Investigating the impact of using nano-fluid as a cooling medium on photovoltaic/thermal panel system performance

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Abstract. Making use of the superior thermal properties of nanofluids is now very common, especially with regard to the cooling of photovoltaic panels to improve overall efficiency. In this work, a novel cooling system manufactured from 3 mm aluminium was attached to the rear of a monocrystalline photovoltaic module, and two volumetric concentrations of SiC/Water nanofluid were tested with different flow rates. These tests were carried out under outdoor climatic conditions in middle of Iraq at Babylon University (32.46 °N, 44.42°E) during both winter and summer. A theoretical model was thus developed in SolidWorks and simulated using ANSYS 18.2. The maximum enhancements in electrical and overall efficiency were found to be 50% and 82.41% in March with a 0.5% nanofluid concentration and 2 L/min flow rate, while the minimum enhancements were 35.4% and 34.01% in June, with a 0.1% nanofluid concentration and 0.5 L/min flow rate. The theoretical results showed good approximation to the experimental results, and the average deviation percentage of electrical efficiency for a photovoltaic/thermal system with nanofluid on 27 March was 5.58%, while on 3 June it was 11%.

1. Introduction

The use of conventional energy resources is the main reason for global warming. To slow climate change, implementing renewable energy is thus vital. Utilising photovoltaic modules is one way of accessing clean energy resources used globally, as photovoltaic cells absorb incident radiation from the sun and convert it to electrical and thermal energy. Part of this absorbed radiation is converted to electricity, while the remaining percentage is converted to heat inside the cells. According to the simple diode equation which is the basis of photovoltaic modules, such increases in cell temperature decrease the open circuit voltage, thus reducing the electrical efficiency, however. Photovoltaic/Thermal (PV/T) solar systems thus generally incorporate cooling systems to cool the modules and increase their electrical efficiency. Recently nanofluids have become widely used as coolants due to their high thermal conductivity, which enhances the heat transfer. Abd-Allah et al. [1] performed research at Benha University, Egypt with the aim of investigating the impact of cooling PV cells with Boehmite-water nanofluid (AlOOH-xH2O) as a coolant. A three-dimensional model of the PV was designed in ANSYS-FLUENT with given boundary conditions and single phase flow of 0.08, 0.1, 0.2, 0.3, and 0.4 L/min in straight channels by solving the governing equations of energy conservation, mass conservation, and
momentum conservation using the finite volume method. Different weight concentrations of Boehmite-water nanofluid (AlOOH-xH2O) were thus examined (0.01%, 0.1%, and 0.5%). The modelled cooling system consisted of an acrylic plate with a thickness of 10 mm containing thirty-two parallel channels (5 mm width by 3.5 mm depth). The heat source was a constant 900 W/m². The results revealed that the performance was improved on using nano-fluid over that with pure water. At low flow rates, less than 200 ml/min, the maximum power increase was 21.87%, with a temperature reduction of 21.6 °C. At flow rates of 0.3 and 0.4 L/min, the flow turned turbulent and the increases of power were 23.4% and 24.6%, respectively for the 0.01% concentration as compared with 22.4% and 22.75%, respectively at the 0.1% concentration. Khanjari et al. [2] carried out a study at the University of Tehran, Iran with the goal of investigating the impact of cooling on PV/T system performance using ANSYS-FLUENT. The cooling fluids used in the simulation were pure water, an Ag/water nanofluid, and an Al2O3/water Nanofluid. The suggested PV/T model consisted of a glass cover, a PV panel integrated with a sheet, and a tube cooling system. Five riser tubes were used in the system. The results revealed that increasing the inlet fluid velocity improved the heat transfer from the PV/T system. The maximum thermal efficiencies of the Al2O3/water nanofluid and the Ag/water nanofluid were 78% and 82.5%, respectively at volumetric fraction of 11%. The maximum electrical efficiency of PV/T using Alumina-water nanofluid was 11.1% at a volumetric fraction of 10% while the best electrical efficiency of PV/T using Ag/water nanofluid was 10.1% at a volumetric fraction of 12%. Lari and Sahin [3] performed a study at the University of Petroleum and Minerals, Saudi Arabia with the aim of designing and analysing a PV/T system with a nanofluid coolant. Active cooling using a silver/water nanofluid and a copper plate heat exchanger was thus added to the design in addition to a sheet and tube cooling system consisting of a 1 mm stainless steel absorber plate fixed to hybrid parallel-serpentine tubes manufactured from stainless steel. The tubes were fixed to the absorber by means of thermal paste with high thermal conductivity and low electrical conductivity. Ag/water nanofluid at 0.5 v.% concentration and a flow rate of 0.026 kg/s was utilised as a coolant, and ANSYS-FLUENT was used to obtain the temperature distribution of the absorber. The results showed that a maximum of 2 °C and 1.3 °C temperature decreases were obtained in August and February, respectively, by using the nanofluid as compared to using pure water in the collector, and the electrical efficiency was improved by 0.9%. The improvement in thermal efficiency when using nanofluid was 18% over that of pure water. Sopian et al.