Arabian Journal of Chemistry (2023) **16**, 105102

King Saud University

Arabian Journal of Chemistry

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ORIGINAL ARTICLE

Experimental study for improving photovoltaic thermal system performance using hybrid titanium oxide-copper oxide nanofluid

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Received 23 April 2023; accepted 19 June 2023
Available online 24 June 2023

KEYWORDS

Hybrid nanofluids;
PVT system;
Electrical power;
Exergy efficiency;
Exergy losses;
Payback period

Abstract Overheating of photovoltaic (PV) cell is one of the most common issues that cause the degradation of their function and reduce conversion efficiency. This work investigates the effect of using a novel TiO_2-CuO hybrid nanofluid to improve the energy and exergy of photovoltaic thermal (PVT) systems by reducing PV cell temperature. Serpentine tubes soldered on an absorbing plate attached behind the PV module were proposed to improve heat removal of the PV module with volume concentrations of 0.2 vol% and 0.3 vol%, with a flow rate of 1.16 L/min. Improving the thermophysical properties of the hybrid nanofluid has reduced the temperature of the PV module by 39% more than the uncooled PV module. The PVT system's electrical power and overall efficiency improved by 77.5% and 58.2%, respectively, at increased volume concentration to 0.3 vol% compared with the uncooled PV module. The exergy analysis indicated an increase in the overall exergy efficiency by 14.97 %, with thermal exergy dropping because of the closer the outlet nanofluid temperature to ambient temperature. Hybrid nanofluid cooling has improved exergy efficiency to 14.97%, reducing exergy losses by 37.9% and entropy generation by 69.6% at 0.3 vol%. The

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Production and hosting by Elsevier

https://doi.org/10.1016/j.arabjc.2023.105102

economic analysis shows a better payback period of 21 months when cooling with a hybrid nanofluid compared with the uncooled PV module.

1. Introduction

In recent decades, renewable energy sources have developed rapidly and use significantly in several applications, particularly in the electricity supply sector. (Østergaard et al., 2020). Solar systems that convert sunlight into heat or electricity are the most effective systems and a better alternative to the environment than other renewable energy systems because rely on solar energy which is available and more sustainable in the future (Dawar et al., 2022). PV modules are the most solar energy technologies applied for generating electrical power, consisting of semiconductor materials that convert solar radiation to electricity (Wang et al., 2021). Since PV modules work outdoors, are constant exposure to changeable weather conditions, such as the intensity of solar radiation, temperature, and wind (Ndiaye et al., 2014). In this regard, overheating of PV cells due to increased ambient temperature which increases directly with increased solar radiation (sunlight) intensity negatively affects their lifespan and performance (Shukla et al., 2017). Generally, the PV module converts about 20% of sunlight into electrical energy, and the rest of the sunlight is converted into heat, causing short and long-term problems. The long-term problems represented by ultraviolet intensity, temperature, and water ingress into PV cells lead to the degradation of the PV module's performance. Besides, rising PV cell temperature is a common issue of PV module operation (short-term problem), which negatively affects the conversion efficiency of the PV cell and then decreases electrical power yield (Kahoul et al., 2021). Overheating of the PV module is a critical issue that causes a reduction in productivity due to a lowering in the open circuit voltage or leads to damage to the PV module (Al-Waeli et al., 2020).

Furthermore, overheating the PV cell temperature reduces the output power, efficiency, durability and lifetime of the PV cells (Michael et al., 2015). Various cooling methods are applied to reduce the PV cell's temperature and increase its performance. Passive cooling techniques are used to improve PV module efficiency with increased operating temperatures since their configurations are simple (Kannan and Vakeesan, 2016). Some passive cooling techniques do not require external power, such pump or fan for cooling the PV module, making them economical to use, such as evaporative cooling (Alktranee and Bencs, 2022), cooling by phase change material (Al-Lami et al., 2022), and heat sink fins (Elminshawy et al., 2022). In contrast, using active cooling techniques is an effective method for the removal of excessive heat from PV cells and improves their performance by using fluids such as air, water or equivalent, thus producing electrical and thermal energy simultaneously (Alktranee and Bencs, 2021). The PVT system is an effective technique for improving the PV module's performance. Consisting of a PV module and an absorbing plate soldered with tubes, which helps absorb excess heat from the rear side of the PV module, thus generating thermal and electrical energy (Kasaeian et al., 2017). Working fluids circulated in the PVT system to heat recovery are key in improving electrical and thermal performance. Despite air or water being the common cooling media used by PVT systems, it does not meet the aim of increasing energy efficiency because of its limited thermal conductivity (Aberoumand et al., 2018).

Recently, nanofluids have attracted attention to be used as a cooling fluid instead of conventional fluids due to their notable thermophysical properties role in heat transfer (Martínez-Merino et al., 2022). Several experiments used nanofluids for cooling the PV module and improving its performance. For instance, a nanofluid consisting of copper oxide (CuO) nanomaterials dispersed in water and ethylene glycol at 2.0 vol% was proposed to cool the rising temperatures of PV cells and increase their performance. The effective cooling of CuO nanofluid has enhanced thermal efficiency by 39.6% due to dropped PV module temperature and improved the electrical efficiency by 6.76% than the base fluid only (Kazem et al., 2022). A study used water and titanium oxide (TiO_2) nanofluid (at 1 wt%,2 wt% and 3 wt% concentrations) as a cooling fluid with two pass heat exchanger circulation to control rising PV cells temperature and increase of the PVT system performance. Circulating TiO_2 nanofluid has increased heat extraction of the PV module and dropped the temperature by 19.0%. Increased volume concentration in water led to increased electrical power to about 44.5 W compared with water which recorded 39.5 W, and the highest efficiency was 19.23% at 3 wt% (Murtadha et al., 2022). Another approach adopted for water/CuO nanofluid with an unglazed PVT system combined with a serpentine coil and thermal absorber sheet has been introduced to evaluate the efficiency of the PVT system that suffered from dropped efficiency by 12.98% due to high cell temperature reached 68.4 °C. Using water and CuO nanofluid dropped the temperature to 15 °C and 23.7 °C, then improved average electrical efficiency by 12.32% and 35.67%, respectively, by comparing the uncooled PV module. The high heat absorption of nanoparticles suspended in water has increased the thermal efficiency of the PVT by 71.17% more than water (58.77%) (Menon et al., 2022).

