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Experimental study of using nano-(GNP, MWCNT, and SWCNT)/water to investigate the performance of a PVT module

Energy and exergy analysis

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Abstract

In this paper, the effects of using carbon-based nanofillers/water nanofluids as a coolant fluid in a photovoltaic thermal system from both energy and exergy viewpoints are experimentally presented. The considered nanoparticles including MWCNTs, SWCNTs, and GNPs are dispersed in deionized water as the base fluid by 0.05 mass%. The experiments are carried out on certain days in August and September at Ferdowsi University of Mashhad, Mashhad, Iran. In order to investigate the consistency of the results, an uncertainty of the experiments is examined. The various mass flow rates are investigated in all cases, and as a result, an optimum mass flow rate of 50 kg h^{-1} based on first and second laws of thermodynamics is selected. According to the results, employing GNP/water, SWCNT/water, and MWCNT/water increase the total average overall energy efficiency by 19.3%, 15.24%, and 9.46% in comparison with pure water, respectively. Additionally, GNP/water, SWCNT/water, and MWCNT/water reduce the total average entropy generation of the module by 2.88%, 1.23%, and 0.82% compared to the pure water, respectively. It has been found that implementation of GNP/water nanofluid leads to more improvement in the module performance among other coolant fluids.

Keywords Photovoltaic thermal system (PVT) · CNTs/water nanofluids · GNP/water nanofluid · Energy analysis · Output exergy and entropy analysis

List of symbols

C_P	Specific heat capacity (J kg^{-1} K^{-1})
$\dot{E}$	Power (W)
$\dot{E}x$	Exergy rate (W)
F	Arbitrary function
FF	Fill factor
$\dot{G}$	Solar irradiation rate (W m^{-2})
I	Electrical current (A)
$\dot{m}$	Mass flow rate (kg s^{-1})
P	Pressure (Pa)
PVT	Photovoltaic thermal
T	Temperature (K)
V	Velocity (m/s)

Greeks

α	Absorptivity
η	Efficiency (%)
σ	Uncertainty
τ	Transmissivity

Subscripts

amb	Ambient
des	Destruction
elec	Electrical
g	Glass cover
in	Inlet
max	Maximum
oc	Open circuit
out	Outlet
pv	PV
sc	Short circuit
th	Thermal
wf	Working fluid

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Introduction

The decrease in nonrenewable energies resources and environmental problems like global warming is of huge concern in the recent century. Using solar energy is one of the useful ways to overcome these problems. Some applications of utilizations of solar energy are solar desalination systems [1, 2], solar collectors [3], and PV cells [4, 5]. Photovoltaic (PV) cells have gained a huge interest in recent decades due to their ability to transform solar energy to electrical power directly. However, typical PV modules have low efficiencies as 4–17% [6, 7]. Therefore, finding a method to increase the efficiency of the PV module is fascinated by many researchers.

It is shown that reducing 1 °C in polycrystalline (pc-Si) and monocrystalline (c-Si) silicon PV cells temperature leads to an increase in the PV electrical efficiency by 0.45% [8]. Additionally, the reduction in PV plate temperature increases the life of the PV modules. Combining a typical PV module with a thermal solar collector is a verified technology to increase the efficiency of PV modules. A photovoltaic/thermal system (PVT) converts solar irradiation energy into both electricity and heat simultaneously. By using a solar collector, the temperature of PV cells decreases, and as a result, the electrical efficiency of module increases. Moreover, the transferred heat to the coolant fluid can be employed in thermal applications. Chow et al. [9] studied a thermosyphon-based water-heating PVT system with and without glass cover from energy and exergy viewpoint. Their results showed that using a glazed PVT system has a better thermal and overall energy outputs. However, from the exergy viewpoint, the increase in values of some parameters like PV cell efficiency, packing factor, the ratio of water mass to collector area, and wind velocity can lead to a better exergy efficiency for an unglazed PVT system, whereas the rise in solar irradiation and ambient temperature is favorable for the glazed system. Yazdanifard et al. [10] studied a water-based PVT module in two different flow regimes including laminar and turbulent. They observed that the turbulent regime has higher total efficiency with respect to laminar flow.

Adding nanoparticle to the base fluid can enhance the thermal properties of the working fluids which are investigated in different studies [11–15]. Therefore, several works have been performed on using these novel fluids in the solar energy systems as well as PVT systems. Some studies investigated the performance of the PVT modules by using nanofluids numerically from energy and exergy point of view [16–20], and some of them are carried out experimentally as well as Sardarabadi et al. [21] which performed an experimental study on the effects of silica/water nanofluid on a PVT system. They showed that the overall energy efficiency of the PVT system with a silica/water nanofluid of 1 and 3 mass% increases by 3.6% and 7.9% compared to the case with pure water, respectively. Sardarabadi et al. [4] experimentally characterize the performance of a PVT system equipped with pure water and three different metal oxide–water nanofluids (Al_2O_3–water, TiO_2–water and ZnO–water nanofluids by 0.2 mass% concentration). They found that ZnO–water and TiO_2–water nanofluids as a coolant fluid in the PVT system lead to a better overall energy and exergy efficiencies as compared to other nanofluids. Furthermore, in terms of entropy generation, ZnO–water nanofluid showed the lowest amount compared to other nanofluids. Sardarabadi and Passandideh-Fard [5] in another study considered the same nanofluids similar to Ref. [4], and experimentally and numerically evaluated the performance of the module. They found that increasing the concentration of nanoparticles from 0.05 to 10 mass% leads to a considerable thermal enhancement while it has a negligible effect on the electrical efficiency. Al-Waeli et al. [22] compared the effects of various nanofluids including the Al_2O_3, CuO, and SiC nanoparticles with water to enhance PVT systems efficiency under indoor laboratory condition. Moreover, they examined various volume fractions of nanoparticles. Their results show that SiC has the highest stability and thermal conductivity compared to Al_2O_3 and CuO nanoparticles. Also, they found that the use of nanofluids decreases the indoor PVT system temperature and increases its power generation. Michael and Iniyan [23] investigated the influence of using CuO/water as a working fluid in a PVT module. They indicated that using CuO with 0.05% volume fraction increases the thermal efficiency of the system by 45.76% compared to the pure water. Ebaid et al. [24] proposed a study on PVT module by using the Al_2O_3 (water–cetyltrimethylammonium bromide mixture) and TiO_2 (water–polyethylene glycol mixture) nanofluids. They studied various flow rates of 500–5000 mL min^{-1} and mass concentrations of nanoparticles including 0.01, 0.05, 0.1 mass%. Their experiment showed better results for Al_2O_3 in comparison with TiO_2. Al-Shamani et al. [25] experimentally evaluated a rectangular tube absorber PVT module by using different nanofluids, e.g., SiO_2, TiO_2, and SiC–water, based under the tropical climate conditions. They found that the electrical and overall efficiency will be maximized when SiC/water nanofluid with a mass flow rate of 0.17 kg s^{-1} is employed.