[4] used CFD ANSYS simulation to investigate and select the optimum round tube design for a collector used in a PV/T system at the National University of Malaysia. The coolants used in their study were pure water and CuO/water and SiO2/water nanofluids. The solar irradiance used in the work varied from 400 to 1,000 W/m², with different coolant mass flow rates achieved by means of a circulating pump connected to the loop of the heat exchanger. The results revealed that the optimum diameter of the absorber round tube was 20 mm, which gave the lowest mean temperature with an optimum flow rate of 0.068 kg/s. The electrical efficiency of PV/T on using SiO2/water nanofluid was increased from 11.93% (without cooling) to 12.13% for the 20mm optimum diameter. The highest electrical efficiency of PV/T when using CuO/water nano-fluid increased from 11.71% (without cooling) to 11.93% for the 20 mm optimum diameter. Bellos and Tzivanidis [5] carried out a study at the National Technical University of Athens, Greece to investigate the annual electrical and thermal improvement in PV/T systems operating with nanofluids. A Cu/water Nanofluid was utilised as a coolant, and the photovoltaic/thermal system and nanofluid storage tank were tested over twelve typical days to determine annual performance. The designed system consisted of a ten tube-collector beneath the PV panel, a circulating pump, pipes, and a storage tank. The flow rate was constant at 3 L/min, with a volumetric concentration of 2%. The results showed that higher electrical and thermal improvements were seen on using Cu/water Nanofluid with the collector operating with a low inlet temperature. The average annual thermal efficiency was 43.8% with nanofluid as compared to 42% with pure water, and the maximum electrical efficiency was 12.6%, as compared to 12.4% for pure water. Sardarabadi and Fard [6] performed a study at the University of Mashhad, Iran, to investigate the impact of using metal oxides, Al2O3, TiO2, and ZnO dispersed in deionised water, as a base fluid to cool PV panels, with constant mass flow rate of 30 kg/h and a concentration of 0.2 %wt. for each nanofluid. The rig consisted of a mono-crystalline silicon module
attached to a sheet-and-tube cooling panel and circulating pumps. The average increases in electrical efficiency were 5.48%, 6.54%, 6.46%, and 6.36% for deionized water, TiO$_2$, ZnO, and Al$_2$O$_3$, respectively. Younis et al. [7] studied the influence of using Al$_2$O$_3$- ZnO-H$_2$O Nanofluid on the thermal and electrical performance of a PV/T system. Experiments were achieved on a setup consisting of an outdoor set of five solar PV/T hybrid collectors connected in series, with closed hydronic loops in which the flow rate was constant at 3.25 L/min, to an indoor storage tank with an integrated heat exchanger. The mass fraction of Al$_2$O$_3$ was 0.05% with a particle size of 5nm and the mass fraction for the ZnO was 0.05%, with a particle size of 10 to 30 nm. The results revealed that the average increase in the electrical efficiency was less than 0.1% in comparison with a module without cooling, which was considered to be due to the low concentration of nanoparticles. The average increase in thermal efficiency was 4.1%. Nasrin et al. [8] performed an indoor study to improve the thermal performance of PV/T systems using a water/multi wall carbon nano-tube nanofluid as a coolant. The system consisted of a PV panel and a thermal collector manufactured from aluminium tubing (serpentine) with no absorber plate. The nanofluid was cooled using a cross flow air heat exchanger with fan, and the radiation simulation system consisted of 120 halogen bulbs to provide light with different intensities. The results revealed that the thermal and electrical efficiencies were increased by 0.14 % and 3.67%, respectively, for PV/T systems with water/MWCNT nanofluid (1% wt.) in comparison with those for pure water. Shahad et al. [9] performed an experimental study at Babylon University, Iraq, to investigate the impact of water cooling on the performance of PV/T systems under Iraqi weather conditions. They used an acrylic pocket type collector fixed to the back of the PV panel so that there was direct contact between the tedlar layer and the cooling water. Different flow rates were tested (0.5, 1, 1.5, and 2L/min), with results that revealed that the maximum enhancements in electrical and overall efficiencies were 18.68% and 81%, respectively in March at a flow rate of 2 L/min. The minimum enhancements in electrical and overall efficiencies were 13.36% and 74.08%, respectively, in July at a flow rate of 0.5 L/min. Michael and Iniyan [10] performed a study in Anna University, India that analysed a PV/T system by fixing a copper thermal collector directly to the photovoltaic cells and removing the tedlar layer, thereby reducing the thermal resistance. They used CuO/water Nanofluid as a coolant with a constant mass flow rate of 0.01 kg/s, and the volumetric concentration of nanoparticles was 0.05%. NaOH was used as a stabilising agent, added slowly during the preparation of the nanofluid until the pH of the solution was between 6 and 7. The collector consisted of a one water channel with depth of 0.002 m, which was manufactured from aluminium and fixed to the back of the PV. The results revealed that the nanofluid increased the thermal efficiency of the PV/T system to 45.76%. The electrical efficiency of the PV/T system was reduced, however, due to the high temperature of the inlet water, prompting a recommendation to use an effective heat exchanger.

