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Experimental Analysis and CFD Simulation of Photovoltaic/Thermal System with Nanofluids for Sustainable Energy Solution

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ABSTRACT

The integration of photovoltaic/thermal (PV/T) systems with nanofluids presents a promising avenue for enhancing sustainable energy solution. This study investigates the performance of such systems through experimental analysis and computational fluid dynamics (CFD) simulations. Nanofluids, engineered colloidal suspensions of nanoparticles in base fluids, are employed to enhance heat transfer within the PV/T system. The experimental setup involves measuring electrical output, thermal efficiency, and overall system performance under varying conditions. Additionally, CFD simulations are conducted to model fluid flow and heat transfer dynamics within the PV/T collector integrated with nanofluids. The results from both experimental and simulation studies provide insights into the synergitic effects of nanofluids on enhancing energy conversion efficiency and thermal management of the PV/T system. The research contributes to the development of sustainable energy solutions by demonstrating the potential of nanofluid-enhanced PV/T systems in improving energy conversion efficiency and thermal management for various environmental conditions.

1. Introduction

The increasing global demand for energy, coupled with the urgent need to address environmental concerns, has driven the quest for sustainable and efficient energy solutions. Among the various renewable energy technologies, photovoltaic/thermal (PV/T) systems have emerged as a promising option due to their ability to simultaneously generate electrical and thermal energy from solar radiation. By integrating photovoltaic (PV) cells with thermal collectors, PV/T systems enhance the

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overall efficiency and energy output, offering a comprehensive solution for clean energy generation. Despite the inherent advantages of PV/T systems, their performance is often limited by the high operating temperature of PV cells, which can significantly reduce electrical efficiency. Recent advancements in nanotechnology have introduced nanofluids as potential high-performance cooling agents. Nanofluids exhibit superior thermal properties compared to conventional heat transfer fluids, making them ideal candidates for enhancing the cooling efficiency of PV/T systems. Kern and Russell [1] introduced the basic concept of a PV/T system operated by two fluids based on laboratory tests. Joshi and Tiwari [2] numerically studied PV/T with an air working fluid, showing that the electrical and total efficiencies (total electrical and thermal efficiency) of the system were 14−15% and 55−65%, respectively. Daghigh *et al.,* [3] studied the effect of using various working fluids on the output behavior of the PV/T systems. Bhattarai *et al.,* [4] numerically and experimentally evaluated the PV/T with water as a working fluid and found that the thermal efficiency and the electrical efficiency were 58.70% and 13.69%, respectively. Sasa *et al.,* [5] compared two classic flat plate solar systems for reasonable energy storage with water and PCM. Higher energy efficiency was obtained using PCM. The average increase in thermal efficiency compared to water was 36%. Sardarabadi *et al.,* [6] experimentally investigated the effects of using silica/water nanofluids with a mass fraction of 3% as cooling fluid on the thermal and electrical efficiency of a PV/T system which showed approximately 7.9% increase in the efficiency. Rejeb *et al.,* [7], in a numerical study, focused on the output efficiency of the PV/T and investigated the effect of using aluminum oxide and copper nanoparticles with mass percentages of 0.1%, 0.2%, and 0.4%. It was found that using water, instead of ethylene glycol, improved the system efficiency. Carbon nanotube (CNT) is a promising candidate for use in a variety of devices due to several attractive properties [8]. Some researchers have investigated the influence of adding carbon nanotubes on PV/T [9]. Fayaz *et al.,* [10] presented a 3D numerical study of PV/T and used simple water and MWCNT-water as the working fluid. The improvement of the PV electrical efficiency with nanofluid was about 10.72% and 12.25% based on the numerical and experimental studies, respectively. Alshaheen *et al.,* [11] used hybrid nanofluids of carbon-based fillers on a photovoltaic heating system. They found that the use of MWCNTs/water, SWCNTs/water, and GNPs/water nanofluids, with a mass fraction of 0.05% improved the total efficiency by 9.46%, 15.24%, and 19.3%, respectively. Sangeetha *et al.,* [12] experimentally investigated the effects of different nanoparticles on PV/T systems at different concentrations. The results showed that the use of nanofluids increased the electrical power of the PV/Ts.

This paper presents an experimental analysis and simulation study of a PV/T system utilizing nanofluids for improved thermal management and overall system performance. The primary objective is to investigate the impact of different nanofluids on the thermal and electrical efficiency of the PV/T system and to identify the optimal nanofluid composition for maximizing energy output. The study involves a comprehensive experimental setup, including the measurement of temperature differences, heat transfer rates, and electrical output under various operating conditions. Additionally, a simulation model is developed to predict the performance of the PV/T system with nanofluids and validate the experimental results.

2. Methodology

The designed experimental setup has been shown at Figure 1. The LM35 sensor, connected to the Arduino board, was also used to record and track the surface temperature and back temperature of the PV module. The ProsKit MT-1210 digital multimeter was used to measure the effective electrical variables. The microscopic image of the nanofluid is shown in Fig**.** 2. Preparation procedures for the MWCNT/water and SWCNT/water-based, 2. Water, MWCNT nanofluid, and SWCNT nanofluid were assessed as the working fluids. The experiments were performed outdoors and each cooling nanofluid. The solar radiation intensity, wind speed, and ambient temperature were measured. As the solar radiation is on the surface of the solar panel, the surface temperature of the panel increases. The thermal parameters were measured by the LM35 sensors. Also, the current and voltage were measured by a multimeter. Properties of the Carbon nanotubes has been mentioned a Table 1.

