Efficiency enhancement of solar cell collector using Fe$_3$O$_4$ / water nanofluid

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Abstract. Increasing temperature of cell’s surface considers one of the most parameters that affected the performance of Photovoltaic thermal collector (PVT).

A numerical study aid by Ansys Fluent was employed in this study to investigate the performance of PV solar cell energy analysis under the same climatic condition of Sherqat-Iraq. A validated CFD model was used in this investigation. It was included six cases four concentrations of ($\text{Fe}_3\text{O}_4$/water) nanofluid, one employed pure water and one used non-cooling PV. The collector of PV/T contains an absorber plate made of Aluminium and serpentine pipe made of copper. The system worked under laminar regime at a constant flow rate (0.0075kg/sec). The results showed that the using of nanofluid as coolant increasing the overall efficiency of PV compared with the water-cooling and non-cooling PV solar cell. It was concluded that the highest thermal and electrical efficiencies are 19.5% and 55.45% respectively when using 1% volume fraction of nanofluid.

Keywords: solar energy, nanofluid, photovoltaic thermal collectors, heat transfer.

1. Introduction

Global warming and environmental pollution phenomenon have increased by using conventional sources such as a fossil fuel. Most researches in the twenty-first-century attempt to improve alternative energy applications. Most significant applications of a solar energy are solar cogeneration systems or photovoltaic thermal collectors (PVTs) which can be defined as solar devices that receive solar radiation to produce electricity and heat energy at the same time.

