Study Effect of Nanofluids on the Performance Enhancement of PV/T Collector

Safae Margoum, Chaimae El Fouas, Hajji Bekkay, Stefano Aneli, Antonio Gagliano, Giovanni Mannino, and Giuseppe M. Tina

Abstract Compared to the photovoltaic (PV) module, which only produces electricity, the photovoltaic/thermal (PV/T) system presents as a promising technology capable of simultaneously producing electrical and thermal energy. In addition, this technology considerably improves the photovoltaic efficiency by cooling the PV cells sensitive to the increase in temperature. This paper investigates the impact of various nanofluids on improving the performance of PV/T systems. Three different fluids, pure water, Al_2O_3/water, and Cu/water are studied as a coolant to reduce the temperature of the PV panel. The performances of the nanofluid-based PV/T system were simulated using a numerical model based on the energy balance equation, developed in MATLAB software. By analyzing the simulation results, it is observed that the use of Al_2O_3/water and Cu/water nanofluids improves the results of the PV/T

S. Margoum (✉) · C. El Fouas · H. Bekkay
Laboratory of Renewable Energy, Embedded System and Information Processing, National School of Applied Sciences, Mohammed First University, 60000 Oujda, Morocco
e-mail: safae.margoum@ump.ac.ma

C. El Fouas
e-mail: c.elfouas@ump.ac.ma

H. Bekkay
e-mail: hajji.bekkay@gmail.com

S. Aneli · A. Gagliano · G. M. Tina
University of Catania, Viale Andrea Doria 6, 95125 Catania, Italy
e-mail: stefano.aneli@unict.it

A. Gagliano
e-mail: agagliano@dii.unict.it

G. M. Tina
e-mail: giuseppe.tina@unict.it

G. Mannino
CNR–IMM, Strada VIII N. 5 Zona Industriale, Catania, CT, Italy
e-mail: giovanni.mannino@imm.cnr.it

H. Bekkay et al. (eds.), *Proceedings of the 3rd International Conference on Electronic Engineering and Renewable Energy Systems*, Lecture Notes in Electrical Engineering 954, https://doi.org/10.1007/978-981-19-6223-3_93

system in terms of electrical and thermal efficiency compared to the pure water-based PV/T system. In particular, dispersing a 2% volume fraction of copper and alumina nanoparticles in water helps to increase the thermal and electrical efficiency of the PV/T by 26 and 1.24% for Cu/water and 10.33 and 0.99% for Al_2O_3/water, respectively.

Keywords PVT collector · Nanofluids · Electrical · Thermal efficiency

1 Introduction

In recent years, solar energy has been widely used for thermal energy generation by solar collectors and electrical energy by photovoltaic (PV) panels [1]. A novel innovative technology has been invented, able to produce simultaneously electrical and thermal energies in a single unit is known as a hybrid solar system (PV/T) [2, 3]. Due to different criteria and parameters, many types of (PV/T) systems can be identified. Regarding the cooling fluid, photovoltaic thermal systems (PVT) can be divided mainly into three types: water-based PVT, air-based PVT, and bi-fluid-based PV/T using both fluids simultaneously air and water [4]. Recently, a new generation of cooling fluids known as nanofluids is investigated as well as applied in the PV/T system. As a result, numerous research works have been conducted in order to predict the electrical and thermal behavior of this type of PV/T systems adopting nanofluids for the cooling effect. From literature, it is proved that nanofluids have better thermo-physical proprieties than basic fluids, which can potentially improve the PV/T system performances compared to the other systems (PV/T using air or water) [5]. An experimental study is conducted by [6], where the effect of the silica/water nanofluid (1 and 3 wt%) as a coolant on the thermal and electrical efficiencies of a PV/T sheet & tubes system is studied, based on the first and second thermodynamic laws. As a result, the electrical and thermal efficiencies were improved by 18.9% and 7.93%, respectively, by dispersing 3 wt% of SiO_2 in water. In the work performed by [7], the impact of applying 0.05% volume concentration of CuO/water nanofluid in a PV/T collector with and without glazing is investigated experimentally. It is concluded that under identical conditions, the electrical efficiency using nanofluid is inferior by 13%, while thermal efficiency is higher by 45% compared to water. In another study [8], a two-dimensional numerical model to study the effects of using (0.1, 0.2, and 0.4 wt%) of (Al_2O_3 and Cu) nanoparticles in water and glycol is developed. According to this study, using a Cu/water with 0.4 wt% as a coolant fluid on the uncovered PV/T system showed a better performance. Another numerical study is performed to examine the use of Ag/water and Al_2O_3/water nanofluids on PVT sheet & tube performances [9]. In comparison to pure water, they found that a 3% volume fraction of Ag and Al_2O_3 nanoparticles enhanced the thermal efficiency by 5.15% and 1.36%, respectively. Furthermore, the electrical efficiency of Ag/water and Al_2O_3/water improved by 1.88% and 0.95%, respectively. In order to evaluate the energy performances of the PV/T system, Al_2O_3, CuO, and SiC nanoparticles have been applied in [10] with several volume fractions of 0.5, 1, 2, 3, and 4% in water. It is depicted that the SiC/water nanofluid is appropriate to improve the PV/T system production. In the work of [11], the impact of MWCNT/water nanofluid on PVT system performances was investigated. They found that by dispersing 1% of MWCNT in water, the electrical and thermal efficiencies were improved by 1.18% and 5%, respectively. The effectiveness of using nanofluids for the cooling of the PV cells is also proved through the results of [12]. They analyzed numerically the utilization of Cu/water end Al_2O_3/water nanofluid in PVT sheet & tube system. Moreover, by adding 2vol% of Cu/water, the thermal and electrical efficiency reached an enhancement of 4.1 and 1.9% while, those of Al_2O_3/water reached up to 2.7% and 1.2%, respectively.