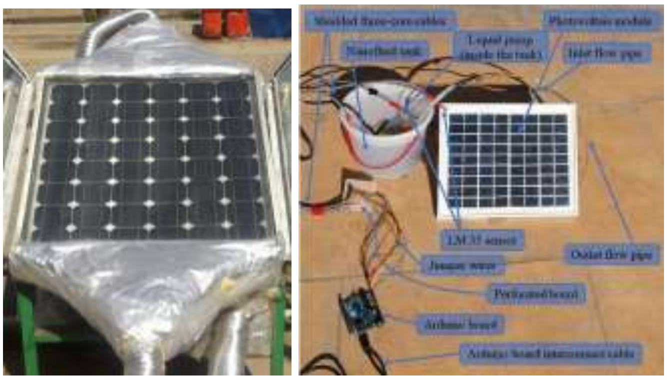


Fig. 1. The applied experimental setup, Main components of the experimental setup

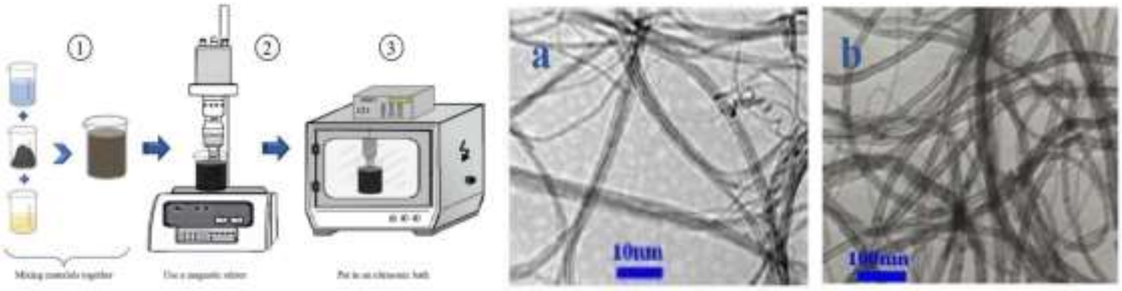


Fig. 2. Preparation procedures for the MWCNT/water and SWCNT/water-based, TEM images of CNTs: (a) SWCNTs; (b) MWCNTs

Table 1
Properties of the Carbon nanotubes (CNTs)

Parameter	SWCNT	MWCNT
Density, ρnp, (kg/m3)	2100	2100
Specific Heat, cpnp, (J/kg · K)	841	711
Thermal conductivity, Knp, (W/m·K)	6000	1500
Outer diameter (nm)	1–2	10–30
Inner diameter (nm)	0.8–1.6	0.8–1.6
Length (um)	5–30	~30
Aspect ratio	500–3000	1000–3000
Electrical conductivity	> 100	>100
Purity	>90%	>90%

3. Results

The inlet temperature and the outlet temperature of the different working fluid is shown at Figure 3 (a) and (b). The maximum difference between the inlet and outlet temperatures was observed at 13:00, indicating the impact of nanofluid on performance. The inlet temperature and the outlet temperature increased from 10 am to 13:00, and then those decreased till 16:30. As it has been described at Figure 3(c), using Single Wall Carbon Nano Tube (SWCNT)/water nanofluid reduced the

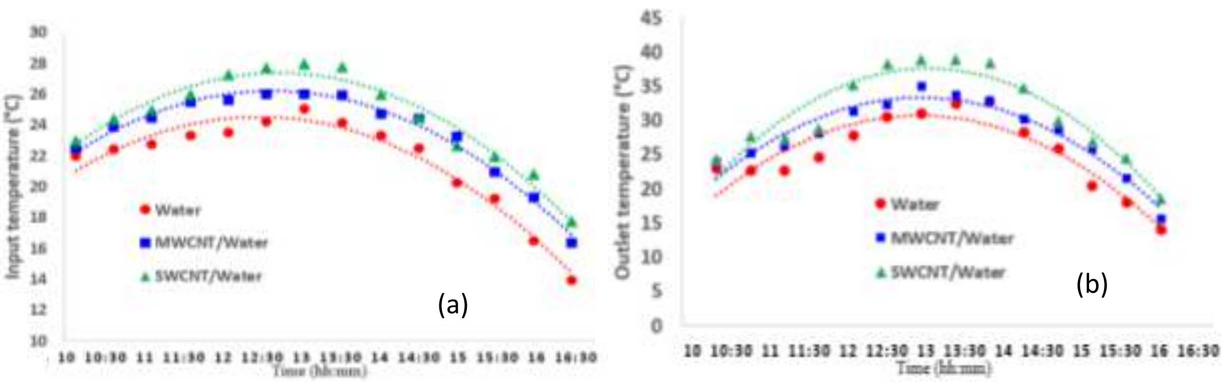
PV surface temperature by 30% and experimental results proved that using Multi Wall Carbon Nano Tubes (MWCNT)/water reduced the PV surface temperature till 48%. Experimental results approved that using nanofluids reduces the PV/T surface temperature due to their enhanced thermal conductivity and heat transfer properties, nanofluids have a higher thermal conductivity compared to conventional fluids, this allows them to absorb and transfer heat more efficiently, leading to improved cooling of the PV surface.

