Nanofluids for High-Efficiency PV/T Systems: A Comprehensive Numerical Assessment

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Abstract. In this work, a three-dimensional numerical investigation is conducted to investigate the performance of a photovoltaic/thermal (PV/T) system on various nanofluids for the objectif to analyze and compare the influence of these nanoparticles on efficiency of PV/T system. Al_2O_3, CuO, TiO_2 and ZnO at concentrations between 0.5% and 2% were evaluated with COMSOL. It was observed that, CuO has good prospects with a maximum thermal efficiency of 75.8% and electrical efficiency of 12.15% at 2%. These results indicate that CuO is a suitable candidate to enhance the performance of PV/T panel.

Keywords. PV/T system, Nanofluid, thermal efficiency, electrical efficiency.

1 Introduction

Faced with growing demand for energy and the need to reduce dependence on polluting fossil fuels, scientists have had to explore renewable energy sources in order to meet this need [1]. More specifically, solar energy, which is the most renewable energy source, is clean, sustainable, and available everywhere in the world. It is the ideal alternative energy source for human progress, as it emits no carbon or other environmental pollutants, which is somewhat lacking in fossil fuels. One of the main applications of solar energy is the generation of electricity using photovoltaic (PV) cells [2]. However, PV systems pose various challenges. The high operating temperature of solar panels is one of the main obstacles that significantly reduces their efficiency [3].

Hybrid photovoltaic/thermal (PV/T) systems have been studied as a solution to the problem of panel heating, in which the conversion of electrical and thermal energy is combined in a

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single device [4]. PV/T technologies are systems that integrate a photovoltaic module with a thermal collector in order to capture excess heat from the photovoltaic module due to solar radiation and transfer it to a heat transfer fluid for various applications. The capability to simultaneously produce electricity and heat from solar radiation increases its efficiency, thereby optimizing energy production, saving space, and reducing installation costs [5]. Current research is also focusing on various innovative concepts and configurations aimed at improving the efficiency of PV/T systems [6]. Nanofluids are attracting considerable interest in this field because their thermal properties are superior to those of traditional fluids and therefore offer better heat transfer performance. For instance, Elhenawy et al. [7] studied the cooling of CPV panels using a nanofluid composed of 0.9 wt% AlO_3 and water. They reported that the nanofluid reduced the surface temperature of the photovoltaic panels by 52%, thereby increasing their electrical efficiency from 15% to 21%. In addition, their thermal efficiency was significantly improved, reaching 65%. In contrast, Chawrey et al. [8] investigated a monocrystalline PV/T system with optical filters containing plasmonic Au and experimental nanofluid (0.0002 wt%) under real outdoor conditions. The performance of the PV was substantially improved by the Au nanofluid filter compared to DI water and bare PV module, which lowered the surface temperature of the PV. The Au filter and DI water in the hybrid system provided a combined thermal and electrical efficiency of about 42%, while for the DI water this figure was 37% (14% was obtained with the bare module). On the other hand, Ahmadlou et al. [9] reported using two CNT-based nanofluids of SWCNT/water and MWCNT/water in a PV/T thermoelectric system. They have shown that the SWCNT/water decreased the PV surface temperature by 30.55%, increased the power output by 51.08% and raised the total efficiency to be 44.94%. The maximum utilization of around 4% was at 13:00. The reasons responsible for increased power of 31.43% and efficiency of 21.77% as well as higher temperature lowering (47.28%) were suggested by the presence of the MWCNT/water in them.

The main objective of this study is to perform a comparative three-dimensional numerical analysis of a PV/T system using different nanofluids as cooling media under identical operating conditions. Unlike previous studies that mainly focused on a single nanofluid or limited concentrations, this work systematically investigates the influence of four nanofluids (Al_2O_3, CuO, TiO_2, and ZnO) at concentrations ranging from 0.5% to 2% on the electrical and thermal behavior of the PV/T collector. The novelty of the present work lies in the unified COMSOL based evaluation of the coupled thermo-electrical behavior, temperature distribution, and cooling effectiveness of these nanofluids in the same PV/T configuration. This comparative approach provides deeper insight into the relationship between nanoparticle type, concentration, and overall system efficiency, allowing the identification of the most suitable nanofluid for enhancing PV/T performance.

