INTRODUCTION

Rising energy needs, global warming, environmental pollution, fossil fuel prices, and concerns about depletion of these fuels in the not-too-distant future are among the reasons why scientists and governments are paying special attention to using renewable energy sources, improving and expanding the related technologies. Solar energy is one of the most widely available types of renewable energy. Solar thermal collectors and photovoltaic (PV)
panels are two of the most efficient and sustainable solar energy systems that are used for heating and electricity generation, respectively. The efficiency of these systems is about 75%–80% and 15%–20%, respectively. In a PV panel, by absorbing solar radiation, part of the energy not used by the solar cells, as well as the energy passing through the empty space between the cells, causes the cell to heat up and increase the operating temperature of the system. In fact, with increasing the amount of radiation, the cell efficiency increases, but with increasing the operating temperature of the cell, the voltage of the open circuit and consequently the efficiency of the cell decrease. Therefore, many efforts have been made to control the operating temperature and then increase the electrical efficiency of the PV panels. One of the most basic ways to improve the performance of these systems is to use a thermal collector integrated with a PV panel, which is known as a combined PV-thermal (PVT) system.

The PVT system, as the third generation of the solar energy-efficient system, has advantages over two separate PV panels and solar collectors including improving the performance of the PV panel and the simultaneous generation of the electrical and thermal power. Therefore, in recent decades, many efforts have been made to improve the performance of this type of solar system such as changing the structure of the PV panel, changing the type of current regime, using different flow channel geometries, changing the type of current regime, using different flow channel geometries, using concentrators and radiation enhancers, and using nanoparticles as spectral filters and cooling fluids.

In a PVT system, the working fluid is of special importance as a heat absorber from the solar cells, and a carrier of thermal energy in the collector. For this reason, if the thermophysical properties of the working fluid are improved, the overall performance of the system will also be enhanced. Nanoparticles have typically higher thermal conductivity, compared to the base fluid; therefore, nanofluids have better heat transfer properties than the common base fluids such as air and water. In many studies, nanofluids have been used as the working fluid in the PVT system, which all have reported enhanced system performance compared to the conventional fluid-based systems. In a numerical study, Elmir et al. investigated the Navier-Stokes and energy equations for the laminar flow of Al2O3/water nanofluid as a cooling fluid in a rectangular channel integrated with a silicon solar panel by finite element method (FEM). They reported that by using the nanofluid, the rate of heat transfer from the panel to the fluid, and thus, the system performance improved. Rajab et al. studied the performance of a PVT system with plate and tube collector in the presence of four types of nanofluid including Al2O3/water, Cu/water, Al2O3/ethylene glycol, and Cu/ethylene glycol as coolant. The results showed that the water-based nanofluids improved the system thermal performance more efficiently than the ethylene glycol-based ones, as well as copper nanoparticles compared to aluminum oxide.

In an experimental study, conducted by Abdullah et al., they used Al2O3/water nanofluid with volume fractions of 0.2%, 0.1%, 0.05%, 0.03%, and 0.075% as a coolant in a PVT system with plate and tube collector. They concluded that at an optimum flow rate of 1.2 L/min, the optimum volume fraction of nanofluids is 0.1%, which reduces the panel temperature by 10°C at maximum radiation and by 8.6°C at average daily radiation. Nasrin et al. used a new form of the collector with 16 baffles to increase heat transfer from the PV panel to the nanofluid. By examining the volume fractions from 0% to 3%, they found that with increasing the nanofluid volume fraction, the thermal conductivity and, consequently, the heat transfer rate increase. They also showed that the PVT system performed better using Ag/water nanofluids in comparison with Cu/water and Al/water nanofluids.

In addition to energy efficiency, the exergy efficiency of the PVT systems, as well as the type of flow regime, was investigated by Yazdanifar et al. using TiO2 and Al2O3 nanoparticles in water and water-ethylene glycol mixture. The results of their study showed that to improve system performance, adding nanoparticles to the laminar flow is more effective than that to the turbulent flow. They also concluded that in the turbulent flow of nanofluids, higher energy and exergy efficiencies can be achieved by increasing the diameter of the nanoparticles, as opposed to the laminar flow. In addition, Al2O3 water-based nanofluids yield higher energy and exergy efficiencies than TiO2 water-ethylene glycol mixture-based fluid. Shahsavvar et al. studied the performance of a PVT system with a sheet and plain serpentine tube collector, by replacing the flat helix tube with a helix tube with 3- and 6-start rifled PVT system. Their experiment’s results showed that using magnetite/water nanofluid with a volume fraction of 2% at the flow rate of 80 kg/h, the 6-start rifled PVT system has, respectively, 22.5% and 3.8% higher total energy efficiency, and 5.9% and 1.9% higher total exergy efficiency, in comparison with the base system and 3-start rifled system.

In an experimental study which is done by Sohani et al., a PV system and four PVT systems were investigated from reliability, energy, efficiency, economic, and environmental point of view. One-year data obtained from the experiment showed that the gained score by the PV system and the PVT systems with the pure water and water-based Al2O3, TiO2, and ZnO nanofluidics is 12.8, 14.2, 13.9, 26, and 33.1 out of 100, respectively, which is shown that the ZnO nanofluid had the best performance. In addition, the use of pure water-based PVT is much better than Al2O3 one due to economic issues.
HORMOZI MOGHADDAM and KARAMI et al.34 used a microgrid PVT system to supply the electric and thermal energy demand by a greenhouse. The indoor and outdoor panels were evaluated by the pure water and water-based single and hybrid nanofluids (SiO$_2$-Al$_2$O$_3$) as the working fluid. The experiment results showed that the outdoor panel using the hybrid nanofluid (SiO$_2$-Al$_2$O$_3$: 0.5–0.5 wt%) has the best electrical and thermal efficiency, which is 1.7% and 8.97% higher than the indoor system, respectively.