The objective of the current study is to investigate the impact on the performance of photovoltaic/thermal solar system of using a SiC/water nanofluid as a coolant.

2. Experimental Setup

A rig was manufactured and installed in Babylon University campus, Iraq (32.46 °N, 44.42°E), consisting of three identical monocrystalline photovoltaic modules. Two of these were modified to have a pocket aluminium collector, with one cooled using SiC/Water nanofluid and the other by pure water, while the back sheet of the third PV module was cooled by the surrounding air, as shown in figure 1. The nanofluid was circulated by pump and cooled by a helical heat exchanger, as shown in figure 2. The tilt angle was adjusted monthly according to the inclination angle, while the PV modules were directed to the south (zero azimuth angle). Figures 2 and 3 show the schematics of the rig.
Figure 1. Rig setup

Figure 2. Schematic of the PV/TN system
Figure 3. Schematic of the PV/T system

3. Numerical Procedure

3.1 Nanofluid Properties

The fluid investigated in this research was SiC/water nanofluid. Dispersing Silicon Carbide nanoparticle in pure water enhances its thermal conductivity and improves heat transfer. The thermal properties of the pure water at a temperature of 298 K [11] are shown in table 1, while the thermal properties of SiC nanoparticles [11] are shown in table 2.

Table 1. Properties of Pure Water

| Property           | Value    |
|--------------------|----------|
| Density            | 998 kg/m$^3$ |
| Viscosity          | 1003*10$^{-6}$ kg/m.s |
| Conductivity       | 0.613 W/m.K |
| Specific Heat      | 4182 J/kg.K  |

Table 2. Properties of SiC Nanoparticles

| Property             | Value     |
|----------------------|-----------|
| Density (kg/m$^3$)   | 3220      |
| Conductivity (W/m K) | 370-490  |
| Specific Heat (J/kg K)| 0.737    |
Two volumetric concentrations were used in this research, 0.1% and 0.5%. The properties of the nanofluid were calculated using the following equations:

1. Volume fraction [12]

\[
\phi = \frac{(m_s / \rho_s)}{(m_f / \rho_f)}
\] (1)

2. Mass density [12]

\[
\rho_{nf} = (1 - \phi) \rho_f + \phi \rho_s
\] (2)

3. Viscosity [13]

\[
\mu_{nf} = (1 + 2.5\phi) \mu_f
\] (3)

4. Thermal conductivity [14]

\[
k_{nf} = k_f \frac{k_s + 2k_f - 2(k_s - k_f)\phi}{k_s + 2k_f + (k_s - k_f)\phi}
\] (4)

5. Specific heat [12]

\[
C_{p_{nf}} = \frac{(1 - \phi) C_p_f + \phi C_p_s}{\rho_{nf}}
\] (5)

The thermal properties for the two volumetric concentrations are thus shown in table 3

| \(\phi(\%)\) | \(k_{nf}\) (W/m K) | \(\mu_{nf}\) (kg/m.s) | \(C_{p_{nf}}\) (J/kg K) | \(\rho_{nf}\) (kg/m³) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| 0.1       | 0.6136          | 660*10⁶         | 4169            | 1002.22         |
| 0.5       | 0.616           | 667*10⁶         | 4125            | 1011.1          |