2 Methodology

2.1 Description of the model geometry

A steady-state numerical simulation of a PV/T module was conducted in COMSOL Multiphysics. The model consisted of nine layers as shown in Fig.1, which were composed of solid and fluid areas: a glass cover, EVA encapsulant, photovoltaic cells, tedlar backsheet, thermal paste, aluminum channel, and a fluid domain. The nanofluids contained CuO, Al2O3, TiO2, and ZnO nanoparticles and were investigated in this research at concentrations of 0.5% to 2% to determine their effect on the PVT system's performance. Finally, the simulation outcomes were analyzed and presented using Origin software. A uniform solar irradiance of 1000 W/m² was applied on the upper surface of the PV/T panel. The solar rays were assumed to be perpendicular to the panel surface, corresponding to an optimal solar incidence condition. The thermal properties utilized in the study are mentioned in Table 1, while the design parameters given in Table 2.

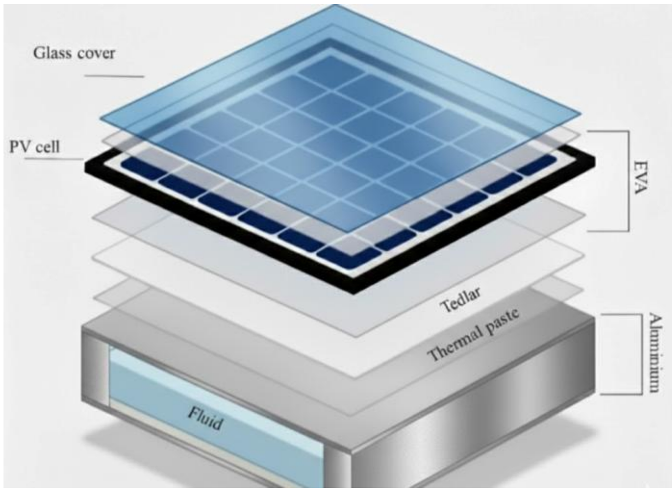


Fig. 1. Schematic of PV/T solar panel.

Table 1. PV/T module thermal properties and materials.

Component	Layer function	Thickness (mm)	K [W/(mK)]	Cp [J/(kgK)]	ρ [Kg/m3]
Glass	Top cover	3	2	500	2450
EVA	Encapsulant	0.8	0.311	2090	950
Silicon	Solar cell	0.1	148	700	2329
Tedlar	Bottom cover	0.05	0.15	1250	1200
Thermal paste	Conductor	0.3	1.9	700	2600
Aluminium	Heat exchanger	1	160	900	2700

Table 2. Model design parameters applied in the simulation [10,11].

Parameter	Value
Length of the collector	1570 mm
Width of the collector	940 mm
Reference operating temperature	25 °C

PV cell efficiency at STC	0.13
Absorptivity of the solar cell α_c	0.9
Solar cell packing ratio p_c	0.95
Transmittance of the glass cover τ_g	0.9
Thermal coefficient of cell efficiency β_c	0.0045/K

To maximize efficiency, it is essential to identify the working fluid properties that influence flow and heat transfer. In this study, water is used as the base fluid, while CuO, TiO_2, Al_2O_3, and ZnO nanoparticles are employed, with their thermophysical properties obtained from the literature [12,13]. Table 3 presents the properties of water and the nanoparticles used in this study. The nanoparticle concentration was varied between 0.5% and 2% by volume in order to ensure a compromise between enhanced thermal performance and acceptable flow characteristics. This range is widely adopted in PV/T nanofluid studies, as higher concentrations may lead to excessive viscosity, particle agglomeration, and increased pumping power requirements, which negatively affect system performance. The effect of nanoparticle volume concentrations on the nanofluid properties is analyzed using the following relations:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\,\rho_{np} \tag{1}$$

$$\left(C_p\right)_{nf} = \frac{(1-\phi)\rho_f C_{p,f} + \phi\,\rho_{np} C_{p,np}}{\rho_{nf}} \tag{2}$$

$$k_{nf} = k_f\,\frac{k_{np}+2k_f-2\phi(k_f-k_{np})}{k_{np}+2k_f-\phi(k_f-k_{np})} \tag{3}$$

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{4}$$

where ϕ is the nanoparticle volume fraction, f denotes the base fluid (water), and np denotes the nanoparticle (CuO, TiO_2, Al_2O_3, ZnO).