The addition of nanoparticles increases the heat transfer coefficient of the fluid. This enhances the rate at which heat is removed from the PV surface, thus reducing its temperature [12-18]. Nanoparticles increase the effective surface area available for heat transfer. This helps in dissipating more heat from the PV surface into the fluid. The presence of nanoparticles in the fluid reduces the thermal resistance between the PV surface and the cooling fluid. This results in more effective heat removal and lower PV surface temperatures [19-24]. Nanofluids enhance convective heat transfer due to improved fluid dynamics and thermal properties, this leads to better heat dissipation from the PV surface to the fluid. Overall, it can be concluded that the use of nanofluids helps in maintaining a lower PV surface temperature, which can improve the efficiency and longevity of the PV/T system [25-28].

The output power of the PV/T system increased with the use of nanofluids due to higher thermal conductivity of nanofluids compared to conventional fluids. This allows them to absorb and dissipate heat more efficiently, resulting in better cooling of the PV cells. Cooler PV cells operate more efficiently, producing more electrical power [29-31].

The addition of nanoparticles to the fluid increases the overall heat transfer coefficient, this enhances the convective heat transfer from the PV cells to the cooling fluid, keeping the cells at a lower, more stable temperature and improving their performance. The output power of the PV/T was increased by 32% by utilizing MWCNT/water, while SWCNT/water nanofluid enhanced the output power by 50% compared to water (Figure 3d). The overall efficiency of the PV/T module is increased by using nanofluids, using MWCNT/water increased the efficiency by 22% while SWCNT/water increased the efficiency by 45% [32-36].

COMSOL Multiphysics software has been used to determine the temperature gradient in the photovoltaic system in order to observe the temperature distribution contours. Figure 4 shows the gridded model of the photovoltaic system, which uses very fine grids to increase the accuracy of calculations.



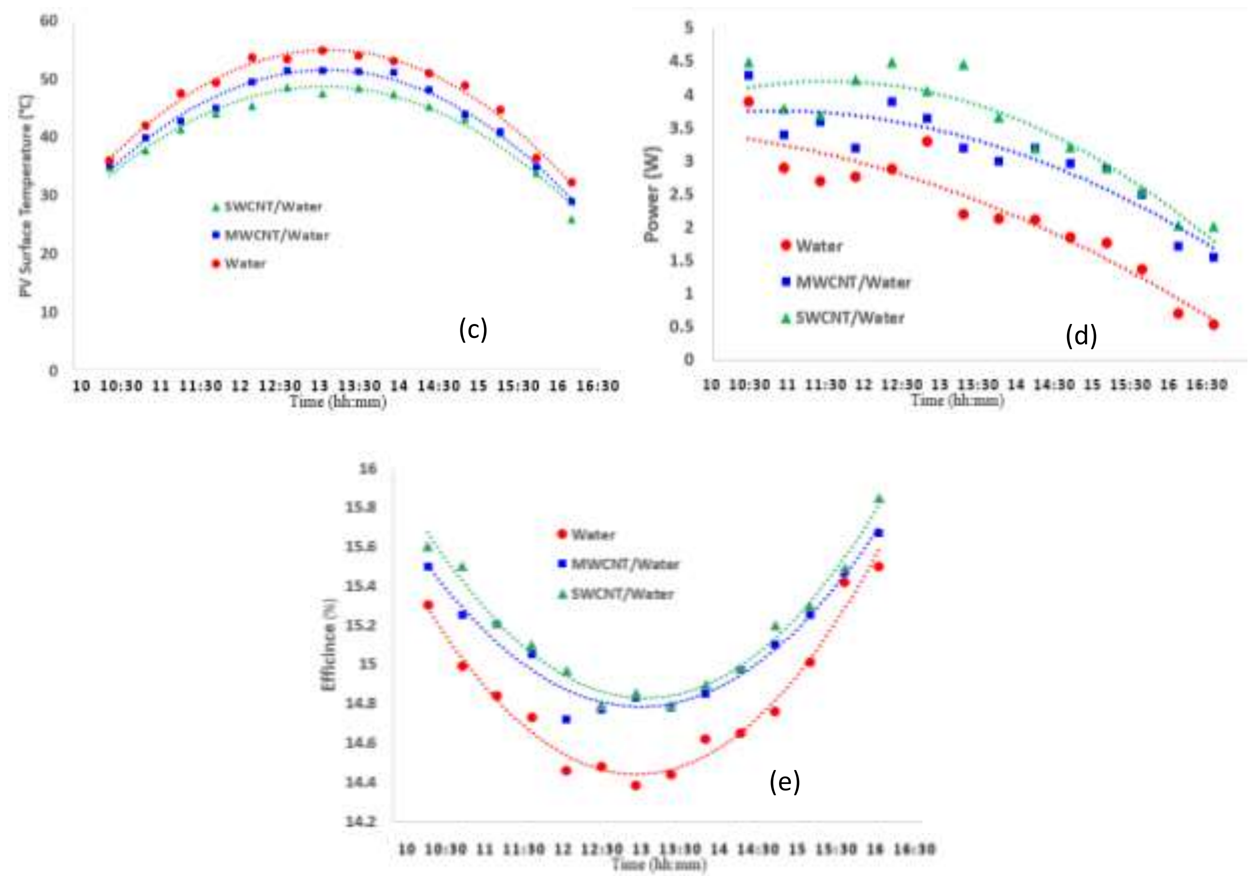
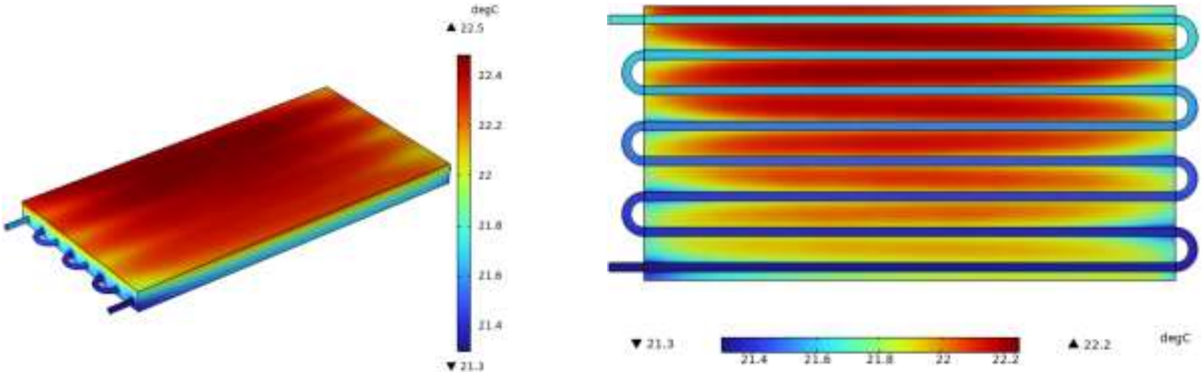