As the literature review shows, the performance of thermal systems using nanofluid as a coolant improves; however, due to the higher nanofluid viscosity compared to the base fluid, increased energy loss and pressure drop, which results in the increase of pumping power, is a challenging factor. Jabbari et al.35 studied the dynamic viscosity of the CNT/water nanofluid at different temperatures and concentrations using molecular dynamics simulation and experimental investigation. They concluded that by increasing the concentration of nanofluids in all temperatures, the dynamic viscosity of the nanofluid is also increased. At the temperature of 25°C, the ratio of the nanofluid viscosity with a volume fraction of 1% to the base fluid is 3.57. Measuring the dynamic viscosity of the Ag-MgO/water hybrid nanofluid by Esfe et al.36 showed that the nanofluid dynamic viscosity ratio increases from 1.061 to 1.381 by increasing the volume fraction from 0.005 to 0.02. Shamsuddin et al.37 showed that in a microchannel heat sink, using CNT/water nanofluid with a volume fraction of 0.1% instead of water increases the pressure drop by 47%. Therefore, in addition to the energy and exergy efficiencies, the study of the hydraulic efficiency of the PVT system, especially in systems with complex geometry, is of great importance, which has received less attention. On the contrary, in recent years, hybrid nanofluids have been studied as a new type of nanofluids to improve nanofluid properties such as thermal conductivity, chemical stability, mechanical strength, and increasing heat transfer.36,38,39 The turbulent flow of hybrid nanofluid MWCNT-Fe$_3$O$_4$/water is experimentally investigated by Sundar et al.40. Their results showed that using hybrid nanofluid increases Nusselt number and pressure drop by 31% and 1.2 times compared to the water as the working fluid, respectively. Krishna et al.41 used MWCNT-CuO/water hybrid nanofluid for cooling of a microchannel heat sink and found that the Nusselt number increases by 4.68% and 12.64% in comparison with CuO/water and MWCNT/water nanofluids, respectively. However, the pressure drop enhances by 300 Pa compared to water. Javadi et al.42 have explored the performance of borehole heat exchangers using four hybrid nanofluids with different volume fractions from 0.05 to 0.2. The results revealed that the heat exchanger has higher effectiveness and lower pressure drop using Ag-MgO/water hybrid nanofluid compared to those using TiO$_2$-Cu/water, Al$_2$O$_3$-CuO/water, and Fe$_3$O$_4$-MWCNT/water nanofluids.

In the present study, two water-based nanofluids including a hybrid nanofluid (Ag-MgO nanofluid) and a mono nanofluid (CNT nanofluid) are selected to simulate and compare the thermohydraulic performance of the PVT system with the rectangular channel. Also, the effect of the operating parameters such as the type and flow rate of the working fluid, volume fraction of nanoparticles, and channel height on Nusselt number and friction factor is investigated.

2 | MATERIALS AND METHODOLOGY

2.1 | Model description

Figure 1 shows a schematic of a 3D model of the PVT system consisting of a PV panel with specific layers, a copper absorber plate, and a rectangular flow channel. The characteristics of the considered PVT are shown in Table 1. To distribute the energy evenly and also to prevent hot spots in the PV panel, a layer of glass has been used on the upper surface of the panel. Solar cells, Tedlar, and two layers of ethylene-vinyl acetate (EVA) are the other layers of the PV panel. To cool the PV panel and generate thermal power, CNT and hybrid Ag-MgO nanofluids have been used. The lateral borders of the whole system are well insulated to reduce heat loss. The overall dimensions of the PV panel are $700 \times 400 \times 4.8$ mm. The thickness of the PV layers and their thermophysical properties are presented in Table 2. Also, the characteristics of nanoparticles and base fluid are listed in Table 3.

2.2 | Nanofluid properties

To calculate the properties of hybrid nanofluid, the relations listed in Table 4 are used.36,43 The thermal conductivity and viscosity of the nanofluid are calculated using the relations presented by Esfe et al.36. They provided very good relations, which have a very good agreement with
experimental data. In these relations, $\varphi_{\text{rep}}$ is the total volume fraction, which is the sum of the volume fraction of nanoparticles in the hybrid nanofluid.

The relations used to calculate the properties of CNT nanofluid are presented in Table 5. For calculating the thermal conductivity and viscosity of this nanofluid, new models have been proposed which are based on static and dynamic mechanisms of thermal conductivity compared to the classical models.44,45 In these models, it is necessary to consider the concentration, size, and aspect ratio of nanoparticles. For this purpose, the thermal conductivity of CNT nanofluid is calculated using the equation obtained by Walker et al.,46 which is presented in Table 5. In this equation, the base fluid particles are assumed to be spherical with a radius of $r_{bf}$ and the CNT nanoparticles are considered as cylindrical with a radius of $r_p$ and length of $l_p$. Also, to calculate the viscosity of nanofluid, the model proposed by Brenner and Condiff47 has been used, in which $\lambda = l_p/d_p$ is the aspect ratio of CNT nanoparticles. In the present study, four different volumetric fractions of 0.5%, 1.0%, 1.5%, and 2.0% are considered.

2.3 Simulation method

To simplify the numerical solution, the following assumptions have been considered14,48:

- The fluid flow in the channel is steady, fully developed, Newtonian, and incompressible.
- The nanofluid flow is considered as single-phase.
- The contact resistance between the different layers of the PVT system is neglected.
- All layers and working fluids have isotropic, temperature-independent physical properties.
- It is assumed that part of the incident radiation is uniformly absorbed by the glass, and the rest is absorbed by the solar cell.
- The thermal energy absorbed by the PV module is calculated using the module efficiency and entered the numerical model as a constant heat flux.