Table 3. Nanoparticles and working fluid properties [12,13].

	Water	CuO	Al_2O_3	TiO_2	ZnO
Density (kg/m3)	998	6320	3970	4250	5600
Thermal conductivity (W/m K)	0.68	32.9	40	8.9	13
Specific heat (J/kg K)	4200	531	765	686	495

2.2 Governing equations

In this study, the thermal performance of the PV/T collector is simulated using a three-dimensional, steady-state approach, coupling conduction in the solid regions with convection in the fluid domain. Heat transfer in the solid layers occurs solely by conduction, while in the

fluid domain, it involves both conduction and convection. Continuity of temperature and heat flux at the solid–fluid interface is ensured through an iterative solution scheme. The flow is assumed to be laminar, incompressible, uniform, and steady.
The governing equations for the solid and fluid domains are as follows:

$$\nabla^2 T_s = 0 \quad (5)$$

$$\nabla \cdot u = 0 \quad (6)$$

$$\rho C_P\left(u \cdot \nabla T_f\right) = \nabla \cdot (k_f \nabla T_f) \quad (7)$$

$$\rho(u \cdot \nabla)u = -\nabla \mathrm{p} + \mu \nabla^2 u \quad (8)$$

2.3 Boundary conditions

The thermal and flow boundary conditions for the PV/T system are defined as follows:
Convective heat flux:

$$n \cdot \mathrm{q} = h_c(T_{amb} - T_s)$$

where n is the outward surface normal, T_s is the surface temperature of the solid layer, and T_{amb} is the ambient temperature.
Fluid inlet:

$$\mathrm{u} = U_0,\ v = 0,\ w = 0,\ T = T_{in}$$

Walls (no slip and insulation):

$$\mathrm{u} = 0,\ n \cdot (\mathrm{k}\, \nabla \mathrm{T}) = 0$$

Outlet:

$$P = P_0$$

Solid–fluid interface: Coupled conditions ensure continuity of temperature and heat flux for conjugate heat transfer.

2.4 Mathematical formulation

The amount of solar energy incident on the PV/T system can be expressed as [14]:

$$E_{in} = \tau_g \alpha_c p_c G A_c \quad (9)$$

The thermal energy transferred to the cooling fluid can be evaluated from [14]:

$$E_{th} = \dot{m} C_f (T_{out} - T_{in}) \quad (10)$$

The instantaneous electrical efficiency of the system is calculated according to [14,15] :

$$\eta_{el} = \eta_{ref}(1 - \beta_{ref}\left(T_c - T_{ref}\right)) \quad (11)$$

The thermal efficiency of the PV/T unit is determined as follows:

$$\eta_{th} = \frac{E_{th}}{E_{in}} \quad (12)$$

Finally, the overall efficiency of the PV/T system is defined as the sum of electrical and thermal efficiencies [15]:

$$\eta_{tot} = \eta_{el} + \eta_{th} \quad (13)$$

2.5 Mesh generation

The PV/T model was discretized in COMSOL Multiphysics using a free tetrahedral mesh for the solid domains and a boundary layer mesh for the fluid region, as shown in Fig.2. This approach produced sufficient mesh resolution to be sufficient to capture the coupling phenomena of thermal and fluid behavior within the systems.