A new serpentine half-pipe geometry has been designed and placed at the backside of the PV module combined on an aluminium plate 3 mm thick to increase the heat transfer and improve the PVT system efficiency. Aluminium oxide (Al_2O_3) nanofluid at different volume concentrations (0.05 to 0.5 wt%) with added surfactants to achieve more nanofluid stability. The results indicated improved electrical and thermal efficiencies by 7.38% and 126.71% at 0.5 wt% compared with pure water cooling (Zamen et al., 2022). An experiment using tungsten trioxide (WO_3) nanofluids circulating into serpentine tubes soldering with a thermal absorber sheet placed at the rear of the PV module at different volume concentrations (0.5 vol% to 1 vol%) has been investigated to reduce PV module temperature and increase its efficiency. The results showed a PV module temperature drop by 21.4%, increasing the power output more than the reference module without cooling by 11.15 W and improving the overall efficiency by 29.6% (Alktranee et al., 2022). An outdoor experiment adopted Multi Walls Carbon Nano Tubes (MWCNT) nanofluid at a range of volume concentration (0%:0.3%) was performed at a mass flow rate of 1.2 L/min for cooling and maximizing the PVT system performance. Adding MWCNT nanomaterials to the host fluid enhanced the thermal absorber characteristic of nanofluid, which caused dropped the PVT system temperature by about 10.3 °C, then improved the PVT system's overall efficiency by 61.23% (Abdallah et al., 2019). Another experimental and numerical study used deionized (DI) water Al_2O_3, TiO_2 and zinc-oxide (ZnO) nanofluids as a cooling fluid with PVT system at 0.2% by weight wt %. The surface temperature of the PVT system and fluid outlet are considered to calculate the PVT electrical efficiency. The results showed that the TiO_2 and ZnO nanofluids resulted in better electrical efficiency than Al_2O_3 and DI water, and the ZnO nanofluid has higher thermal efficiency than other fluids (Sardarabadi and Passandideh-Fard, 2016).

Hybrid nanofluids are a new trend of cooling fluids used for cooling systems due to their superior thermal properties (Huang et al., 2016). In this domain, an experimental study adopting Al_2O_3/ZnO hybrid nanofluid was conducted to evaluate the efficiencies of the PVT system at different volume concentrations and mass flow rates. The study indicated that at 0.47 vol% of Al_2O_3 mixture ratio in the hybrid nanofluid and 0.1 kg/s of mass flow rate, the PV cells temperature dropped by 21%, then the thermal and electrical efficiencies were improved by 55.9 % and 13.8%. The hybrid nanofluid has improved the thermal efficiency by 91%, representing a 34% improvement in the performance of the PVT system compared with cooling by water (Wole-Osho et al., 2020). A numerical analysis was carryout on the geometry of the PVT collector consisting of solar cells, absorber plate and serpentine channel (Karaaslan and Menlik, 2021). The study adopted CuO/Fe hybrid nanofluid and mono CuO nanofluid as cooling fluids at various inlet velocity of the fluids to investigate the effect of working fluids applied on the PVT system performance. Numerical results showed that increasing inlet fluid velocity has improved thermal efficiency with increasing pressure drop. Besides, hybrid nanofluid has increased the thermal and electrical efficiencies by 5.4% and 2.14% at 2 vol% compared to water, while the mono nanofluid reached 3.33% and 1.32%. These results confirm the advantage of the hybrid nanofluids for PVT cooling over mono nanofluid. Another experimental investigation used CNT/Al_2O_3 hybrid nanofluid circulated in a spiral tube attached at the rear of the PVT system to investigate lower the rising temperature of the PV cells and increased its efficiency (Sathyamurthy et al., 2021). Electrical power was increased by 21.4% more than water, the electric efficiency recording 7.15% due to heat removal from the backside of the PVT system. Thus, the overall PVT efficiency was improved by 27.3%.

The literature experimental studies have adopted various types of mono and hybrid nanofluids in different cooling approaches, achieving interesting results and remarkable improvements in the PVT system performance. Regarding hybrid nanofluid as a cooling fluid, some important gaps, such as the synthesis method of the nanocomposite material and the binary ratio of the loaded nanocomposite material, are still not verified well. Besides, experimental studies that evaluate the exergy efficiency of the PVT systems are limited, leaving an incomplete thermal analysis. This work investigates the effects of a novel hybrid nanofluid consisting of TiO_2 nanowires (NWs) loaded on CuO nanoparticles (NPs) in the binary ratio of 50%:50% of TiO_2 NWs and CuO NPs as a hybrid nanofluid at different volume concentrations use as a cooling fluid. The hybrid nanofluid is circulated in serpentine tubes placed on the backside of PV module at a flow rate of 1.4 L/min to control the PV module temperature and improve its energy efficiency of the PVT system. An exergy analysis is deeply investigated to evaluate the thermal exergy, exergy efficiency, exergy losses and entropy generation in the PVT system. Moreover, an uncertainty analysis has been performed to ensure the measurements' reliability. The energy and exergy analysis obtained has been compared with previous studies in the literature to demonstrate the performance of a hybrid nanofluid by improving the PVT system efficiency. Finally, an economic analysis is conducted to calculate the payback period of the PVT system.

2. Experimental setup and procedure

2.1. Instruments

Experiments were conducted in Miskolc City, Hungary, from 8:30 am to 3:00 pm. Two polycrystalline PV modules of 50 W were used. The first PV module was uncooled as a reference, and the second one was cooled with deionized (DI) water and nanofluid. The PVT system is comprised of a copper absorber plate integrated with serpentine copper tubes soldered together which are placed behind the PV module using high thermal conductivity grease HP. High-performance insulation (type SLENTEX) was placed on the copper pipes, and an aluminium plate covered the PV module to minimise thermal losses then set the PVT system at a tilt angle of 14.8°. Twenty-one thermocouples (T type, accuracy ± 0.5 °C) were used to measure the temperature on different points of the system; on each the surface and backside of the PV module and the PVT system, four thermocouples were distributed. Another thermocouple is placed at the inlet, outlet of the PVT system, the inside nanofluid tank, in the water tank and one for measuring the ambient temperature. The outlet of the PVT system is connected to a copper coil that was immersed inside the water tank, and the outlet of the coil is connected to the nanofluid tank. Fig. 1 shows the experimental setup of the reference PV module and PVT system. Data logger of type National instrument model NI cDAQ-9178 consists of 24 channels, was used for measuring temperatures, voltages, currents of PV modules, the solar radiation measured by solar sensor (SS11.303, accuracy ± 0.1 W/m^2) and flow rate measured by flow rate sensor (YF-S201, accuracy ± 10%). The data logger was connected with IN SignalExpress 2015 software,recording and reading the data every 10 min.