Among the various nanoparticles, many researchers experimentally reported that the carbon-based suspensions like graphene nanoplatelets (GNPs) and carbon nanotubes (CNTs) have higher thermal conductivity than those of other nanoparticles in a similar volume fraction [26]. The CNTs can be composed of a single-walled carbon nanotubes (SWCNTs) or multiwalled carbon nanotubes (MWCNTs). The use of carbon-based nanofluids in PVT modules is rare in the literature. For example, Nasrin et al. [27] experimentally studied a PVT system with MWCNT–water-based nanofluid under an indoor solar simulator. They proposed and investigated a new thermal collector design. They observed a 3.67% enhancement in the thermal performance of the module by using MWCNT/water nanofluid compared to pure water. Fayaz et al. [28] evaluated the performance of the PV/T module by using the MWCNTs–water nanofluid in a novel design of thermal collector. The study was performed under controlled indoor conditions, where the solar irradiation, ambient temperature, and working fluid inlet temperature were kept constant with the values of 1000 W m^{-2}, 25, and 32 °C, respectively, and volume flow rates varied in the range of 30–120 L h^{-1}. Considering the flow rate of 120 L h^{-1}, the results showed that using MWCNT–water nanofluid increases the overall energy by 5.73% compared to the pure water. The same authors in another study [29] experimentally and numerically investigated the same MWCNT–water nanofluid-based collector in the PV/T module and fixed the working fluid mass flow rate, inlet temperature, and ambient temperature, and studied the effects of the solar irradiation and mass fractions of MWCNT nanoparticles (0–1 mass%). They stated that in a PVT module equipped with a 1 mass% MWCNT–water nanofluid, for every 100 W m^{-2} increment in irradiation, the thermal and electrical output power, in order, increases by 113.14 and 17.48 W. Abdallah et al. [30] experimentally investigated the effects of using low concentrations of MWCNT nanofluid (0–3% volume fraction) at a constant volume flow rate of 1.2 L min^{-1}, based on outdoor test conditions, on a PVT system performance. The optimum performance of the proposed PVT system was attained at a volume fraction of 0.075%. Furthermore, they introduced five correlations for performance of the PVT system according to varying weather conditions.

Surveying the literature reveals that although many researchers investigate the effects of using different nanofluids on the performance of PVT modules, the study and comparison of using highly conductive carbon-based nanomaterials, e.g., MWCNTs, SWCNTs, and GNPs, in a PVT module are rare. Therefore, this study aims to fill this gap by investigating the effects of using three nanofluids including MWCNT/water, SWCNT/water, and GNP/water with a mass fraction of 0.05% on the thermal and electrical efficiencies of a PVT system. Moreover, the system is studied from the exergy and entropy generation viewpoints. The experiments are performed on selected days during 2 months of August and September at Ferdowsi University of Mashhad, Mashhad, Iran. Additionally, to evaluate the reliability of the measurements, an uncertainty analysis is performed for the experiments.

Experimental setup and uncertainty analysis

Experimental setup

The experimental setup includes two 40 W monocrystalline silicon photovoltaic modules, one of which is equipped with a copper thermal serpentine collector as shown in Fig. 1a, b (the PVT module). The PV modules are made by Suntech Company in China. The schematic diagram of the experimental setup is shown in Fig. 2. The properties and geometrical specifications of the PV module and serpentine tube collector are summarized in Tables 1 and 2.

PVT and PV modules are mounted on the south with a constant tilt angle of 32°. To measure the inlet and outlet temperature of working fluid through the tube and PV cells temperature, a PT-100- and K-type thermocouples were used, respectively. As can be seen in Fig. 2, the hot fluid after passing from the bottom of the PV plate is stored in 25-L storage tank, where a helical copper-coiled heat exchanger is used to cool down the fluid. This warm water that is stored in the tank can be used for the low thermal applications. It is worthy to mention that to circulate the working fluid, a centrifugal pump was used. The flow rate and pressure of the working fluid at the inlet and outlet of collector were measured by a rotary flow meter (LZB10) and a pressure transmitter (Atek-100 mbar), respectively. Additionally, the solar irradiation to the PV modules and the ambient temperature are measured by a solar power

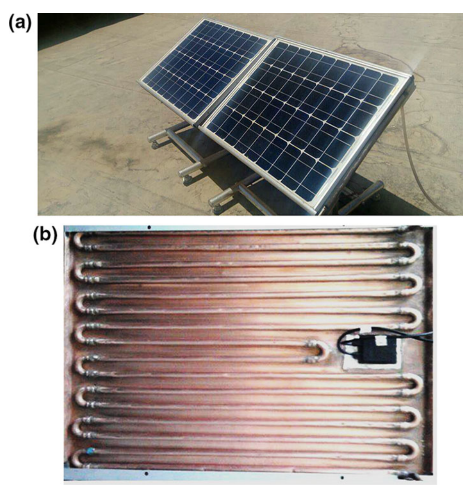


Fig. 1 A view of the **a** PV and PVT modules and **b** serpentine tube collector

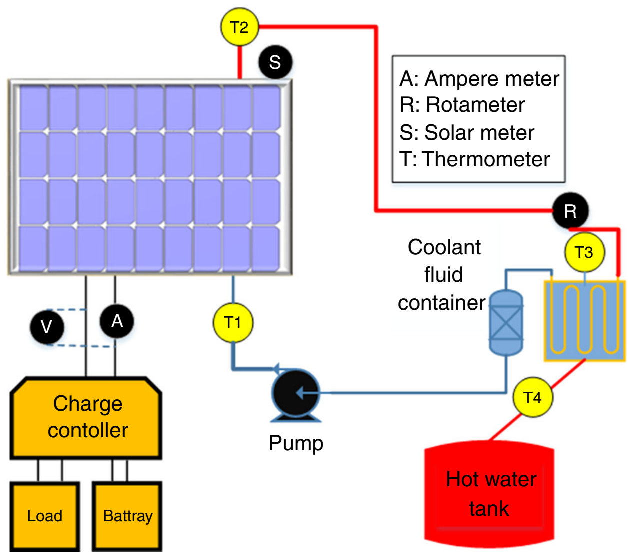


Fig. 2 Serpentine tube collector attached to the backside of the photovoltaic module

Table 1 PV module type and specifications

Parameter	Value	Unit
Type	Monocrystalline silicon	–
Maximum power	40	W
Cell dimension	0.125 × 0.0625	m × m
Number of cells	36	–
Packing factor	0.726	–
Open-circuit voltage	21.6	V
Short-circuit current	2.57	A

Table 2 Properties and specifications of the serpentine tube collector

Parameter	Value	Unit
Material	Copper	–
Sheet thickness	0.4	W
Inner diameter of the pipes	0.01	m
Outer diameter of the pipes	0.012	m
Effective area	0.3	m^2
Tube length	6	m

meter (TES-133, Taiwan) and a Hg thermometer, respectively. To measure short-circuit currents and open-circuit voltages, a digital multimeter (UT 71C/D/E) is used.