The electrical efficiency of the PVT is 15% to 20% approximately and thermal efficiency about 75% to 80% [1]. There are many parameters, which effect on the performance of PVT collectors, for instance, the intensity of solar radiation, solar cell panel angle and increase the surface temperature of the cell. The last factor, the surface temperature of the cell, considers the base problem for reduction of the solar cell efficiency. The cooling of the cell surface increases the overall efficiency and the lifetime of PVT [2]. The cooling techniques of PVT cell can be classified into passive cooling and active cooling. The passive cooling consists of natural water/air cooling and PCM (phase change material such as paraffin wax) cooling. The active cooling includes forced water/air cooling, nanofluid cooling and refrigerant cooling. Nanofluid is played as the active role for enhancement of the physical properties of base fluids such as thermal conductivity, heat transfer coefficient, density, viscosity, specific heat transfer coefficient. The nanofluid can be defined as a stability mixture of infinitesimal particles called nanoparticles and base fluid such as (water, thermal oil, ethyl glycol and refrigerant). The nanoparticles have a diameter (from 1nm to 100 nm) which have different types based on metal, carbon-based and composite nanoparticles [1-2]. The
nanofluids utilized in several thermal applications such as solar systems, refrigeration systems, heat exchangers and other applications. Teo et al., [2] studied an experimental investigation to indicate the electrical efficiency of the PVT system. Thermal part of the PVT includes a parallel array of ducts. The study reveals that the solar cells with and without cooling, is change the electrical efficiency. Syaﬁqah et al., [3] studied a numerical investigation by using ANSYS to observe the performance of a photovoltaic thermal collector with utilized air and water as a coolant. The greatest environment temperature of (21 °C) and the intensity of radiation was (979 W/m²) according to the weather condition on Dhahran, Saudi Arabia. The results showed that using the water as the coolant has the greatest output power saving compared to air consequently, the water coolant consider more efficient from air coolant. Soltani et al., [4] conducted a comparative study for photovoltaic thermal collector consists of natural cooling, forced air cooling, water cooling and SiO₂-Water and Fe₃O₄-Water nanofluid to compare a performance of cooling for them. The results of this study proved that the nanofluids have better cooling than other methods. Additionally, the SiO₂ -Water nanofluid has a better heat transfer coefficient that achieved the best cooling medium. Rejeb et al., [5] indicated a numerical study by using of four types of nanofluids consist of Al₂O₃ or Cu nanoparticles into water or ethylene glycol base fluids in three cities of Lyon (France), Mashhad (Iran) and Monastir (Tunisia) to estimate the performance of a sheet and tube PV/T. they concluded that water-based nanofluids are more activity in comparison with ethylene glycol-based nanofluids. Khanjari et al., [6] explained a numerical analysis by using of Al₂O₃/water and Ag/water nanofluid in a sheet and tube for cooling of PV/T system. They showed that the energy and exergy efficiency of system boost more when they used Ag/water nanofluid. Also, they revealed that the overall energy and exergy efficiency has a positive effect by increased nanoparticle concentration, while they decrease with increases velocity. Xu and Kleinstreuer. [7] exhibited a computational analysis which used a nanofluid to cool a high concentration photovoltaic cells. They concluded increasing of the nanoparticle concentration boosted electrical efficiency with decreasing of entropy generation. Furthermore, higher electricity output due to decrease the inlet temperature. Khanjari et al., [8] achieved a CFD analysis of a PVT system by using of (Ag-water) and (Al₂O₃-water) nanofluids. It was observed that the boost in the electrical efficiency of (Ag-water) was higher than (AL₂O₃-water). Xu and Kleinstreuer [9] conducted a numerical study of the cooling of a concentrated silicon solar cell by effect of (AL₂O₃-water) nanofluid and the Maxwell’s model used of a multi-junction solar cell for thermal conductivity. The authors concluded that nanofluids are not the most actively working medium for the triple-junction solar cells in comparison with the silicon one. Moreover, this study showed that using diathermic oil replacing of water will get better enhancement for other thermal applications. Generally, they approved that the electrical and thermal efficiencies enhanced by using nanofluids. Xu and Kleinstreuer [10] projected a mathematical study (2-D modelling) to reveal the effect of utilizing (Al₂O₃-water) as a coolant for a photovoltaic cell exposure to greatly concentrate irradiation. The channel was subjected to heat conduction and turbulent nanofluid convection. the efficiency of the system affected by varying of nanoparticle volume fraction. Elmir et al., [11] exhibited a numerical simulation for a one-way channel at the backside of the photovoltaic thermal collector system, the nanofluid (AL₂O₃-water) from ( θ=0%) to (10%) passed inside this channel. The PV/T cells were made from silicon, and the incline angle of the PV/T panel was fixed at 30°. The heat transfer rate increased by (27% at θ=10%) when revealing low values of Reynolds number (Re=5). Hassani et al., [12] indicated a numerical study on two concentrated PVT system modules. The first module (D-1) was containing two separate channels, one of them for the optical nanofluid and the second channel for the thermal nanofluid. The (Ag) has diameter (10nm) nanoparticles found in the optical nanofluid which is distributed in (Therminol VP-1). The results showed when the volume fraction raised from (0.001% to 1.5% ), the overall efficiency increased sharply for (GaAs and SI ).
Rahbar et al., [13] exhibited a mathematical modelling of a system containing a parabolic through concentrator with the concentrated photovoltaic system working on (Ag-water) nanofluid to run an Organic Rankine Cycle. The results shows when using the nanofluid as a coolant medium in CPVT system, the electrical, thermal, and overall efficiencies increase (1.8%, 3.3%, and 5.1%) respectively. This study addressed to inspect the electrical and thermal efficiencies of (PV/T) by using nanofluid under Sherqat city (30 km south of Mosul) climatic conditions. The simlution study of PV/T ANSYS/FLUENT model has been used Fe$_3$O$_4$/water nanofluid with concentration from 0.25 to 1% to improve the performance of PV/T.

2. Mathematical Model

The PV/T shown in figure 1, is the schematic diagram of the system undertaken in this study. The equations are summarized to evaluate the performance of the hybrid photovoltaic cell that cooled by using (Fe$_3$O$_4$/water), distilled water and without cooling. These equations included calculations the thermophysical properties of nanofluid, solar angles, solar irradiation that falls on the tilt photovoltaic cells in addition to insert thermal equations that include calculations of the total heat transfer coefficient, heat gain energy equation, the efficiency factor of thermal collector, heat removal factor and thermal efficiency for each solar cell. Finally inserting of electrical equations such as short circuit current, open-circuit voltage and electrical efficiency.