In this work, the impact of dispersing 2% of copper and alumina nanoparticles in water as cooling fluids on the electrical and thermal efficiency of PVT sheet & tube system is examined numerically. Furthermore, the results were compared with those of water-based PVT. This work is organized into three main sections: Sect. 2 presents the mathematical model of nanofluid-based PVT. The results and discussion are illustrated in Sect. 3. Finally, the conclusion is shown in Sect. 4.

2 Mathematical Models of the Nanofluid-Based PVT Systems

This work investigates numerically the performance of a PV/T system using three types of cooling fluids: pure water, Al_2O_3/water, and Cu/water. Hence, The PV/T model is developed based on the energy balance established for each layer and the set of obtained Eqs. (1)–(8) is solved by RUNGE–KUTTA 4 (RK4) method in MATLAB software depending on [13]. The PV/T hybrid system studied in this research consists mainly of a single glass cover, a photovoltaic module, a Tedlar, a metal sheet absorber, a set of tubes, a cooling fluid, and an insulation layer for reducing the heat loss with the ambient. The whole design of the PV/T system and its components is presented in Fig. 1.

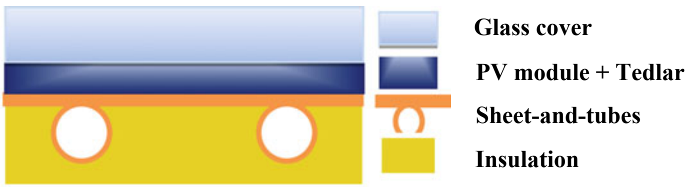

Fig. 1 PV/T “sheet & tubes” system design

2.1 Energy Balance Equation of the PV/T Systems

In this section, the energy balance for each layer of the PV/T system is established as shown in Table 1. Moreover, the set of obtained equations is written considering the different heat exchange by conduction, convection, and radiation and the effect of external excitation, e.g., solar radiation (see Fig. 2), ambient temperature. Furthermore, to simplify the calculation, the following assumptions are taken into account:

- The heat flux is only in one direction, from the top to the bottom of the PV/T system;
- The heat loss at the edges of the PV/T system is neglected;
- The material properties of each component are constant;
- The water and nanofluid mass flow rates in tubes are uniform.

2.2 Thermo-Physical Properties of Cooling Fluids

In this section, the common expressions adopted to determine the main key thermo-physical properties of cooling fluids influencing the PV/T system behavior are presented in Table 2.

3 Results and Discussion

3.1 Simulation Input Parameters

3.1.1 Effect of Volume Fraction on the PVT Performances

In this study, the thermal conductivity and heat capacity are analyzed in function of volume fraction in order to evaluate the impact of different nanofluids on the electrical and thermal behaviors of the PV/T system. Figure 3a and b show respectively the variations of the specific heat capacity Cp_{nf}/Cp_{bf} and of the thermal conductivity $\lambda_{nf}/\lambda_{bf}$ as a function of the volume fraction of Cu/water and Al_2O_3/water.