Considering steady-state conditions, the heat transfer equation in solid layers is as follows:

$$\nabla \cdot (k VT)_s + q = 0$$

\[(1)\]

The fluid flow in the channel is steady, fully developed, Newtonian, and incompressible.

- The nanofluid flow is considered as single-phase.
- The contact resistance between the different layers of the PVT system is neglected.
- All layers and working fluids have isotropic, temperature-independent physical properties.
- It is assumed that part of the incident radiation is uniformly absorbed by the glass, and the rest is absorbed by the solar cell.
- The thermal energy absorbed by the PV module is calculated using the module efficiency and entered the numerical model as a constant heat flux.

### TABLE 1 Characteristics of the PVT system

| Parameter                     | Value   |
|-------------------------------|---------|
| Glass transmissivity, $\tau_g$ | 0.9     |
| Glass absorptivity, $\alpha_g$ | 0.1     |
| Glass emissivity, $\varepsilon_g$ | 0.9     |
| EVA transmissivity           | 1       |
| PV cells absorptivity, $\alpha_c$ | 0.85   |
| PV cells transmissivity, $\tau_c$ | 0      |
| PVT module’s tilt angle      | 30      |
| PV module’s reference electrical efficiency, $\eta_s$ | 0.15     |
| Thermal coefficient of PV cell efficiency, $\beta$ | 0.0045   |
| PV packing factor, $P_w$      | 0.85    |
| Reference temperature, $T_{ref}$ (°C) | 25     |
| Ambient temperature, $T_{amb}$ (°C) | 35     |
| Fluid inlet temperature, $T_{in}$ (°C) | 32     |
| Solar radiation, $G$ (W/m²)  | 1000    |
| PVT area, $A$ (m²)           | 0.7 × 0.4 |

### TABLE 2 Thermophysical properties and thickness of the layers of the PVT system

| Layer       | Density (kg m⁻³) | Specific heat capacity (J kg⁻¹ K⁻¹) | Thermal conductivity (W m⁻¹ K⁻¹) | Thickness (mm) |
|-------------|-----------------|-------------------------------------|----------------------------------|----------------|
| Glass       | 2200            | 830                                 | 0.76                             | 3              |
| EVA         | 960             | 2090                                | 0.35                             | 0.5            |
| PV cells    | 2330            | 700                                 | 148                              | 0.3            |
| Tedlar      | 1200            | 1250                                | 0.2                              | 0.1            |
| Absorber    | 8960            | 385                                 | 401                              | 0.4            |

### TABLE 3 Properties of base fluid and nanoparticles

| Component          | Density (kg m⁻³) | Specific heat capacity (J kg⁻¹ K⁻¹) | Thermal conductivity (W m⁻¹ K⁻¹) | Viscosity (kg m⁻¹ s⁻¹) |
|--------------------|-----------------|-------------------------------------|----------------------------------|------------------------|
| Water              | 997.1           | 4179                                | 0.613                            | 8.98 × 10⁻⁴            |
| CNT (d = 20 nm, l = 35 µm) | 2100          | 796                                 | 3000                             | –                      |
| MgO                | 3560            | 955                                 | 45                               | –                      |
| Ag                 | 10,500          | 235                                 | 429                              | –                      |
where $k$ and $T$ are the thermal conductivity and temperature, respectively. The index $s$ is related to the solid layers. Only in glass layers and PV cells, $q$ has the quantity, which is equal to the absorbed solar radiation by these layers. Other layers have no absorbed radiation.

The mass, momentum, and energy conservation equations for the fluid flow are written as the following:

$$ \nabla \cdot ( \rho U ) = 0 $$

$$ \nabla \cdot ( \rho U ) = - \nabla P + \nabla \cdot \left( \mu \nabla U \right) + \rho g $$

$$ \nabla \cdot ( \rho C_p U ) = \nabla \cdot ( k \nabla T ) $$

For evaluating the hydraulic performance of the PVT system, Nusselt number and friction factor are calculated using the following relations:

$$ N_u = \frac{h D_h}{k_{nf}} = \frac{q D_h}{k_{nf} ( T_{abs} - T_b )} $$

$$ f = \frac{2 \Delta P D_h}{\rho_{nf} U^2} $$

where $q$, $T_{abs}$, and $T_b$ are heat flux, the absorber plate temperature, and bulk temperature in different sections of the flow channel, respectively.

In this study, the solar radiation, the ambient and inlet fluid temperatures, and the flow rate are considered 1000 W/m$^2$, 35°C, and from 8 L/h to 32 L/h, respectively.

The boundary conditions to solve the governing equations on the PVT performance are as follows:

1. For the fluid field, the velocity inlet ($U = U_{in}$), the inlet temperature ($T = T_{in}$), and pressure outlet ($P_{out} = P_{out} = 0$) are considered.
2. The lateral surfaces of the different layers of the PV panel and the lateral and lower surfaces of the flow channel are completely adiabatic ($n \cdot (k \nabla T) = 0$).
3. The glass upper surface is of the wall type, and heat from this surface is dissipated through convection and radiation. The heat transfer equation is defined in the form of the following equation:

$$ \dot{q}_{loss} = h_w ( T_w - T_s ) + \sigma \varepsilon ( T_{sky}^4 - T_s^4 ) $$

where $\sigma$, $\varepsilon$, and $h$ are, respectively, Stefan-Boltzmann constant, the glass emissivity, and the convective heat transfer coefficient, which can be calculated using the following relations:

$$ h_w = 5.7 + 3.8 V_w \text{ if } V_w < \frac{5 m}{s} $$

$$ h_w = 6.47 + ( V_w )^{0.78} \text{ if } V_w > \frac{5 m}{s} $$

| TABLE 4 | Applied relations for the thermophysical properties of the Ag-MgO/water hybrid nanofluid$^{36,43}$ |
|----------|-------------------------------------------------------------------------------------------------|
| Property                      | Applied relations                                                                                   |
| Total volume fraction         | $\varphi_{nf} = \varphi_{Ag} + \varphi_{Mgo}$                                                      |
| Density                       | $\rho_{nf} = \rho_{nf} (1 - \varphi_{nf}) + (\rho_{Ag} + \rho_{Mgo})$                            |
| Specific heat capacity        | $(\rho C_p)_{nf} = (1 - \varphi_{nf}) (\rho C_p)_{Ag} + (\varphi C_p)_{Mgo}$                    |
| Thermal conductivity         | $k_{nf} = \left( \frac{0.1747 \times 10^{5} + \varphi_{nf}}{114.73 \times 10^{5} - 0.1498 \times 10^{5} \varphi_{nf} + 0.1157 \times 10^{6} \varphi_{Ag} + 0.1997 \times 10^{5} \varphi_{Mgo}} \right)$ |
| Viscosity                     | $\mu_{nf} = \left( 1 + 32.795 \varphi_{nf} - 7214 \varphi_{nf}^2 + 714600 \varphi_{nf}^3 - 0.1941 \times 10^{5} \varphi_{nf}^4 \right) \mu_{Ag}$ |

| TABLE 5 | Relations for the thermophysical properties of the CNT/water nanofluid$^{46,47}$ |
|----------|-----------------------------------------------------------------------------------|
| Property                          | Applied relations                                                                                   |
| Density                           | $\rho_{nf} = \rho_{nf} (1 - \varphi) + \rho_{CNT} \varphi$                                       |
| Specific heat capacity            | $(\rho C_p)_{nf} = (1 - \varphi) (\rho C_p)_{Ag} + \varphi (\rho C_p)_{CNT}$                  |
| Thermal conductivity             | $k_{nf} = k_{nf} \left( 1 + \frac{2 \varphi C_p h_{nf}}{l_p} \right)$                            |
| Viscosity                        | $\mu_{nf} = (1 + \eta \varphi) \mu_{nf} \eta = \frac{0.3112 - 0.5}{0.78 - 1.13} + 2 - \frac{1.872}{2}$ |

0 $\leq$ $\varphi_{nf}$ $\leq$ 0.02
where \( V_w \) is the wind velocity. In this study, the convective heat transfer coefficient is taken 10 W/m²°C.

In addition, \( T_{sky} \) is the sky temperature, which is obtained using the following relation:\(^5^0\):

\[
T_{sky} = 0.0522T_{amb}^{1.5} \quad (9)
\]

1. The incident radiation on the system is generated uniformly as the thermal energy in the layers of glass and solar cells.
2. The no-slip wall condition has been applied on the channel walls.

Figure 2 indicates the considered boundary conditions schematically.

The PV cells convert part of the radiation entering the panel into electrical power. Consequently, the electrical efficiency of the PVT system is defined as follows:

\[
\eta_{el} = \frac{E_{el}}{E_{sun}} \quad (10)
\]

where \( E_{sun} \) and \( E_{el} \) are the incident radiation and electrical power, respectively, which are calculated using the following equations:\(^9\):

\[
E_{el} = P_{sc} \tau_g \eta_{ac} \eta_{sc} E_{sun} \left[ 1 - \beta \left( T_{cell} - T_{ref} \right) \right] \quad (11)
\]

\[
E_{sun} = G A \quad (12)
\]

In Equation (11), \( \eta_{ac}, T_{ref}, \) and \( \beta \) are the standard PV panel efficiency, the standard temperature, and the temperature coefficient, which are equal to 0.15, 298.15 K, and 0.0045.

The PVT thermal output and efficiency can also be calculated as follows:

\[
E_{th} = m c_p, nf \left( T_{out} - T_{in} \right) \quad (13)
\]

\[
\eta_{th} = \frac{E_{th}}{E_{sun}} \quad (14)
\]

Finally, the PVT overall efficiency is obtained by:

\[
\eta_o = \frac{E_{el} + E_{th}}{E_{sun}} \quad (15)
\]

In order to solve the governing equations, the computational fluid dynamics (CFD) method was used in ANSYS Fluent 18.2 software. The mass, momentum, and energy equations are discretized and solved by the finite volume method in the steady-state conditions. Considering the pressure-based solver as a suitable solver for the steady and incompressible flow regime, the position of the panel is adjusted at an angle of 30° to the adjustment horizon and gravity acceleration has been applied as an important parameter. To discrete the pressure and momentum equations, the second-order upwind scheme is used and the velocity and pressure equations are coupled by the SIMPLE method.\(^1^4\) The convergence criteria of the equations of continuity, momentum, and energy, respectively, are considered as \(10^{-6}, 10^{-5}, \) and \(10^{-7}\), respectively.

The grid independence test of the CFD model is performed comparing the cell temperature, Nusselt number, and friction factor by using five different grids. The solar radiation, channel height, and flow rate are considered 1000 W/m², 10 mm, and 8 L/h, respectively, and water is used as the working fluid. According to the results presented in Table 6, the relative error observed for the studied parameters has almost no change from 939,120 elements onwards. Therefore, this number of elements has been used to continue the studies.

### 2.4 Model validation

The developed 3D model is validated with numerical and experimental results of the study, done by Rahmanian and Hamzavi.\(^1^4\) They considered the performance of a PVT with a similar configuration to this study and an area of 164 × 99.2 cm² in the climatic conditions of Jahrom city in Iran. Table 7 presents the average temperature of PV cells in two different operating conditions. The results show that the maximum relative error obtained with experimental and numerical results is 1.7% and 3.7%, respectively, which confirms the accuracy of the developed model.