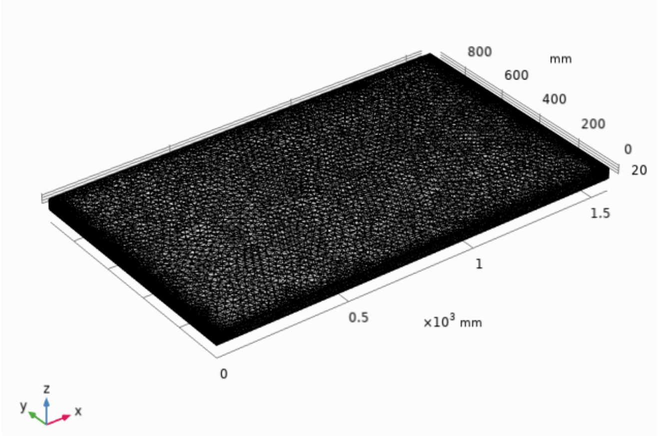
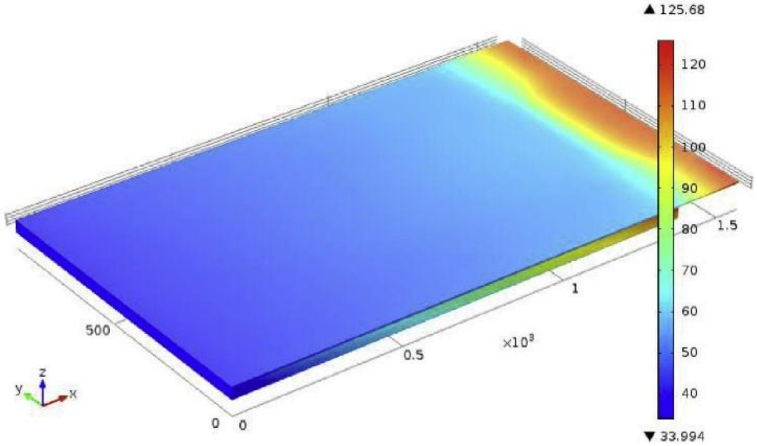


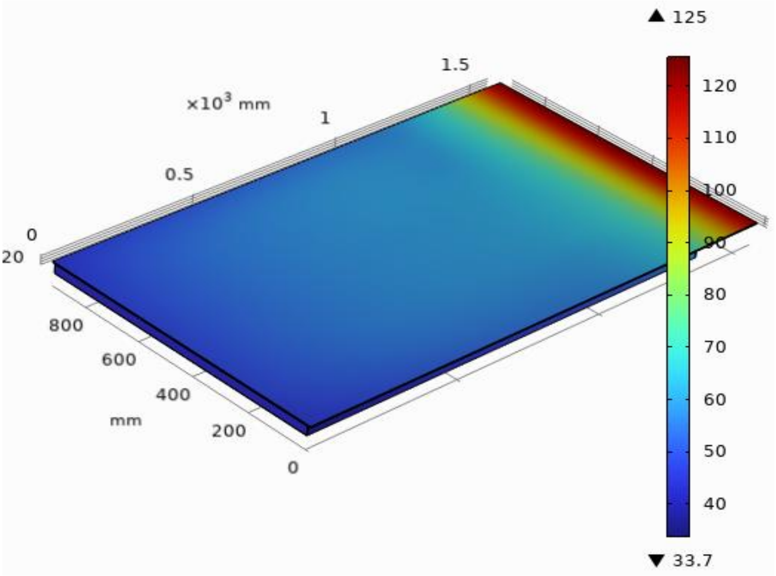
Fig. 2. PV/T Mesh.

2.6 Model Validation

The accuracy of the present simulation was verified by comparing its results with both numerical and experimental data. Specifically, with the results reported by Nahar et al. [15]. The numerical simulation used parameters such as solar radiation of 1000 W/m², ambient temperatures of 34°C, inlet temperatures of 34°C, and inlet velocities of 0.0007 m/s. As shown in Fig .3 the temperature distribution obtained by Nahar et al. [15] ranged from 33.994°C to 125.68°C, whereas the present simulation predicted a temperature range between 33.7°C and 125°C, demonstrating good agreement and confirming the reliability of the developed model.



(a)



(b)

Fig. 3. Surface temperature distribution throughout the PV/T panel : (a) Nahar et al. [15]and (b) Current study.

Additionally, the electrical efficiency of the PVT system at different inlet velocities (0.0003, 0.0004, 0.0005, 0.0006, and 0.0007 m/s) was compared. As demonstrated in Fig. 4, the numerical results are in good agreement with those of Nahar et al. [15], confirming that the developed numerical model can reliably predict the performance of the PVT system.