From Fig. 3a, it can be seen that the thermal conductivity of the two studied nanofluids varies linearly with the volume fraction and exhibits almost the same rate of variation. When the volume fraction varies from 0 to 2%, the thermal conductivity for Cu/water reaches 8.3%, while for Al_2O_3/water does not exceed 7.9%. So as a result, the thermal conductivity of the nanofluid increases as the nanoparticle volume fraction increases, which leads to a better cooling capacity. It is worth noting that adding nanoparticles to the base fluid in the tube enhances thermal conductivity and thickens the boundary layer along the tube's surfaces [9].

Table 1 Governing equation of the PV/T system layers

Layer	Equations	
Glass (upper layer)	$m_g C_g \frac{\mathrm{d}T_{gext}}{\mathrm{d}t} = \left[A_g G - A_{\mathrm{gg}}\left(T_{g_{\mathrm{ext}}}^4 - T_{\mathrm{sky}}^4\right) - A_g h_{\mathrm{wind}}\left(T_{g_{\mathrm{ext}}} - T_{\mathrm{amb}}\right) - A_g h_{\mathrm{cond},g}\left(T_{g_{\mathrm{ext}}} - T_{g_{\mathrm{int}}}\right)\right]$	(1)
Glass (lower layer)	$m_g C_g \frac{dT_{g_{\mathrm{int}}}}{dt} = \left[A_g G_g + A_g h_{\mathrm{cond,g}}\left(T_{g_{\mathrm{int}}} - T_{g_{\mathrm{ext}}}\right) - A_g h_{\mathrm{cond,g\ pv}}\left(T_{g_{\mathrm{ext}}} - T_{\mathrm{pv}}\right)\right]$	(2)
PV module	$m_{\mathrm{pv}} C_{\mathrm{pv}} \frac{\mathrm{d}T_{\mathrm{pv}}}{\mathrm{d}t} = \left[A_g G_{\mathrm{gpv}} + A_g h_{\mathrm{cond,gpv}}\left(T_{g_{\mathrm{int}}} - T_{\mathrm{pv}}\right) - A_{\mathrm{pv}} h_{\mathrm{cond,pvted}}\left(T_{\mathrm{pv}} - T_{\mathrm{ted}}\right) - A_g G_{g0}\left(1 - \left(T_{\mathrm{pv}} - T_r\right)\right)\right]$	(3)
Tedlar	$m_{\mathrm{ted}} C_{\mathrm{ted}} \frac{\mathrm{d}T_{\mathrm{ted}}}{\mathrm{d}t} = \left[A_{\mathrm{pv}} h_{\mathrm{cond,pv\ ted}}\left(T_{\mathrm{pv}} - T_{\mathrm{ted}}\right) - A_{\mathrm{ted}} h_{\mathrm{cond,ted\ p}}\left(T_{\mathrm{ted}} - T_p\right)\right]$	(4)
Absorber	$m_p C_p \frac{\mathrm{d}T_p}{\mathrm{d}t} = \left[A_{\mathrm{ted}} h_{\mathrm{cond,ted\ p}}\left(T_{\mathrm{ted}} - T_p\right) - A_{\mathrm{p\ tube}} h_{\mathrm{cond,p\ tube}}\left(T_p - T_{\mathrm{tube}}\right) - A_{\mathrm{p\ iso}} h_{\mathrm{cond,p\ iso}}\left(T_p - T_{\mathrm{iso}}\right)\right]$	(5)
Tubes	$m_{\mathrm{tube}} \frac{\mathrm{d}T_{\mathrm{tube}}}{\mathrm{d}t} C_{\mathrm{tube}} = \left[A_{\mathrm{ptube}} h_{\mathrm{cond,ptube}}\left(T_p - T_{\mathrm{tube}}\right) - A_{\mathrm{fluid}} h_{\mathrm{conv,tubefluid}}\left(T_{\mathrm{tube}} - T_{\mathrm{fluid}}\right) - A_{\mathrm{tubeiso}} h_{\mathrm{cond,tubeiso}}\left(T_{\mathrm{tube}} - T_{\mathrm{iso}}\right)\right]$	(6)
Cooling fluid	$m_{\mathrm{fluid}} C_{\mathrm{fluid}} \frac{\mathrm{d}T_{\mathrm{fluid}}}{\mathrm{d}t} = \left[A_{\mathrm{fluide}} h_{\mathrm{conv,tube\ fluid}}\left(T_{\mathrm{tube}} - T_{\mathrm{fluid}}\right) - \dot{m} C_{\mathrm{fluide}} T_{\mathrm{fluid}}\right]$	(7)
Insulation	$m_{\mathrm{iso}} C_{\mathrm{iso}} \frac{\mathrm{d}T_{\mathrm{iso}}}{\mathrm{d}t} = \left[A_{\mathrm{tube\ iso}} h_{\mathrm{cond,tube\ iso}}\left(T_{\mathrm{tube}} - T_{\mathrm{iso}}\right) + A_{\mathrm{p\ iso}} h_{\mathrm{cond,p\ iso}}\left(T_p - T_{\mathrm{iso}}\right) - A_{\mathrm{iso}} h_{\mathrm{wind}}\left(T_{\mathrm{iso}} - T_{\mathrm{amb}}\right)\right]$	(8)