Nanofluid preparation

The pure water as a base fluid and MWCNTs, SWCNTs, and GNPs as nanoparticles are used in this study. All nanofluids are purchased from VCN Materials Co. in Iran.

Table 3 Properties of the nanoparticles used in the present study

Particle	Parameter	Value
MWCNT	Purity/%	95
	Diameter/nm	20–30
	Length/μm	5–10
	Density/g cm^{-3}	2.1
SWCNT	Purity/%	95
	Diameter/nm	5–20
	Length/μm	2
	Density/g cm^{-3}	2.1
GNP	Purity/%	99.5
	Diameter/nm	1–20
	Length/μm	< 40
	Density/g cm^{-3}	1.9–2.2

The properties of nanofluids are listed in Table 3. In order to evaluate the stability of three different samples as a major effective parameter on nanofluids properties, the zeta potential method was used. The zeta potential of GNP–water, SWCNT–water, and MWCNT–water nanofluids is shown in Fig. 3a–c, respectively. According to the figure, the mean zeta potential values for GNP–water, SWCNT–water and MWCNT–water nanofluids (0.05 mass%) are − 37.42, − 39.33 and − 34.12 mV, respectively, which shows a good results for the nanofluids stability.

Uncertainty analysis

To examine the reliability of the experiments, an uncertainty analysis must be performed. The uncertainty of a function like F, if F is a function of 'm' independent linear parameters as $F = f(\sigma_1, \sigma_2, \ldots, \sigma_m)$, can be defined as [11]:

$$\partial F = \left(\left(\frac{\partial F}{\partial \sigma_1} \partial \sigma_1 \right)^2 + \left(\frac{\partial F}{\partial \sigma_2} \partial \sigma_2 \right)^2 + \cdots + \left(\frac{\partial F}{\partial \sigma_{\mathrm{m}}} \partial \sigma_{\mathrm{m}} \right)^2 \right)^{0.5} \tag{1}$$

where $\partial \sigma_1$ and $\frac{\partial F}{\partial \sigma_1}$ are the parameter σ_1 uncertainty and the partial derivative of F with respect to parameter $\partial \sigma_1$. The uncertainties of experimental measurement devices are summarized in Table 4. The maximum uncertainty in this study was less than 4% for all cases.

Thermodynamic analysis

In order to analyze the performance of the PV and PVT modules, energy and exergy analyses are performed. The first law of thermodynamics only determines the quantity

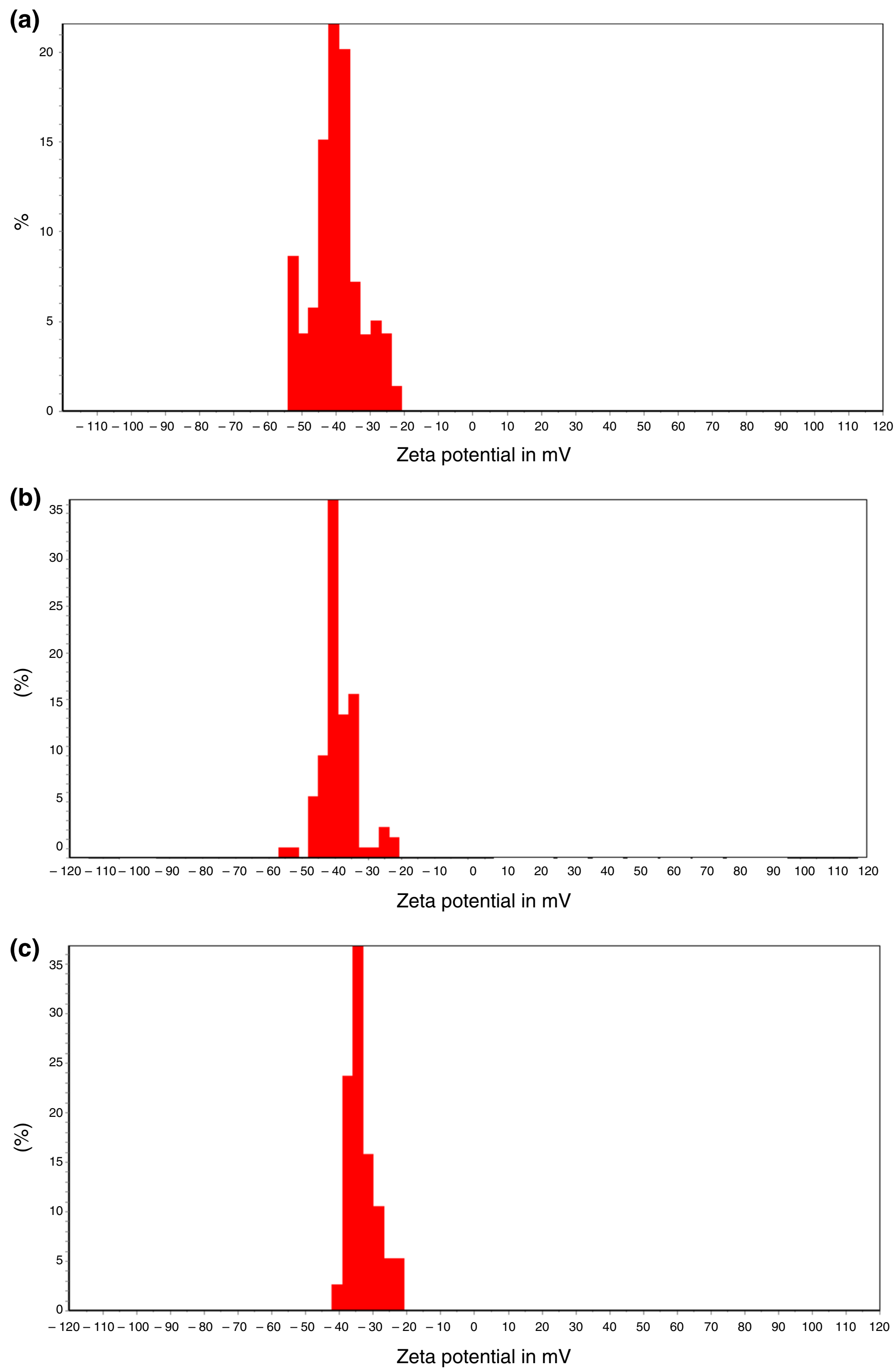


Fig. 3 Zeta potential of nanofluids: **a** GNP–water; **b** SWCNT–water; and **c** MWCNT–water

of the energy, while an exergetic analysis shows the maximum quantity of work. Therefore, both of them along with their efficiencies are investigated in this study.