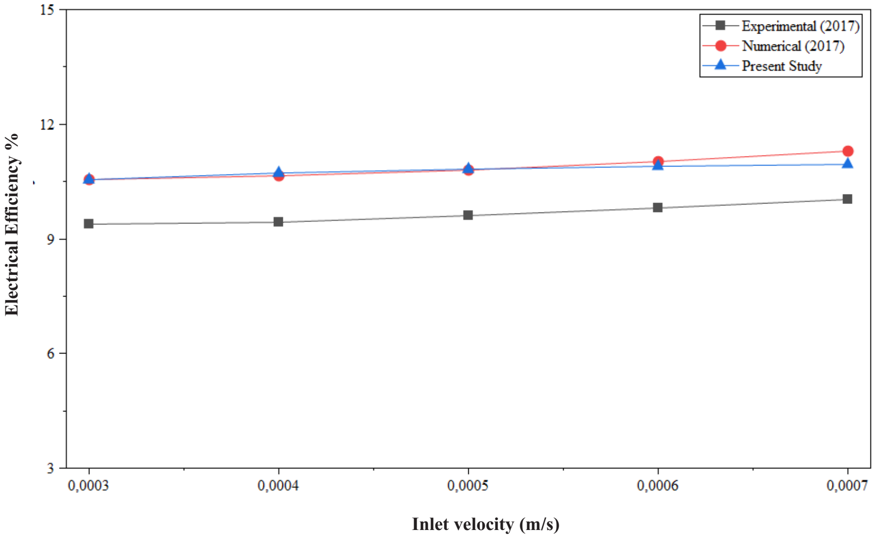


Fig. 4. Electrical efficiency obtained in our study and by Nahar et al. [15].

3 Results and discussion

Numerical simulations were conducted to analyze the thermal and electrical performance of the hybrid PV/T system under different nanofluid concentrations and inlet conditions. The simulated model represents a rectangular water channel attached to the back surface of a PV module through a thin aluminum plate and thermal paste layer. The model geometry, boundary conditions, and material properties were defined based on previous validated works Nahar et al. [15].

Fig. 5 shows the predicted velocity profile for the PVT system flow channel. The colored contours represent the velocity field of the fluid motion from 0 to 1.3 x 10^{-3} according to the sequential color scale shown on the right. The velocity profile is almost uniform in the central part of the channel and reaches a maximum value at the center, while its amplitude gradually decreases as it approaches the walls due to viscous boundary layers. This suggests that the designed channel guarantees a stable laminar flow and good fluid mixing inside the entire collector length, which is crucial in achieving uniform heat extraction from the PV plate.

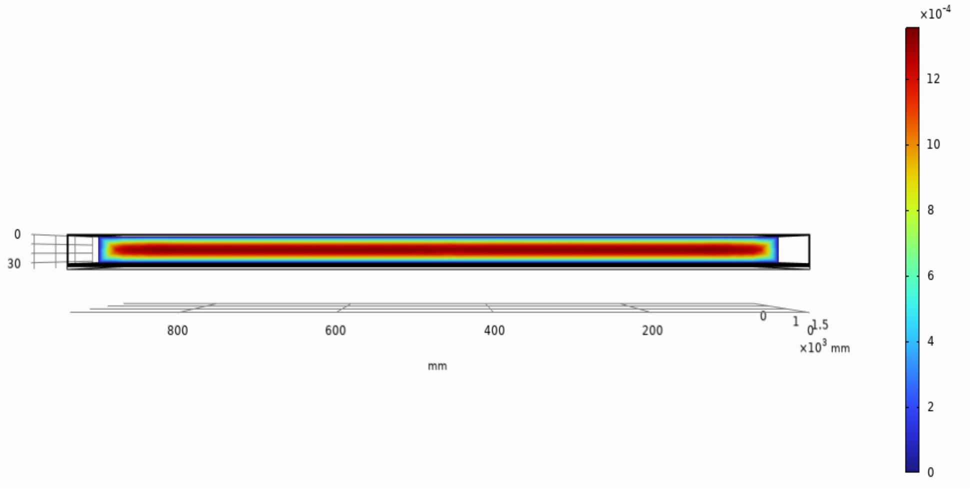
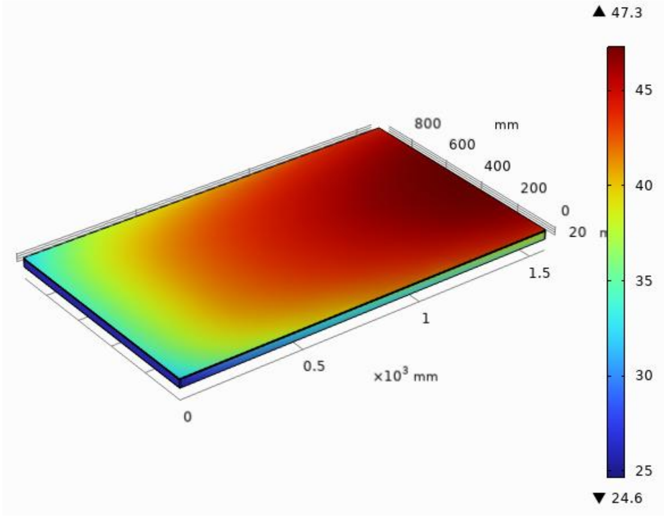