Fig. 3. (a) Variation of the inlet temperatures for different working fluids, (b) Variation of the outlet temperatures for different working fluids, (c) Effect of different working fluids on the surface temperature of the PV, (d) Variation of electrical power generated in the PV module for different coolants used in the experiment, (e) The panel efficiency under three methods of system cooling

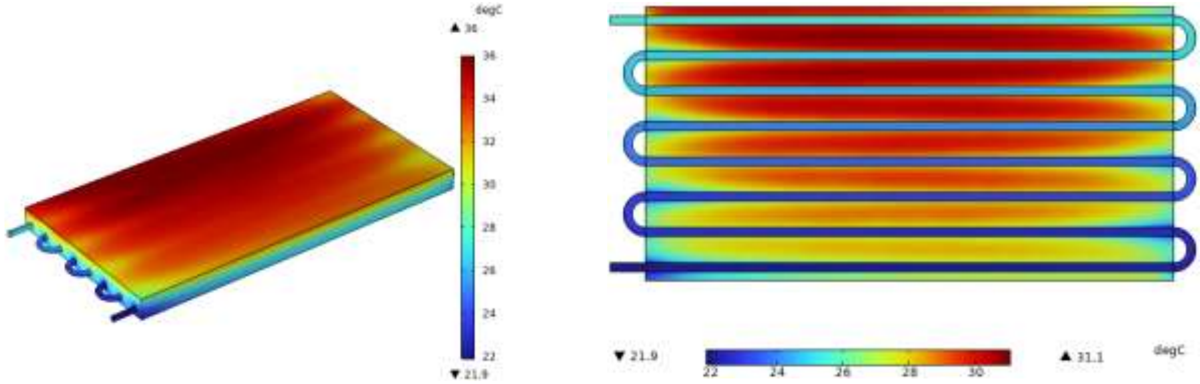
Domain elements 1148865 | Boundary elements 108328 | Edge elements 8014

Fig. 4. domain elements, boundary elements and edge elements of grids.

As can be seen from Figure 4, the maximum number of elements is 1148865, so that in this number of elements, the difference in the gradient of the results has reached below 2% due to changes in the grid. Figure 5 shows the temperature gradient distributed on the surface of the photovoltaic system at a mass flow rate of 0.03 kg/s shows at different times of the day. The surface temperature of the photovoltaic system reaches its lowest level near the inlet of the working fluid for cooling the system, while approaching the end of the cooling tubes, this temperature reaches its highest level because the temperature of the working fluid of the system increases. As it can be seen, the maximum temperature of the system on the surface of the solar panel is seen at 14:00 in the afternoon and at C, because at this time the amount of solar radiation approaches its maximum [37-40]. Figures 6 and 7 show the temperature gradient distributed on the surface of the photovoltaic system in the different of mass flow rates at 12 and 14 afternoons. The surface temperature of the photovoltaic system reaches its lowest level near the inlet of the working fluid for cooling the system, while approaching the end of the cooling tubes, this temperature reaches its highest level because the temperature of the working fluid of the system increases. Figures 6 and 7 show that at a lower mass flow rate, the cooling rate of the solar panel is better, and the reason is that at a low mass flow rate, the speed of the working fluid passing through the system decreases, so the amount of time the fluid stays in the system increases, which results in an increase Heat exchange takes place between the solar panel and the cooling coils. In fact, conduction and convection heat transfer takes place in a more effective way.