3.2 Model Geometry

Drawing the model geometry is the first step in the simulation process. Figure 4 shows a sketch of the model geometry, with suggested PV/T and PV/TN models that include a glass cover, photovoltaic cells, a tedlar layer, an aluminium cooling panel, and cooling fluid. The geometry and the domain of the model were designed by the SolidWorks 2016 and then imported to an ANSYS 18.2 workbench. The characteristics and dimensions of various layers of the model are shown in Table 4, while the model geometry and three model domains are presented in figure 5. The properties of the solid layers are presented in table 5.
Table 4. Dimensions of Different Sections of the Model

| Layer         | Thickness (mm) | Width (mm) | Length (mm) | Type of Domain |
|---------------|----------------|------------|-------------|----------------|
| Glass         | 3              | 540        | 1200        | Solid          |
| PV Cell       | 0.01           | 540        | 1200        | Solid          |
| Tedlar        | 0.2            | 540        | 1200        | Solid          |
| Al            | 3              | 540        | 1200        | Solid          |
| Liquid        | 6              | 540        | 1200        | Fluid          |
| Polystyrene Board | 50        | 540        | 1200        | Solid          |

Table 5. Thermo-physical Properties of Solid Layers [12]

| Layer              | Thermal Conductivity (W/m. °C) | Density (kg/m³) | Specific Heat Capacity (J/kg. °C) |
|--------------------|--------------------------------|-----------------|-----------------------------------|
| Glass              | 1.8                            | 3000            | 500                               |
| PV Cell            | 148                            | 2330            | 677                               |
| Tedlar             | 0.2                            | 1200            | 1250                              |
| Al                 | 237                            | 2700            | 902                               |
| Polystyrene Board  | 0.03                           | 32              | 1300                              |
3.3 Simulation Assumptions

1. The fluid is incompressible, with uniform properties, and the system is in a quasi-steady state.
2. The pure water and nanoparticles are in thermal equilibrium, forming a single phase nanofluid.
3. Flow at the inlet is one-directional.
4. There is a laminar flow region.
5. Some part of the energy entering PV cells is converted into electrical energy, with the remaining portion contributing to an increase in the temperature of cells and nanofluid.
6. Solar irradiance is perpendicular to the PV panels.
7. Radiation heat loss from PV panel is negligible.
8. The bottom surface of the PV/T and the sides of the cooling panels are adiabatic.

3.4 Governing Equations

The governing differential equations as solved by ANSYS are the continuity equation, energy equation, and momentum equation. The pressure-velocity based solver was selected, which solves the momentum equation to obtain the velocity field. For the pressure field, this was extracted by solving the pressure correction equation obtained by manipulating the continuity and momentum equations. The energy equation allowed the setting of input parameters related to heat transfer in the boundary conditions and for outputs related to energy such as temperature to be obtained, as shown in Figure 6.

![Figure 5. Geometry and Domains of Three PV Systems](image)
1- Glass layer

The first layer is glass, which absorbs the heat from solar radiation; the transfer of the heat in this layer is by conduction, as shown in equation (6) [13]:

$$\frac{\partial}{\partial x}\left( k_g \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left( k_g \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left( k_g \frac{\partial T}{\partial z} \right) = 0$$  

2- PV layer

At this layer, heat transfer is by conduction, as represented in equation 7:

$$\frac{\partial}{\partial x}\left( k_{pv} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left( k_{pv} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left( k_{pv} \frac{\partial T}{\partial z} \right) = 0$$  

3- Tedlar layer

In this solid domain, the energy equation is

$$\frac{\partial}{\partial x}\left( k_{tedlar} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left( k_{tedlar} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left( k_{tedlar} \frac{\partial T}{\partial z} \right) = 0$$  

4- Aluminium plate (Al)

The energy equation in this domain is
\begin{equation}
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = 0
\end{equation}

5- Fluid domain

The energy equation, in Cartesian coordinates, is written as [6]

\begin{equation}
\rho \ C_p \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) = \left( \frac{\partial P}{\partial x} + \frac{\partial P}{\partial y} + \frac{\partial P}{\partial z} \right) + k f \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \left( \sigma_{xx} \frac{\partial u}{\partial x} + \sigma_{yy} \frac{\partial v}{\partial y} + \sigma_{zz} \frac{\partial w}{\partial z} \right) - \left[ \tau_{xy} \left( \frac{\partial u}{\partial y} + \frac{\partial w}{\partial x} \right) + \tau_{xz} \left( \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right) + \tau_{yz} \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right]
\end{equation}