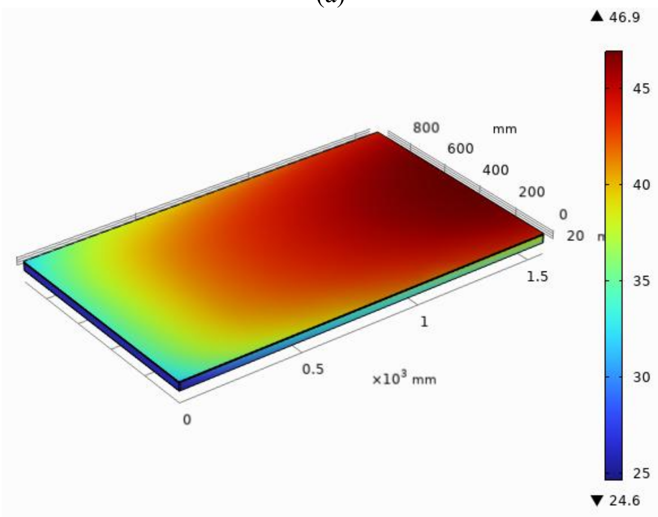
Fig. 5. 2D profile of velocity distribution.

Fig. 6 illustrates the temperature distribution on PV/T collector surface using two different working fluids; pure water and 2% CuO nanofluid. Under the constant parameters of 800 W/m² irradiation, 25°C ambient temperature and 0.001 m/s inlet velocity. the surface temperature of the nanofluid is slightly lower than that of water. This discrepancy likely signifies better heat absorbing and transporting ability of the nanofluid. The gradual decrease in temperature from the outlet to the inlet also strongly indicate that there exists heat removal longitudinally along a collector length.

When the working fluid flows from the outlet to the inlet, the surface of the collector gradually cools down, confirming that heat is effectively dissipated along the flow path. A detailed comparison between the two test cases reveals a slight decrease in temperature, from approximately 47.3°C with pure water to approximately 46.9°C with CuO nanofluid. This modest but consistent decrease highlights the slightly superior cooling capacity of the nanofluid and its improved thermal conductivity under the same operating conditions.



(a)



(b)

Fig. 6. Surface temperature distribution in the PV/T system using (a) pure water and (b) a nanofluid containing 2% CuO.

Fig. 7 shows that as the NP concentration increased, the photovoltaic cell temperature decreased for all nanofluids, thus indicating a cooling effect of NPs in PV/T. When pure water is selected as the working fluid, the cell temperature results in about 39.82 °C, whereas when the nanoparticle concentration increases to be 2%, it slightly decreases to reach around 39.52, 39.53, 39.59 and 39.58 °C for CuO, Al_2O_3, TiO_2 and ZnO respectively. CuO nanofluid shows the lowest temperature among those cells due to its high thermal conductivity and higher heat transfer than other nano particles. While about 0.3 °C difference globally, this improvement is significant because a small decrease in temperature has the potential to improve electrical efficiency and long-term stability of PV cells. The findings thus indicate that the addition of a small quantity of nanoparticles, specifically CuO, can significantly enhance the cooling performance.

