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Research paper

Effect of zirconium oxide nanofluid on the behaviour of photovoltaic–thermal system: An experimental study

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ABSTRACT

Recently, photovoltaic technology applications have occupied a wide range in electric generation. The temperature rising higher than the operating temperature permissible is the weak point facing this technology, which significantly influences the performance of the photovoltaic cells. Using nanofluids as the coolant of photovoltaic (PV) modules is an effective method, circulating nanofluids in the heat exchanger attached to the backside of the PV module to absorb excess heat and enhance the performance of the PV module. The current work investigates using zirconium oxide (ZrO_2) nanofluid as a coolant at different volume concentrations (0.015 vol%, 0.025 vol%, 0.0275 vol%) in deionized (DI) water to reduce the temperature of the photovoltaic PV cells and then analyses the performance from the energy/exergy viewpoints. The results indicate that the PV module temperature was reduced by 10.2 °C when cooled by ZrO_2 nanofluid at 0.0275% volume concentration in DI water compared to the reference PV module, resulting in remarkable system energy and exergy enhancement. Besides, the cooling by DI water has decreased the PV module temperature by 5.1 °C. The overall efficiencies gradually increment with an increase in volume concentration by 8.9%, 18.8 % and 24.4%, respectively, compared with PV modules cooled by DI water. Using ZrO_2 nanofluids with 0.0275 vol% could enhance the exergy efficiency by 66.8% and reduce the exergy losses and entropy generation by 7% and 26%, respectively.

1. Introduction

Diversification of energy sources has become inevitable due to the increasing demand for fossil fuels as the main source of energy supply for industrial, agricultural, and domestic applications. Fossil fuel uses cause serious environmental impact due to greenhouse gas emissions to the atmosphere causing global warming and climate change (Alktranee and Bencs, 2020). Alternative energy sources are employed to mitigate the adoption of fossil fuel uses and their problems, such as solar, wind, geothermal, tidal energy, etc., as sustainable energy sources (Bayrak et al., 2017). The current energy sector needs some comprehensive developments, including taking advantage of renewable energy sources that provide clean energy to tackle the challenges of climate change and increased energy demand (Yaghoubirad et al., 2022). In recent years, solar and wind energy have occupied a wide range of renewable energy applications due to their potential to overcome energy demand and contribute to tackle environmental concerns (Shoaei et al., 2022). Solar energy technology is a popular energy source applied in most parts of the world, which can provide electric and thermal energy. Photovoltaic (PV) cells are one of the main branches of solar energy application applied in different fields (Firoozzadeh et al., 2021). PV cells are made from semiconductors material, which works to convert a part of coming solar radiation from the sun to electrical energy by a physical process (Jamal et al., 2019). The efficiency of a PV module primarily depends on the incident solar radiation, the ambient temperature, the material, and the size of the PV cell (Al-Amri and Abdelmagid, 2021).

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Nomenclature

A	Area of the module m^2
C_p	Specific heat kJ/kg °C
CuO	Copper Oxide
S	Solar radiation W/m^2
I_{SC}	Short circuit current
I_{pv}	Current A
K	Thermal conductivity W/m K
$\dot{m}$	Mass flow rate L/min
P_{pv}	Electrical power W
P_{inc}	The percentage improve of the electrical power %
Q_u	Thermal energy W
$\dot{S}gen$	Entropy generation W/°C
T	Temperature °C
V_{pv}	Voltage V

Subscript

amb	Ambient
DI	Deionized
FF	Fill factor
bf	Base fluid
in	Input
np	Nanoparticles
out	Output
PV	Photovoltaic
V_{OC}	Open circuit voltage
PVT	Photovoltaic–thermal

Greek symbols

η_{th}	Thermal efficiency %
$\eta_{\ ov}$	Overall efficiency %
$\eta_{\ ov}$	Overall efficiency %
$\eta_{\ el}$	Electrical efficiency %
ρ	Density Kg/m^3
μ	Viscosity
$\dot{E}x$	Exergy
$\eta_{\dot{E}x}$	Exergy efficiency %
φ	Volume concentration %

Exposure to intense solar radiation with increased ambient temperatures of the PV module during operation cause overheating of the PV cells, negatively reflecting the PV module's efficiency (Parkunam et al., 2020). Rising PV cell temperature is an intrinsic problem that leads to a drop in the open-circuit voltage, damaging the PV panel or reducing its productivity (Al-Waeli et al., 2020). The scholars approved the inverse relation between the output power production of the PV module and the surface temperature; an increase of 1 °C of the PV cells causes a decrease in the efficiency of PV cells by 0.25% (Ponnusamy and Desappan, 2014; Garavand et al., 2012). Reducing the PV module's temperature is an important issue for the permanence of its work. Therefore, different cooling techniques are used to enhance of conversion efficiency of the PV module and their performance at temperature increases (Nasrin et al., 2018). The cooling methods for the PV module include passive cooling (no external source) and active cooling (no external source) methods (Hamzat et al., 2021). In recent decades different passive cooling methods have been applied by attaching some cooling techniques to the backside of PV modules. For instance, a heat sink consisting of aluminium and copper fins (Arifin et al., 2020) uses evaporative cooling consisting of pin fins with a moist wood wool pad (Hasan and Attar, 2019), integrating fins with cotton wicks (Chandrasekar and Senthilkumar, 2016), and using a layer of synthetic clay (Alami, 2014). Cooling by desiccants (Simpson et al., 2017) and cooling by phase change material (Abdollahi and Rahimi, 2020).

On the other hand, various active cooling techniques are applied to reduce temperatures, whether using air or liquids such as water or equivalent (Alktranee and Bencs, 2021). A properly designed active cooling system contributes to maintaining the temperature of the PV module at a low level preventing their efficiency reduction. Extraction of excessive heat from PV modules is a very crucial area to improve the electrical power output. Photovoltaic–Thermal PVT system combines PV and solar thermal collectors together to generate electrical and thermal energies simultaneously (Aberoumand et al., 2018). The thermal collector placed at the backside of the PV module is comprised of a heat exchanger to decrease the temperature of the PV cells due to the circulation of the fluids, extracting heat from the PV module and increasing its electrical efficiency (Chiang et al., 2022). Several investigations were conducted on the design and development of PVT systems by Menon et al. (2022b), Hasan et al. (2022) and Cao et al. (2022) due to the PVT systems improved thermal and electrical performance. The cooling fluid used in the PVT system for heat recovery is an interesting topic. Various heat transfer fluids are employed as cooling fluids circulating in channels placed on the backside of the PVT system to reduce the PV cell temperature (Kazem et al., 2021). Despite the commonly used PVT system that uses water as a coolant fluid, it does not meet the desired goal of improving performance due to the low thermal conductivity of water (Aberoumand et al., 2018).

In recent years, the use of nanofluids attracted attention because this fluid gives better heat transfer capacity due to their high thermal properties compared to conventional fluids (Le Ba et al., 2022b). For instance, an experimental study of the PVT system used a nanofluid consisting of carbon black nanoparticles mixed with water at different concentration ratios from 0–0.4 wt% to control rising PV cell temperature. The results indicated that a 0.21 wt% concentration ratio of nanoparticles in water lowered the surface temperature and increased the output power by 7% compared with pure water (Firoozzadeh et al., 2021). Experimental and numerical study used TiO_2/water nanofluid to enhance the electrical efficiency of a PVT system. The experimental results were compared with numerical results obtained using ANSYS 18.2. The results showed that the average PVT temperature was lowered using TiO_2/water nanofluid due to the high thermal characteristic of the nanofluid, which accelerated heat transfer from the PV cells and increased their efficiency. Using TiO_2 nanofluid has decreased the PVT system temperature by 9.9 °C. Besides, the electrical efficiency of the PVT system cooled with water and TiO_2 nanofluid was increased by 12.22% and 13.04%, respectively, compared with the reference PV module which recorded 10.93% (Arifin et al., 2022). The performance of the unglazed PVT system was evaluated using water and CuO nanofluid circulated by the cooling system consisting of sheets and tubes placed at the backside of the PV module. The temperature of the PVT system dropped to 15 °C and 23.7 °C with the used water and nanofluid compared with the PV module without cooling, which reached 68.4 °C. Reduction of PV cells temperature increases the average electrical efficiency to 35.67% with nanofluid and 12.98% with water, while without cooling is 12.32%. The overall efficiency of the PVT system with nanofluid was higher by 21% than the water-cooled due to the high heat absorption by CuO nanoparticles (Diwania et al., 2022).