The continuity equation in Cartesian coordinates is

\begin{equation}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\end{equation}

The effects of surface stresses are accounted for explicitly, while the source terms \( S_{Mx}, S_{My}, \) and \( S_{Mz} \) in equations 11, 12, and 13 include contributions from body forces only. For example, the body force due to gravity is modelled by \( S_{Mx} = 0, S_{My} = -\rho g \cos \beta, \) and \( S_{Mz} = -\rho g \sin \beta. \)

The gravity force can significantly influence the buoyancy force and, consequently, the convection terms. Thus, gravitational acceleration, which is a function of the setup tilt angle, must be activated in the simulation procedure. The vectors of gravity acceleration are defined as [2]

\begin{align*}
&g_z = -g \cdot \sin \beta \\
&g_y = -g \cdot \cos \beta \\
&g_x = 0
\end{align*}

\begin{align*}
&\beta = \psi - \delta \\
&\delta = 23.45 \sin \left( 360 \frac{284+n}{365} \right)
\end{align*}
3.5 Grid Study

A grid independence test was implemented to ensure the accuracy of the calculated solutions. The simulation results for six different mesh sizes for average back sheet temperature were utilised, and the results of the mesh refinement study are shown in table 6. Further refinement on the grid with 8,104 nodes showed no considerable effect on the numerical solutions, merely increasing the computational cost and time. The mesh with 8,104 node elements was thus selected as an appropriate computational domain, as shown in figure 7.

Table 6. The number of elements and nodes of mesh independent study

| nodes  | element | Average Back Cell Temperature (°C) |
|--------|---------|-------------------------------------|
| 8104   | 1056    | 41.859                              |
| 11792  | 1560    | 41.859                              |
| 21332  | 2880    | 41.858                              |
| 47112  | 6480    | 41.856                              |
| 180048 | 25228   | 41.855                              |
| 713276 | 100912  | 41.854                              |

Figure 7. Accuracy of prediction temperature with number of nodes

3.6 Electrical Model

Analysis of the PV panel output performance was conducted in PVsys simulation software, which requires the manufacturing specifications of the PV module under consideration. The module specifications are thus shown in table 7, while figure 8 shows the basic data used by the PVsys software.
Characteristics of PV cells affected by irradiance and temperature were modelled using a circuit model. The PV module has a non-linear voltage-current (V-I) characteristic, modelled using current sources, diodes, and resistors. A single-diode model was used to simulate PV characteristics in the PVsys software.

The following I-V relationships were used to predict the electrical power output of the PV equivalent circuit [14]:

\[ I = I_L - I_D = I_L - I_a \left[ \exp \left( \frac{V + IR_s}{a} - 1 \right) \right] \]  
(18)

\[ I_L = \frac{G}{G_{ref}} \left[ I_{L,ref} + M_{I,sc} (T_c - T_{c,ref}) \right] \]  
(19)

\[ I_a = I_{a,ref} \left( \frac{T_{c,ref} + 273}{T_c + 273} \right) \exp \left[ \frac{e_{gap}N_s}{q_{a,ref}} \left( 1 - \frac{T_{c,ref} + 273}{T_c + 273} \right) \right] \]  
(20)

\[ I_{a,ref} = I_{L,ref} \exp \left( -\frac{V_{oc,ref}}{a_{ref}} \right) \]  
(21)

\[ a_{ref} = \frac{2V_{mp,ref} - V_{oc,ref}}{I_{sc,ref} - I_{mp,ref}} + \ln \left( 1 - \frac{I_{mp,ref}}{I_{sc,ref}} \right) \]  
(22)

\[ a = \frac{T_c + 273}{T_{c,ref} + 273} a_{ref} \]  
(23)

\[ R_s = \frac{a_{ref} \ln \left( 1 - \frac{I_{mp,ref}}{I_{sc,ref}} \right) + V_{oc,ref} - V_{mp,ref}}{I_{mp,ref}} \]  
(24)

| Table 7. Specification of the PV Model from Datasheet (ISTAR 100-W) [15] |
|-----------------------------------------------|
| Maximum power rating \((P_{\text{max}})\) | 100 W |
| Maximum power voltage \((V_{mp})\)         | 17.3 V |
| Maximum power current \((I_{mp})\)         | 5.8 A  |
| Short circuit current \((I_{sc})\)          | 6.3 A  |
| Open circuit voltage \((V_{oc})\)           | 21 V   |
| Temperature coefficient \(\mu_{I,sc}\)     | 0.002  |
4. Results and Discussion

The experimental tests were performed during selected days in February, March, and June. The same climatic conditions were thus applied to CFD simulation to allow comparison with the experimental results.