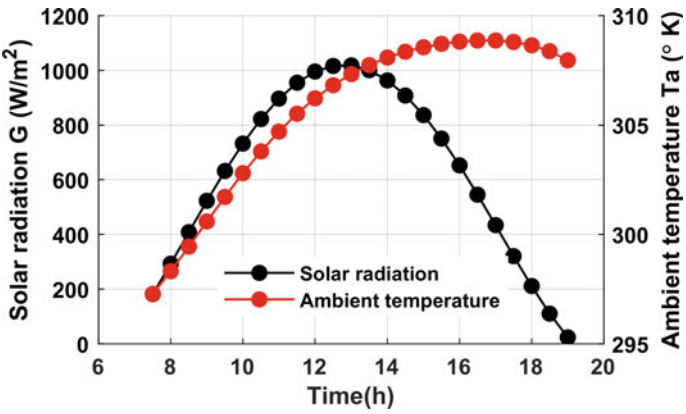

Fig. 2 Hourly variation of solar radiation and ambient temperature

Table 2 Thermo-physical properties of cooling fluids

Nanofluid		
Density (Kg/m^3) [14]	$\rho_{nf} = \rho_{np} + \phi\rho_{bf}$	(9)
Heat capacity (J/Kg.K) [14, 15]	$c_{p,nf} = c_{p,np} + (1-\phi)c_{p,bf}$ $c_{p,nf} = \frac{c_{p,np}+(1-\phi)c_{p,bf}}{\rho_{nf}}$	(10) (11)
Thermal conductivity (W/m.K) [16]	$k_{nf} = \frac{k_{np}+2k_{bf}-2(k_{bf}-k_{np})}{k_{np}+2k_{bf}+2(k_{bf}-k_{np})}k_{bf}$	(12)
Dynamic viscosity (Pa.s) [1]	$\phi < 0.05,\ \mu_{nf} = (1+2.5)_{bf}$ $0.05 < \phi < 0.1,$ $0.05 < \phi < 0.1,\ \mu_{nf} = \left(1+2.5+6.5^2\right)\mu_{bf}$	(13) (14)
Nanofluid Nusselt number [17, 18]	Cu/Water [17]: $\mathrm{Nu_{nf}} =$ $0.0059\left(1+7.628^{0.6886}\mathrm{Pe_{nf}^{0.001}}\right)\mathrm{Re_{nf}^{0.9238}Pr_{nf}^{0.4}}$ Al_2O_3 [18]: $\mathrm{Nu_{nf}} = 0.085\ \mathrm{Re_{nf}^{0.71}Pr_{nf}^{0.35}}$	(15) (16)
Pure water		
Dynamic viscosity (Pa.s) [19, 20]	$_{bf} = 2.70110^{-10}\mathrm{T}^2 - 1.84910^{-7}\mathrm{T} + 3.19910^{-5}$	(17)
Nusselt number [19, 20]	$\mathrm{Nu_{water}} = \frac{4.4+\left(0.00398\left(\mathrm{Re_{water}Pr_{water}}\frac{\mathrm{Dint}}{\mathrm{L}}\right)\right)^{1.66}}{1+\left(0.0114\left(\mathrm{Re_{water}Pr_{water}}\frac{\mathrm{Dint}}{\mathrm{L}}\right)\right)^{1.62}}$	(18)