![Figure 1. Schematic diagram of PV/T.](image)

2.1. Thermophysical properties of nanofluid

The density, specific heat, viscosity and thermal conductivity are evaluated to represent the thermophysical properties of nanofluid as [14]:

$$\rho_{nf} = (1 - \varphi)\rho_w + \varphi \times \rho_p$$  \hspace{1cm} (1)

$$C_{p_{nf}} = \frac{(1 - \varphi)(\rho c_p)_w + \varphi(\rho c_p)_p}{(1 - \varphi)\rho_w + \varphi \times \rho_p}$$  \hspace{1cm} (2)

$$\mu_{nf} = (1 + 2.5\varphi)\mu_w$$  \hspace{1cm} (3)
The thermophysical properties of solid nanoparticles, base fluid and Fe3O4/water nanofluid are indicated in tables 1 and 2 respectively.

Table 1. Thermo Physical properties of pure water and (Fe3O4) Nano-Particles.

| Material          | ρ ($g/cm^3$) | k (w/m.k) | Cp (J/kg.K) | Re (pa.s) |
|-------------------|--------------|-----------|-------------|-----------|
| Water             | 0.9982       | 0.6       | 4182        | 0.001003  |
| Fe3O4 Particle    | 5.2          | 6         | 670         | 0.00106   |

2.2. Electrical model equations:

These equations include calculations of $I_{SC}$, $V_{OC}$, $P_{MAX}$ under effect of under the influence of the surface temperature of the cell, as well as the intensity of solar radiation [15].

The short-circuit current is evaluated by using this equation:

$$I_{SC}(T) = I_{SC}(T_{ref}) \frac{G}{1000} \left( \beta_{I_{SC}} * \left( T - T_{ref} \right) + 1 \right)$$ (5)

The open-circuit voltage is calculated by using this equation:

$$V_{OC}(T) = V_{OC}(T_{ref}) \left( \beta_{V_{OC}} * \left( T_s - T_{ref} \right) + 1 \right) + \beta_{V_{OC}} \ln \left( \frac{G}{1000} \right)$$ (6)

the maximum power is estimated by using the equation follow:

$$P_{MAX}(T) = P_{MAX}(T_{ref}) \frac{G}{1000} \left( \beta_{P_{MAX}} * \left( T - T_{ref} \right) + 1 \right)$$ (7)

On the other hand, the thermal model equations included the overall heat transfer coefficient for each layer of PV/T in addition to heat balance equations that used to estimate thermal efficiency for collector. These equations used for some assumptions [16]:

1- The system considered to be in a stable heat transfer over time.
2- The permeability of the EVA layers is approximately 100%.
3- Neglecting the heat capacity of glass, silicon, aluminium and copper because the specific heat value or the tendency of temperature is very low along its fish.
4- One-way thermal flow.
5- Neglecting the thermal loss of the sides of the normal and hybrid solar cells.
6- The filling factor (the ratio between the surface area of the solar collector and the surface area of the photovoltaic cell) is equal to one.
2.3. **Thermal equations for non-cooling photovoltaic cell**

The equilibrium summarized by representing the thermal resistances of the PV cell, as well as showing the total energies in and out of it, as shown in the figure 2a [17].

The efficiency is calculated as:

\[ \eta_e = \frac{P_{\text{Max}}}{A \times G} \]  \tag{8}

Where:

\[ P_{\text{Max}} = FF \cdot I_{SC}(T_c), V_{OC}(T_c) \]  \tag{9}

2.4. **Thermal equations for cooling photovoltaic cell**

The equilibrium summarized by representing the thermal resistances of PV/T cell, as well as showing the total energies in and out of it, as shown in the figure 2b [17].