4.1 Temperature Field of Back Sheet

Figure 9 shows the temperature contours of the PV, PV/T, and PV/TN models with boundary conditions in March at an ambient temperature of 21.1 °C, a solar irradiance of 940 W/m², air velocity of 2.3 m/s, a flow rate of 2 L/min, and the volumetric concentration of SiC/water nanofluid of 0.5 %. The maximum temperature of the PV, PV/T and PV/TN systems were 63.2 °C, 40.96 °C, and 38.16 °C, respectively. The high thermal conductivity of the SiC/water nanofluid improved the heat transfer rate. Figure 9a shows that, in the non-cooled PV module, the temperature field was symmetrical about the axes of the module due to similar boundary conditions all around causing a temperature gradient such that the maximum temperature was in middle of PV module. Figures 9b and 9c show the lowest temperature at the inlet of the cooling fluids which absorb the heat from module; thus, the temperature increases in the direction of flow in these cases.
Figure 9. Temperature Contours of Back Sheet for PV, PV/T and PV/TN Systems in March at 12:30 PM
It was noted experimentally that the back sheet temperature of the PV modules was influenced by many factors, including ambient temperature, solar radiation, the temperature of the inlet cooling fluid, and its flow rate. High solar radiation increased the temperature of the back sheet due to larger part of the non-converted solar energy being stored as heat inside PV cells. Low ambient temperature increased the rate of heat transfer from the PV module by convection. The wind speed in Iraq has no major influence, however, due to the high ambient temperature, especially during summer. Figures 10 and 11 show the variations in the measured average back sheet temperatures with flow rates for PV/TN and PV/T systems, respectively.

**Figure 10.** Variation in measured average back sheet temperature with flow rate at 0.5% nanofluid concentration in March

**Figure 11.** Variation in measured average back sheet temperature with flow rate at 0.1% nanofluid concentration in June

The average back sheet temperature of the PV/TN system was lower than that of the PV/T system for all flow rates and nanofluid concentrations due to the high thermal conductivity of SiC/water nanofluid, which improves the rate of heat transfer. Increasing the flow rate of both pure water and SiC/water nanofluid decreases the back sheet temperature due to forced convection, however.
4.2 Electrical Efficiency

Figures 12, 13, and 14 show the experimental variation of measured instantaneous electrical efficiency during selected days in March and June for PV, PV/T, and PV/TN systems, respectively. Electrical efficiency was high in the morning due to lower ambient temperatures, while the electrical efficiency during March was higher than that during June because the solar radiation in March is relatively higher than that in June. The ambient temperature in March is also lower, affecting heat transfer by convection and the temperature of the inlet cooling fluid for PV/T and PV/TN systems. The electrical efficiency of the PV/TN system was higher than that of the PV/T system due to the high thermal conductivity of the SiC/water nanofluid, which increases the heat transfer rate and cools the back sheet. Using a 0.5% concentration of SiC/water nanofluid in March has clear impact on enhancing heat transfer as compared with the 0.1% concentration. Good agreement was found between the predicted and measured results for the PV module, with an average deviation of 8.9% in March and 13.26% June. For the PV/T system, the average deviation in March was 6.63, with 9.21% for June, and for the PV/TN system the average deviation in March was 5.58%, with 11% in June.

![Figure 12](image1.png)  
**Figure 12.** Comparison between experimental and theoretical results for electrical efficiency of a PV module on (a) 27 March and (b) 3 June

![Figure 13](image2.png)  
**Figure 13.** Comparison between the experimental and theoretical results for electrical efficiency of a PV/T module on (a) 27 March and (b) 3 June
Figure 14. Comparison between the experimental and theoretical results for electrical efficiency of a PV/TN module on (a) 27 March (b) 3 June

Figure 15) shows the experimental daily average electrical efficiencies for the PV, PV/T, and PV/TN systems in two months. The maximum daily average efficiencies were 7.31%, 9.4%, and 10.96% respectively in March, due to low ambient temperature which improves energy conversion, while the minimum daily average efficiencies were 6.33%, 8.24%, and 8.58%, respectively in June due to high ambient temperatures, which reduce heat transfer by convection and increase the temperature of inlet cooling fluids.