2.2. Synthesis and preparation of TiO_2-CuO nanofluid

The hybrid TiO_2 NWs/CuO NPs has been synthesised with a similar procedure followed by M. A. Shehab (Shehab, 2022). The amount of (Cu $(CH_3COO)_2{\cdot}H_2O$) was calculated and dissolved in 100 mL of ethanol and stirred vigorously for 30 min. Later, 0.5 g of TiO_2 NW was added to the solution under vigorous stirring for 1 h. The mixture was put in an autoclave and heated to 150 °C in a static furnace for 12 h. The product was collected using vacuum filtration, washed, and then calcined at 500 °C for 2 h. The final composition is (50%:50%) of the TiO_2 NWs and CuO NPs. The XRD has been performed to describe and identify the crystal structure of nanocomposite material. The diffraction peaks located at 29.1°, 43.7° and 58.2° correspond to (310), (603) and (−911) refer to $K_2Ti_6O_{13}$ (PDF no. 40–0403). The diffraction peaks located at 25.3°, 48°, 53.9° and 55.1 indexes to (101), (200), (105) and (211) originating to anatase phase (JCPDS 21–1272). The other peak at 27.4° corresponds to (110) related to the rutile phase (JCPDS no-21–1276). Furthermore, the peaks at 32.5°, 35.5°, 38.7°, 48.8°, 61.5° 66.2° and 67.9° corresponding to (110), (−111), (111), (−202), (−113), (−311) and (113) refer to copper oxide (JCPDS card number 45–0937). All these results agree with (Ahmadi and Koozegar Kaleji, 2021), as shown in Fig. 2 (a). The prepared hybrid nanocomposite was tested to know its morphology using a transmission electron microscope (TEM). CuO NPs were dispersed homogeneously on the TiO_2 NWs surface, as shown in Fig. 2 (b). TiO_2 NWs have several microns length and diameter range (2–6 nm), while the diameter range of CuO is 36–87 nm. The most important step towards preparing stable nanofluids is the entire dispersion of nanomaterials into the base fluids to enhance the thermal properties of nanofluids (Asadi, 2019). The hybrid nanofluid was prepared in the laboratory of Applied Nanomaterials, University of Miskolc, using a two-physical method with a mixture ratio of 50:50 for each nanomaterial. The quantity of nanocomposite was weighted by a standard electronic balance (BOECO BAS, **a**ccuracy 0.0001 g) and suspended in water, then mixed for 30 min with a magnetic stirrer. Using an ultrasonicator helps to fragment large clusters of nanomaterials into smaller individual nano-

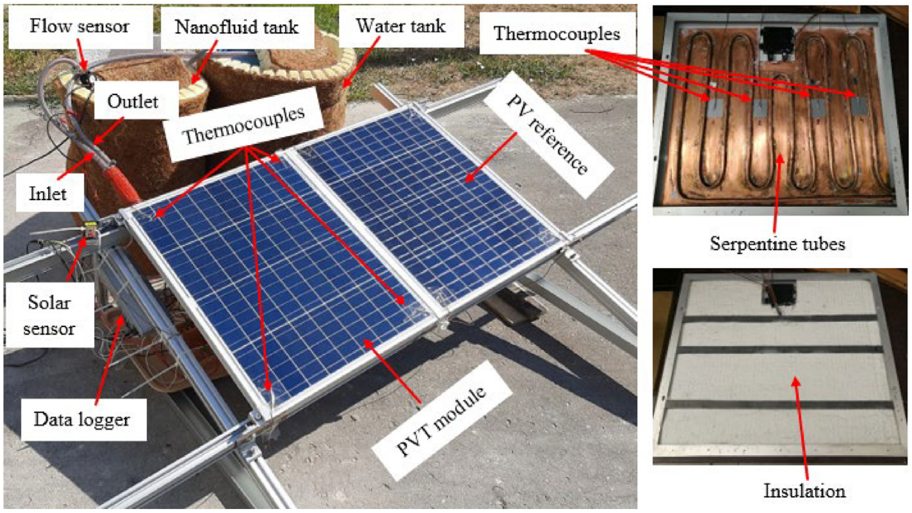

Fig. 1 A sight of the experimental setup.

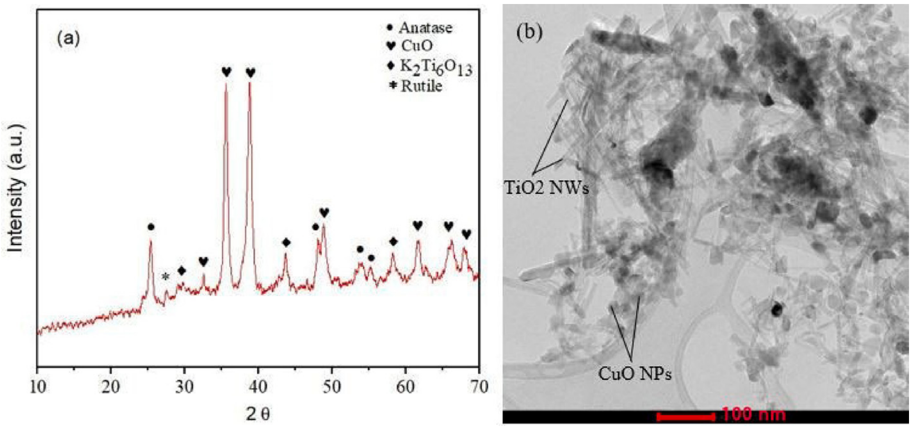

Fig. 2 (a) XRD analysis, (b) TEM image of hybrid nanocomposite.

materials. A probe-type ultrasonicator (Bransonic) with a Voltage of 240 V and 48 kHz was used for 60 min after stirring to attain a homogeneous mixture and enhance the thermal properties of prepared nanofluid. The visualization methods were used to examine the nanofluid stability of hybrid nanofluid after 4 h and three days, as shown in Fig. 3. Two volume concentrations of TiO_2-CuO nanocomposite, (0.2 vol% and 0.3 vol%), were selected which were determined according to the formula presented by (Bang and Chang, 2005) and (Harish et al., 2011). According to time sediment of nanomaterials in the base fluid, it was observed good stability of the hybrid nanofluid which directly used after the sonication process.

In this study, thermophysical properties of the hybrid TiO_2-Cuo nanocomposite were measured at the University of Miskolc, polymer department. The specific heat was measured by (Mettler-Toledo DSC 823e), and the thermal conductivity by a thermal conductivity analyzer (C-Therm TCi). The density was measured with (pycnometer A). Table 1 shows the thermal properties of the nanomaterials used in the present experiment.

2.3. Energy analysis

The electrical efficiency is important factor in evaluating the PVT system performance, which represents the maximum electrical power produced from the PV module divided by the incident solar radiation on the PV module surface, which can be calculated from Eq. (1) (Namjoo et al., 2011).

$$\eta_{el} = \frac{P_{PV}}{A_c \times S} \tag{1}$$

Where P_{PV} is the electrical power produced from the PV module, calculated from Eq. (2). A_c is the PV system surface area, and S is the solar radiation.

$$P_{PV} = I_{PV} \times V_{PV} \times \text{ FF} \tag{2}$$

where I_{PV} and V_{PV} are the output current and output voltage of the PVT system, respectivily. FF is the fill factor and was obtained by Eq. (3).

$$\text{FF} = \frac{V_{\text{PV}} \times I_{\text{PV}}}{V_{\text{oc}} \times I_{\text{sc}}} \tag{3}$$