(a)



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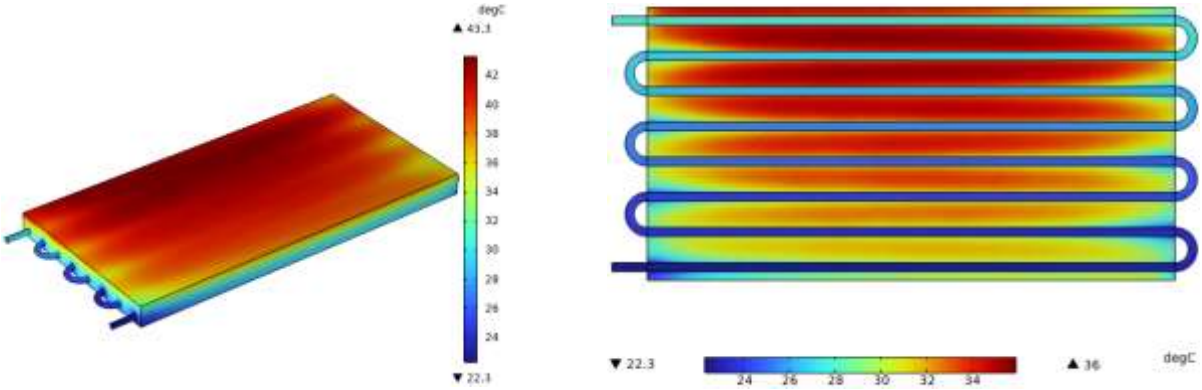
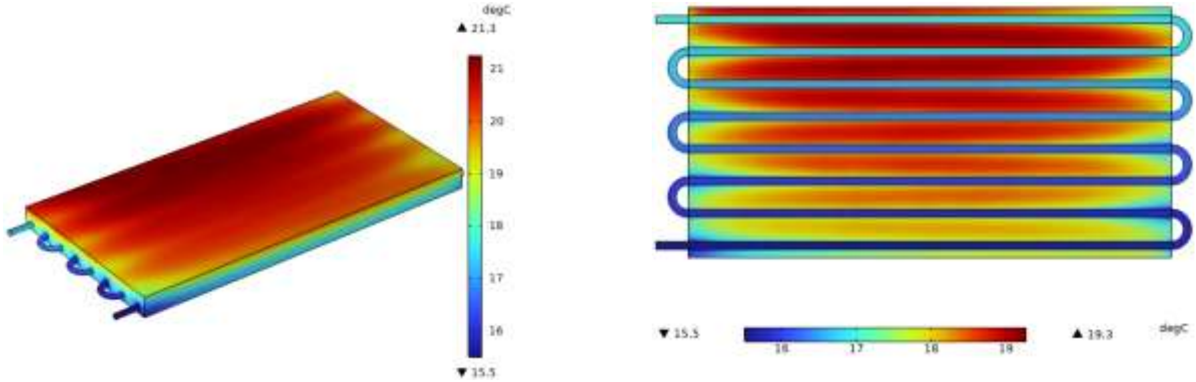
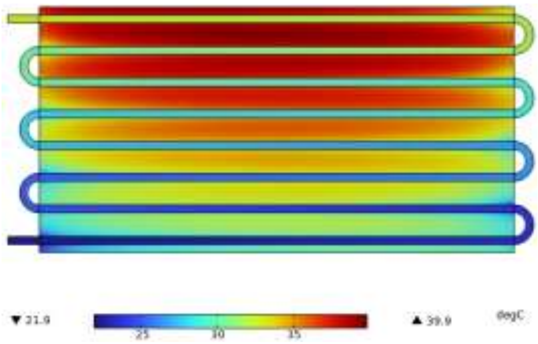


(c)

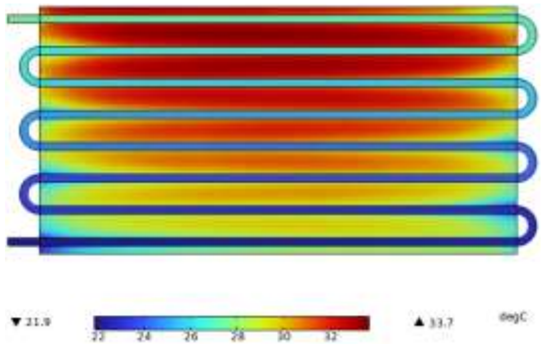


(d)

Fig. 5. Variation of temperature at 0.03 kg/s at a) 10:00, b) 12:00, c) 14:00, d) 16:00



(a)



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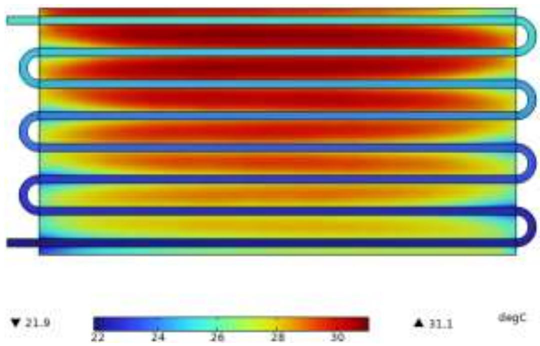
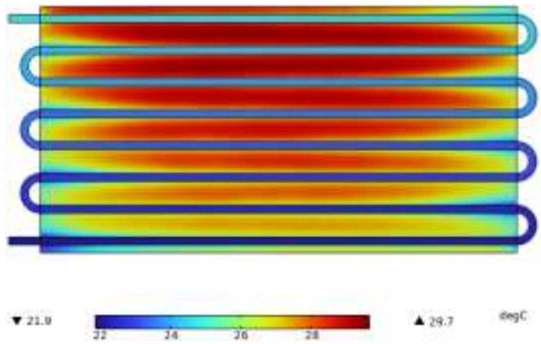