Regarding the specific heat, it is clear from Fig. 3b that increasing the nanoparticles volume fraction from 0 to 4% produces a significant decrease of both nanofluids specific heat capacities; this is due to the low specific heat values of the nanoparticles heat capacity. At 2% of volume fraction, the specific heat capacity $\mathrm{Cp_{nf}/Cp_{bf}}$

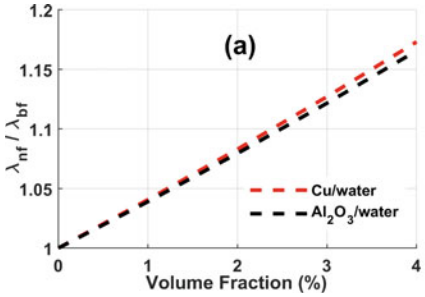

Fig. 3 **a** Thermal conductivity, **b** heat capacity of nanofluid studied

decreased to 0.92% for the Al_2O_3/water nanofluid and 0.84% for the Cu/water nanofluid. As known, the specific heat is defined as the amount of energy required to raise the temperature of a unit mass of a substance by one degree Kelvin. It is evident from the definition and at the same condition that any substance with lower specific heat must provide a higher temperature according to other fluids [21].

3.1.2 Effect of Mass Flow Rate on the PVT Performances

Figure 4a and b display the effect of the fluid mass flow rate on the electrical and thermal performance of the PV/T system using Cu/water, Al_2O_3/water, and pure water. It is observed that the electrical efficiency increases slightly as the mass flow rate rises, while thermal efficiencies increase rapidly with the mass flow rate rises until a maximum value of 62.5, 55, and 50% for Cu/water, Al_2O_3/water, and pure water, respectively, noted at a mass flow rate of 0.04 kg/s. After that, a slow increase of the efficiencies is observed by increasing the mass flow rate. In what follows, the mass flow rate value is taken as 0.04 kg/s.

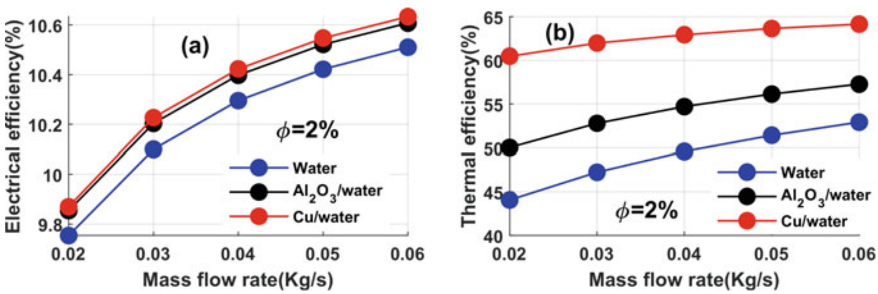

Fig. 4 Variation of **a** electrical efficiency, **b** thermal efficiency versus mass flow rate using pure water, Al_2O_3/water, and Cu/water nanofluids

3.2 PV/T System Performances

3.2.1 Electrical Performance

The electrical performances are calculated using the equations presented in [19]. The effect of the dispersing 2% of copper (Cu) and alumina (Al_2O_3) nanoparticles in pure water on the electrical performance of the PVT module is shown in Fig. 5. In particular, the variations of PV cell temperature (a), electrical efficiency (b), and electrical power (c), for three fluids: pure water, Cu/water, and Al_2O_3/water are depicted. According to Fig. 5a, at 13:00, the PV temperature of the PV/T panel reached the values of 54.2 °C, 54.67 °C, and 56.57 °C for Cu/water nanofluid, Al_2O_3/water nanofluid, and the pure water, respectively. According to this figure, it was noticed that the use of nanofluids leads to the decrease of the PV cell temperature by 4% in the case of Cu/water, and 3.3% in the case of Al_2O_3/water when compared with the pure water.