Figure 16. Electrical efficiency for selected days in March and June

4.3 Thermal Efficiency

Figure 16 shows the daily average thermal efficiencies of PV/T and PV/TN systems for selected days in March and June with 0.1% volumetric concentrations of SiC/water nanofluid. Various volumetric flow rates of pure water and nanofluid were tested (0.5, 1, 1.5, and 2 L/min). The daily average thermal efficiency of the PV/TN system was higher than that of the PV/T system for all flow rates due to the high thermal conductivity that improves heat gain and increases the nanofluid outlet temperature. In March, with flow rates of 0.5, 1, 1.5, and 2 L/min, the daily average thermal efficiencies of PV/T and PV/TN were 40.67%, 50.67%, 58.52%, and 63.57% and 48.91%, 54.07%, 60.89%, and 68.52%, respectively, while in June with the same flow rates, the daily average thermal efficiencies of PV/T and
PV/TN were 23.42%, 22.9%, 26.46%, and 27.96% and (25.43%, 26%, 28.5%, and 30.06%, respectively. Increasing the flow rate appears to enhance the thermal efficiency.

**Figure 16.** Daily Average Thermal efficiency of PV/T and PV/TN with SiC/water nanofluid for selected days in 2019

Figure 17 shows the differences between the theoretical and experimental results for overall efficiencies for PV/T and PV/TN systems with different flow rates and a nanofluid concentration of 0.1%. Good agreement was found between the theoretical and experimental results for all flow rates. The average deviation percentages of PV/T and PV/TN at 0.5 L/min were 5.34% and 6.99%, respectively, while at the 2 L/min flow rate, the average deviation percentages of PV/T and PV/TN were 9.77% and 7.72%, respectively. Heat losses from the insulation material and measurement uncertainty are the main reasons for the deviations.

**Figure 17.** Comparison between experimental and theoretical overall efficiency for different flow rates in June
5. Conclusion

1) The maximum temperatures of the PV panel were 63.5 °C and 75.2 °C for March and June, respectively.
2) The maximum temperatures of PV/T system were 39.1 °C and 45.6 °C for March and June, respectively.
3) The maximum temperatures of the PV/TN system were 37.9 °C and 44.3 °C for March and June, respectively.
4) The average electrical power of the PV/TN system was higher than that of the PV/T system because the SiC/water nanofluid has higher thermal efficiency, which increases the heat transfer rate and decreases the back cell temperature.
5) The maximum enhancements in electrical efficiencies for PV/TN and PV/T were 36.7% and 31.3%, respectively, in March, while the minimum enhancements were 35.4% and 30.1%, in June.
6) The maximum enhancements in overall efficiencies of PV/TN and PV/T were 82.41% and 73.77%, respectively, in March, while the minimum enhancements were 34.01% and 31.66%, in June.

Nomenclature

| Symbol | Description | Unit |
|--------|-------------|------|
| A      | Area        | m²   |
| a      | Temperature function | V    |
| C_p    | Specific heat | J/kg.K |
| e_g    | Band gap of material for Si=1.17 | eV   |
| g      | Gravity     | m/s² |
| G      | Solar Irradiance | W/m² |
| h      | Heat convection coefficient | W/m².K |
| I      | Current     | A    |
| k      | Thermal conductivity | W/m.K |
| M      | Temperature coefficient | A/°C |
| ṁ      | Mass flow rate | kg/s |
| n      | Days number | .... |
| N      | Number of cells | .... |
| P      | Pressure    | Pa   |
| Q      | Heat transfer | W    |
| q      | Charge of an electron= 1.6021773 *10^19 | C    |
| R      | Resistance  | Ohm  |
| T      | Temperature | °C   |
| U      | Bulk velocity | m/s |
| u      | Velocity in x-direction | m/s |
| v      | Velocity in y-direction | m/s |
| V      | Voltage     | V    |
| ˙V     | Volumetric flow rate | L/min |
| w      | Velocity in z-direction | m/s |
| wt     | weight      | N    |
### Abbreviation