(c)



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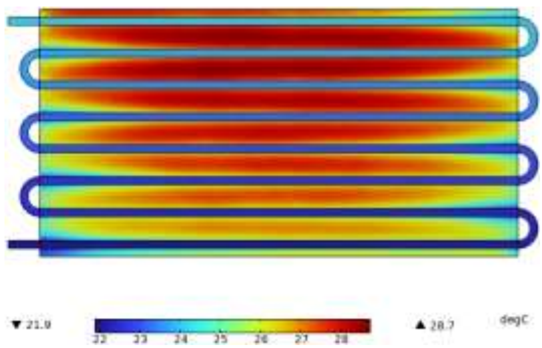

(e)

Fig. 6. Temperature gradient distributed on the surface of the photovoltaic system. Cut Plane Temperature at 12:00 at a) 0.01, b) 0.02, c) 0.03, d) 0.04 and e) 0.05 kg/s

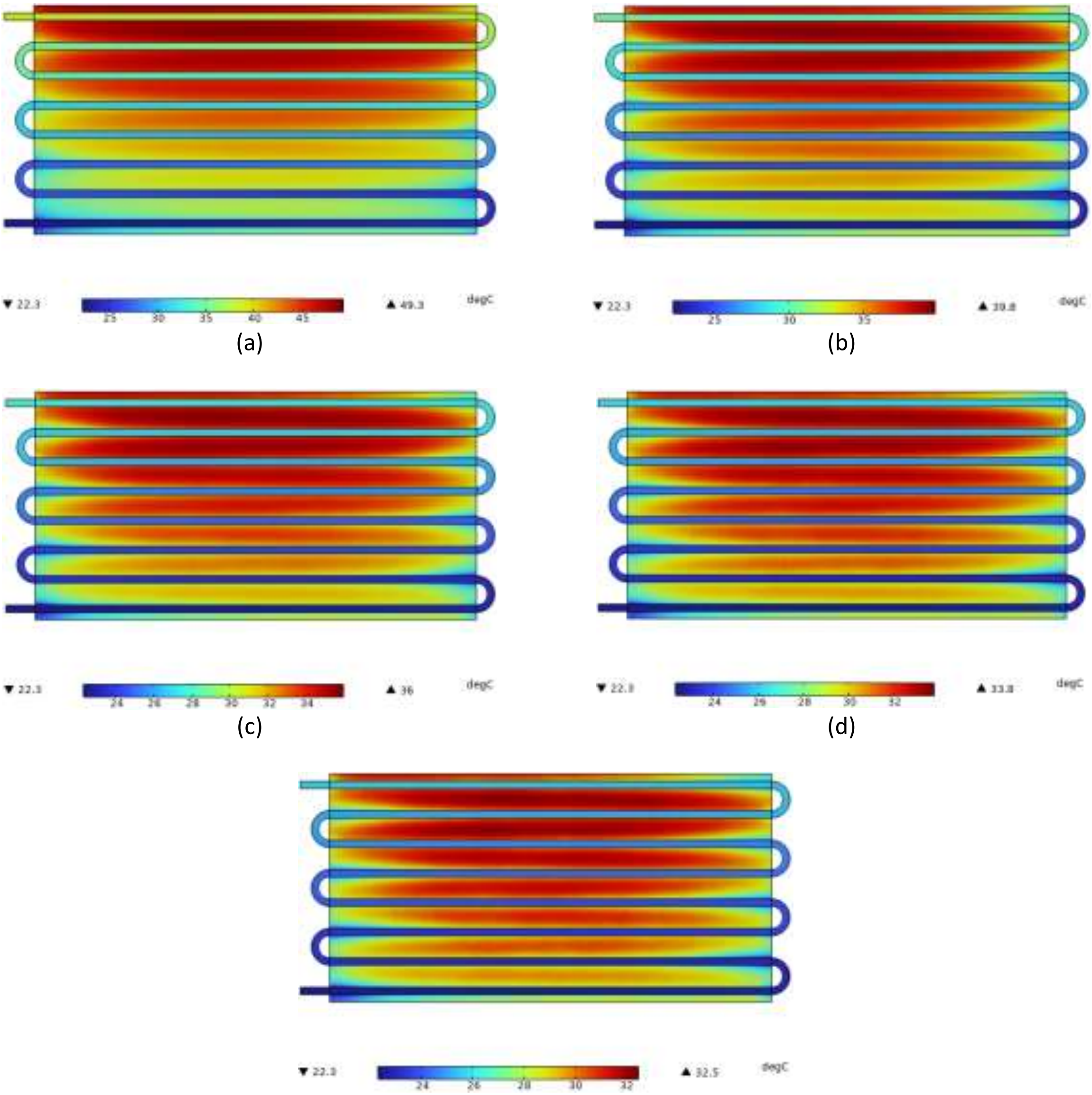

Fig. 7. Temperature gradient distributed on the surface of the photovoltaic system at 14:00 afternoon. Cut Plane Temperature at 14:00 at a) 0.01, b) 0.02, c) 0.03, d) 0.04 and e) 0.05 kg/s

Figure 8 shows the surface temperature of the photovoltaic system at 12:00 and 14:00 at 5 different mass flow rates. In fact, the desired contours show the progress of the thermal front and different temperature lines on the surface. As can be seen, the surface temperature in the center of the solar panel increases because the cooling degree of the cooling fluid decreases. Also, the temperature increase in the center of the solar system is higher at 14:00 than at 12:00 because solar radiation and heat flux are higher at 14:00. The solar panel has a lower temperature at the entrance of the working fluid to the system, so that this cooling is more visible at 12:00 than at 14:00 at the entrance of the panel [41-44].