A new geometry of the PVT system has been studied with Al_2O_3/water nanofluid applied with a concentration of (0.05–0.5 wt%) as a coolant working fluid to evaluate their effect on the performance of the PVT system. The cooling system attached at the backside of the PV module consists of the serpentine half-pipe; the PV cells are assembled on an aluminium plate of a 3 mm thickness, with removes the Tedlar to increase the heat transfer in the cooling section. The results show a remarkable increment of the PVT efficiency, especially at cooling by nanofluid with a concentration of 0.5 wt% of nanoparticles into pure water. The thermal and electrical efficiency was enhanced by 126.71%, 7.38% compared with pure water, and the overall efficiency of the PVT system is 93.73%, which confirms the feasibility of nanofluids as a better coolant than water (Sardarabadi et al., 2017a). Cooling models have been proposed for the PV module 60 W consisting of copper tubes at different diameters 9.53, 12.70 and 15.88 mm with multiple tubes loops at 180° and water is used as a cooling fluid with a flow rate range of 0.5 to 2.5 lit/min. The finite element method is used to consider the solar radiation equation in COMSOL Multiphysics software to obtain better-operating conditions for the PV module. At a mass flow rate of 2.5 lit/min and 9.53 diameter with 11 loops, maximum electrical efficiency has been achieved by 14.8%. While the maximum thermal efficiency recorded is 79.1% at a 1.5 lit/min mass flow rate, 15.88 mm diameter with 11 loops, thus reduction of the flow rate to 0.68 lit/min leads to a lowering of the PV module temperature and the pressure drop (Aghakhani et al., 2022).

Experimental investigations were conducted on the performance of the PVT system using two types of nanofluids, Cu/water and TiO_2/ water, at the variation of mass flow rate. The experimental outcomes show enhancing of the PVT electrical efficiency to 5.98% at a 1% volume concentration of Cu/water nanofluid, and at a higher mass flow rate, the temperature of the PV module is reduced to 17.18 °C. Thereby enhancing the electric and thermal efficiency of the PVT system by 2.58% and 5.43%, respectively (Tian et al., 2021). A cooling technique was proposed by Al-Waeli et al. (2020), consisting of a heat exchanger attached at the backside of the PV module with circulated silicon carbide nanofluid into the exchanger. In addition, a PCM was integrated with the heat exchanger to reduce the degradation of PV modules at rising cell temperatures. The proposed cooling technique has improved the output power by 97.5% compared with the conventional PV module, which incrementing the electrical efficiency by 13.7% compared to 7.1% for the conventional PV module.

Energy analysis is not enough for PVT system performance evaluation since it gives the quantitative energy produced. Therefore, exergy analysis is important to show the actual performance of the PVT system (Yazdanpanahi et al., 2015). Exergy analysis received considerable attention in the past decade, particularly in mechanical and chemical engineering (Dincer and Cengel, 2001). The energy and exergy analyses are necessary to evaluate the PVT system performance and assess the internal and external parameters influencing the PVT system (Namjoo et al., 2011). Energy and exergy analysis of the PVT system was conducted by using ZnO, TiO_2 and Al_2O_3 nanoparticles dispersed in DI water as coolant fluids at a mass flow rate of 30 kg/h. Based on the data measured, the TiO_2 and ZnO nanofluids gave better energy and exergy efficiencies than Al_2O_3 nanofluids. The overall exergy efficiencies of the PVT were enhanced by 15.45% ZnO/water, 15.93% TiO_2/water, and 18.27% Al_2O_3/water compared with water cooling, which recorded 12.34%. Al_2O_3/water has a better enhancement of entropy generation (Bang and Chang, 2005).

A numerical analysis has been done of the PVT system using MgO/water nanofluid that circulated into copper tubes placed at the backside of the PV module, the volume concentration of nanoparticles was 0 and 1% in the base fluid and the volume flow rate from 0.5–4 L/min. The results indicated that it enhances the exergy output by lowering nanofluid flow rates while increasing the flow rate above 0.5 L/min causes reduces the efficiency. The exergy efficiency increased by 0.45% by adding 1% volume concentration nanoparticles and 0.5 L/min volume flow rate (Harish et al., 2011). New hybrid cooling approaches were applied to the PV cells, using two PCM types (SP15-gel and SP31), coupled with flat heat pipes with and without hybrid nanomaterials to assess the PV cell's thermal regulation and investigate the effectiveness of the hybrid cooling in different seasons. A mathematical model was built and solved using MATLAB software to evaluate the energy and exergy performance of the PV cells. Results demonstrated that using hybrid cooling of SP15-gel and SP31 PCMs has reduced the PV cell temperature to 20.9 °C and 18.3 °C and enhanced the PV module efficiency by 9% and 11.5%, respectively, compared to conventional PV cells. In contrast, using nanomaterials with hybrid cooling has increased the system efficiency to 54.45% and 56.45% with SP15-gel and SP31. The average exergy efficiency of the PV module was recorded as 13.23% when SP31 was used with hybrid nanomaterials, while maximum exergy of 14.98% was achieved with SP15-gel and hybrid nanomaterials (Gad et al., 2023).

Another investigation was conducted on using Ag/water nanofluid to improve the energy and exergy efficiencies of the PVT system under different flow regimes and nanoparticle concentrations (Zamen et al., 2022). The results exhibited significant enhancement of energy and exergy efficiencies of the PVT system attributed to the increased volume concentrations of the nanoparticles in the base fluid and flow rate that were close to turbulent flow (Le Ba et al., 2022a). Accordingly, using 4 wt% nanofluids has achieved an increment of PVT output power by 35% and 10%, and the exergy efficiency increased by 50% and 30% compared with a PVT system cooled by water PV module and without cooling.

The literature adopted various nanoparticles at specific volume concentrations, which achieved remarkable enhancement in the PVT system performance. However, some kinds of nanomaterials have not been verified for preparing nanofluids that can be used as a coolant for the PVT system. In the literature, few studies have investigated exergy analysis and entropy generation for PVT systems. The ZrO_2 nanofluid is a new nanofluid used to cool the PV modules and no investigation has been conducted on this kind of nanofluid in the literature. Therefore, this study investigates the using ZrO_2 nanofluid as a cooling fluid at different volume concentrations and constant mass flow rate. The energy and exergy efficiencies of the PVT system using this nanofluid are analysed from thermodynamic viewpoints and comparing their effect with DI water as a coolant. The effect of increased volume concentrations of ZrO_2 on the PVT system's entropy generation and exergy losses is also evaluated. Finally, the results obtained are compared with those of previous studies to quantify the ability of nanofluid applied to improve the PV module performance.

2. Experiment description

2.1. Study location

The experiments were conducted under hot climate conditions of Basra city, in the south of Iraq, on the latitude 30.5°N and longitude 47.8°E, of semi-desert climate. The summer season is sweltering and dry in which the ambient temperatures reach 50 C in some days, the average wind speed is between 4 and 9 m/s and the relative humidity rises due to the Arabian Gulf reaching up to 90% (Al-Muhyi and Aleedani, 2022). Experiments were conducted in May 2022 on sunny days from 7:00 am to 5:00 pm, with no significant variation in the ambient temperature

Table 1
Electrical characteristics under standard test conditions (1000 W/m^2, 25 °C).