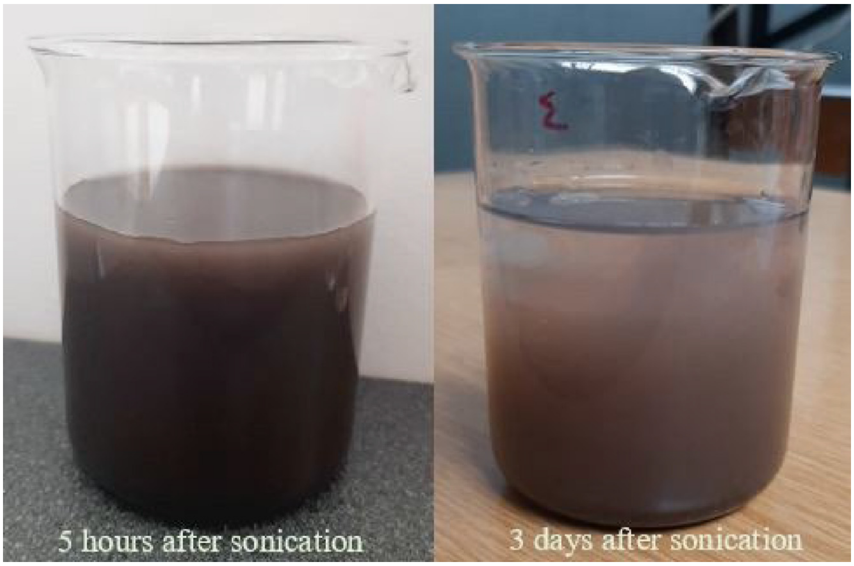

Fig. 3 Stability of hybrid nanofluids at different periods.

Table 1 Nanomaterials and base fluid properties.

Nanomaterials properties	DI water (Giwa et al., 2020)	TiO_2-CuO
Shape	————	NWs-NPs
Color	————	Black
Specific heat	4182 (J/kg·K)	1121
Thermal conductivity	0.61 (W/m·K)	79.9
Density	998 (kg/m^3)	2791

The percentage of electrical power improvement due to using hybrid nanofluid cooling is determined according to Eq. (4) (Abdallah et al., 2019):

$$\%\mathrm{P}_{\mathrm{inc}} = \frac{\mathrm{P}_{\mathrm{cooled}} - \mathrm{P}_{\mathrm{ref}}}{\mathrm{P}_{\mathrm{ref}}} \times 100 \tag{4}$$

Depending on the temperature of the PV surface, the back-side and the PVT system, the average temperature is calculated by Eq. (5).

$$T_{avg} = \frac{\mathrm{T}_{\mathrm{surface}} + \mathrm{T}_{back}}{2} \tag{5}$$

Thermal efficiency is another important factor to evaluate the thermal energy produced by the system, and determined by Eq. (6) (Namjoo et al., 2011).

$$\eta_{th} = \frac{\dot{Q}_u}{A_c \times S} = \frac{\dot{m} C_P \Delta T}{A_c \times S} \tag{6}$$

where, $\dot{Q}_u$ represents the thermal energy absorbed by the PV module, which can be calculated by Eq. (7). $\dot{m}$ is the mass flow rate and it was equal to 0.148 L/min in the current experiment. C_P, T_{out} and T_{in} are the specific heat of working fluid, the outlet and inlet temperatures, respectively.

$$\dot{Q}_u = \dot{m} C_p \Delta T = \dot{m} C_p \times (T_{\mathrm{out}} - T_{\mathrm{in}}) \tag{7}$$

Mixing nanomaterials into the base fluids produce nanofluid with new properties since both nanomaterials and base fluids have different properties. Nanofluid's thermophysical properties are important factors contributing to enhance fluid properties, which can be calculated from Eqs. (8)–(11) (Haddad et al., 2016).

$$C_{p,nf} = \frac{\phi \cdot (\rho_{np} \cdot C_{p,n}) + (1-\phi) \cdot (\rho_{bf} C_{p,bf})}{\rho_{nf}} \tag{8}$$

$$\rho_{nf} = \phi \cdot \rho_{np} + (1-\phi) \cdot \rho_{bf} \tag{9}$$

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\varnothing(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - \varnothing(k_{np} - k_{bf})} \tag{10}$$

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2.5}} \tag{11}$$

where ρ_{nf}, ρ_{bf}, ρ_{np} are the density of nanofluid, base fluid and nanomaterials. $C_{p,nf}$, $C_{p,bf}$, $C_{p,np}$ are the specific heat of the nanofluid, base fluid and nanomaterials, respectively. k_{np}, k_{bf}, k_{nf} are the thermal conductivity of nanomaterials, base fluid and nanofluid. ϕ is the volume concentration of nanomaterial in the base fluid, which can be calculated from Eq. (12) (Adun, 2021).

$$\varphi = \left[\frac{\frac{m_{\mathrm{ap}}}{\rho_{np}}}{\frac{m_{\mathrm{np}}}{\rho_{\mathrm{np}}} + \frac{m_{\mathrm{bf}}}{\rho_{bf}}}\right] \times 100 \tag{12}$$

where m_{np}, m_{bf} are the mass of the nanomaterials and the base fluid.

2.4. Exergy analysis

Exergy analysis is essential to show the quality of energy produced by a thermal system when it is in a thermodynamic equilibrium with the surrounding (Jha et al., 2020). Thus, it is an important tool for evaluating the system's energy quality. Evaluating the PVT system exergy requires knowing the amount of its input and output of the PVT system. For a better understanding of the exergy flows in the PVT system, Fig. 4 shows the exergy flow of the PVT system. The exergy balance of the PVT system can be expressed according to Eq. (13):

$$\begin{aligned} \sum \dot{E}x_{\text{in}} &= \sum \dot{E}x_{\text{out}} + \sum \dot{E}x_{\text{loss}} \\ \Rightarrow \dot{E}x_{\text{solar}} + \dot{E}x_{\text{fluid, ,in}} &= \dot{E}x_{\text{electrical}} + \dot{E}x_{\text{fluid, out}} + \dot{E}x_{\text{loss}} \end{aligned} \tag{13}$$

$\dot{E}x_{\text{solar}}$ is solar exergy, $\dot{E}x_{\text{fluid,in,}}$ $\dot{E}x_{\text{fluid, out}}$ are the fluid exergy inlet and outlet of the PVT system, which calculate from Eq. (15). $\dot{E}x_{\text{electrical}}$ is electrical exergy , $\dot{E}x_{\text{loss}}$ is the exergy losses. Several equations were proposed to assess solar exergy absorbed by the PVT system; equation (14) is the common equation used for solar exergy calculation.

$$\dot{E}x_{\text{solar}} = A_C \times S \times \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_{sun}}\right)^4\right] \tag{14}$$

Where $T_{amb,}$ is the ambient temperature and T_{sum} sun temperature (5800 K) (Fudholi, 2018). $\dot{E}x_{\text{thermal}}$ represents the thermal exergy of the system, which calculated from Eq. (15) (Sardarabadi et al., 2017).

$$\begin{aligned} \sum \dot{E}x_{\text{thermal}} &= \dot{E}x_{th} \\ &= \dot{m}_f \\ &\cdot C_{p,f}\left[\left(T_{f\text{ out}} - T_{f\text{ in}}\right) - T_{\text{amb}} \ln\left(\frac{T_{f\text{ out}}}{T_{f\text{ in}}}\right)\right] \end{aligned} \tag{15}$$