Also, in the flow rate of lower masses such as 0.01 kg/s the temperature of the working fluid at the end of the panel increases because the amount of heat transfer time increases due to the increase in the retention time of the fluid.

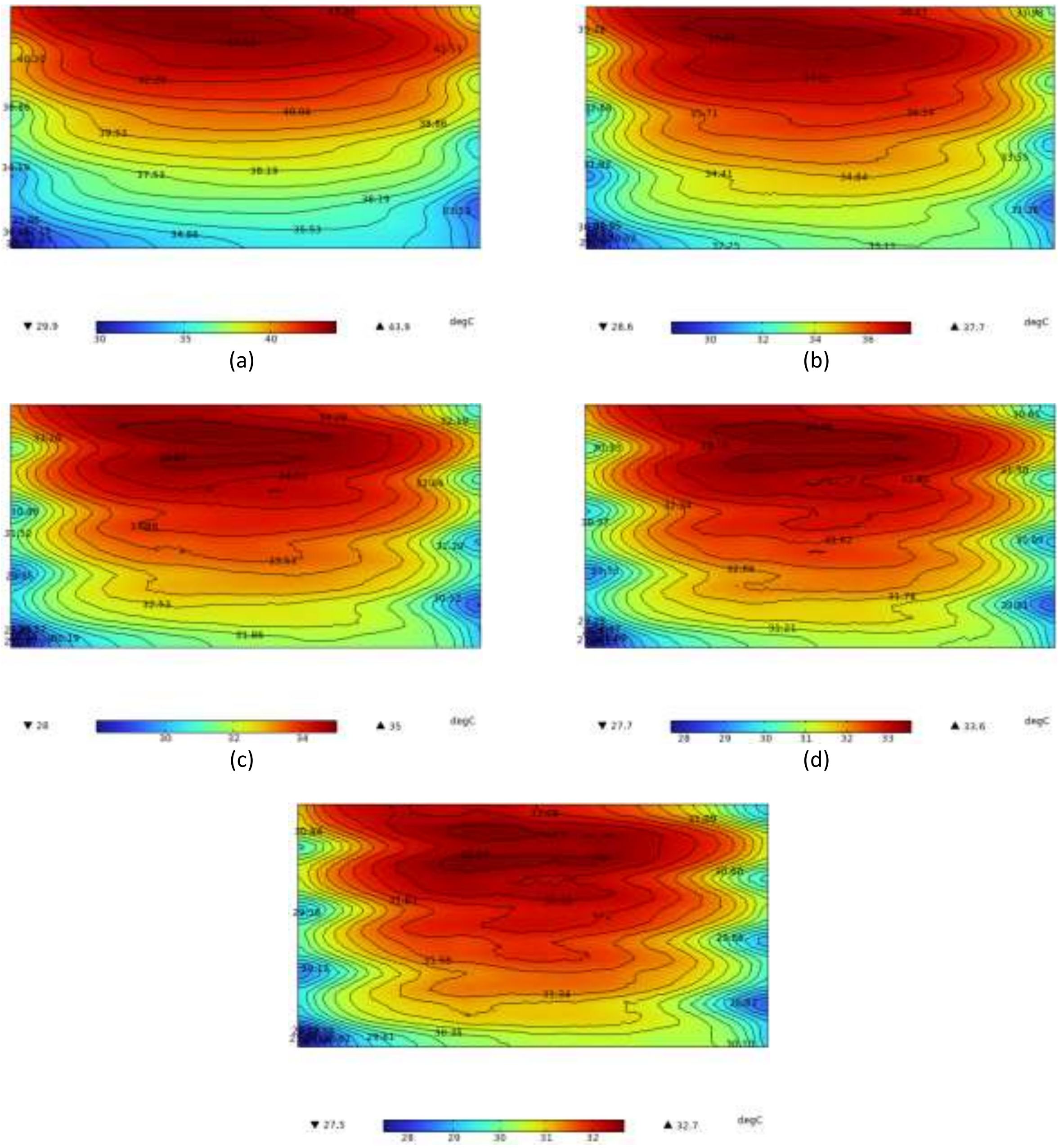

Fig. 8. The surface Temperatures at 12:00 and 14:00 at a) 0.01, b) 0.02, c) 0.03, d) 0.04 and e) 0.05 kg/s

Figure 9 shows the amount of pressure drop in the different mass flow rates of passing through the system. In fact, the maximum pressure drop of the system is in the mass flow rate of 0.05 kg/s it is 49 kPa and the pressure drop corresponding to the mass flow rate of 0.01 kg/s is 4 kPa. The reason for this difference is that due to the small diameter of the cooling coils as well as the large curves in the flow of the fluid, the pressure drop at higher mass flow rates increases sharply. Also, at higher mass flow rates, due to the increase in friction between the fluid and the coil wall, the pressure drop changes significantly. At higher Reynolds numbers, due to the decrease in the thickness of the boundary layer, the friction of the internal layers of the fluid with the wall of the heating coils increases drastically, which causes an increase in pressure drop.