Energy analysis

The energy balance equation for the PV and PVT module can be written as:

Table 4 Equipments used with their accuracy and uncertainty

Equipment	Measurement section	Accuracy	Maximum uncertainty (in experiments)
Digital multimeter-UT71C/D/ECNT	Ampere	± (0.8% + 1) A	0.02 A
Digital multimeter-UT71C/D/E	Voltage	± (0.5% + 1) V	0.05 V
Pyranometer-TES133	Solar irradiation	± 10 W/m^2 + 0.38 Wm^{-2} (for T_{ref} + 1 °C)	5.5 W m^{-2}
K-type thermocouple	Temperature (PV cells)	± 0.5 °C	0.15 °C
PT100 thermocouple	Temperature (fluid)	± 0.15 to ∓ 0.25 °C	0.15 °C
Hg thermometer	Temperature (ambient)	± 0.5 °C	0.3 °C
Rotameter-LZB10	Mass flow rate	± 2 kg h^{-1}	1.2 kg h^{-1}

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} + \sum \dot{E}_{lost} \tag{2}$$

where $\dot{E}_{in}$, $\dot{E}_{out}$, and $\dot{E}_{loss}$ are input, output, and losses of energy, respectively. For PVT module Eq. (1) can be rewritten as follows:

$$\dot{E}_{sun} + \dot{E}_{mass,in} = \dot{E}_{elec} + \dot{E}_{mass,out} + \dot{E}_{loss} \tag{3}$$

$\dot{E}_{sun}$ is the incident solar radiation and can be calculated by:

$$\dot{E}_{sun} = \dot{G}A \tag{4}$$

where G is the solar irradiation. The two energy terms in Eq. (3) related to mass flow rate can be calculated as:

$$\dot{E}_{th} = \dot{E}_{mass,out} - \dot{E}_{mass,in} = \dot{m}C_{P,w}\left(T_{wf,out} - T_{wf,in}\right) \tag{5}$$

$\dot{m}$ and $C_{P,w}$ are the mass flow rate and specific heat capacity of working fluid. $T_{wf,in}$ and $T_{wf,out}$ are inlet and outlet temperatures of the working fluid. The thermal efficiency (η_{th}) can be expressed as:

$$\eta_{I,th} = \frac{\dot{E}_{th}}{\dot{E}_{sun}} \tag{6}$$

The electrical output power of the PV module can be calculated based on [4]:

$$\dot{E}_{elec} = V_{oc} \times I_{sc} \times FF \tag{7}$$

where V_{oc} and I_{sc} are the open circuit voltage and the short circuit current. FF is filled factor and is defined as follows [31]:

$$\mathrm{FF} = \frac{P_m}{V_{oc} \times I_{sc}} \tag{8}$$

P_m is the maximum output of electrical power which is calculated as [4]:

$$P_m = V_{max} \times I_{max} \tag{9}$$

The electrical efficiency is expressed as:

$$\eta_{I,elec} = \frac{\dot{E}_{elec}}{\dot{E}_{sun}} \tag{10}$$

It should be noted that the power consumption by pump is very low; therefore, it is not taken into account in efficiency calculation [32]. The overall efficiency of PVT module based on the thermal and electrical output power can be evaluated as follows:

$$\eta_{I,overall} = \frac{\dot{E}_{th} + \dot{E}_{elec}}{\dot{E}_{sun}} \tag{11}$$

Exergy analysis

The exergy balance equation can be written similar to the energy balance for PVT module:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{des.} \Rightarrow \sum \dot{E}x_{sun} + \sum \dot{E}x_{mass,in} = \sum \dot{E}x_{elec} + \sum \dot{E}x_{mass,out} + \sum \dot{E}x_{des.} \tag{12}$$

The $\dot{E}x_{sun}$, $\dot{E}x_{elec}$, and $\dot{E}x_{th}(= \dot{E}x_{mass,out} - \dot{E}x_{mass,in})$ are given by Eqs. (13)–(15) [9, 33, 34]:

$$\dot{E}x_{sun} = \dot{G}A\left(1 - \frac{T_{amb}}{T_{sun}}\right) \tag{13}$$

$$\dot{E}x_{elec} = \dot{E}_{elec} \tag{14}$$

$$\dot{E}x_{th} = \dot{E}_{th}\left(1 - \frac{T_{amb}}{T_{f,out}}\right) \tag{15}$$

According to Eqs. (12)–(15), overall exergy and destruction exergy will be defined as:

$$\dot{E}x_{oveall} = \dot{E}x_{elec} + \dot{E}x_{th} \tag{16}$$

$$\dot{E}x_{des.} = \dot{E}x_{sun} - \dot{E}x_{overall} \tag{17}$$

where T_{amb},T_{sun}, and $T_{f,out}$ refer to the ambient, sun (≅ 5800 K), and working fluid outlet temperature, respectively. The sources of exergy destruction include pressure drop of coolant fluid in the tube, convection loss by ambient, thermal radiation to the sky, and reflectance of solar irradiation with ambient.

The thermal, electrical, and overall exergy efficiencies of the PVT module are defined as:

$$\eta_{\text{II,th}} = \frac{\dot{E}x_{\text{th}}}{\dot{E}x_{\text{sun}}} \tag{18}$$

$$\eta_{\text{II,elec}} = \frac{\dot{E}x_{\text{elec}}}{\dot{E}x_{\text{sun}}} \tag{19}$$

$$\eta_{\text{II,overall}} = \frac{\dot{E}x_{\text{overall}}}{\dot{E}x_{\text{sun}}} \tag{20}$$

Moreover, to extend the investigation, the entropy generation analysis is carried out. The entropy generation rate is determined based on the amount of loss of exergy [34]:

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

Results and discussion

The experimental data were measured on certain days in August and September from 9:30 a.m. to 3.30 p.m., and the experiments were conducted at the Ferdowsi University of Mashhad, Mashhad, Iran (Latitude: 36.26° and Longitude: 59.35°). It is noteworthy that the performance of the PVT system completely depends on the weather conditions such as solar irradiation and ambient temperature, where an unexpected change in weather conditions during the day results in an error, for example a change due to the cloudy weather or variations in the wind speed. Based on the measured data location (Mashhad, Iran), to have more reliable results and less uncertainty, experiments are conducted over the months of August and September, where the weather conditions are relatively steady. There are several experimental studies in Iran, Mashhad climate conditions, where their experiments on the PVT system are conducted in similar months as done in the current research [4, 5]. The average daily measurement of solar irradiation rate per unit area and the ambient temperatures is taken in Fig. 4. According to this figure, the daily average solar irradiation and ambient temperature in the span of the day are 892.46 W m^{-2} and 339.07 K, respectively. In this study, the coolant fluid is considered to be laminar ($Re < 2300$) which is used in various numerical [29, 30, 35] and experimental studies [5, 36].