$\dot{m}_f \cdot C_{p,f} T_{f\text{ out}}$, $T_{f\text{ in}}$ are the mass flow rate, the specific heat of fluids, inlet and outlet temperatures of the fluid, respectively. Thus, the thermal exergy efficiencies can be calculated by Eq. (16).

$$\eta_{\dot{E}x_{th,eff}} = \frac{m_{nf} C_{p,nf}\left[\left(T_{f\text{ out}} - T_{f\text{ in}}\right) - T_{\text{amb}} \ln\left(\frac{T_{f\text{ out}}}{T_{f\text{ in}}}\right)\right]}{A_C \times S \times \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_{sun}}\right)^4\right]} \times 100 \tag{16}$$

The electrical exergy of the PVT system equivalent to the electrical power produced (Chow et al., 2009), which was calculated by Eq. (17), $\eta_{\dot{E}x_{ele,eff}}$ is the electrical exergy efficiency of the PVT system which is calculated by Eq. (18).

$$\dot{E}x_{ele} = P_{pv} = V_{pv} \times I_{pv} \times \text{FF} \tag{17}$$

$$\eta_{\dot{E}x_{ele,eff}} = \frac{V_{pv} \times I_{pv} \times \text{FF}}{A_C \times S \times \left[1 - \frac{4}{3} \times \left(\frac{T_a}{T_{sun}}\right) + \frac{1}{3} \times \left(\frac{T_a}{T_{sun}}\right)^4\right]} \times 100 \tag{18}$$

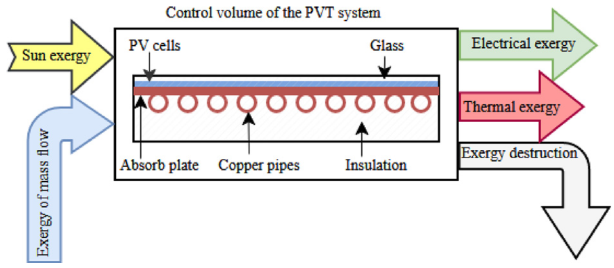

Fig. 4 Exergy flow diagram of the PVT system.

The overall exergy efficiency of the PVT system can be calculated using Eq. (19).

$$\eta_{\dot{E}x} = \eta_{\dot{E}x_{th,eff}} + \eta_{\dot{E}x_{ele,eff}} \tag{19}$$

Exergy destruction (exergy loss) is the parameter produced due to heat transfer losses and the friction in the tubes, which can be calculated by Eq. (20) (Farzanehnia and Sardarabadi, 2019). Entropy generation is a thermodynamic parameter in each thermal system. It can show the irreversibilities and the losses in the system. Moreover, determining entropy generation helps to evaluate the irreversibility of the system by the control volume system, which is calculated by Eq. (21).

$$\sum \dot{E}x_{\text{loss}} = \dot{E}x_{\text{solar}} - \dot{E}x_{th} - \dot{E}x_{ele} \tag{20}$$

$$\dot{S}_{\text{gen}} = \frac{\dot{E}x_{\text{loss}}}{T_{\text{amb}}} \tag{21}$$

2.5. Uncertainty analysis

During any measurements, errors occurred by humans or in calibration and measurements. The uncertainty analysis is significant to ensure the reliability and accuracy of data measured during the experiment. The uncertainty analysis method followed in this experiment is introduced by (Michael and Iniyan, 2015). The uncertainty of electrical and thermal efficiencies can be determined assuming negligible uncertainty in both the area of the PVT system and the specific heat of fluid according to Eq. (22) and Eq. (23), as follows:

$$\eta_{elec} = f(I, V, S) \tag{22}$$

$$\eta_{therm} = f(T, \dot{m}, S) \tag{23}$$

Thereby, the uncertainty equations are expressed in Eq. (24) and Eq. (25):

$$\left[\left(\frac{U_{\eta_{elec}}}{\eta_{elec}}\right)^2\right]_{\text{elec}} = \sqrt{\left(\frac{U_v}{V}\right) + \left(\frac{U_I}{I}\right) + \left(\frac{U_S}{S}\right)} \tag{24}$$

$$\left[\left(\frac{U_{\eta_{therm}}}{U_{\eta_{therm}}}\right)^2\right]_{therm} = \sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right) + \left(\frac{U_S}{S}\right) + \left(\frac{U_T}{T}\right)} \tag{25}$$

Where U, $\dot{m}$, T, S, I, and V denotes the uncertainty, water mass flow rate, the temperature, the solar collector, voltage, current, and the accuracy of the devices and sensors used. The calculated electrical and thermal efficiency uncertainties were 1.08 % and 1.78 %, respectively.

2.6. Economic analysis of the PVT system

The economic analysis is important to show the payback period, and the feasibility of nanofluid applied for the long term (Jordan et al., 2016). The economic analysis considered operation costs (including pump and flow sensor), daily maintenance (maybe non-existent on some days of the month), and electrical consumption and others. In addition to the purity of the morphology of nanomaterials, synthesising nanomaterials in the laboratory and preparing the nanofluid have significantly reduced the cost of nanofluids compared to purchasing from companies. The nanofluid supply cost for each day was calculated after dividing the total price by annual days. Table 2

Table 2 Feasibility of using hybrid nanofluid for cooling PVT system.

Elements/aspects	PVT system	Conventional PV
Configuration	179.86 $	39.76 $
Maintenance	0.007 $/ day	0.00397 $/day
Nanofluid supply	0.173 $/day hybrid nanofluid	–
Operation cost	0.00363 $/ day	–
Energy productivity	0.443 $/day	0.0543 $/day
Net profit	0.2834	0.05033
Payback period	634 days	790 days

involves the components of the PVT system configuration, such as a PV module, an absorbing part, copper tubes, an aluminium cover, insulation, the pump, a flow sensor, plastic tanks, etc. The net profit is calculated from Eq. (26) (Pounraj, 2018).

$$\text{Net profit} = \text{Energy produces cost (electric and thermal energy)} \quad (26)$$

3. Results and discussions

In this study, the active cooling method has been adopted to reduce the PV temperature by using absorb plates and serpentine tubes with hybrid nanofluids as a working fluid. The purpose of using a hybrid TiO_2-CuO nanofluid as a cooling fluid is to improve the performance of the PV module by decreasing cells temperature. The experiment was conducted under climatic conditions of Miskolc city, Hungary, in August 2022 from 8:30 AM to 3 PM. Fig. 5 shows the average ambient temperature and solar radiation values recorded throughout the experiments. At the experimental beginning, both solar radiation and ambient temperature were low, then gradually increased to reach a maximum between 12:20 PM and 13:50 PM with 32.6 °C and 903.5 W/m^2, respectively, at noon, then dropped at sunset.