Characteristics	Values
Nominal power (P_{max})	50 W
Short circuit current (I_{SC})	2.88 A
Open circuit voltage (V_{OC})	22.28 V
Maximum power current (I_{max})	2.71 A
Maximum power voltage (V_{max})	18.43 V
Nominal module efficiency	15(%)

and solar radiation during the experiment days. Thus, the location was suitable to investigate the PVT system energy and exergy by means of cooling with DI water and ZrO_2 nanofluid under hot climate conditions.

2.2. Experimental procedure

Three PV modules type polycrystalline were used in this experiment by (0.65 m × 0.55 m × 0.3 m) dimensions. The first PV module was a reference without cooling, the second PVT module used water as a cooling medium, and a nanofluid cooled the third PVT module. The PVT system combines the PV module and heat exchanger, which consists of an absorber copper plate integrated with flow channels (tubes) attached at the backside of the PV module. In previous studies, different flow channels have been employed, which attach to the backside of the PV module, such as web flow channels, spiral flow channels and direct flow channels. The flow channel design positively affects the output electrical power and enhances its performance by reducing the PV modules' temperature (Kazem et al., 2020). The current study used copper tubes arranged in serpentine configuration, soldered with copper plates placed on the backside of the PV modules by soldering alloy type TOPEX, made from 60%Sn 40%Pb, as soldering wire with a thickness of 1.5 mm that melts at 160–180 C.

The absorber plate attached at the backside of the PV module by thermal grease type HP, which has high thermal conductivity, with no gap between the absorber plate and the backside of the PV module. Then, a layer of thermal wool was placed on the serpentine tubes to completely cover the PV module's backside and reduce heat losses, and then covered by an aluminium plate. The modules are fixed at a tilt angle of 29° towards the southern; Table 1 shows the electrical characteristics of the PV module. Four thermocouples are distributed on each surface of the PVT modules, and three are on the backside. Thermocouples were placed in the inlet and outlet of the first and second PVT module to measure the temperature of the cooling medium during the experiment period. Fig. 1 shows the experimental setup of the test procedure of the PVT systems, which are cooled by DI water and ZrO_2 nanofluids. The fluids are circulated in the serpentine tubes by two pumps with a mass flow rate of 0.7 L/min set by flow sensors. The temperatures of the inlet/outlet fluid, and the backside surface of the PV and PVT system were measured by thermocouples (Type K). All measuring data are recorded by a data logger every 10 min throughout the time of the experiment.

2.3. Instruments

A solar power meter (Type SM206) was used manually for measured solar radiation for each hour. A multi-channel Arduino (AT mega 2560) data logger consists of 24 thermocouples (Type K, range -200 °C to 1350 °C) for measuring temperature, sensors to measure the voltage (Module 25 V), and sensors to measure the current (ACS712, up to 30 A). The data logger is set to record the data each 10 min during the experiment and save the data in the memory of 8 GB. Two pumps were used for circulating water and nanofluid between the PV modules and tanks. The flow rate sensor (Model: YF-S201) was placed among the nanofluid container (10 l) and the inlet pipe of the PVT system with a mass flow rate of 0.7 L/min. The outlet of the nanofluid connected to the copper coil is placed into the water tank for 35 l to reduce the nanofluid temperature. In contrast, the inlet and outlet of the second PV module are connected to another copper coil in the water tank.

Table 2
The properties of the nanoparticles and base fluid.

Properties	DI Water (Giwa et al., 2020)	ZrO_2 (Colak, 2021)
Density (kg/m^3)	997	5890
Thermal conductivity (W/m K)	0.613	2.7
Heat capacity (J/kg K)	4179	0.455

2.4. Preparation of ZrO_2/DI water nanofluid

Preparing a stable nanofluid is important for heat transfer applications. Mixing nanoparticles into base fluid play a vital role in improving heat transfer behaviour; Table 2 shows the properties of ZrO_2 nanoparticles applied in the current experiments. The ZrO_2 nanoparticles were utilized and supplied by (Research Nanomaterials, Inc., Houston, TX, USA) with a particle size of 20 nm, white colour, with 99.95% purity, and SEM image in Fig. 2 shows the morphology of the ZrO_2 according to provide by the vendor. A two-physical method has been used to prepare nanofluids by suspending ZrO_2 nanoparticles in DI water. Three volume concentrations of ZrO_2 nanoparticles were selected, 0.015 vol%, 0.025 vol%, and 0.0275 vol%, which were suspended in DI water according to the formula applied by Dincer and Cengel (2001) and Harish et al. (2011), as in Eq. (1). Firstly, the quantity of nanoparticles dispersed into DI water was scaled by an electronic scale (type: BOECO BAS of 0.0001 g). Then mixed the scaled nanoparticles with DI water on a magnetic stirrer for 35 min and used an ultra-sonication (Bransonic type 220, Voltage: 240 V, Vf: 48 kHz) for 50 min to avoid the agglomeration of nanoparticles and obtain a stable suspension for a long period. The visualization and time sediment method examined the deposition of the ZrO_2 nanoparticles after 4 h and three days, as shown in Fig. 3. The stability of the nanofluid prepared was fairly good, which was used directly after the sonication process.

$$\varphi = \left[\frac{\frac{m_{\mathrm{np}}}{\rho_{np}}}{\frac{m_{\mathrm{np}}}{\rho_{\mathrm{np}}} + \frac{m_{\mathrm{bf}}}{\rho_{bf}}} \right] \times 100 \quad (1)$$

where φ is the volume concentration, m_{np} the mass of the nanoparticle, m_{bf} the mass of the base fluid, ρ_{np} the density of the nanoparticle, ρ_{bf} is the density of the base fluid.

3. Thermodynamic analysis

This section conducts a thermodynamic analysis of the PVT system according to the thermodynamic point of view (first and second law) of thermodynamics (Agrawal and Tiwari, 2011). Both laws evaluate the quantitative energy and quality exergy of the PVT modules, respectively.

3.1. Energy analysis

The efficiency of the PVT system consists of electrical and thermal, determination of the efficiency of the PVT system depends on its input and output. For electric efficiency, the solar radiation (G) and PVT module area (A) represent the inputs (P_{in}), while output voltage (V_{out}) and current (I_{out}) represent the (P_{out}).

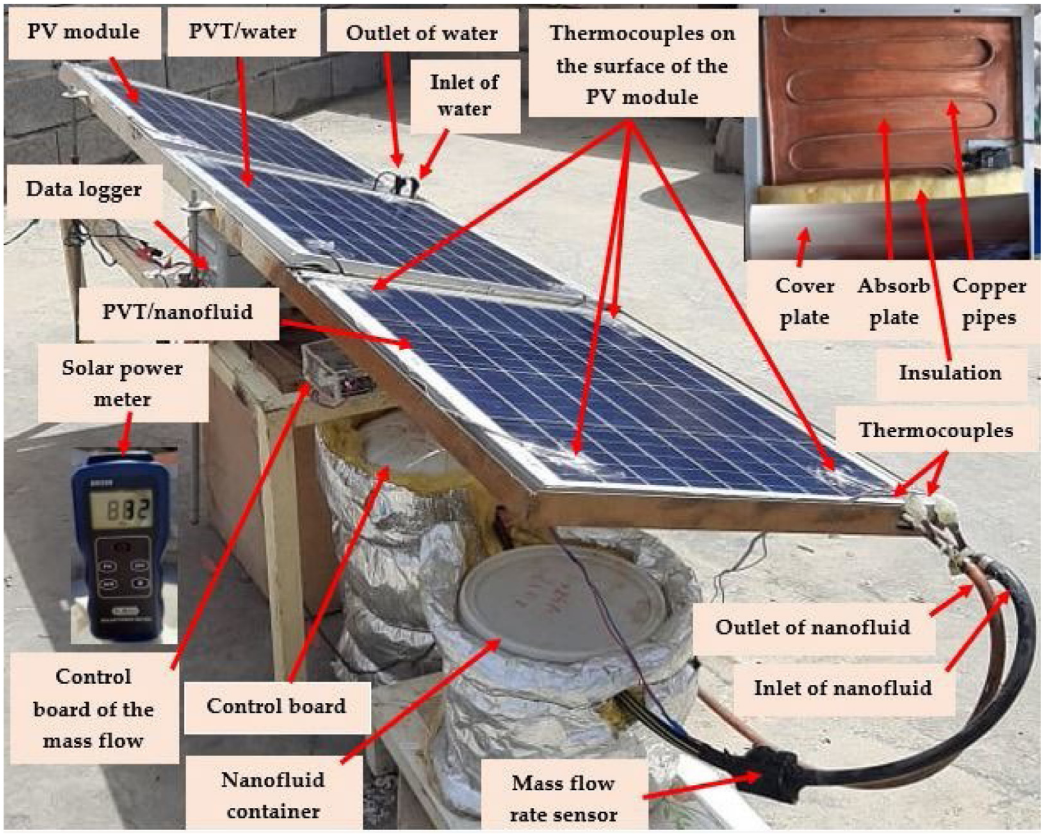

Fig. 1. A view of the experimental setup of the PVT system.

