cell temperature in different cases with PCMs and hybrid nanofluids.

nanofluids reduces the cell's temperature and is a suitable method to increase efficiency in solar systems [58,59].

Fe3O4-MWCNT hybrid nanofluid causes the surface cell temperature to be lower and the outlet fluid temperature to be higher due to its higher heat capacity and more excellent thermal conductivity than other fluids studied. This hybrid nanofluid results in a 0.3 % decrease in surface cell temperature and a 0.14 % increase in outlet fluid temperature compared to pure water when PCM is not used. Another noteworthy point in the figure is the significant changes in cell surface temperature when using PCM and PCM composite compared to the case without PCM. For example, adding 1.5 % Fe3O4-MWCNT hybrid nanofluid to the system when using PCM and PCM composite decreases the surface cell temperature by 6 and 10 K compared to the NO PCM case. From a physical point of view, the resistance of PCMs against an increase in

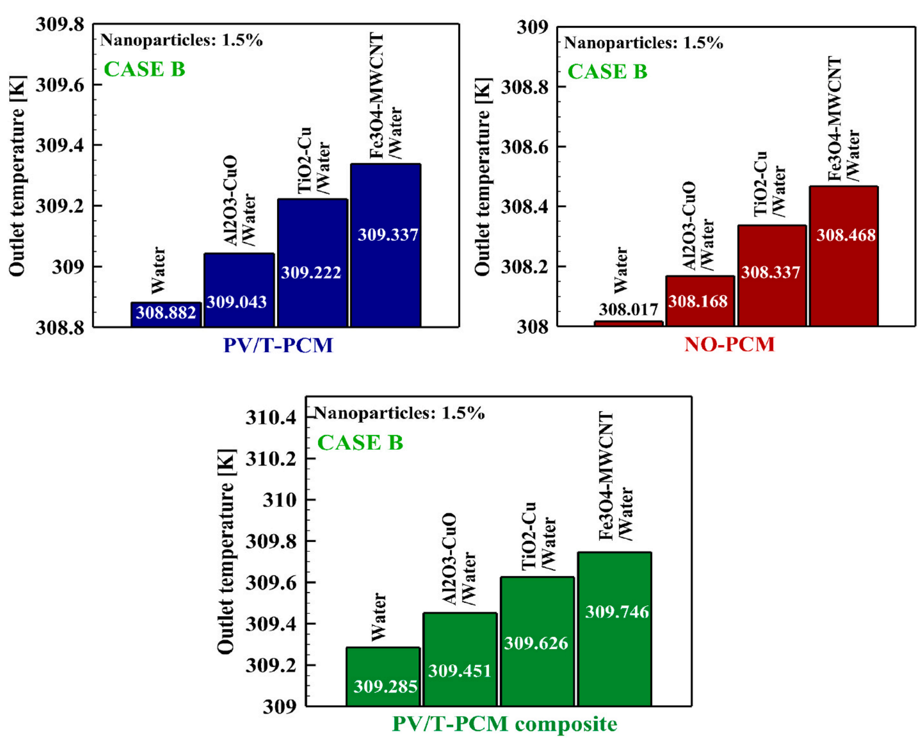

Fig. 9. Outlet temperature in various cross sections with PCMs and hybrid nanofluids.

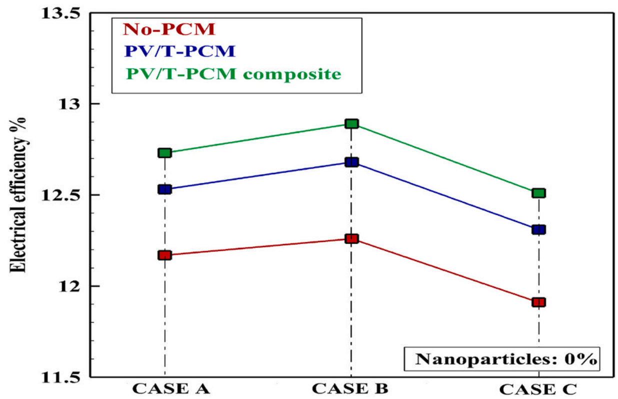

Fig. 10. Electrical efficiency in different cross sections with PCMs and without PCM.