Generally, adding nanoparticles to the base fluid (pure water) results in a rise in the thermal conductivity of the fluid, which in turn increases the heat transfer coefficient of the coolant fluid. However, dispersing nanoparticles in the fluid may lead to reduction in the specific heat capacity and also increase in the viscosity of coolant fluid which are unfavorable parameters in the heat transfer coefficient. It has been found that the most favorable parameter on the heat transfer coefficient is thermal conductivity [17]. In this study, in order to improve the performance of the PVT module, the effects of using GNP–water, SWCNT–water, and MWCNT–water nanofluids and pure water on PVT efficiencies are examined. The experimental results based on first and second law of thermodynamics are provided in three sections. First, to find the optimum mass flow rate, a comparative study is carried out for various nanofluids in different mass flow rates. Then, thermal and electrical efficiencies are evaluated for each case, and finally, exergy analysis and entropy generation are performed.

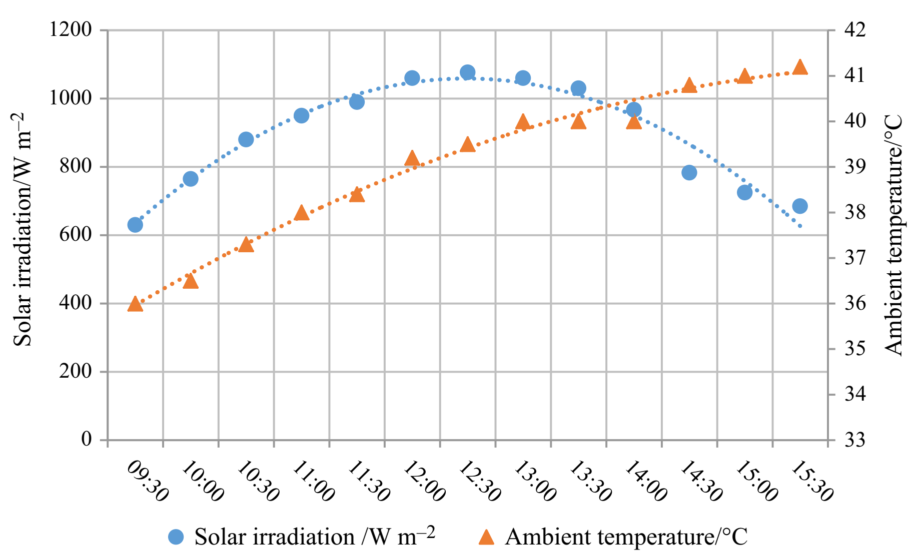


Fig. 4 Average daily variation in solar irradiation and ambient temperature in the period of the tests (the tests are conducted from August 15 to September 15)

The optimum mass flow rate

In this study, various mass flow rates are examined, and an optimum mass flow rate is introduced. In order to investigate various flow rates, a constant average solar irradiation of 1077 W m^{-2} and the average ambient temperature of 39.5 K at 12:30 p.m. are selected. A number of experiments are examined on GNP–water, MWCNT–water, and SWCNT–water nanofluids by 0.05 mass% and pure water in a series of considered mass flow rates which are 30, 50, and 70 kg h^{-1}. To verify more precisely, investigations are performed based on both first and second laws of thermodynamics. Figures 5 and 6 show total exergy and energy efficiencies for GNP–water, SWCNT–water, MWCNT–water, and pure water in different mass flow rates, respectively. According to these figures, the mass flow rate of 50 kg h^{-1} has a better performance based on total energy and exergy efficiencies compared to other considered mass flow rates. Consequently, the mass flow rate of 50 kg h^{-1} is selected as an optimum mass flow rate and used for other investigations presented in the next sections.

Energy analysis

The energy analysis of the PVT module and the typical PV is examined. It is noteworthy that in this study typical PV is introduced as a reference module and thus the PV surface temperature reduction compared to the reference module in each case is presented in Fig. 7. By using a thermal collector, whether by using pure water or nanofluids with water base as coolant fluid in the span of the day, the average temperature of the PV plate considerably reduces.

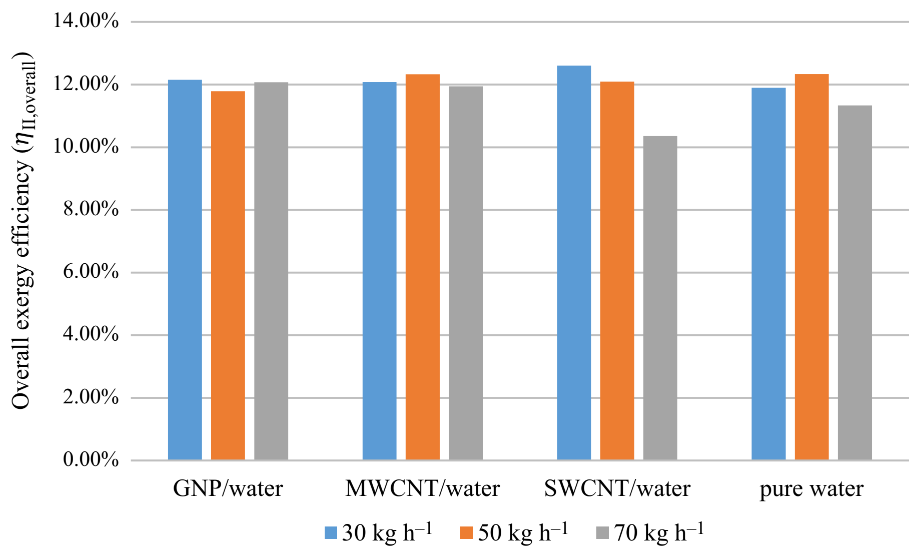


Fig. 5 Overall exergy efficiency in various mass flow rates in the average climate condition of 12:30 p.m. over the days of August 15–September 15