The inputs of the theoretical equations include the ambient temperature, the inlet temperature of the fluid, the physical properties of the fluid, dimensions of component and the fluid flow rate of the hybrid solar cells. Moreover, the outputs of the theoretical equations are the cell surface temperature, fluid exit temperature and the efficiency of thermal and electrical energy for solar cells.

\[ \text{(a) non-cooling PV.} \quad \text{(b) PVT.} \]

**Figure 2.** Thermal resistance of PV.

3. **Simulation study**

3.1. **Governing equations of heat energy**

Some equations applied in this CFD simulation such as continuity equation, momentum equation and energy equation [18]. The Continuity equation:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \]  \tag{10}

Momentum equation:

\[ \rho \frac{\partial \vec{u}}{\partial t} = \frac{\partial (-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + S_{Mx} \]  \tag{11}
Also, Navier Stokes equation:

\[
\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} = -\frac{\nabla p}{\rho} + \frac{u}{\rho} (\vec{v} \cdot \nabla) \vec{v}
\]  \tag{12}

Energy equation:

\[
\rho c_p \left( u \frac{\partial T}{\partial t} + v \frac{\partial T}{\partial t} + w \frac{\partial T}{\partial t} \right) = K \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \mu \varphi
\]  \tag{13}

3.2. CFD analysis

In this study, evaluate the performance of three photovoltaic solar cells one of them cooled by distilled water, second of them cooled by \((Fe_3O_4/water)\) by using four-volume concentrations \((0.25\%, 0.5\%, 0.75\% \text{ and } 1\%)\) in \((5 \text{ L})\) of water and other without cooling PV under the effect of climate conditions of Sherqat city in Iraq \((35^\circ38\text{N and } 43^\circ18\text{E})\). The volume flow rate is constant and equal to \((450 \text{ mL/min})\), ambient temperature \((305.1 \text{ k})\) and inlet temperatures are \((305.6 \text{ K})\) and solar irradiation \((830 \text{ w/m}^2)\). All data of solar systems illustrated in table 3.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
\textbf{Characteristic} & \textbf{Magnitude} \\
\hline
Photovoltaic solar cell and capacity & 36 cells, polycrystalline, 100W \\
Open circuit voltage Voc & 22.43 V \\
Short circuit current Isc & 2.8593 A \\
Maximum power voltage & 18.84 \\
Maximum power current & 2.6761 \\
Glass thickness & 0.003m \\
Silicon layer thickness & 0.00022m \\
Tedlar thickness & 0.0005m \\
Absorber plate and thickness & Aluminium, 0.0003m \\
Insulation and thickness & Foam, 0.02m \\
Area of PV cell & 0.3 m\(^2\) \\
Absorptivity of glass & 0.04 \\
Transmissivity of glass & 0.96 \\
Absorptivity of silicon & 0.9 \\
Reference temperature & 25 \(^\circ\)C \\
Thermal conductivity of glass & 1 W/m.K \\
Thermal conductivity of silicon & 148 W/m.K \\
Thermal conductivity of Tedlar & 0.35 W/m.K \\
Thermal conductivity of absorber Plate & 202.4 W/m.K \\
Thermal conductivity of insulation & 0.04 W/m.K \\
Thermal conductivity of copper & 308 W/m.K \\
Pipe configuration & Serpentine figure, 9.5 m length, 0.006m inside diameter, 0.008m outside diameter and distance between centre to centre diameters 0.04 m. \\
Fixed tilt angle & 35 \(^\circ\), facing south \\
Conversion factor & 0.38 \\
Packing factor & 1 \\
Fill factor & 0.786 \\
\hline
\end{tabular}
\caption{Characteristic of solar system.}
\end{table}
The assumptions of this numerical study are the Iraq environment of solar intensity and temperature are applied with two sides insulation as shown in figure 3. In order to achieve the performance of PV solar cell at different cases (three types of photovoltaic solar cells one of them cooled by (Fe₃O₄/water), second of them cooled by distilled water and other non-cooling) the test rig has been performed. The numerical analysis of PV and PV/T solar cells explain distribution temperature for all layers and distribution. The incident solar irradiation on the top surface of the PV cell assumed as heat flux, which is penetrated the glass layer and absorbed by silicon layer some of the solar irradiation will lose to ambient. The parts of the PV solar cell has been described as in Table 4.