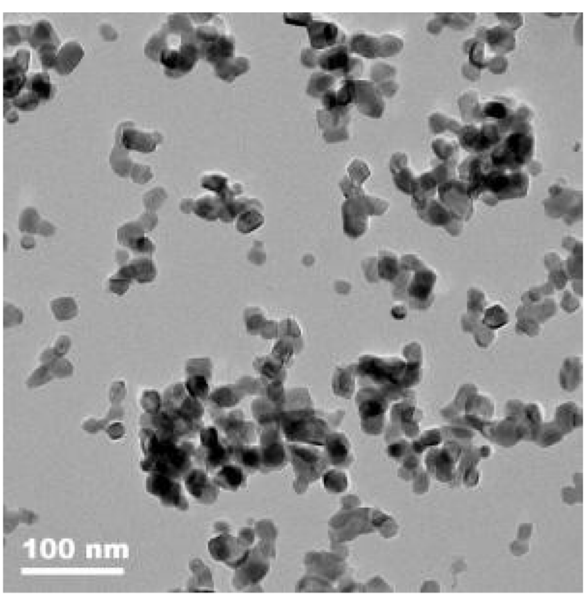

Fig. 2. TEM image of the ZrO_2 nanoparticles.

The fill factor *(FF)* represents the maximum power conversion efficiency of the PV module (Hu and White, 1983); thus, the electric efficiency calculates from Eq. (3)

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{V_{out}\, I_{out \cdot FF}}{A\, S} \tag{2}$$

$$\mathrm{FF} = \frac{V_{\mathrm{mp}} I_{\mathrm{mp}}}{V_{\mathrm{oc}} I_{\mathrm{sc}}} \tag{3}$$

The absorbed heat by circulating fluid into pipes placed at the backside of the PVT system, the output parameter, thereby the thermal efficiency of the PVT system can calculate from Eq. (4) (Yu et al., 2019).

$$\eta_{th} = \frac{\dot{m} C_p \left(T_{out} - T_{in}\right)}{\mathrm{AS}} \tag{4}$$

where $\dot{m}$, C_p is the mass flow rate (L/min) and specific heat of the fluid (J/kg °C), in the case used nanofluid, the specific heat of the nanofluid ($C_{p,nf}$) is taken into account, which calculates from Eq. (6) (Xuan and Roetzel, 2000) instead of the specific heat of the water. T_{inlet}, T_{out} are inlet and the output temperatures of the fluid (° C). The overall efficiency of the PVT system is a collection of the thermal and electrical efficiencies, which calculate from Eq. (5) (Yazdanifard et al., 2017):

$$\eta_{ov} = \eta_{el} + \eta_{th} \tag{5}$$

Mixing nanoparticles into the base fluid causes changes in the thermophysical properties of the mix because both nanoparticles and base fluid have different properties. Thermophysical properties of nanofluids (density, specific heat, thermal conductivity, and viscosity) are significant factors contributing to enhancing their properties and positively reflecting on their performance, which can calculate from Eq. (7) (Pak and Cho, 1998), Eq. (8) (Yu and Choi, 2003) and Eq. (9) (Brinkman, 1952).

$$C_{p_{nf}} = C_{p_{np}} \phi + (1 - \phi) C_{p_{bf}} \tag{6}$$

where $C_{p_{nf}}$ is the specific heat of nanofluid, $C_{p_{np}}$ is the specific heat of nanofluid, nanoparticles, and $C_{p_{bf}}$ is the specific heat of the base fluid.

$$\rho_{nf} = \varphi \rho_{np} + (1 - \varphi) \rho_{bf} \tag{7}$$

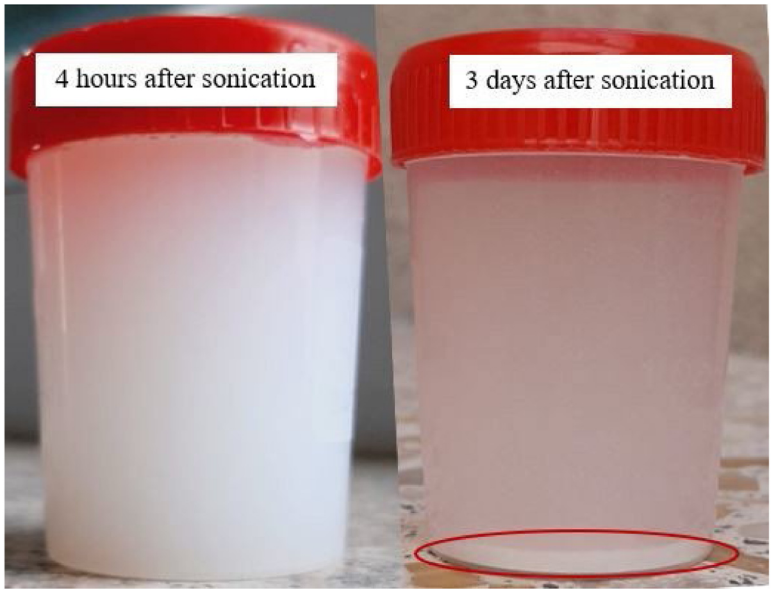

Fig. 3. Deposition of the ZrO_2/water nanofluids at different periods.

Table 3
Thermophysical properties of ZrO_2 nanofluid.

Volume concentration %	Density (kg/m^3)	Specific heat (J/kg K)	Viscosity (Pa s)	Thermal conductivity (W/m K)
0.015	1070.395	4116.322	0.00945	0.635124
0.025	1119.325	4074.536	0.009695	0.641857
0.0275	1131.558	4064.09	0.009757	0.646231

where ρ_{nf}, ρ_{np}, ρ_{bf} are the density of nanofluid, the volume concentration and density of nanoparticles and ρ_{bf} is the density of the base fluid.

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\emptyset\left(k_{np} - k_{bf}\right)}{k_{np} + 2k_{bf} - \emptyset\left(k_{np} - k_{bf}\right)} \quad (8)$$

where k_{nf} is the thermal conductivity of the nanofluid, k_{bf}, thermal conductivity base fluid, and k_{np} thermal conductivity nanoparticles.

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2.5}} \quad (9)$$

where μ_{nf}, μ_{bf} the viscosity of the nanofluid and base fluid.

The thermal conductivity of ZrO_2 nanofluid has increased with an increased volume concentration of ZrO_2 nanoparticles in the base fluid, as shown in Table 3, which positively enhanced heat transfer convection of the PVT system. Other properties, such as density and specific heat, are impacted by an increased volume concentration of ZrO_2 in the base fluid, where the nanofluid's density increases, affecting the nanofluid's stability due to deposition of nanoparticles by gravity, as shown in Fig. 3. Eventually, increased density and viscosity of the nanofluid had increased the pumping power consumption.