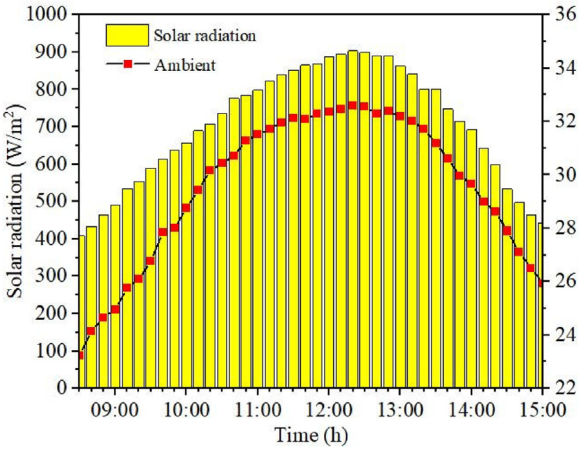

Fig. 5 Ambient temperature and solar radiation during experimental period.

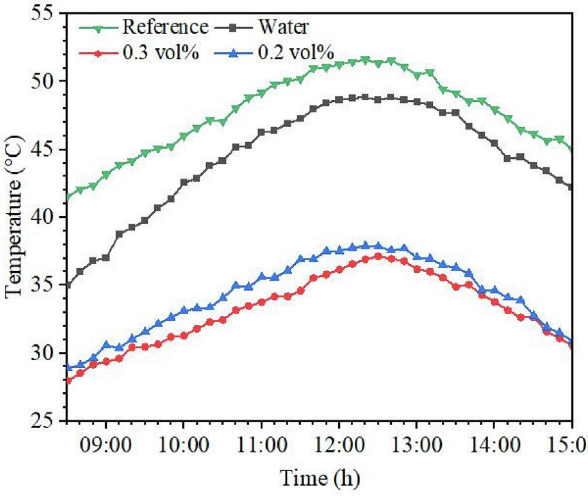

Fig. 6 Effect of cooling by DI water and hybrid nanofluid of the PVT system temperature.

3.1. Energy analysis results

Increased intensity of incident solar radiation on the PV module increases PV module temperature as a result of increased solar radiation rate absorbed by the PV cell. Thereby the electrical efficiency of the PV module and PVT system is directly influenced by solar radiation and ambient temperature. The heat transfer mechanism between the absorbing plate and serpentine tubes, then by heat convection to hybrid nanofluids that pass inside tubes, helped reduce the PV module temperature rise. Fig. 6 showed that the peak temperature of the reference PV module was 51.6 °C. However, it was decreased averagely to 48.85 °C with the water cooling at 0.2 vol% and 0.3 vol% of hybrid nanomaterials in the base fluid, the average temperature dropped to 37.9 °C and 37.1 °C, respectively. The loaded CuO NPs over the TiO_2 NWs has increased their surface area and improved the thermal characteristics, which led to an increase in convective heat transfer and a decrease in the PV module temperature. The flowing hybrid nanofluid at different volume concentrations inside the serpentine tubes attached beneath the PV module helps to extract the excessive heat and reduce the temperature by 36.1%-39%, compared with the uncooled PV module. Cooling by water has achieved a slight decrease in temperature by 5.6% than the uncooled PV module, confirming the effectiveness of hybrid nanofluid as a cooling fluid proposed.

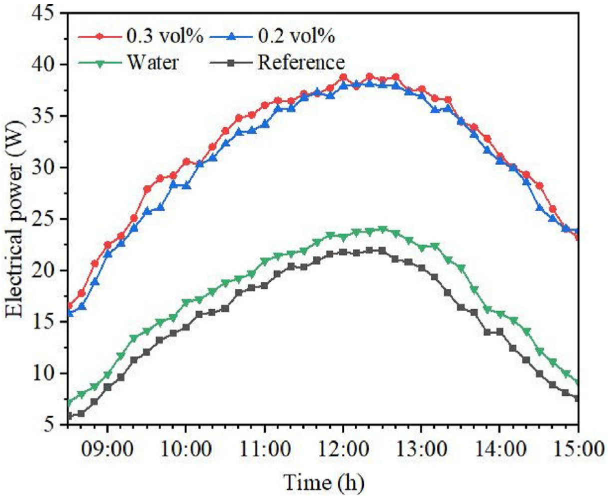

Fig. 7 Effect of hybrid nanofluid in increase electrical power of the PVT system.

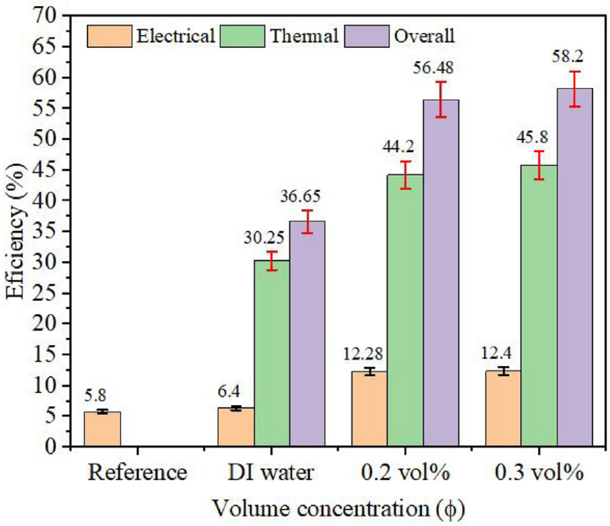

Fig. 8 PVT system efficiency at various volume concentration.

The proposed cooling approach has decreased the PV module temperature and improved its performance. Removing excessive heat from the backside of the PVT system using DI water and hybrid nanofluids helps to increase electrical power compared to the uncooled PV module. Fig. 7 shows the maximum power generated by the uncooled PV module and PVT system cooled by water and hybrid nanofluid at different volume concentrations. The electrical power of uncooled PV modules has recorded a lower value of about 21.9 W, which confirms the reduced conversion efficiency of the PV cell's work due to increased temperature. Circulation of water inside serpentine tubes with absorbing plate has slightly increased the electrical power to 24.2 W. Using hybrid nanofluids at 0.2 vol % and 0.3 vol%, has increased the electrical power to 38.1 W and 38.88 W, respectively. Loading CuO NPs on TiO_2 NWs at equal ratios, and then, dispersion in DI water has improved the hybrid nanofluid's thermal properties by increasing the hybrid nanofluid's thermal conductivity and heat capacity. Improving the nanofluid's thermal conductivity has increased the PV module's absorbing heat and then reduced its temperature. The electrical power produced was increased by 73.9 5% and 77.5% with the used hybrid nanofluid at 0.2 vol% and 0.3 vol%, respectively. Besides, the DI water has improved the electrical power by 10.4% compared to the uncooled PV module.