### 3 RESULTS AND DISCUSSION

#### 3.1 Effect of nanofluid volume fraction

In this study, water, hybrid Ag-MgO, and CNT nanofluid with volume fractions of 0.5%–2% are considered as the working fluid of the PVT system. The channel height and
flow rate are 10 mm and 8 L/h, respectively. The effect of nanofluid volume fraction on the average PV panel temperature is shown in Figure 3. As can be seen, the average temperature of the PV panel decreases by using nanofluid as the working fluid instead of water and increasing the volume fraction from 0.5% to 2%, which indicates an increase in heat transfer from the PV panel to the working fluid. Using CNT and Ag-MgO nanofluids with a volume fraction of 2%, the PV cell temperature decreases by 0.92% and 0.3%, respectively, compared to water. This is because of the higher thermal conductivity of CNT nanofluids compared to the hybrid nanofluids. In addition, compared to Salari et al., the use of CNT nanofluid with a volume fraction of 2% in the present model increases the PV panel cooling by 24.3%, which is due to the increase in the direct heat exchange rate of the rectangular channel compared to a tube collector.

Salari et al. investigated the performance of a combined PVT/PCM system and reported the reduction in the panel temperature by 0.74°C by replacing the working fluid with MWCNT nanofluid at a mass concentration of 3%.

Figure 4 shows the variation of the outlet fluid temperature with the nanofluid volume fraction. As observed in Table 2, the thermal conductivity of CNT is much higher than that of silver and magnesium oxide nanoparticles, which results in higher thermal conductivity of CNT nanofluids than that of the hybrid nanofluids. Therefore, as Figure 4 indicates the heat transfer from the absorber plate increases with increasing the volume fraction, and as a result, the outlet fluid temperature increases. The maximum outlet fluid temperature using 2% v/v CNT nanofluid is 0.38°C and 0.61°C higher than that of the hybrid nanofluid and water, respectively.
The impact of the nanofluid volume fraction on the electrical and thermal efficiency of the PVT system is depicted in Figure 5. According to Equations (11) and (13), decreasing the PV panel temperature and increasing the outlet fluid temperature causes the increase in the electrical and heat power of the PVT system. Therefore, the use of nanofluids with higher volume fractions improves the system performance. The electrical efficiencies of 8.84%, 8.85%, and 8.88% and thermal efficiencies of 56.97%, 57.40%, and 58.28% are obtained for water, the hybrid, and CNT nanofluids with 2% v/v, respectively.

The pressure drop is directly affecting the pumping power and hydraulic performance of the PVT system. The effect of the nanofluid volume fraction on the friction factor is shown in Figure 6. It is found that using nanofluid instead of the base fluid and also increasing the nanofluid volume fraction results in the increase of the friction factor. Considering the constant flow rate of 8 L/h, the Reynolds number is in the range of 4–12 for water and nanofluids with different volume fractions. Because of very low Reynolds numbers, the friction factor is much higher than 1, so that the values of 5.28, 6.51, and 13.84 are obtained for water, hybrid, and CNT nanofluids with a volume fraction of 2%. These are because of the variation of the thermophysical properties of the working fluid, especially the increase in viscosity due to the increase in the volume fraction and thus the reduction in the Reynolds number at a constant flow rate. This increase in the friction factor using CNT nanofluid is considerably higher than that using the hybrid nanofluid, due to the extreme increase in the viscosity of CNT nanofluid with increasing nanofluid volume fraction.

3.2 | Channel height

The fluid channel height is one of the parameters affecting the thermal performance of the PVT system by changing the heat transfer rate. In addition, at a constant flow rate, changes in channel height cause variation in fluid velocity and Reynolds number. At the flow rate of 8 L/h and volume fraction of 2%, three heights of 5 mm, 10 mm, and 15 mm are investigated. The temperature distribution at the channel outlet is shown in Figure 7. It is found that for a constant flow rate, as the channel height decreases, the temperature distribution at the channel outlet becomes more uniform and the outlet fluid temperature increases. When the channel height increases from 5 mm to 15 mm, it is observed that the layers of fluid that are farther away from the absorber plate experience a relatively high decrease of the temperature, which is larger using the hybrid nanofluid due to its lower thermal conductivity in comparison with CNT/water nanofluid.

To better investigate the heat transfer rate and pressure drop, the effect of the channel height on the Nusselt number and the friction factor as the most important parameters of thermohydraulic performance are studied and the results are shown in Figure 8. As observed in Figure 8A, with increasing the channel height, the Nusselt number and consequently the ratio of the convection heat transfer to the conduction heat transfer decreases. Therefore, although the Nusselt number of the hybrid nanofluid is slightly larger than that of CNT nanofluid, the total heat transfer using CNT nanofluid is higher due to the higher thermal conductivity and consequently the higher conduction heat transfer in the fluid layer. As the channel height increases from 5 mm to 15 mm, the difference in the Nusselt number of the hybrid and CNT nanofluids increases from 0.35% to 0.71%.

As shown in Figure 8B, it is obvious that at a constant flow rate, the friction factor increases with decreasing channel height. However, the use of hybrid nanofluids reduces the friction factor by about 52.8% for all three channel heights compared to CNT nanofluids, which is a very significant amount. In this study, due to the low flow rate and simple channel shape, the pressure drop changes with channel height insignificantly, and as a result, the optimal value of 10 mm channel height is selected.

Figure 9 shows the electrical and thermal power variation of the PVT with channel height. It is observed that with increasing the channel height, the electrical and thermal power of the system decreases due to the increase in PV cell temperature and decrease in the outlet fluid temperature. In the case of using the hybrid and CNT nanofluids as the working fluid, the maximum difference between the thermal and electrical power of the PVT system is 3.62 W and 0.11 W, respectively, which is related to the 15 mm channel height.
3.3 | Nanofluid flow rate

The working fluid flow rate is one of the main parameters affecting the heat transfer rate, which is more significant in the PVT system due to the direct effect of the flow rate on electrical power along with thermal power. In the present study, the effect of flow rates of 8 L/h to 32 L/h on the electrical, thermal, and hydraulic system performance has been studied using the 2% v/v hybrid and CNT nanofluids in the channel with a height of 10 mm.