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| CFD    | Computational Fluid Dynamics                     |
| PV     | Photovoltaic                                     |
| PV/T   | Photovoltaic/Thermal Cooled by water             |
| PV/TN  | Photovoltaic/Thermal Cooled by Nanofluid         |
| SiC    | Silicon Carbide                                  |
| STCs   | Standard Conditions                              |
| GHI    | Global Horizontal Irradiation                    |
| PCM    | Phase Change Material                            |
| PVC    | Polyvinyl Chloride                               |
| Al     | Aluminium                                        |

### Greek Letters

| Symbol | Description | Unit       |
|--------|-------------|------------|
| µ      | Dynamic viscosity | Pa. s     |
| α      | Absorptivity | degree     |
| β      | Tilt Angle   | degree     |
| δ      | Declination angle | degree |
| η      | Efficiency   |           |
| ρ      | Mass density | kg/m³      |
| τ      | Shear stress | N/m²       |
| φ      | Volumetric fraction |          |
| ψ      | Latitude     | degree     |

### Subscript

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| atm    | Atmospheric                                       |
| c      | Cell                                             |
| D      | Diode                                            |
| f      | fluid                                            |
| g      | Glass                                            |
| in     | inlet                                            |
| L      | Light                                            |
| mp     | Maximum Power Condition                          |
| nf     | Nanofluid                                        |
| o      | Stationary condition                             |
| 0      | Dark saturation                                  |
| oc     | Open Circuit                                     |
| out    | outlet                                           |
| ref    | At Standard Condition (G=1000 W/m², T=25 °C)     |
| s      | solid                                            |
| sc     | Short Circuit                                    |
| sh     | shunt                                            |
| x      | X-axis                                           |
| y      | Y-axis                                           |
| z      | Z-Axis                                           |
References

[1] Abd-Allah S R, Abdellatif O E and Yousef El-Kady E S 2016 Performance of Cooling Photovoltaic Cells using Nanofluids Performance of Cooling Photovoltaic Cells using Nanofluids Eng. Sci. Res. J. no. 25 pp. 1–15.

[2] Khanjari Y, Pourfayaz F and Kasaeian A B 2016 Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system Energy Convers. Manag., vol. 122 pp. 263–278.

[3] Lari M O and Sahin A Z 2017 Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications Energy Convers. Manag., vol. 149, no. June pp. 467–484.

[4] Sopian K, Al-shamani A N, Mat S, Hasan H A and Azher M 2016 Optimizing Nanofluids with the Optimum of Round Tube Design on the Performance of PVT Collector The 3rd Engineering Science and Technology International Conference.

[5] Tzivanidis C.2017 Yearly performance of a hybrid PV operating with nanofluid, Renew. Energy, vol. 113 pp. 867–884.

[6] Sardarabadi M and Passandideh-Fard M 2016 Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT), Sol. Energy Mater. Sol. Cells, vol. 157 pp. 533–542.

[7] Younis A, Onsa M, AlhorrY and Elsarrag E 2018 The Influence of Al 2 O 3 - ZnO-H 2 O Nanofluid on the Thermodynamic Performance of Photovoltaic- Thermal Hybrid Solar Collector System, Innov. Energy Res., vol. 7, no. 1 pp. 1–8.

[8] Nasrin R, Rahim N A, Fayaz H and Hasanuzzaman M 2018 Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research, Renew. Energy, vol. 121 pp. 286–300.

[9] Shahad H, Abbood M H and Dakhel Z J 2019 Experimental Investigation of the Performance of Photovoltaic Module and Water Cooled Photovoltaic/Thermal System under Middle of Iraqi Climatic Conditions International Journal of Engineering & Technology, 8,1.5 P 237-247.

[10] Michael J J and Iniyan S 2015 Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide - water nanofluid Sol. Energy, vol. 119 pp. 439–451.

[11] Al-Waeli A H, Chaichan M T , Kazem H A and Sopian K 2017 Comparative study to use nano-(Al2O3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors Energy Convers. Manag., vol. 148 pp. 963–973..

[12] Popovici C G, Hud\csteanu S V , Mateescu T D and Cherechecs N C. 2016 Efficiency improvement of photovoltaic panels by using air cooled heat sinks Energy Procedia, vol. 85 pp. 425–432.

[13] Holman J P 2001 Heat transfer, eighth SI metric edition Mc Gran--Hill B. Co.

[14] Alwan A A and Hassan A M 2018 Development of Electrical Power Output Simulation for Photovoltaic Cell J. Eng. Appl. Sci., vol. 13 pp. 10713–10724.

[15] http://www.istarphotosolar.com 2019 ISTAR photovoltaic modules.