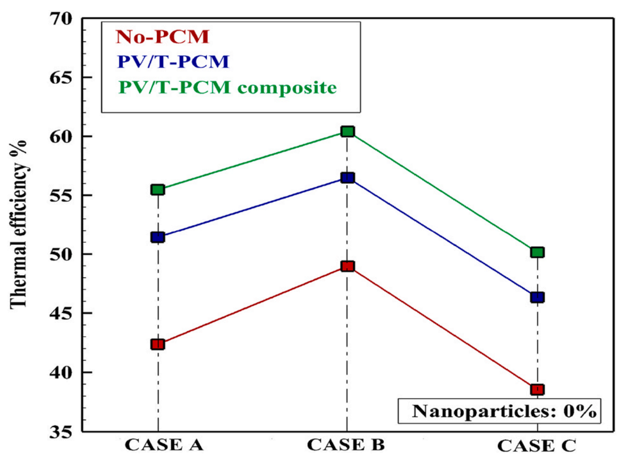

Fig. 11. Thermal efficiency in different cross sections with PCMs and without PCM.

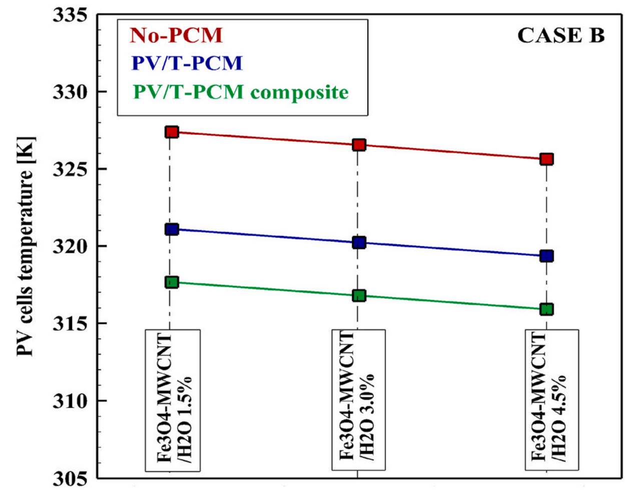

Fig. 12. The impact of nanoparticle concentration on PV cell temperature.

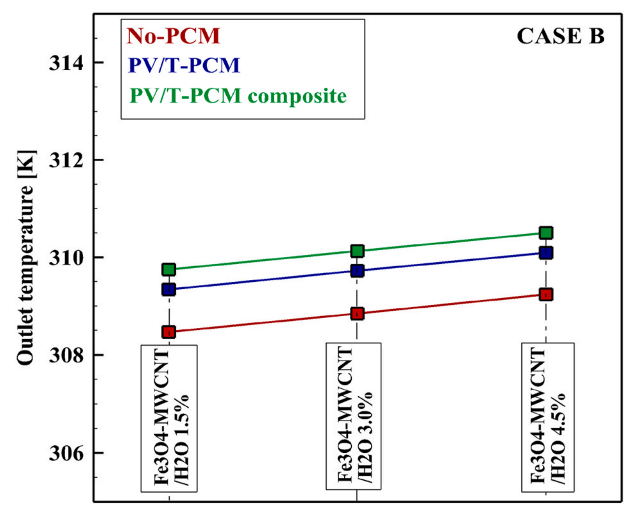

Fig. 13. The impact of nanofluid concentration on outlet temperature.

ambient temperature and their own disappears after complete melting. At this point, nanofluids can delay the complete melting of PCM and be a suitable method for cooling the system.