Figure 10 shows the variation of the Nusselt number and friction factor with flow rate. As can be seen, by increasing the flow rate, the Nusselt number increases, and the friction factor decreases; thus, the thermohydraulic performance of the PVT system improves. This is because of the velocity increase which results in the increase of the Reynolds number. The reason for the higher Nusselt number and lower friction factor of the hybrid nanofluid compared to CNT nanofluid is the higher thermal conductivity and viscosity of the CNT nanofluid, respectively. The maximum difference of the Nusselt number and the minimum difference of the friction factor is obtained as 0.14 and 1.83, respectively, at a flow rate of 32 L/h.

The effect of flow rate on PV panel and outlet fluid temperatures is indicated in Figure 11. The results show that with increasing the flow rate from 8 L/h to 32 L/h, the average panel temperature decreases by 6.38°C and 6.58°C for the hybrid and CNT nanofluids, respectively, and the outlet fluid temperature decreases by 12.35°C and 12.60°C, respectively. The decrease in panel temperature and outlet fluid temperature with increasing flow rate is due to the increase in Nusselt number and increase in fluid mass flow, respectively. It should be noted that the change rate of the cell and outlet fluid temperatures, with increasing flow rate from 8 L/h to 20 L/h, is higher than that from 20 L/h to 32 L/h, which is due to the change rate of Nusselt number. Increasing the nanofluid flow rate, in addition to lowering the PV panel temperature, causes a more uniform panel temperature variation along with the panel, which results in better PV panel performance. The temperature distribution at the panel upper surface using the 2% v/v hybrid nanofluid the flow rates of 8 L/h, 20 L/h, and 32 L/h is shown in Figure 12.

Higher heat transfer rates and lower panel temperatures by increasing flow rates increase electrical and thermal power and, consequently, increase the efficiency of the PVT system.
the PVT system, as shown in Figure 13. As can be seen in Figure 13A, in the case of using the hybrid nanofluid, by changing the flow rate from 8 L/h to 20 L/h, the electrical and thermal power increases by 0.61 W and 21.34 W, respectively, while by changing the flow rate from 20 L/h to 32 L/h, these values are 0.18 W and 6.09 W, respectively. However, in the case of using CNT nanofluid, the obtained values are slightly higher. The maximum difference between the electrical and thermal power, in the case of using hybrid nanofluid in comparison with CNT nanofluid, is 0.10 W and 3.38 W, respectively, which occurs at the flow rate of 32 L/h. According to the results, for reducing the pumping power, a flow rate of 20 L/h is optimum.

By changing the flow rate, a similar trend with power is observed for the electrical and thermal efficiencies of the PVT system, as shown in Figure 13B. It is concluded that at an optimum flow rate of 20 L/h, the electrical and thermal efficiencies for the hybrid and CNT nanofluids are 9.07%, 65.02%, 9.10%, and 66.19%, respectively.

4 | CONCLUSIONS

In this study, the steady-state, incompressible flow of the hybrid Ag-MgO and CNT nanofluids was used as the cooling fluid in the PVT system. At a radiation rate of 1000 W/m², the effect of the nanofluid volume fraction, flow rate, and flow channel height on average PV panel temperature, outlet fluid temperature, friction factor, and Nusselt number was evaluated. The results can be summarized as follows:

- The increase in the nanofluid volume fraction has a positive and negative effect on the thermoelectric and hydraulic performance of the PVT system, respectively. The maximum electrical and thermal power and friction factor are 24.86 W, 163.19 W, and 13.84 for CNT nanofluid with 2% v/v, respectively.
- The results show that the outlet fluid temperature gradient increases and the pressure drop reduces by increasing the height of the flow channel from 5 mm to 15 mm.
- Among the operating parameters, the nanofluid flow rate has the greatest impact on the performance of the PVT system.
- By variation of the flow rate from 8 L/h to 32 L/h, the difference between the minimum and maximum temperature of the PV cell surface reduces from 15.56°C to 6.28°C for the 2% v/v hybrid nanofluid and from 16.06°C to 5.93°C for 2%v/v CNT nanofluid, indicating a more uniform temperature distribution at higher flow rates.
It is concluded that the PVT system has better thermoelectric performance using CNT nanofluids than the hybrid nanofluids; however, it has much better thermohydraulic performance using the hybrid nanofluids than CNT nanofluids. In addition, due to the minimum and maximum temperature differences of the panel surface at low flow rates, the hybrid nanofluid yields a smaller temperature difference, indicating a more uniform temperature distribution than the CNT nanofluids. Therefore, for the PVT systems with the complex fluid channels and low flow rates, hybrid nanofluid, and with simple fluid channels and higher flow rates, the use of CNT nanofluid as a working fluid is recommended.
NOMENCLATURE

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| A      | Area (m$^2$)                                     |
| L      | Length (m)                                       |
| $c_p$  | Specific heat capacity (J kg$^{-1}$ K$^{-1}$)    |
| k      | Thermal conductivity (W m$^{-1}$ K$^{-1}$)       |
| q      | Heat flux (W m$^2$)                              |
| d      | Diameter (m)                                     |
| G      | Solar irradiation (W m$^{-2}$)                   |
| E      | Power (W)                                        |
| T      | Temperature (°C)                                 |
| P      | Pressure (Pa)                                    |
| $P_{sc}$ | PV packing factor                              |