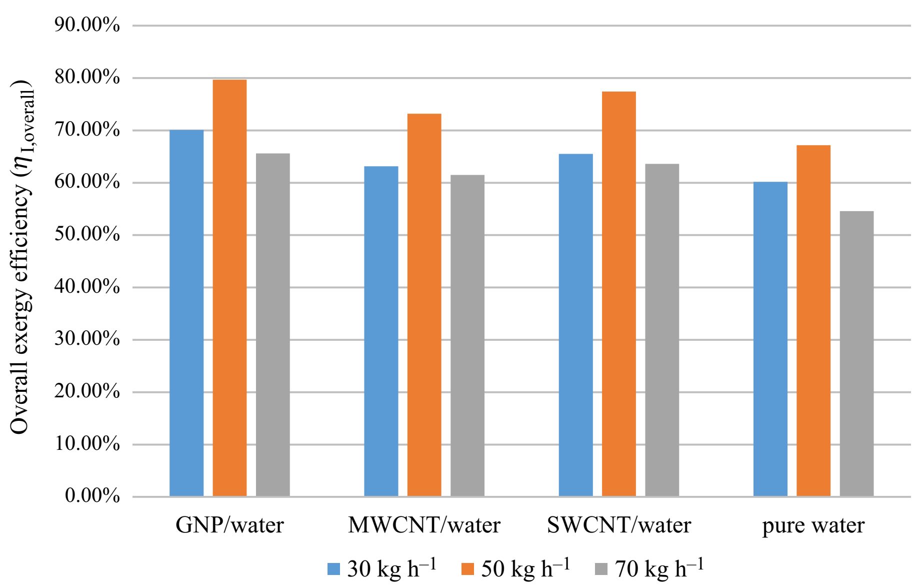


Fig. 6 Overall energy efficiency in various mass flow rates in the average climate condition of 12:30 p.m. over the days of August 15–September 15

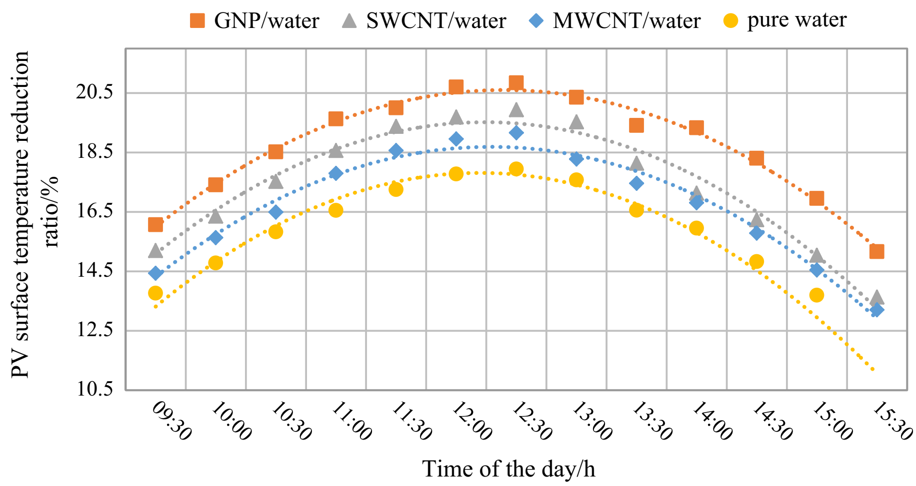


Fig. 7 Average daily variations in PV surface temperature reduction compared to the reference module (the tests are conducted from August 15 to September 15)

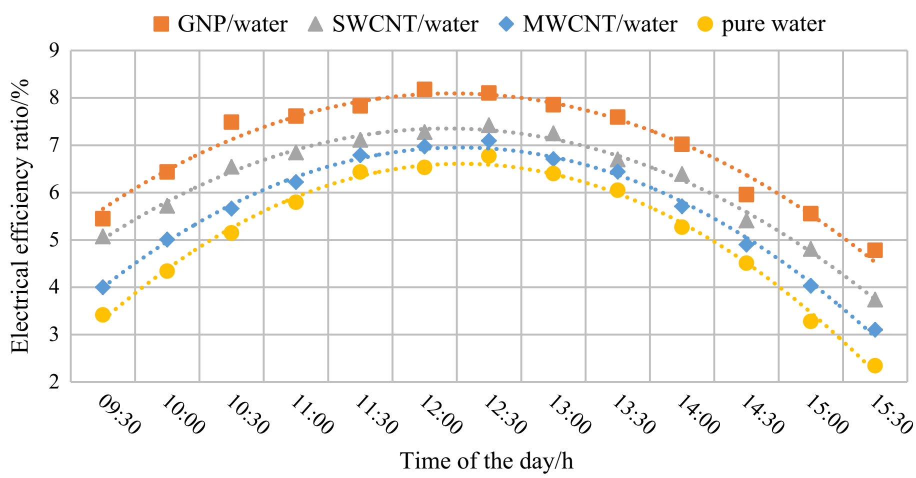


Fig. 8 Average daily variation in electrical efficiency increment compared to the reference module (the tests are conducted from August 15 to September 15)

By increasing the solar irradiation, the temperature of the PV plate increases; in other words, along the day, the temperature of the PV plate has a similar trend like the solar irradiation.

According to Fig. 7, during the time 9:30 a.m. to 12:30 p.m. o'clock, by increasing the solar irradiation, the reduction in PV plate temperature increases by 4.78%, 4.8%, 4.73%, and 4.5% for GNP–water, SWCNT–water, MWCNT–water, and pure water, respectively. However, at the end of the day, the temperature difference of the PVT module with respect to the typical PV plate reduces. Therefore, at the peak of solar irradiation around 12:30 p.m., using thermal collector leads to a highest PV plate temperature reduction compared to a typical PV module. Moreover, it has been found that GNP–water nanofluid among other nanofluids leads to a more PV plate temperature reduction.

Figure 8 shows the average daily variations in electrical efficiency increment compared to the reference module. Generally, the electrical efficiency of the module directly relates to the PV plate temperature [17]; thus, according to Fig. 8, the highest electrical efficiency compared to the reference module in the span of the day is obtained in the peak solar irradiation such that PV plate electrical efficiency enhancement in comparison with the reference module is 8.1%, 7.42%, 7.09%, and 6.77% for GNP–water, SWCNT–water, MWCNT–water, and pure water, respectively.

As illustrated in Fig. 9, in the span of the day, using nanofluids increases the temperature difference of the collector inlet and outlet of working fluid which is more pronounced in the peak of solar irradiation. At 12:30 p.m. o'clock, using nanofluids increases the temperature difference of the collector compared to the pure water for GNP–water, SWCNT–water, and MWCNT–water nanofluids by 24.24%, 15.15%, and 12.12%, respectively, which indicates that GNP–water nanofluid has a better thermal efficiency among all cases.