The PV panel temperature using Cu/water is the lowest. Moreover, Cu/water has a higher heat transfer coefficient than Al_2O_3/water. As a result, dispersing nanoparticles in the base fluid helps to increase the thermal conductivity of the substances that in turn enforce the heat transfer between the PVT collector layers. A diminution in PV temperature led to improve the PV electrical efficiency as proved in Fig. 5b. As observed, the electrical efficiencies are inversely proportional to the PV cell temperatures. As the PV temperature of the PV/T system increases, the electrical efficiency gain decreases and reaches a minimum value at 13:00 of about 10.42% and 10.39%, respectively, for Cu/water, Al_2O_3/water nanofluids, and 10.29% for pure water. Higher electrical efficiency is demonstrated by both nanofluids cases.

As shown in Fig. 6, the use of nanofluids slightly improves the electrical productions of the PV/T system, by about 1% at 13:00 the maximum electrical power of the PV/T reached 115.95 W, 115.66 W, and 114.53 W for Cu/water, Al_2O_3/water, and pure water, respectively. From an electrical viewpoint, the use of Cu/water nanofluids, which has the higher thermal conductivity in comparison with the other investigated cooling fluid, increases the heat transfer exchange in the PV/T system, and consequently, improving the system's electrical output.

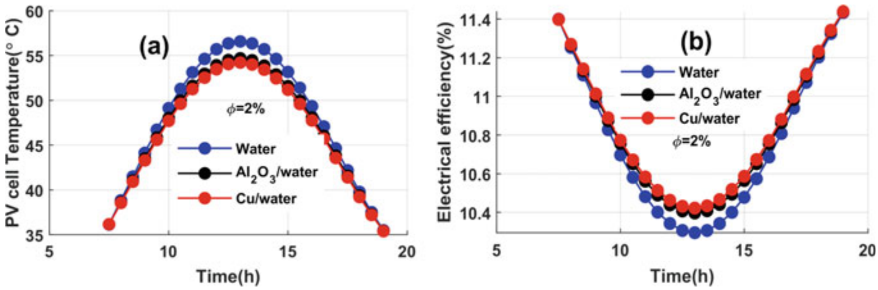

Fig. 5 Evolutions of PV temperature **a** electrical efficiency, **b** of PV/T systems

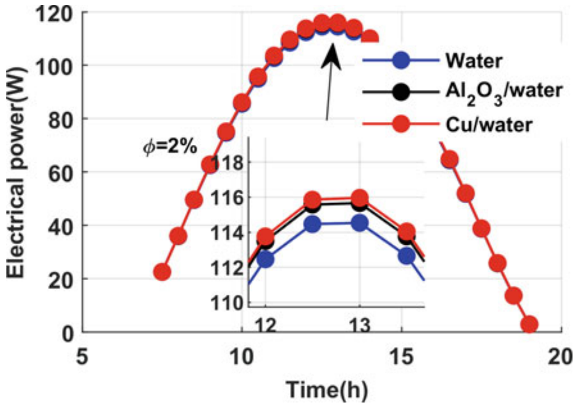

Fig. 6 Electrical power evolutions of PV/T systems

3.2.2 Thermal Performance

In this section, the impact of nanofluids on the thermal performances has been examined in which are calculated utilized the formula reported in [22]. Figure 7a presents the variation of the outlet temperature of the PVT system for the three working fluids: pure water, Cu/water, and Al_2O_3/water nanofluids.

At 13:00, it was noted that the working fluid outlet temperature reaches the higher value, (59.7 °C), for Cu/water nanofluid compared to the other working fluids, Al_2O_3/water (57.5 °C) and pure water (55.7 °C). A difference of 3.9 °C was recorded between Cu/water and pure water. This conclusion is in good agreement with the fact that the specific heat of the nanofluid Cu/water decreases by 15% for the volume fraction of 2% nanoparticles. Figure 6b depicts the thermal efficiency of the PV/T system for the three studied cooling fluids. Cu/water and Al_2O_3/water nanofluids significantly improve the thermal efficiency of the PV/T system. The thermal efficiency reaches its maximum value of 63.9 and 55.7% for Cu/water and Al_2O_3/water, respectively, against 49.58% in the case of pure water. As a result, an enhancement of 26.9 and 10.3%, was obtained by adding copper and alumina in the base fluid (water), respectively.