The effectiveness of hybrid nanofluid decreased the PV module temperature and increased the power generation of the PVT system, therefore positively improved the electrical efficiency of the PVT system. In Fig. 8, it can be observed that the electrical and thermal efficiencies with the error range of efficiencies (I), the reference PV module recorded electrical efficiency of about 5.8 % due to a drop in the electrical power. Besides, cooling the PVT system with DI water increased the electrical efficiency to 6.2%. The hybrid nanofluid usage has improved the electrical power efficiency of the PVT system to 9.2% and 10.3%, at 0.2 vol% and 0.3 vol%, respectively, attributed to the reduced PV module temperature. The higher heat transfer capacity of hybrid nanofluids used has decreased the operation temperature of the PV module, thus incrementing the thermal efficiency of the PVT system. Increasing the volume concentration of nanomaterials in DI water circulated in tubes has an effect on the thermal efficiency values as shown in Fig. 8 due to increased heat exchange between absorb plate and the backside of the PV module and the effect of nanomaterials thermal conductivity. The increment in volume concentration achieved a relative increase in the thermal efficiency due to increased thermal conductivity of nanofluids. Compared with DI water, using a hybrid nanofluid has increased thermal efficiency to 50.2% and 41.7% with increased volume concentration by 0.2 vol% and 0.3 vol%, respectively. Thereby increasing the overall efficiency of the PV module to 36.25%, 56.48%, and 58.2% with cooling by DI water and hybrid nanofluid at different volume concentrations compared with the reference PV module. Table 3 compares the results of current study with previous studies that used mono nanofluids (such as CuO, TiO_2) and hybrid nanofluids for cooling PVT systems. It can be remarked that the hybrid TiO_2-CuO fluid achieved good performance by temperature drops and increment in the electrical and thermal efficiency attributed to the improving thermal characteristics of hybrid nanofluids. By comparing some factors such as the size of the PVT system, the design of the heat exchanger used, the flow rate and operation conditions, etc, the results obtained in this study have achieved better than other results of literature studies, which confirmed the effectiveness of the hybrid nanofluid used.

3.2. Exergy analysis results

Exergy analysis shows the actual work of the PVT system and determines its losses similar to energy analysis. The exergy analysis shows the effect of the increase in solar irradiance and temperature on the exergy efficiencies of the system. Based on Eq. (14), the solar energy is determined for the minimum, average, and maximum values during experiments days of 320.58, 654.33, and 897, $W/m^2$and respectively. According to Eq. (17), the electrical exergy was equal to the electrical power produced by the PVT system. The electrical exergy produced was higher than thermal exergy, in contrast to thermal energy in energy analysis because of the outlet fluid's temperature convergence with air temperature. Moreover, cooling the

Table 3 Energy efficiency of the present study compared with the literature.

Ref.	PV module power	Nanofluidsapplied	Temperature drop %	Electrical efficiency %	Thermal efficiency %
Presentstudy	50 Watts	TiO_2-CuO/ 0.2 vol%	13.7	9.2	50.2
		TiO_2-CuO/ 0.3 vol%	14.5	10.3	41.7
(Jidhesh et al., 2021)	250 W	CuO	12	11.2	43
(Menon et al., 2022)	100 W	CuO	15	12.9	71.1
(Rukman et al., 2019)	80 W	TiO_2	12.3	7.32	41
(Murtadha and A. A. dil Hussein, A. A. H. Alalwany, S. S. Alrwashdeh, and M. Ala'a, , 2022)	50 W	TiO_2	9.6	18.8	45
(Sathyamurthy et al., 2021)	150 Watts	CNT/Al_2O_3	15	17.2	27.23
(Hooshmandzade et al., 2021)	35 Watts	Al_2O_3-SiO_2	19.2	1.99	9.09
(Wole-Osho et al., 2020)	250 Watts	Al_2O_3-ZnO	21	13.8	55.9
(Adun, 2021)	250 Watts	Al_2O_3-ZnO-Fe_3O_4	5.14	13.43	54.11

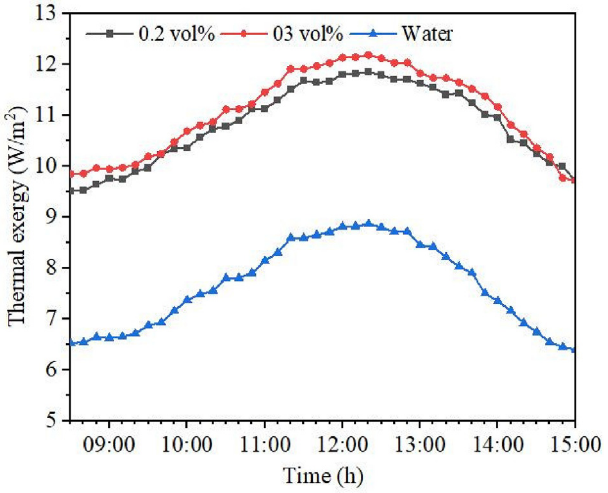

Fig. 9 Effect of hybrid nanofluid cooling on thermal exergy of the PVT system.

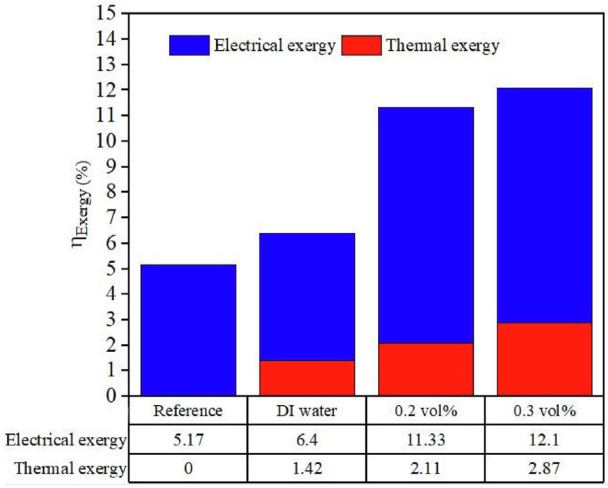

Fig. 10 Exergy efficiency of the PVT system cooled by DI water and hybrid system.

PVT system with hybrid nanofluid achieved better thermal exergy than cooling by DI water due to the high thermal properties of nanofluid, as shown in Fig. 9. Based on Eq. (15), it can be observed that the thermal exergy depends on the difference between the $T_{f\text{ out}}$, $T_{f\text{ in}}$ fluid temperature, ambient temperature, the logarithm of $\left(\frac{T_{f\text{ out}}}{T_{f\text{ in}}}\right)$, and the specific heat of fluids applied. The convergence of $T_{f\text{ out}}$ to ambient temperature led to dropping the thermal exergy, which significantly influenced the thermal exergy efficiency. Nevertheless, using nanofluid has achieved a remarkable improvement of thermal exergy to 11.86 W/m^2 and 12.18 W/m^2, at 0.2 vol% and 0.3 vol%, respectively, while the cooling by DI water reached 8.8 W/m^2, as shown in Fig. 9.