3.2. Exergy analysis and entropy generation

Exergy evaluation of the PVT system helps to provide a suitable thermal system analysis according to a thermodynamic point of view. Depending on the second law of thermodynamics, this section present compares exergy analysis with the conventional energy analysis that adopts the first law of thermodynamics. Exergy analysis shows the maximum of produced work achieved by the system based on the conservation of mass and energy principle for enhancing the system's energy (Dincer and Rosen, 2005; Dincer, 2007). The input and output of the PVT system are the important parameters that identify the control volume of the PVT system, as shown in Fig. 4, assuming the PVT system in the case of the semi-steady condition. Thus, the exergy balance of the PVT system is expressed by Maadi et al. (2017) as:

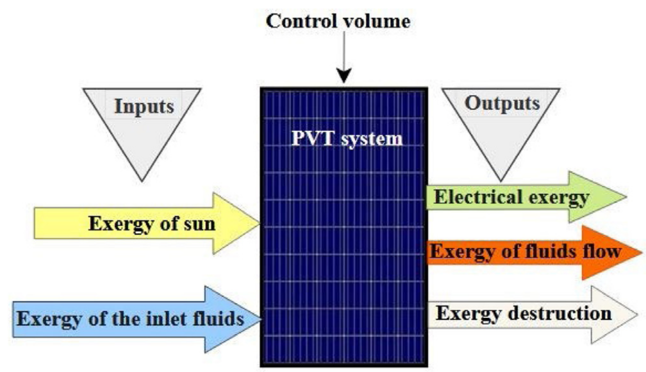

Fig. 4. Exergy control volume of a PVT system.

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{\text{out}} + \sum \dot{E}x_{loss} \quad (10)$$

The ratio of the outputs to inputs of any system represents their efficiency based on the control volume; it can calculate the exergy efficiency (Ψ) of the PVT system from:

$$\Psi = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \quad (11)$$

The inlet exergy comes from absorbing solar irradiation by the PVT system ($\dot{E}x_{solar}$), which is obtained by Eq. (12) (Chow et al., 2009; Alomar and Ali, 2021).

$$\dot{E}x_{in} = \dot{E}x_{sun} = \left(1 - \frac{T_a}{T_{sun}}\right) S \quad (12)$$

Ta, T sun is the ambient and sun temperature, which is considered as (5800 K) respectively (Fudholi et al., 2018). The output exergy of the PVT system ($\dot{E}x_{\text{out}}$) is the sum of electrical exergy

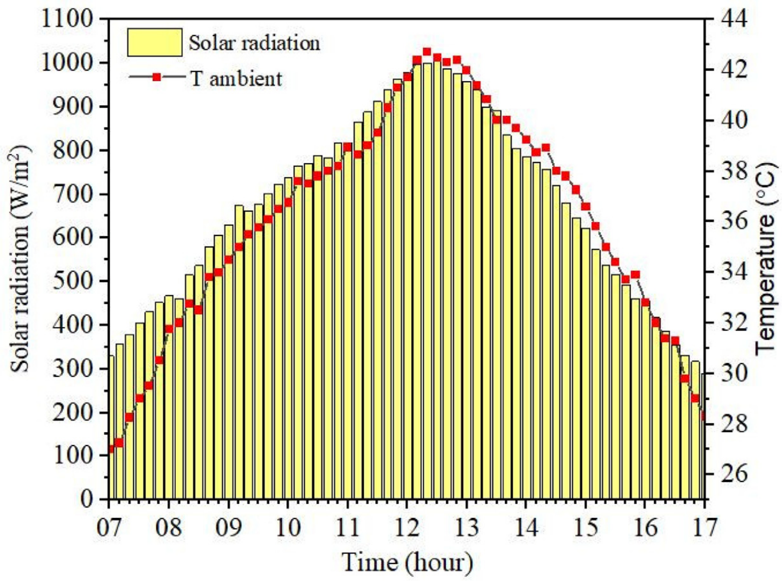

Fig. 5. Average ambient temperature and solar radiation during the experiments.

($\dot{E}x_{\text{ele}}$) and thermal exergy ($\dot{E}x_{\text{th}}$), which is estimated by Eq. (13).

$$\dot{E}x_{\text{out}} = \dot{E}x_{\text{ele}} + \dot{E}x_{\text{th}} \quad (13)$$

Chow et al. (2009) show that the electrical exergy is the same as that of the electrical energy output, which can be found by Eq. (14), thermal exergy by Eq. (15)

$$\dot{E}x_{\text{ele}} = V_{\text{oc}}.I_{\text{sc}} \cdot \text{FF} \quad (14)$$

$$\dot{E}x_{th} = \dot{m}C_p\left[(T_{out} - T_{in}) - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right] \quad (15)$$

using both electrical and thermal exergy efficiency calculated from Eqs. (16) and (17) (Maadi et al., 2017).

$$\varepsilon_{el} = \frac{\dot{E}x_{ele}}{\dot{E}x_{\text{sun}}} \times 100 \quad (16)$$

$$\varepsilon_{th} = \frac{\dot{E}x_{th}}{\dot{E}x_{\text{sun}}} \times 100 \quad (17)$$

The exergy losses (exergy destruction) are the other important parameter evaluated which occurs study due to the losses in the heat transfer and frictional losses in the system (Maadi et al., 2017), which are calculated from:

$$\dot{E}x_{\text{lost}} = \dot{E}x_{\text{in}} - \dot{E}x_{\text{ele}} - \dot{E}x_{\text{th}} \quad (18)$$

Another thermodynamic parameter considered in this study is entropy generation which refers to the irreversibility of the system, which is calculated (Maadi et al., 2017).

$$\dot{S}_{\text{gen}} = \frac{\dot{E}x_{\text{lost}}}{T_{\text{a}}} \quad (19)$$

4. Results and discussion

According to the climatic conditions of Basra city, Iraq, the climate conditions were sunny, the sky was clear, and no significant variation was recorded regarding ambient temperature or solar radiation measured during the experiment days. Fig. 5 shows the average values of the ambient temperature and solar radiation recorded. The maximum ambient temperature was 42.7 °C, specifically at 12:20 pm, then gradually lowered until sunset. In the early morning hours, the solar radiation values were increased until noon, when the recorded maximum solar radiation was 1004 W/m^2. According to the Iraqi Agricultural Meteorological Centre, the average wind speed was 2.75-2.37 m/s (Iraqi Agrometeorological network, 2022) during the experiment days.

The density and viscosity of the ZrO_2 gradually increased with the increased volume concentrations of nanoparticles in the base fluid. However, the density and viscosity of ZrO_2 nanofluid did not exceed 13.44%, 6.73%, compared with DI water at adding 0.0275% of nanoparticles in the base fluid. The limited increase of ZrO_2 density and viscosity affects nanofluid circulation; even a slight increase in the density causes more energy to be spent on the nanofluid circulation, which was reported by Kazem et al. (2021). On the other side, the gradual increase of nanoparticles in the base fluid has increased the thermal conductivity of ZrO_2 nanofluid by about a 5.42% compared to DI water at adding 0.0275% of nanoparticles, which positively influenced the PVT system performance. Therefore, this study adopts specific volume concentrations to avoid the increase of fluid density and viscosity and reduce circulation energy consumption.