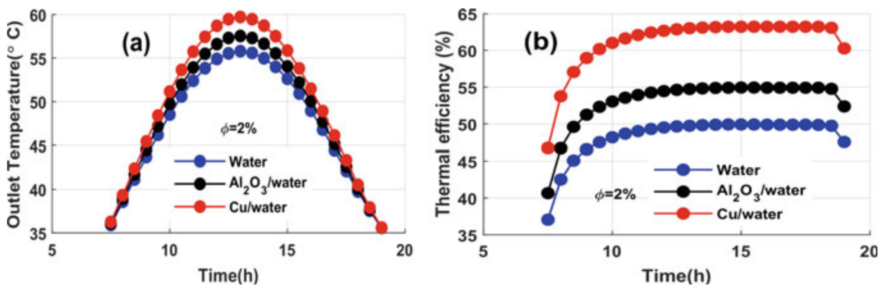

Fig. 7 Evolutions of fluid outlet temperature (**a**) thermal efficiency (**b**) of PV/T systems

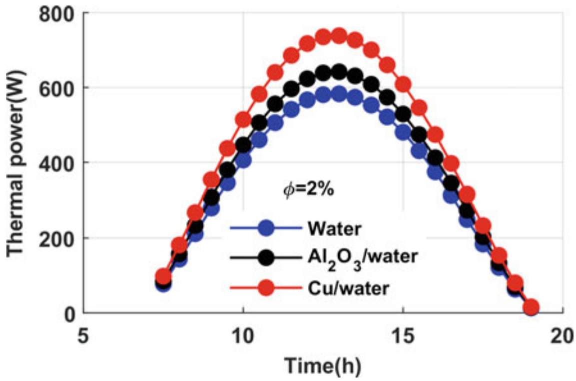

Fig. 8 Thermal power evolutions of PV/T systems

The daily thermal power PV/T for the investigated fluids is illustrated in Fig. 8. At 13:00, the thermal power reaches its maximum value of 737.01 W, 640.59 W, and 580.61 W for Cu/water, Al_2O_3/water, and pure water, respectively. The use of nanofluids allows to enhance the thermal performance of PV/T collector. Indeed, an increase in thermal power of 26.9% for Cu/water and 10.3% for Al_2O_3/water was recorded. These results were noted against the use of pure water.

4 Conclusion

In this work, a numerical study of the PV/T system using different cooling fluids, e.g., Cu/water, Al_2O_3/water, and pure water was carried out. According to the simulation results obtained, the following conclusions can be observed:

- Compared to pure water, Cu/water and Al_2O_3/water nanofluids provide better performance for the PVT system;
- Using Cu/water and Al_2O_3/water nanofluid as cooling fluids with a mass flowrate of 0.04 kg/s leads to reducing the PV temperature by 2.36 °C and 1.89 °C, respectively;
- The improvement of Cu/water and Al_2O_3/water nanofluids-based PV/T with 2% of nanoparticles reached by 1.24% and by nearly 0.99% at 13:00, respectively;
- The maximum electrical power produced by the PVT collector occurred at 13:00 is 115.95, 115.66, and 114.53 W for Cu/water, Al_2O_3/water, and water, respectively;
- The nanofluid increases the thermal efficiency of the PV/T system by 26% for Cu/water and by 10.33% for Al_2O_3/water;
- The thermal performance of the Cu/water nanofluid-based PVT system was found to be the highest compared to the Al_2O_3/water nanofluid-based PVT and the pure water-based PV/T, which are 737.01 W, 640.59 W, and 580.61 W, respectively.