Fig. 9 shows the effect of hybrid nanofluids on fluid outlet temperature for CASE B in the presence of PCMs and NO PCM. As can be seen, using PCM COMPOSIT performs better than PCM and NO PCM.

Fusion temperature and enthalpy of fusion are two critical points for PCMs that assign each PCM's performance and thermal performance. The lower surface temperature of the cell increases the electrical efficiency, and the fluid's outlet temperature directly relates to the system's thermal efficiency. Electricity is more critical than heat, so the efficiency of a PV/T system in utilizing electricity is crucial for its overall performance. Fig. (10) shows the impact of PCMs on electrical efficiency in different cross sections. Electrical efficiency for CASE B, which has the highest electrical efficiency compared to CASE A and CASE C, increases when using PCM and PCM composite, respectively 2.4 and 4.8 % compared to the NO PCM state.

Fig. (11) clearly shows that adding PCMs to the PVT system improves its ability to generate more thermal efficiently. According to formula (9), using PCMs helps increase thermal efficiency. Using PCM and PCM composite for CASE B, which has the highest thermal efficiency, can increase thermal efficiency by 16.3 and 23.4 %, respectively compared to the NO PCM state. PCM composite works better than PCM because it increases the outlet temperature of the fluid.

3.3. The effect of hybrid nanoparticle concentration on the PVT system

High-concentration nanofluids, which consist of very small and highly concentrated particles, can be used to enhance the performance of solar systems. According to Table 5, increasing the concentration of the Fe3O4-MWCNT hybrid nanofluid increases thermal conductivity and improves system cooling. To find out the impact of nanofluid concentration, the rectangular cross-section (CASE B), which demonstrated better performance in the previous section of the article, was used.

Fig. 12 shows that using a higher concentration of hybrid nanofluid reduces the PVT cell temperature by increasing the thermal conductivity coefficient. Using PCM composite at 3 % and 4.5 % concentrations will decrease the surface cell temperature by 0.25 % and 0.56 % compared to the hybrid nanofluid with the concentration of 1.5 %.

Fig. (13) shows the variations of the fluid outlet temperature at variant concentrations of hybrid nanofluid. As the concentration of nanofluid increases, there is a corresponding rise in the fluid outlet temperature. The Brownian motion causes enhanced heat transfer within the fluid, resulting in a higher outlet temperature. Regarding the effect of PCMs, it can be pointed out from this figure that with an increase in the concentration of nanofluid, the complete melting of PCMs is delayed, which is in favor of the cooling of the PVT system because after melting, the temperature starts to increase, reducing the temperature gradient of the fluid and structure. With an increase in

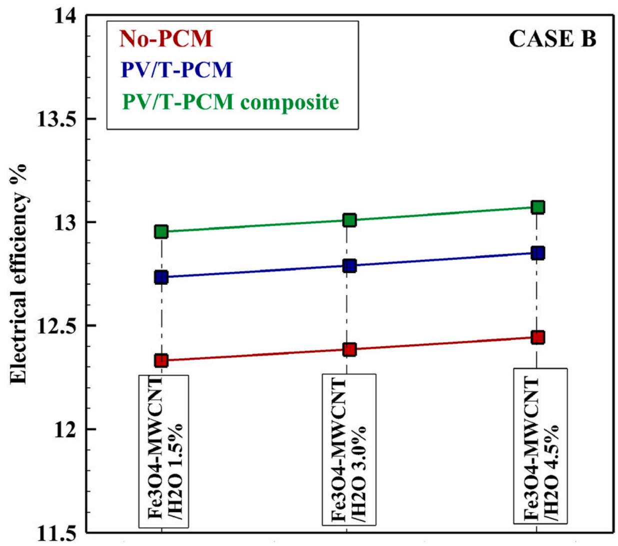

Fig. 14. The effect of nanofluid concentration on electrical efficiency.

concentration from 1.5 to 4 % for the case using a PCM composite, the fluid outlet temperature increases by 0.4 %.