4.1. Energy analysis results

4.1.1. Temperature profile of the PVT system

Direct exposure to intensive solar radiation makes the PV module surface temperature higher than the backside; four thermocouples have been placed at the surface and backside to measure the thermal behaviour of each side of the PV modules. The thermocouples distributed on the surface and backside for measuring the PV module's temperature show a very slight variation of the measured temperature. It has adopted the average temperature of the temperatures measured for both sides to assess the thermal behaviour of the PVT system considering the ambient temperature. Fig. 6 shows the variation of the average temperature of the PVT system at different volume concentrations of ZrO_2 fluids, compared with DI water as coolant and the reference PV module. The difference between the reference PV module temperature and the PVT system cooled by nanofluid and DI water can be noticed during the experiment. The results indicated that the PV module temperature reduced by 10.2 °C compared with the reference PV module cooling by ZrO_2 nanofluid at 0.0275% volume concentration in DI water, whereas cooling by DI water decreased the PV module temperature to 5.1 °C. The average temperature of the reference PV module was recorded at 58.2 °C;

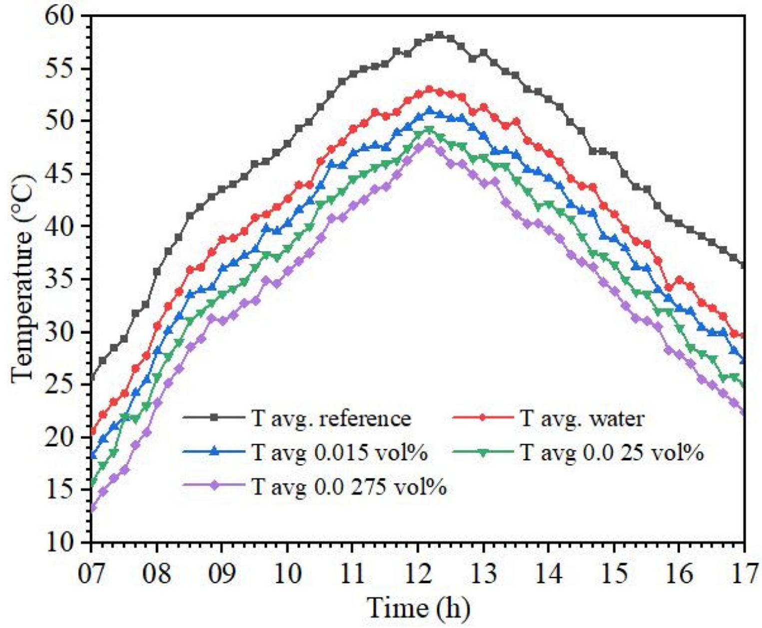

Fig. 6. The average temperature of the PVT system at different volume concentrations of ZrO_2 nanofluid.

circulated DI water in the serpentine pipes attached to the backside of the PV module helped absorb the heat and reduced the PV module temperature by 9.7%. Circulate ZrO_2 nanofluids achieved a remarkable reduction in the PVT system temperature, the gradual increase of the volume concentration of the ZrO_2 nanofluid is accompanied by a noticeable decrease in temperature. At volume concentrations 0.015 vol%, 0.025 vol%, and 0.0275 vol%, the PVT system temperatures have been reduced to 14%, 18.1% and 21.2%, respectively. Thereby, improving the thermal conductivity of fluids leads to increased heat absorption at the backside of the PV module; using ZrO_2 nanofluid has achieved higher heat absorbed from the PV module than water.

4.1.2. The PVT system performance

The temperature increase is associated with an increase in solar radiation, and the absence of cooling during the PV modules' operation period affects their performance. Fig. 7(a) confirms the necessity of having a cooling system to enhance the performance of the PV module. It can be observed that the electrical power output of the reference PV module is a minimum level compared to others that have been coolant. Reduced PV module temperatures effectively contribute to enhancing their performance due to cooling. Increasing the nanofluid thermal conductivity helped to improve the convection heat transfer between the tubes soldered on the absorbent plate and the circulated fluid, which reduced the temperature of the PV cells. The increased volume concentration of ZrO_2 nanofluid with a constant mass flow rate of 0.7 L/min gradually increased the electrical power output. Using nanofluids at different concentrations of 0.015 vol%, 0.025 vol%, 0.0275 vol% incremented the electrical power output by 11.4 W, 14.7 W and 17.2 W, respectively, compared to DI water that recorded 8.5 W. The maximum electrical power of the reference PV module was recorded at 18 W.

Fig. 7 (b) shows the effect of volume concentrations of ZrO_2 nanofluids and water on the enhancing of electrical power, replacing nanofluid with water resulted in a noticeable enhancing due to their thermal properties. The electrical power increased by 17.2 W at 0.0275 vol% compared with DI water. Enhancement of the electrical power output is positively reflected in the electrical efficiency of the PVT system; Fig. 7(c) indicates the growth in the electrical efficiency with increasing volume concentrations of the ZrO_2 nanofluids. At 0.0275 vol%, the electrical efficiency of the PVT system was enhanced by around 54% compared to DI water. Thermal efficiency is an important parameter to evaluate the thermal performance of a PVT system which is affected by the temperature, design of the cooling system applied and type of cooling fluid. Fig. 7(c) show the values of thermal efficiency at different volume concentration; during the experiment's days, the thermal efficiency starts with a low value and then increase to reach a maximum value at noon and then drop until the end of the experiment. Increasing the volume concentration of ZrO_2 nanoparticles in base fluid enhanced the heat removal capacity because of the increased thermal conductivity and convection heat transfer coefficient of the ZrO_2 nanofluid. Removing excess heat of the PV module has increased the thermal efficiency of the PVT system by 26% using DI water, while maximum thermal efficiency was 30.2% at 0.0275vol%. The reference PV module recorded the lowest electrical efficiency, which is attributed to rising PV cell temperature. On the other hand, using ZrO_2 nanofluid increased the electrical efficiency by 11.4% at 0.0275 vol%, while the use of DI water increased the electrical efficiency by 7.4%. The overall efficiency of the PVT system has been boosted by 8.9%, 18.8% and 24.4%, respectively, compared with DI water cooling at 0.0275 vol%.

The present results may not be better than the results in the literature studies considering some factors, such as the PVT system size, type of nanofluids, volume concentrations, design of the heat exchanger, and measurement conditions, but they highlighted a new type of nanofluid that could be used as a cooling fluid to improve the energy and exergy of the PVT system. The limited volume concentrations of ZrO_2 have enhanced the PVT performance compared with DI water and better than some studies that used different nanofluids with higher concentrations. Table 4 shows the effect of ZrO_2 nanofluid on reduced PVT system temperature and incrementing the electrical and thermal efficiencies compared with other studies.

4.2. Exergy analysis results

According to the second law of thermodynamics, the section evaluates the effect of using ZrO_2 nanofluid and water on the

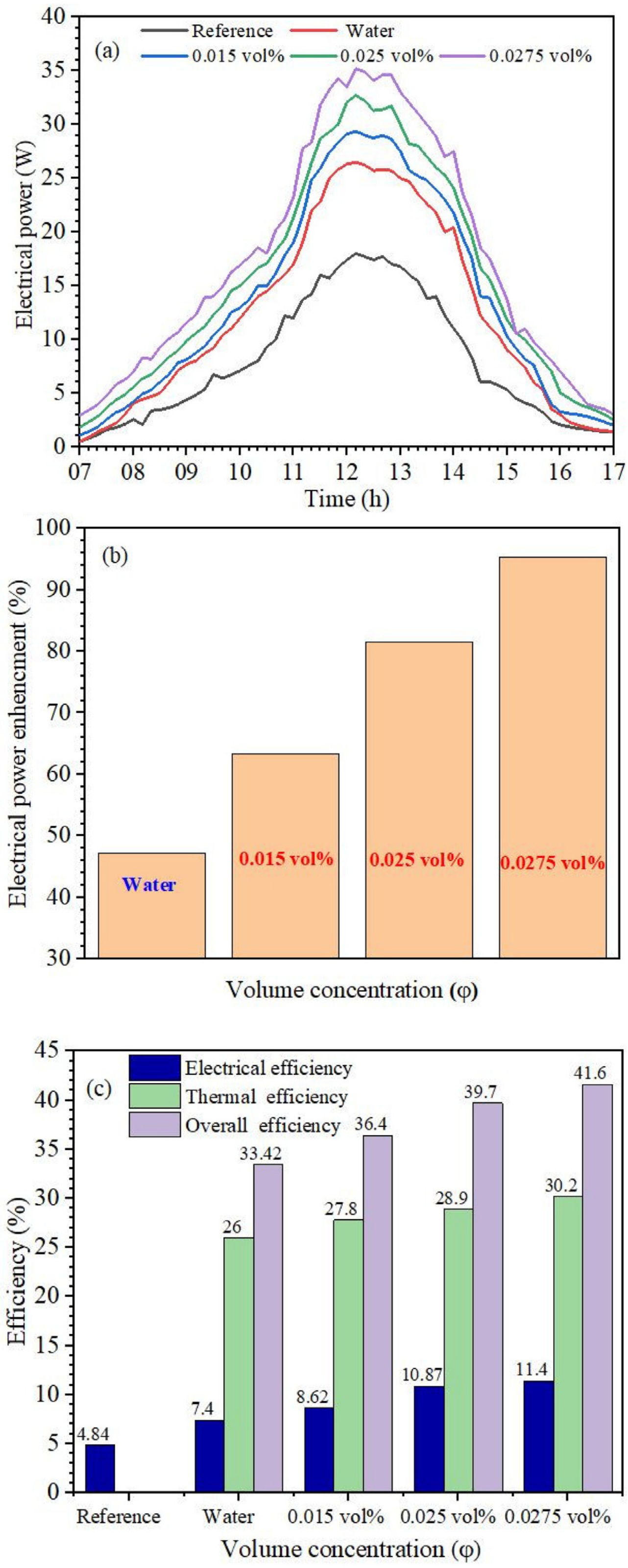

Fig. 7. Performance of the PVT system (a) Electrical power, (b) electrical power-enhancing and (c) overall efficiency as a function of volume concentration.