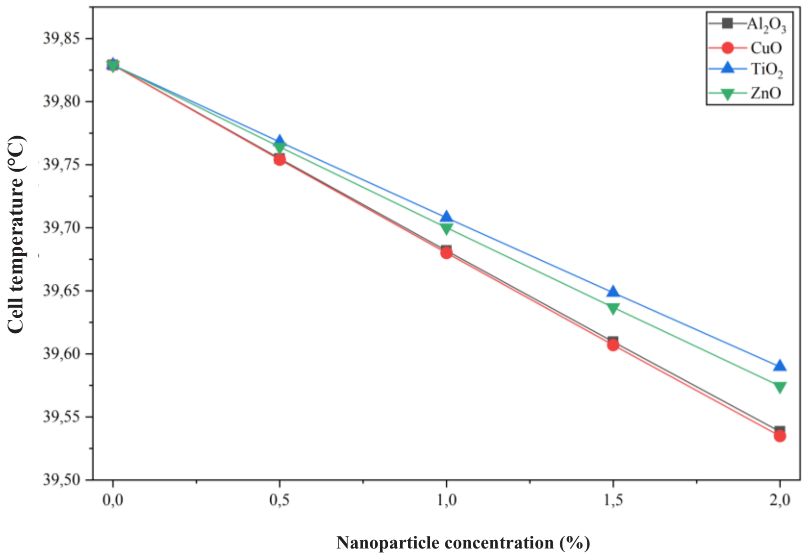


Fig. 7. Influence of nanofluid type and nanoparticle concentration on cell temperature.

The drop in cell temperature resulted from the increasing in NP concentration also contributes to a slight improvement in panel performance, as shown in Fig. 8. Since photovoltaic efficiency decreases as the cell becomes warmer, the slight cooling provided by the nanofluids actually increases efficiency slightly. With pure water, efficiency is approximately 12.13%. At a nanoparticle concentration of 2%, Al_2O_3 and CuO both reach approximately 12.15%, TiO_2 12.147%, and ZnO 12.148%. CuO offers the best performance at 12.1503%, while TiO_2 presents the lowest. These resuls make sense since CuO kept the cell the coolest as illustrated in graph above (Fig.7).

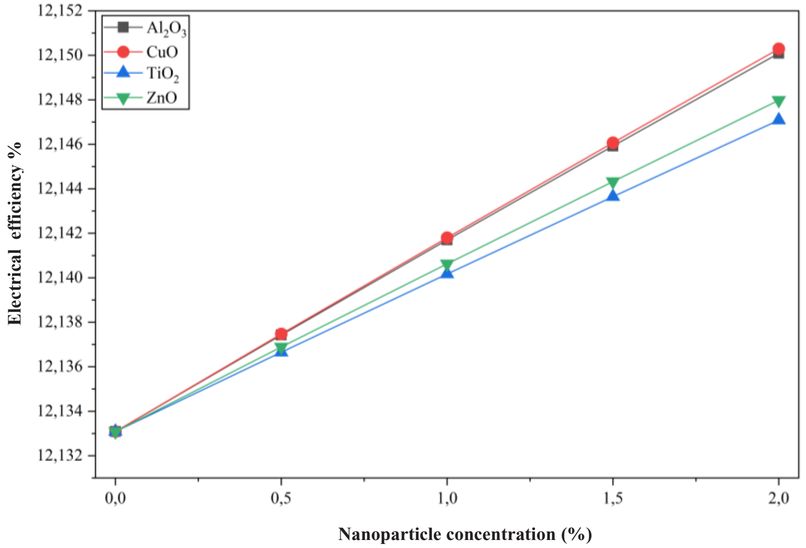


Fig. 8. Influence of nanofluid type and nanoparticle concentration on electrical efficiency.

Fig. 9 shows that the temperature difference (ΔT) changes depending on the concentration of nanoparticles. For all nanofluids, ΔT increases slightly, from 8.61 °C with pure water to approximately 8.7 °C at a concentration of 2%. This means that adding nanoparticles helps the fluid to carry heat more efficiently. ZnO has the highest ΔT reached 8.7, meaning it absorbs more heat, while TiO_2 and Al_2O_3 follow closely behind around 8.68 °C, on the other hand CuO this time presents the lowest value around 8.67 °C. But a higher ΔT does not always mean better performance: it also depends on the system's ability to remove heat from the photovoltaic surface to prevent it from overheating. In this sense, CuO offers the best performance, combining good heat absorption with rapiid heat transfer, which helps to keep the cell at a lower temperature.