The changes in electrical efficiency when using nanofluid hybrids at different concentrations are shown in Fig (14) for both PCM and no-PCM states. As the cell surface temperature increases, the efficiency of electricity decreases. However, using nanofluids with more concentration can lower the temperature of the cell surface, resulting in improved electricity performance. The electrical efficiency for PCM composite, PCM, and no PCM states, when the nanofluid concentration reaches 1.5 to 4%, should increase by 2.31, 0.83, and 0.80 %, respectively.

3.4. PCM liquid fraction and exergy efficiency

Fig. 15 illustrates the PCM liquid fraction for case B, which had the best performance among different geometries at various concentrations of the Fe3O4-MWCNT hybrid nanofluid (1.5–4%). Using a higher concentration of the hybrid nanofluid increases the heat transfer coefficient and causes a rise in thermal permeability, resulting in a higher liquid fraction.

Energy investigation depends on the basic standards of the primary law of thermodynamics, while exergy examination is grounded in the principles of the second law of thermodynamics. Exergy examination is a method of analyzing energy that distinguishes between useable and unusable energy. The exergy terms can be calculated by assuming the status of the dead case, where the T0 is set to 298K, the pressure is set to 100 kPa, and the sun's temperature is considered to be 5774K. The action of the exergy performance is very similar to the behavior of the electrical performance. Fig. 16 shows exergy efficiency when Fe3O4-MWCNT 4.5 wt% is used in different geometries. According to the results, CASE B is more efficient than the other two patterns. The PV/T model is highly effective as it can produce hotter fluid while keeping the PV cool, making it superior to other models. This means that CASE B has better exergy performance according to Equation (10). The evaluation between PCM and PCM composite reveals that the PCM composite exhibits more significant superiority in enhancing exergy efficiency when compared to PCM. This study showed that using PCM composite increases exergy efficiency as one of the critical parameters in solar systems compared to PCM. In Refs. [46,60], PCM composite performance was better than PCM in terms of thermal and electrical efficiency and exergy. Therefore, researchers should pay more attention to the performance of PCM composite.

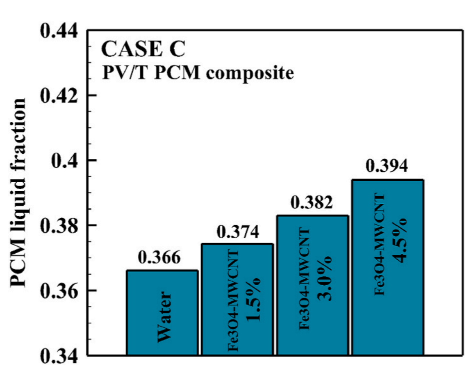

Fig. 15. Liquid fraction for various nanofluid concentration.

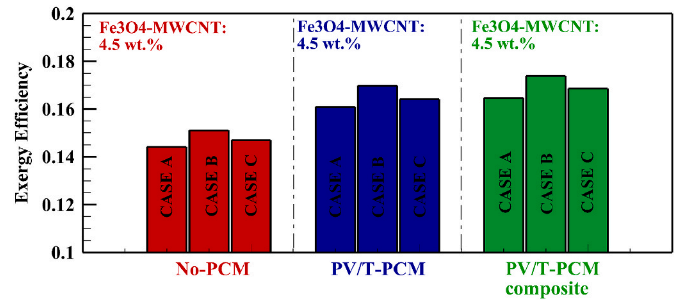

Fig. 16. Exergy productivity of PV/T system in various cases by PCMs and without PCM.