Greek symbols

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| $\tau$ | Transmissivity                                   |
| $\alpha$ | Absorptivity                                     |
| $\epsilon$ | Emissivity                                     |
| $\rho$ | Density (kg m$^{-3}$)                            |
| $\eta$ | Energy efficiency (%)                            |
| $\mu$ | Dynamic viscosity (kg m$^{-1}$ s$^{-1}$)         |
| $\phi$ | Nanoparticle volume fraction                     |

Subscripts

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| $bf$  | Base fluid                                      |
| $amb$ | Ambient                                          |
| $p$   | Particle                                        |
| $nf$  | Nanofluid                                       |
| $el$  | Electrical                                      |
| $th$  | Thermal                                          |
| $out$ | Outlet                                          |
| $in$  | Inlet                                            |
| $ref$ | Reference                                       |

FIGURE 12 Temperature distribution at the top surface of the PV panel for the hybrid nanofluid with 2% v/v

FIGURE 13 Variation of the (A) electrical and thermal power and (B) electrical and thermal efficiency for nanofluids flow rate with 2% v/v

REFERENCES

1. Zou C, Zhao Q, Zhang G, Xiong B. Energy revolution: from a fossil energy era to a new energy era. Nat Gas Industry B. 2016;3(1):1-11.
2. Jia Y, Alva G, Fang G. Development and applications of photovoltaic-thermal systems: a review. Renew Sustain Energy Rev. 2019;102:249-265.

ORCID

Maryam Karami © https://orcid.org/0000-0003-4771-2446
3. Shahsavaran A. Experimental evaluation of energy and exergy performance of a nanofluid-based photovoltaic/thermal system equipped with a sheet- and sinusoidal serpentine tube collector. *J Clean Prod.* 2021;287:125064.

4. Rahman MM, Hasanuzzaman M, Rahim NA. Effects of operational conditions on the energy efficiency of photovoltaic modules operating in Malaysia. *J Clean Prod.* 2017;143:912-924.

5. Teo HG, Lee PS, Hawlader MNA. An active cooling system for photovoltaic systems. *Appl Energy.* 2012;90(1):309-315.

6. Sargunanathan S, Elango A, Mohideen ST. Performance enhancement of solar photovoltaic cells using effective cooling methods: a review. *Renew Sustain Energy Rev.* 2016;64:382-393.

7. Chow TT. A review on photovoltaic/thermal hybrid solar technology. *Appl Energy.* 2010;87(2):365-379.

8. Kazemian A, Khatibi M, Maadi SR, Ma T. Performance optimization of a nanofluid-based photovoltaic thermal system integrated with nano-enhanced phase change material. *Appl Energy.* 2021;295:116859.

9. Yazdanifard F, Ebrahimnia-Bajestan E, Ameri M. Investigating the performance of a water-based photovoltaic/thermal (PV/T) collector in laminar and turbulent flow regime. *Renewable Energy.* 2016;99:295-306.

10. Pang W, Cui Y, Zhang Q, Wilson GI, Yan H. A comparative analysis on performances of flat plate photovoltaic/thermal collectors in view of operating media, structural designs, and climate conditions. *Renew Sustain Energy Rev.* 2020;119:109599.

11. Joshi AS, Tiwari A, Tiwari GN, Dincer I, Reddy BV. Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system. *Int J Therm Sci.* 2009;48(1):154-164.

12. Shahsavaran A, Ameri M, Gholampour M. Energy and exergy analysis of a photovoltaic-thermal collector with natural air flow. *J Sol Energy Eng.* 2011;134(1):011014.

13. Aberoumand S, Ghamari S, Shabani B. Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: an experimental study. *Sol Energy.* 2018;165:167-177.

14. Rahamanian S, Hamzavi A. Effects of pump power on performance analysis of photovoltaic thermal system using CNT nanofluid. *Sol Energy.* 2020;201:787-797.

15. Karami N, Rahimi M. Heat transfer enhancement in a PV cell using Boehmite nanofluid. *Energy Convers Manage.* 2014;86:275-285.

16. Sardarabadi M, Hosseinzadeh M, Kazemian A, Passandideh-Fard M. Experimental investigation of the effects of using metal-oxides/water nanofluids on a photovoltaic thermal system (PVT) from energy and exergy viewpoints. *Energy.* 2017;138:682-695.

17. Karimi F, Xu H, Wang Z, Chen J, Yang M. Experimental study of a concentrated PV/T system using linear Fresnel lens. *Energy.* 2017;123:402-412.

18. Ceylan İ, Gürel AE, Ergün A, Tabak A. Performance analysis of a concentrated photovoltaic and thermal system. *Sol Energy.* 2016;129:217-223.

19. Hemmat Esfe M, Kamyah MH, Valadkhanii M. Application of nanofluids and fluids in photovoltaic thermal system: an updated review. *Sol Energy.* 2020;199:796-818.

20. Abbas N, Awan MB, Amer M, et al. Applications of nanofluids in photovoltaic thermal systems: a review of recent advances. *Phys A.* 2019;536:122513.

21. Ebrahimnia-Bajestan E, Charjooue Moghadam M, Niazmand H, Daungthongsuk W, Wongwises S. Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers. *Int J Heat Mass Transf.* 2016;92:1041-1052.

22. Sani E, Barison S, Pagura C, et al. Carbon nanohorn-based nanofluids as direct sunlight absorbers. *Opt Express.* 2010;18(5):5179-5187.

23. Wong KV, De Leon O. Applications of nanofluids: current and future. *Adv Mech Eng.* 2010;2:519659.

24. Khanjari Y, Pourfayaz F, Kassaee AB. Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system. *Energy Convers Manage.* 2016;122:263-278.

25. Lari MO, Sahin AZ. Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications. *Energy Convers Manage.* 2017;149:467-484.

26. 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.

27. Elmir M, Mehdaoui R, Mojtabi A. Numerical simulation of cooling a solar cell by forced convection in the presence of a nanofluid. *Energy Procedia.* 2012;18:594-603.