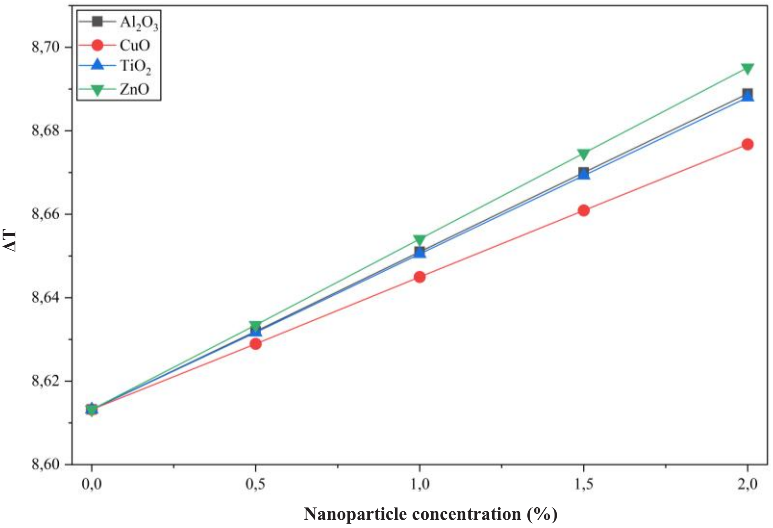


Fig. 9. Influence of nanofluid type and nanoparticle concentration on temperature difference (ΔT).

These thermal effects are shown in Fig. 10, where the thermal efficiency increases slightly compared to pure water (75.54%). it rises to 75.79% for Al2O3, 75.80% for CuO, 75.73% for TiO2, and 75.74% for ZnO at 2%. This improvement is due to better thermal conduction and fluid movement within the nanofluids, which allows for greater recovery of useful thermal energy. The gain for CuO, approximately 0.3%, may seeem small, but it still makes a noticeable difference in the total energy conversion.

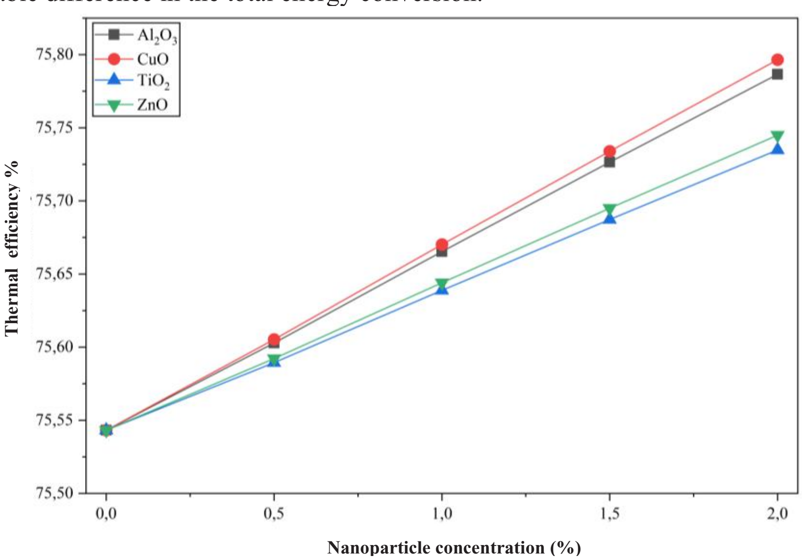


Fig. 10. Influence of nanofluid type and nanoparticle concentration on thermal efficiency.

4 Conclusion

In the present study, a 3D steady state simulation was conducted in COMSOL Multiphysics for the hybrid PV/T collector to investigate effect of nanofluids (CuO, Al_2O_3, TiO_2 and ZnO) at different concentrations levels (0.5-2%). The numerical results showed that the use of nanoparticles enhances the heat removal and reduces cell temperature up to 0.30 °C, compared to the pure base fluid (water). CuO nanofluid with 2% volume concentration of all investigated fluids obtained the lowest cell temperature (39.52 °C) offering the correspondingly highest electrical efficiency (12.1503%) and thermal efficiency (75.80%). It is closely followed by Al_2O_3, which also shows improved performance. By comparison, the base fluid produced 12.13% and 75.54%, respectively. Although the absolute benefits are modest, around 0.17% electrically and 0.26% thermally, they point towards a significant improvement inenergy harvesting via enhanced thermal conductivity (thermal conductivity of CuO is equal to 32.9 W/m·K) and convective heat transfer. These improvements confirm that nanofluid based cooling can significantly stabilize PV cell temperature under 800 W/m² irradiation.

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