Figure 10 illustrates the average daily variations in the overall efficiency of the PVT module. The average daily overall efficiency of the module for GNP–water, SWCNT–water, and MWCNT–water compared to the pure water

Fig. 9 Average daily variation in inlet and outlet collector temperature difference (the tests are conducted from August 15 to 15 September)

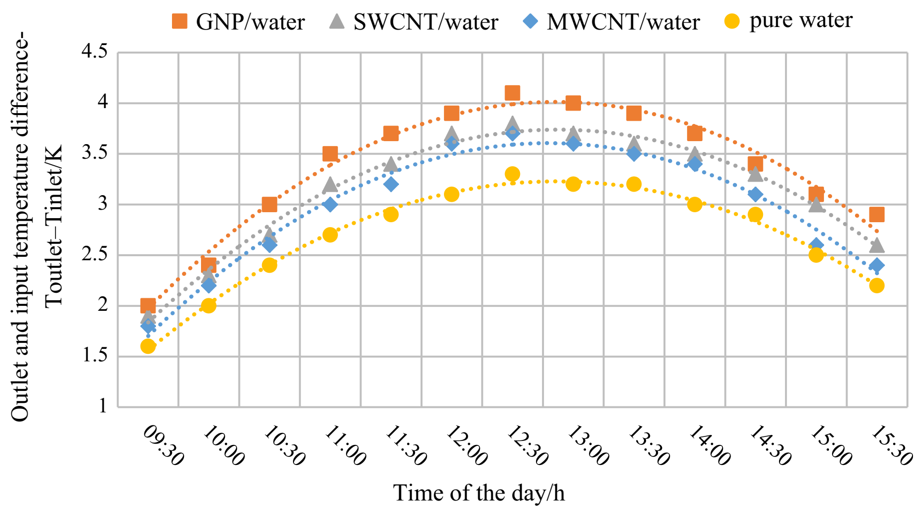
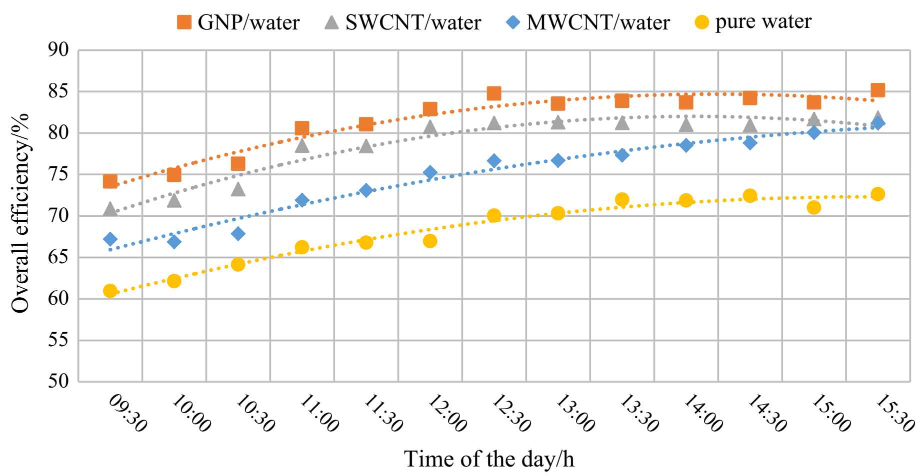


Fig. 10 Average daily variations in the overall efficiency of the PVT module (the tests are conducted from August 15 to September 15)



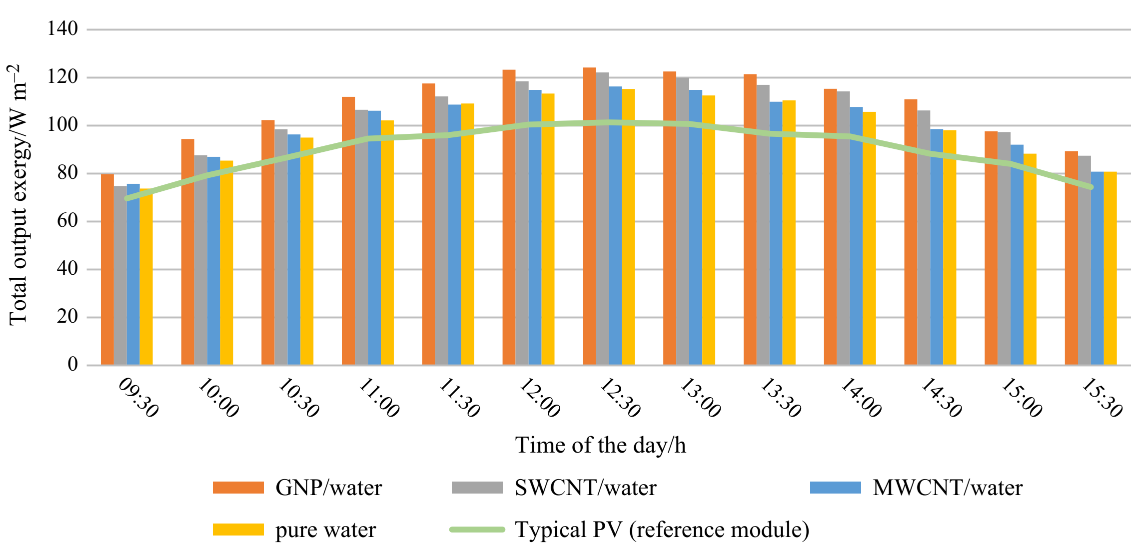


Fig. 11 Average daily variations in the PVT total output exergy using different nanofluids and PV module (the tests are conducted from August 15 to September 15)

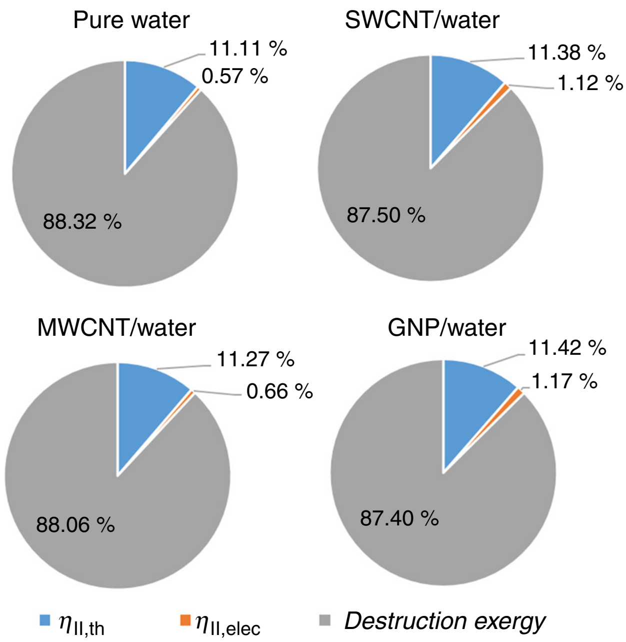


Fig. 12 Average share of the different portions of input exergy for different working fluids (the tests are conducted from August 15 to September 15)

increases by 19.3%, 15.24%, and 9.46%, respectively. As can be seen, using GNP–water nanofluid significantly increases the overall efficiency of the module. According to the aforementioned results, along the day, although ambient temperature and solar irradiation have a significant effect on the performance of the modules, the speed of wind has a less effect [30].