thermal exergy and electrical exergy efficiency, entropy generation and exergy losses of the PVT system. Based on Eq. (12), the inlet exergy that comes from solar irradiation has been calculated for the maximum, average and minimum solar exergies during experiments days to be 997 W/m^2, 668.33 W/m^2 and 328.58 W/m^2, respectively. Fig. 8 shows the value of the thermal exergy that was significantly lower than the electrical exergy due to the closer of the fluid outlet temperature of the PVT system to the ambient temperatures, which agrees with a study conducted by Sardarabadi et al. (2014). The increase of ZrO_2 nanoparticles in the base fluid reduced the specific heat of the nanofluid, as shown in Table 4. In contrast, the thermal conductivity is increased, incrementing the thermal exergy efficiency of the PVT system compared to the DI water. The output thermal exergy is influenced by the specific heat of the working fluid and mass flow rate. Because the high thermal conductivity of the nanofluid, it was noticed that the thermal exergy is enhanced more with the ZrO_2 nanofluid than with DI water. To evaluate the quality of the thermal and electrical efficiencies, Fig. 8(b) shows the effects of ZrO_2 nanofluid on the PVT system's thermal and electrical exergy efficiencies. The low thermal exergy value significantly affects the thermal exergy efficiency; however, a relative increment of the thermal exergy was noticed by increases in the volume concentrations of ZrO_2 nanofluid compared with DI water. The overall exergy efficiency is impacted by the thermal exergy efficiency, the electrical exergy efficiency, the exergy of solar radiation and ambient temperature. Thereby, the exergy efficiency effectively contributes to the increment of the overall exergy efficiency of the PVT system, the maximum overall exergy efficiency obtained at 0.0275 vol% is 11.86%, while cooling by DI water was 7.11%, which confirms the feasibility of ZrO_2 nanofluid as a working fluid. Using nanofluids as a coolant for the PVT system instead of conventional fluids help enhances the performance of the PVT system due to its high thermal conductivity that increases the convective heat transfer. Compared with previous studies, it can be observed from Table 5 that using ZrO_2 nanofluid achieved better thermal and electrical exergy efficiencies than other studies used different nanofluid with volume concentration higher than that investigated in the current study, which confirms the ability of ZrO_2 nanofluid for cooling PVT systems.

Evaluation of exergy loss and entropy generation of each thermodynamic system is important for specifying the system losses and irreversibilities. In this study, the exergy loss of the PVT system was calculated using Eq. (18) with ZrO_2 nanofluid and water. Fig. 9(a) shows the high exergy losses of the PVT system and PV module without cooling due to a drop in the overall exergy efficiency of the systems lower than the input exergy, specifically thermal exergy efficiency and increased temperature of the PV module surface. Using ZrO_2 nanofluids helps to reduce the exergy losses by about 7% at 0.0275 vol% compared to DI water because of their effects on heat transfer. It can be stated that using ZrO_2 nanofluid resulted better performance by reducing the exergy loss of the PVT system compared with other studies conducted by Alktranee et al. (2022), Hosseinzadeh et al. (2018) and Sardarabadi et al. (2017a), which used different nanofluids and higher volume concentrations than the present study. Increasing the surface temperature of the PV cells increases the heat transfer between the system and the environment, which increases the entropy generation. In the PVT system, the entropy generation is affected by the heat transfer and fluid friction into the PVT system (Maadi et al., 2017). Fig. 9(b) indicates variation in entropy generation due to heat transfer reduced by using DI water and nanofluid as a coolant. Using ZrO_2 nanofluid at different volume concentrations reduced entropy generation; at 0.0275 vol%, the entropy generation has reduced by 26% compared with DI water, which confirms the potential of ZrO_2 nanofluid as a coolant fluid.

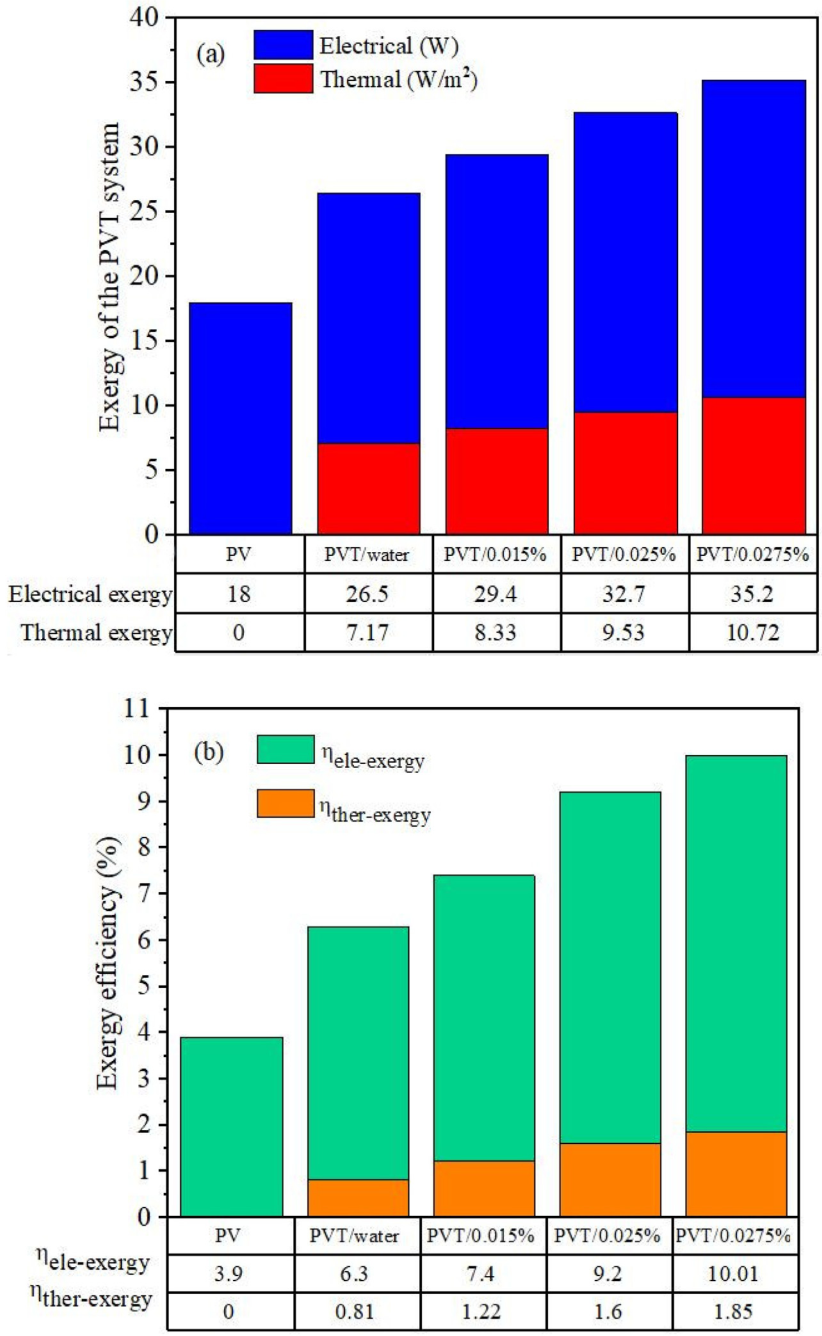

Fig. 8. Exergy of the PVT system (a) electrical and thermal exergy (b) electrical and thermal efficiency.