28. Rejeb O, Sardarabadi M, Ménéo C, Passandideh-Fard M, Dhaou MH, Jemni A. Numerical and model validation of uncovered nanofluid sheet and tube type photovoltaic thermal solar system. *Energy Convers Manage.* 2016;110:367-377.

29. Abdallah SR, Elsemary IMM, Altonhmy AA, Abdelrahman M, Attia AAA, Abdellatif OE. Experimental investigation on the effect of using nano fluid (Al2O3-Water) on the performance of PV/T system. *Therm Sci Eng Progr.* 2018;7:1-7.

30. Nasrin R, Hasanuzzaman M, Rahim NA. Effect of nanofluids on heat transfer and cooling system of the photovoltaic/thermal performance. *Int J Numer Meth Heat Fluid Flow.* 2019;29(6):1920-1946.

31. Yazdanifard F, Ameri M, Ebrahimnia-Bajestan E. Performance of nanofluid-based photovoltaic/thermal systems: a review. *Renew Sustain Energy Rev.* 2017;76:323-352.

32. Shahsavaran A, Jha P, Arici M, Estellé P. Experimental investigation of the usability of the rifled serpentine tube to improve energy and exergy performances of a nanofluid-based photovoltaic/thermal system. *Renewable Energy.* 2021;170:410-425.

33. Sohani A, Shahverdian MH, Sayyadi 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 Ins Chem Eng.* 2021;124:351-358.

34. Hooshmandzade N, Motelli A, Mousavi Seyedi SR, Biparva P. Influence of single and hybrid water-based nanofluids on performance of microgrid photovoltaic/thermal system. *Appl Energy.* 2021;304:117769.

35. Jabbari F, Saedodin S, Rajabpour A. Experimental investigation and molecular dynamics simulations of viscosity of CNT-water nanofluid at different temperatures and volume fractions of nanoparticles. *J Chem Eng Data.* 2019;64(1):262-272.

36. Hemmat Esfe M, Abbassian Arani AA, Rezaie M, Yan W-M, Karimipour A. Experimental determination of thermal conductivity and dynamic viscosity of Ag-MgO/water hybrid nanofluid. *Int Commun Heat Mass Transfer.* 2015;66:189-195.
37. Shamsuddin HS, Tong LW, Mohd-Ghazali N, Estellé P, Maré T, Mohamad M. Nanofluid-Cooled Microchannel Heat Sink with Carbon Nanotube; 2021.
38. Yarmand H, Gharehkhani S, Ahmadi G, et al. Graphene nanoplatelets-silver hybrid nanofluids for enhanced heat transfer. Energy Convers Manage. 2015;100:419-428.
39. Asadi A, Asadi M, Rezaniakolaei A, Rosendahl LA, Afand M, Wongwises S. Heat transfer efficiency of Al2O3-MWCNT/thermal oil hybrid nanofluid as a cooling fluid in thermal and energy management applications: an experimental and theoretical investigation. Int J Heat Mass Transf. 2018;117:474-486.
40. Sundar LS, Singh MK, Sousa AC. Enhanced heat transfer and friction factor of MWCNT-Fe3O4/water hybrid nanofluids. Int Commun Heat Mass Transfer. 2014;52:73-83.
41. Murali Krishna V, Kumar MS, Mahesh O, Kumar PS. Numerical investigation of heat transfer and pressure drop for cooling of microchannel heat sink using MWCNT-CuO-Water hybrid nanofluid with different mixture ratio. Mater Today: Proc. 2021;42:969-974.
42. Javadi H, Urchueguia JF, Mousavi Ajarostaghi SS, Badenes B. Impact of employing hybrid nanofluids as heat carrier fluid on the thermal performance of a borehole heat exchanger. Energies. 2021;14(10):2892.
43. Abu-Libdeh N, Redouane F, Aissa A, et al. Hydrothermal and entropy investigation of Ag/MgO/H2O hybrid nanofluid natural convection in a novel shape of porous cavity. Appl Sci. 2021;11(4):1722.
44. Brinkman HC. The viscosity of concentrated suspensions and solutions. J Chem Phys. 1952;20(4):571.
45. Garnett JM. XII. Colours in metal glasses and in metallic films. Philos Trans Roy Soc Lond. Ser A. 1904;203(359–371):385-420.
46. Walvekar R, Faris IA, Khalid M. Thermal conductivity of carbon nanotube nanofluid-Experimental and theoretical study. Heat Transf-Asian Res. 2012;41(2):145-163.
47. Brenner H, Condiff DW. Transport mechanics in systems of orientable particles. IV. Convective transport. J Colloid Interface Sci. 1974;47(1):199-264.
48. Salari A, Kazemian A, Tao M, Hakkaki-Fard A. Nanofluid based photovoltaic thermal systems integrated with phase change materials: Numerical simulation and thermodynamic analysis. Energy Convers Manage. 2020;205:112384.
49. Sardarabadi M, Passandideh-Fard M. Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT). Sol Energy Mater Sol Cells. 2016;157:533-542.
50. Swinbank WC. Long-wave radiation from clear skies. Quart J Roy Meteorol Soc. 1963;89(381):339-348.
51. Baloch AAB, Bahaidarah HMS, Gandhidasan P, Al-Sulaiman FA. Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling. Energy Convers Manage. 2015;103:14-27.
52. Selimefendigil F, Okulu D, Mamur H. Numerical analysis for performance enhancement of thermoelectric generator modules by using CNT–water and hybrid Ag/MgO–water nanofluids. J Therm Anal Calorim. 2021;143(2):1611-1621.

How to cite this article: Hormozi Moghaddam M, Karami M. Heat transfer and pressure drop through mono and hybrid nanofluid-based photovoltaic-thermal systems. Energy Sci Eng. 2022;10:918–931. doi:10.1002/ese3.1073