Figure 10 shows the difference between the numerical and experimental results at different times of the day and at different mass flow rates at different outlet and inlet temperatures, as can be seen from Figure 10, the maximum calculation error is less than 5%, which shows that the results are in good agreement and accuracy.

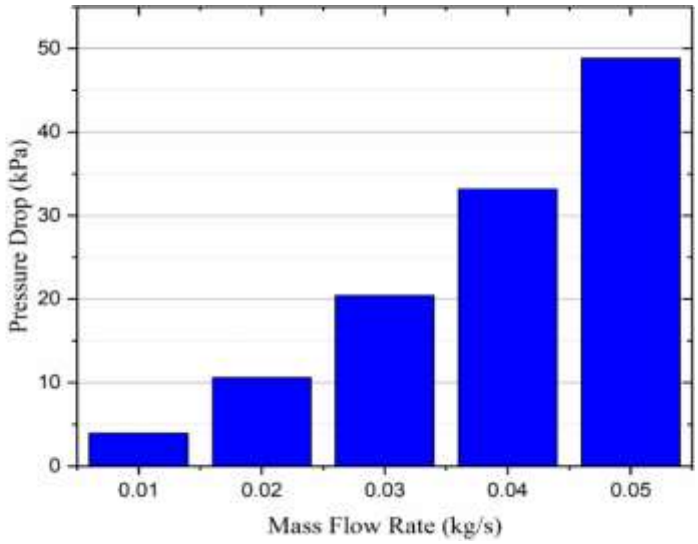

Fig. 9. Pressure drop (kPa) at different of mass flow rates

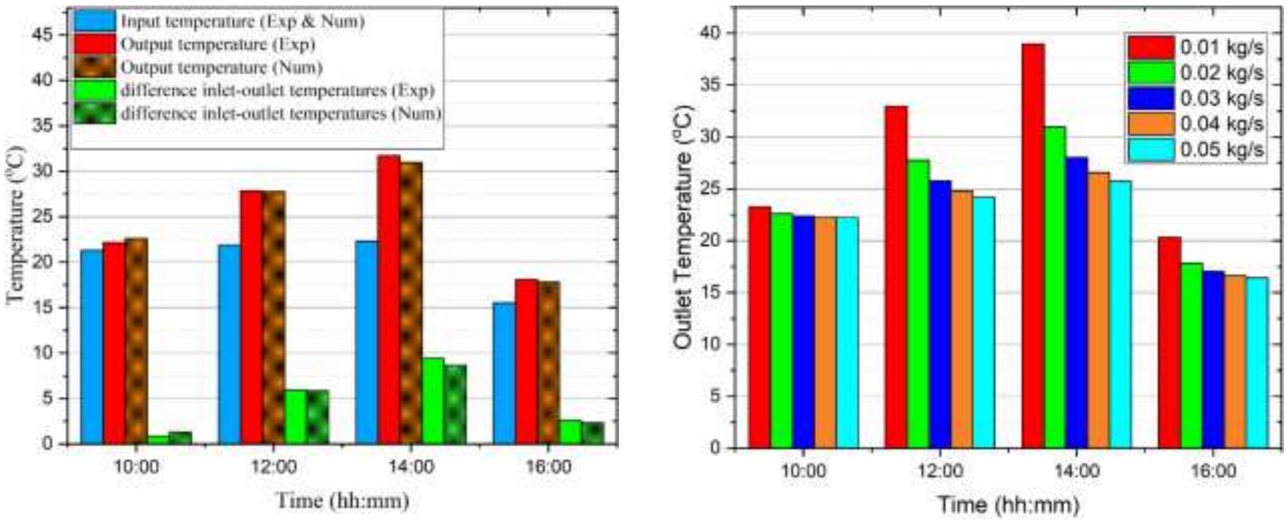

Fig. 10. Validation and accuracy of numerical and experimental results

4. Conclusions

This paper presents an experimental analysis and simulation study of a PV/T system utilizing nanofluids for improved thermal management and overall system performance. The primary objective is to investigate the impact of different nanofluids on the thermal and electrical efficiency of the PV/T system and to identify the optimal nanofluid composition for maximizing energy output. The study involves a comprehensive experimental setup, including the measurement of temperature differences, heat transfer rates, and electrical output under various operating conditions. Additionally, a simulation model is developed to predict the performance of the PV/T system with nanofluids and validate the experimental results. The experiments were performed outdoors and conducted throughout November from 10 a.m. to 4:30 p.m. In general, using SWCNT/water lowered the surface temperature of PV by 30.55%, and using MWCNT/water reduced it by 47.28%. The use of CNTs nanofluids had a significant effect on the surface temperature drop of the solar panel. The cooling nanofluids reduced the cell surface temperature by 15 °C to 30 °C. The output power of the PV module was increased by 32% when MWCNT/water was used. Also, SWCNT/water nanofluids increased the output power by 51%, compared to water. The overall efficiency of the PV module is found to be dependent on the surface temperature. In this study, using MWCNT/water enhanced efficiency by 22%, while SWCNT/water increased the efficiency of the PV/T module by 45%. The simulation results approved and verified by experimental results, it has been approved that there is maximum 5% difference between simulation and outdoor results.

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