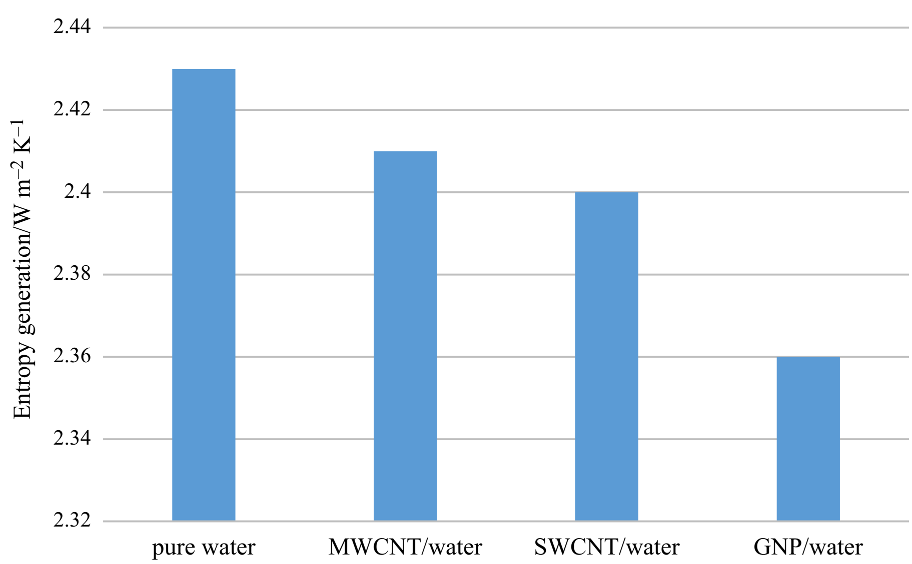
Exergy analysis

According to the second law of thermodynamics, all the processes contain irreversibility, which highlights the importance of a system review based on the second law beside the first law analysis. It is noteworthy that the exergy of PVT systems can be evaluated from the output exergy viewpoint and entropy generation viewpoint.

In this section, a module with various nanofluids and pure water coolant fluid is investigated based on the second law of thermodynamics. In Fig. 11, in the span of the day, the average daily variations for the PVT module by using different nanofluids and PV module available exergy are compared. Obviously, the total output exergy of the PVT module is significantly better than the PV reference module. As illustrated in Fig. 11, at the peak of solar irradiation (around noon), modules have the highest total output exergy, which is due to the higher input solar irradiation exergy. The total average output exergy during the conducted tests of the various coolant fluids increases by 20.85%, 16.72%, 12.13%, and 10.5% compared to the PV reference module, respectively, for GNP–water, SWCNT–water, MWCNT–water nanofluids, and pure water. Similar to the previous results, GNP–water nanofluid indicates the highest output exergy.

Figure 12 shows the share of the total average of the thermal, electrical, and destruction exergies for GNP–water, MWCNT–water, SWCNT–water nanofluids, and pure water. In contrast to energy analysis, thermal exergy efficiency has the smallest portion between different kinds of

Fig. 13 Entropy generation of PVT module with different nanofluids (the tests are conducted from August 15 to September 15)



exergies. As can be seen, destruction exergy consists of a large portion of the input exergy, and by using GNP–water, SWCNT–water, and MWCNT–water nanofluids compared to the pure water, it reduces by 0.92%, 0.26%, and 0.82%, respectively. In addition, thermal exergy efficiency of the GNP–water, SWCNT–water, and MWCNT–water nanofluids in comparison with the pure water increases by 0.6%, 0.55%, and 0.09%, respectively. Therefore, in contrast to energy analysis, various nanofluids do not have a considerable effect on the exergy efficiency enhancement.

The entropy generation is a suitable parameter in order to show the irreversibilities of the system; in other words, minimizing entropy generation leads to increasing output power. In this research as shown in Fig. 13, the effects of using different CNTs, GNP nanofluids, and pure water on entropy generation are examined. It is noteworthy the entropy generation is due to exergy loss of the total PVT. As can be seen, using nanofluids lead to a more reduction in the entropy generation in PVT module. Among the various considered nanofluids, the total average entropy generation of the module for GNP–water, SWCNT–water, and MWCNT–water decreases by 2.88%, 1.23%, and 0.82% compared to pure water, respectively.

Conclusions

In this study, the effects of using various nanofluids including GNP–water, SWCNT–water, and WMCNT–water with a mass fraction of 0.05% on the performance of a PVT module based on first and second laws of thermodynamics are experimentally studied. The tests are conducted on the outdoor climate conditions, and the average daily variations data are reported. The key findings of this study are listed as follows:

- At the peak time of the solar irradiations, using PVT module leads to a reduction in the PV cells temperature compared to the PV module, which in turn improves the electrical efficiency.
- It has been found that adding highly conductive carbon-based nanomaterials to the water improves the thermophysical properties of the water and leads to a better performance of the PVT module.
- The mass flow rate of 50 kg h^{-1} among the considered mass flow rates showed a better performance with respect to the exergy and energy efficiencies.
- A comparative study on the average daily overall energy efficiency for various nanofluids is performed. The overall efficiency of the GNP–water, SWCNT–water, and MWCNT–water compared to the pure water increases by 19.3%, 15.24%, and 9.46%, respectively.
- The average output exergy during the day for various coolant fluids with respect to the reference module increases by 20.85%, 16.72%, 12.13%, and 10.5% for GNP–water, SWCNT–water, MWCNT–water nanofluids, and pure water, respectively.
- The entropy generation of PVT module decreases by 2.88%, 1.23%, and 0.82% for GNP–water, SWCNT–water, and MWCNT–water nanofluids compared to the pure water, respectively.
- GNP–water with 0.05 mass% has the best performance among all considered nanofluids with respect to the first and second laws of thermodynamics.

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