5. Conclusion

This study investigates the effect of using ZrO_2/water nanofluid and DI water as a cooling fluid and their effect on the energy and exergy of the PVT system. The results obtained are compared with previous studies to exhibit the ability of the ZrO_2 nanofluids to improve the PVT system performance Based on the results, some conclusions could be summarized, as follows:

- Gradual increase of ZrO_2 nanoparticles volume concentration in the base fluid has increased the thermal conductivity of nanofluid and improved heat transfer convection, leading to increased heat absorption at the backside of the PV module. Thus, the PVT systems temperature is reduced by 21.2% at 0.0275 vol% compared to DI water.

- Reduction of the PVT systems temperature effectively enhanced the energy produced. The electrical power of the PVT system was enhanced by 32.8% at 0.0275 vol% of ZrO_2, compared with DI water.

- The electrical efficiency of the PVT system was enhanced by 54%, and the thermal efficiency increased by 16.15% with increased volume concentration to 0.0275 vol%, compared with DI water.

- Thermal exergy of the PVT system was lower than the electrical exergy, due to slight difference of fluid outlet temperature of the PVT system and the ambient temperature. Despite that, a remarkable increment of the thermal exergy has been found with increased ZrO_2 volume concentrations by 49.5% compared with DI water.

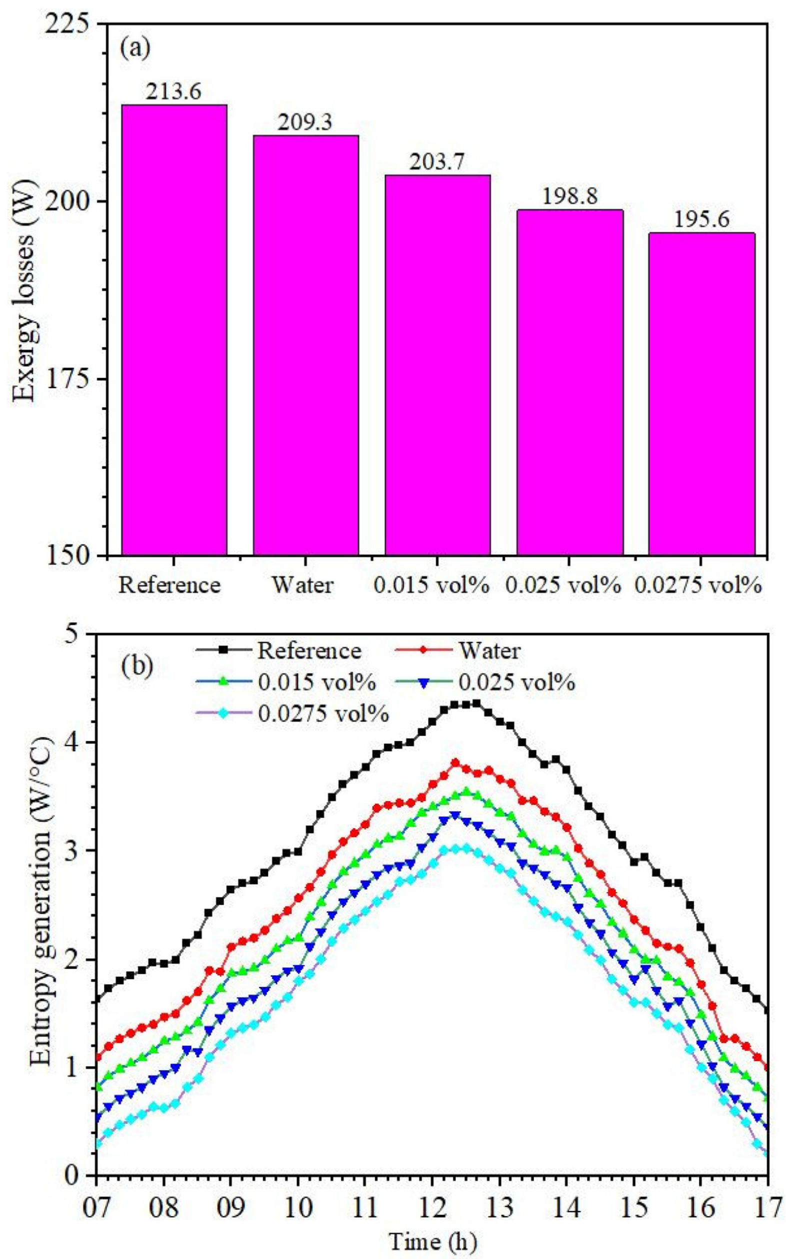

Fig. 9. Exergy evaluation of the PVT system (a) exergy losses (b) entropy generation.

Table 4
Comparison of the study results with previous studies.

Ref.	PV module peak power	Type of nanofluid	Volume concentration %	Temperature drop %	Electrical efficiency %	Thermal efficiency %
Current study	50 W	ZrO_2	0.015	14	8.62	27.8
			0.025	18.1	10.87	28.9
			0.0275	21.2	11.4	30.2
Alktranee et al. (2022)	50 W	WO_3	1	21.4	9.82	30.1
Menon et al. (2022a)	100 W	CuO	0.05	15	12.9	71.1
Rukman et al. (2019)	80 W	TiO_2	1	12.3	7.32	41
Al Ezzi et al. (2022)	100 W	Fe_2O_3	2	27.57	10–13.3	43–59
Zamen et al. (2022)	90 W	Al_2O_3	0.5	9.1	11.63	82.26
Kazem et al. (2021)	100 W	SWCNTs	2	19	25.2	51

Table 5
Exergy efficiencies compared with previous studies.

Ref.	PV module peak power	Type of nanofluid	Volume concentration %	Thermal exergy %	Electrical exergy %
Current study	50 W	ZrO_2	0.015	1.22	7.4
			0.025	1.6	9.2
			0.0275	1.85	10.0
Sardarabadi et al. (2017b)	40 W	Al_2O_3	0.2	1.01	10.87
		ZnO	0.2	1.18	10.99
		TiO_2	0.2	0.91	11.02
Alktranee et al. (2022)	50 W	WO_3	0.5	0.76	7.87
			0.75	0.91	8.81
			1	1.2	9.3
Hosseinzadeh et al. (2018)	40 W	ZnO	0.2	0.89	11.48
		PCM	–	1.6	12.01
			0.1	0.25	15.25
Firoozzadeh et al. (2021)	60 W	Carbon black	0.2	0.52	15.98
			0.3	0.34	15.55
			0.4	0.19	14.45

- The overall exergy efficiency of the PVT system incremented using nanofluid by 66.8% at 0.0275 vol% compared with DI water due to the high thermal conductivity which enhanced the convective heat transfer.

- Exergy losses and energy generation has reduced by 7% and 26%, respectively at 0.0275 vol% compared to DI water due to enhanced thermal properties of the nanofluid

- The PV module without cooling is exposed to significant degradation in its performance due to rising temperature.

The current study can be extended by improving the thermal properties of ZrO_2 nanofluid through adding another type of nanomaterials to form a hybrid nanofluid, applied for a new cooling system design.

CRediT authorship contribution statement

Mohammed Alktranee: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Mohammed Ahmed Shehab:** Conceptualization, Formal analysis, Investigation, Writing – review & editing. **Zoltán Németh:** Investigation, Review & editing, Supervision, Funding acquisition. **Péter Bencs:** Conceptualization, Investigation, Review & editing, Supervision, Funding acquisition. **Klara Hernadi:** Investigation, Review & editing, Funding acquisition.

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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