Circulating the hybrid nanofluid in the tubes increases heat exchange between absorbing plates which have less temperature than the backside of the PV module, which helps increased heat conduction by removing excess heat from the backside of the PV module and reducing their temperature, improving the electrical exergy. Fig. 10 shows the effect of DI water and

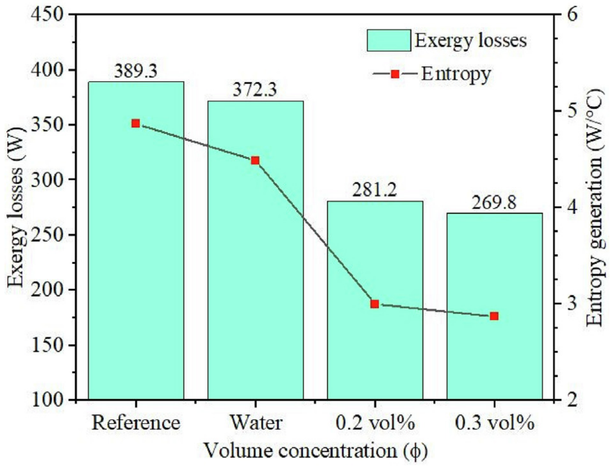

Fig. 11 Exergy losses and entropy generation.

Table 4 Exergy analysis of the present study compared with the literature.

Ref.	PV module power W	Nanofluids applied	Volume concentration %	Thermal exergy %	Electrical exergy %
Presentstudy	50	TiO_2-CuO	0.2	2.11	11.33
			0.3	2.87	12.1
(Alktranee et al., 2022)		$_3$	0.5	0.76	7.87
			0.75	0.91	8.81
			1	1.2	9.3
(Sardarabadi et al., 2017)		Al_20_3	0.2	1.01	10.87
		ZnO	0.2	1.18	10.99
		TiO_2	0.2	0.91	11.02
Firoozzadeh et al., 2021)			0.1	0.25	15.25
			0.2	0.52	15.98
			0.3	0.34	15.55
			0.4	0.19	14.45
(Hosseinzadeh et al., 2018)		ZnOPCM	0.2	0.89	11.48
			–	1.6	12.01

hybrid nanofluid at 0.2 vol% and 0.3 vol% by increasing electrical exergy efficiency to 5.4 %, 11.33 %, and 12.18%, respectively. The thermal exergy drop has influenced the thermal exergy efficiency of the PVT system because of the low quality of thermal exergy. The overall exergy efficiency of the PVT system is the sum of the thermal exergy and the electrical exergy efficiencies. Enhancing hybrid nanofluid's thermal properties has increased the PVT system's overall exergy efficiency to 13.44% and 14.97% at different volume concentrations. In contrast, overall exergy efficiency with cooling by DI water did not exceed 7.82 %. An increase in volume concentration of nanomaterials in the DI water remarkably influences the improvement of the exergy efficiency.

It is important to evaluate exergy loss and entropy generation to specify the PVT system losses and irreversibility's. The exergy loss increases with the overheating of the PV module surface. Enhancing the thermal characteristics of hybrid nanofluids helped to reduce the exergy losses. Fig. 11 shows a reduction of exergy losses by 32.3%, 37.9% at 0.2 vol% and 0.3 vol%, respectively. In contrast, using DI water has reduced the entropy generation by about 4.5% compared to the uncooled PV module. Overheating of the PV module has increased the entropy generation as well because of increased heat transfer between the PVT system and the environment. Minimizing the entropy generation value is necessary to minimize the work lost in the PVT system. Fig. 11 shows the effect of hybrid nanofluid by lowering the entropy generation. Compared with the uncooled PV module, hybrid nanofluid has reduced the entropy generation by 62.2 % and 69.6%, while DI water by 8.46 %, which confirms the effectiveness of hybrid nanofluid used. Moreover, using hybrid nanofluids effectively reduces exergy loss due to their efficient effects on heat transfer.

Table 4 shows the effect of hybrid TiO_2-CuO nanofluids on the exergy efficiencies of the PVT system in the current study. The exergy analysis results showed that the limited suspension of TiO_2-CuO nanocomposite in DI water provides high exergy efficiency compared with other studies, confirming the effectivity of hybrid nanofluids for cooling.

3.3. Payback period

The successful synthesising of nanomaterials in the laboratory and preparing the nanofluids has reduced the cost of nanofluids Compared with companies' prices produced of nanomaterials. Applied TiO_2-CuO nanofluid achieved a payback period of about 21 months compared with conventional PV modules, which have a payback period of about 26 months, confirming the effectiveness of using nanofluids in improving the PVT system efficiency and its economic feasibility.

4. Conclusions

This experimental study investigates the effect of DI water and hybrid TiO_2-CuO nanofluids on the PVT system performance at different volume concentrations compared with the typical PV module. The quantity and quality of the PVT system productivity were evaluated depending on the energy and exergy analysis. The following conclusion summarizes the main findings of this study, as follows:

- The hybrid TiO_2-CuO nanocomposite has been successfully synthesized using a solvothermal method and dispersed into a base fluid (DI water) using the ultrasonication technique.
- Using hybrid nanofluid at different volume concentrations helps to extract the excessive heat and reduces PV module temperature by 36.1% and 39% at 0.2 vol% and 0.3 vol% compared with 5.6% by the DI water cooling over the uncooled PV module. The PVT system electrical power could be improved by 73.95% and 77.5% at increased volume concentrations due to improving the hybrid nanofluid's thermal properties, while using DI water reached only 10.4%.
- The hybrid TiO_2-CuO nanofluid increased the PVT system electrical efficiency by 9.2%, 10.3%, and 6.2% at using DI water. In comparison, the electrical efficiency of the uncooled PV module was 5.8 %.
- High thermal characteristics of hybrid nanofluids has increased heat transfer convection, and then, improved the thermal efficiency of the PVT system by 50.2% and 41.7%, compared with DI water.
- The hybrid TiO_2-Cuo nanofluid achieved an increase in the overall efficiency of the PVT system, reaching 36.25% and 56.48% at 0.2 vol% and 0.3 vol%, respectively.

- Convergence of the outlet fluids temperature with ambient temperature has decreased the thermal exergy, and thus, reduced thermal exergy efficiency.
- Cooling by hybrid nanofluid has improved the electrical exergy efficiency by 11.33 % and 12.18%, while slight improvement was reported using DI water. The overall exergy efficiency has increased to 13.44 %, 14.97 % and 6.28 % at 0.2 vol%, 0.3 vol% and DI water.
- The exergy losses were reduced by 32.3% and 37.9% due to enhancing the thermal characteristics of hybrid nanofluids, while used DI water has reduced it by 4.5% compared to the reference module. The effective cooling by hybrid nanofluid has reduced the entropy generation by 62.2 % and 69.6%, at 0.2 vol% and 0.3 vol% compared with the case of DI water.
- Cooling the PVT system with TiO_2-CuO nanofluid achieved better economic feasibility with a payback period of 21 months compared with reference PV modules, which have 26 months.

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.

Acknowledgement

The authors would like to thank Bozzay Peter Laboratory of Department of Fluid and Heat Engineering, Faculty of Mechanical Engineering, University of Miskolc and Informatics for support to this research.

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