References

1. Jia Y, Ran F, Zhu C, Fang G (2020) Numerical analysis of photovoltaic-thermal collector using nanofluid as a coolant. Sol Energy 196:625–636. https://doi.org/10.1016/j.solener.2019.12.069
2. El Fouas C, Hajji B, Gagliano A, Tina GM, Aneli S (2020) Numerical model and experimental validation of the electrical and thermal performances of photovoltaic/thermal plant. Energy Convers Manage 220:112939. https://doi.org/10.1016/j.enconman.2020.112939
3. Ventura C, Tina GM, Gagliano A, Aneli S (2021) Enhanced models for the evaluation of electrical efficiency of PV/T modules. Sol Energy 224:531–544. https://doi.org/10.1016/j.solener.2021.06.018
4. Abdulalah A, Misha S, Tamaldin N, Mohd Rosli MA, Sachit F (2018) Photovoltaic thermal/solar (PVT) collector (PVT) system based on fluid absorber design: a review. J Adv Res Fluid Mech Therm Sci 48:196–208
5. Aneli S, Gagliano A, Tina GM, Hajji B (2021) Analysis of the energy produced and energy quality of nanofluid impact on photovoltaic-thermal systems. In: Proceedings of the 2nd International conference on electronic engineering and renewable energy systems, Singapore, pp 739–745. https://doi.org/10.1007/978-981-15-6259-4_77
6. Sardarabadi M, Passandideh-Fard M, Zeinali Heris S (2014) Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units). Energy 66:264–272. https://doi.org/10.1016/j.energy.2014.01.102.
7. Michael JJ, Iniyan S (2015) Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide–water nanofluid. Sol Energy 119:439–451. https://doi.org/10.1016/j.solener.2015.06.028
8. Rejeb O, Sardarabadi M, Ménézo C, Passandideh-Fard M, Dhaou MH, Jemni A (2016) Numerical and model validation of uncovered nanofluid sheet and tube type photovoltaic thermal solar system. Energy Convers Manage 110:367–377. https://doi.org/10.1016/j.enconman.2015.11.063
9. Khanjari Y, Pourfayaz F, Kasaeian AB (2016) Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system. Energy Convers Manage 122:263–278. https://doi.org/10.1016/j.enconman.2016.05.083
10. Al-Waeli AHA et al (2017) Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: an experimental study. Energy Convers Manage 151:693–708. https://doi.org/10.1016/j.enconman.2017.09.032
11. Nasrin R, Rahim NA, Fayaz H, Hasanuzzaman M (2018) Water/MWCNT nanofluid based cooling system of PVT: experimental and numerical research. Renew Energy 121:286–300. https://doi.org/10.1016/j.renene.2018.01.014
12. Hissouf M, M'barek F, Najim M, Charef A (2020) Numerical study of a covered photovoltaic-thermal collector (PVT) enhancement using nanofluids. ScienceDirect, 15 Mar 2020. https://www.sciencedirect.com/science/article/pii/S0038092X20300906?via%3Dihub. Accessed 15 Jun 2021
13. El Fouas C, Chereches N-C, Hudisteanu SV, Hajji B, Turcanu F-E, Chereches M (2022) Numerical and parametric analysis for enhancing performances of water photovoltaic/thermal system. Appl Sci 12:646. https://doi.org/10.3390/app12020646
14. Pak BC, Cho YI (1998) Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles. Exp Heat Transfer 11(2):151–170. https://doi.org/10.1080/08916159808946559
15. Xuan Y, Roetzel W (2000) Conceptions for heat transfer correlation of nanofluids. Int J Heat Mass Transf 43(19):3701–3707. https://doi.org/10.1016/S0017-9310(99)00369-5
16. Maxwell JC (1873) A treatise on electricity and magnetism. Clarendon Press
17. Xuan Y, Li Q (2003) Investigation on convective heat transfer and flow features of nanofluids. J Heat Transfer 125(1):151–155. https://doi.org/10.1115/1.1532008
18. El Bécaye Maïga S, Tam Nguyen C, Galanis N, Roy G, Maré T, Coqueux M (2006) Heat transfer enhancement in turbulent tube flow using Al_2O_3 nanoparticle suspension. Int J Numer Methods Heat Fluid Flow 16(3):275–292. https://doi.org/10.1108/09615530610649717

19. Fouas CE, Hajji M, Bouselham L, Hajji B, Mehdi AE, Bouali H (2017) Analysis and design of an energy system based on PV/T water collector for building application. In: 2017 International renewable and sustainable energy conference (IRSEC), Dec. 2017, pp 1–5. https://doi.org/10.1109/IRSEC.2017.8477361
20. Hajji M, Naimi SE, Hajji B, El Hafyani ML (2014) A comparative study between two structures of hybrid photovoltaic/thermal (PV/T) collectors for water pumping systems. In: 2014 International renewable and sustainable energy conference (IRSEC), Oct. 2014, pp. 235–240. https://doi.org/10.1109/IRSEC.2014.7059745
21. Said Z et al (2015) Performance enhancement of a flat plate solar collector using Titanium dioxide nanofluid and polyethylene glycol dispersant. J Clean Prod 92:343–353. https://doi.org/10.1016/j.jclepro.2015.01.007
22. Duffie JA, Beckman WA, Blair N (2020) Solar engineering of thermal processes, photovoltaics and wind. Wiley