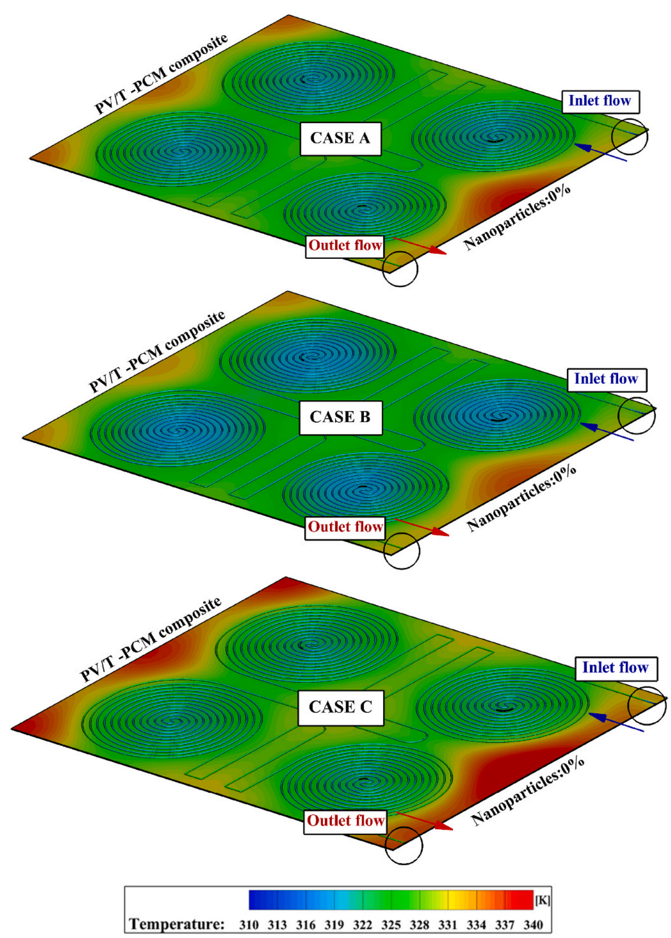

Fig. 17. PVT cell contours in different studied cross sections.

3.5. The cell temperature of the PV/T system

Fig (17) illustrates the impact of variant cross-sectional areas on the surface temperature of the cell when using composite with and without nanofluid. As it can be seen, using a rectangular cross-section (case b) causes the sheet temperature of the cell to be lower than other cross-sectional areas for the reasons mentioned earlier. The coolest part of the fluid is in the inlet section, while the hottest part is where there is an air gap. Due to the absence of cooling tubes and PCM, the temperature in these areas is high, and because of the low thermal conductivity of the air, it cannot provide suitable cooling for the cell.

4. Conclusion

This article investigated the numerical effects of using rectangular, circular, and triangular cross-sections along with PCM and hybrid nanofluids in a PVT system. Additionally, the influence of different nanofluid concentrations on various parameters such as fluid outlet temperature, cell temperature, and electrical and thermal efficiency was evaluated. The principal outcomes obtained are as follows:

- The use of a rectangular-shaped cross-section (CASE B) resulted in better performance in all the studied factors due to its larger heat transfer area compared to other cross-sectional shapes.
- Using PCM and PCM composite helps lower the temperature of the cell greatly. The PCM composite is more effective than using just PCM in making the cell cooler and the fluid outlet temperature hotter.
- Using carbon-based hybrid nanoparticles improves the efficiency of the solar system compared to other hybrid nanofluids.
- By nanofluids with higher concentration, the temperature of the cells can be reduced, and both electrical and thermal efficiency can be improved.
- When using Fe_3O_4-MWCNT (4.5 %) along with PCM and PCM composite, the exergy efficiency can be increased by 13.3 % and 16.2 % compared to the no PCM condition.

5. Future scope

The results of this numerical simulation showed that using Fe_3O_4-MWCNT 4.5 wt% along with a rectangular cross-section can significantly increase the efficiency of the PV/T systems. For further research, this design can be investigated in a laboratory. Also, using green nanofluids that can reduce the environmental disadvantages of nanofluids can be a valuable research topic for this article. Also, using fins to improve the performance of this system and investigating the amount of pressure drop can provide the necessary ground for use on industrial scales.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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