| Parts      | ρ (kg/m³) | k (w/m.k) | Cp (J/kg.K) |
|------------|-----------|-----------|-------------|
| Glass      | 3000      | 1         | 500         |
| Silicon    | 2330      | 148       | 677         |
| Tedlar     | 960       | 0.35      | 2090        |
| Absorber   | 2719      | 202.4     | 871         |
| Pipe       | 8978      | 387.6     | 381         |
| Insulation | 80        | 0.04      | 1120        |

Figure 3a presents the methodology of CFD simulation which used design modeller of ANSYS 2020 R1 software draw the geometric of PV/thermal system. The mesh that used is Hexa type and some triangle type with (845874 nodes) and (753760 elements) as shown in figure 3b. The system coupling of steady-state thermal and ANSYS/FLUENT software used to present the heat transfer between layers of PV/T solar cell. The grid independent test has been conducted for validation of meshing that selected in this study with the data of Ebaida [19].

4. Results and Discussion

In this part, the results discussed for each case of PV and PV/T solar cell, under solar radiation (830 W/m²) and ambient temperature (32.1°C) with low heat transfer coefficient (5.05), the surface of PV solar cell reaches to 53.428°C as shown in figure 4.
Figure 4. Temperature distribution of non-cooling PV.

Under same conditions of non-cooling and inlet temperature of pure water (32.6 °C), the average surface temperature of PV/T cell decreased to (41.42395 °C) and average outlet temperature was (45.11934 °C), furthermore the electrical and thermal efficiencies were (65.23212% and 7.046632%) respectively as shown in figure 5. For PV/T cell with four Fe₃O₄/water nanofluid volume concentrations 0.25% and 1%, the surface temperature of the PV/T cell decreased to 41.32612 °C and 41.24937 °C respectively. Likewise, both the thermal and electrical efficiencies increased to 66.24922% and 7.135032% for 0.25% volume concentrations while increased to 68.22034% and 7.287797% respectively for 1% volume concentrations as shown in figure 5b.
The total pressure dropped inside flow directly proportional with increased volume fraction of nanofluid but this drop was slightly. The inlet pressure for pure water and (0.25%, 0.5%, 0.75%, and 1%) volume fraction of nanofluid equal to (102422 Pa, 102435 Pa, 102437 Pa, 102439 Pa, 102441 Pa) respectively as shown in figure 6.

This study noted that the surface temperature of PV/T decreased with increasing the volume fraction concentrations as shown in figure 8. The lowest temperature achieved by case of (1% volume fraction), where the temperature reached to (314.15 K). This reduction was (3.76%) compared with non-cooling PV cell.
This study conducted the temperature of the hybrid cell increased with increasing the volume concentration of nanoparticle moreover the highest outlet temperature was (39°C) at volume fraction (5%). Figure 7, showed the change outlet temperature concerning volume fraction: This study showed that thermal and electrical energies proportional directly with volume fraction concentrations of (Fe3O4/water) nanofluid as shown in figure 8, the highest thermal and electrical energies were (169.8687W & 18.1466W) that achieved at (0.01% volume fraction).

![Figure 8. Thermal and electrical energy with volume concentrations.](image)

Thermal and electrical efficiencies increased with increasing volume fraction of (Fe3O4), highest efficiencies achieved at volume fraction (5%), were increased by (37.60651%) compared with cooling by pure water as shown in figure 9a. Furthermore, the electrical efficiency increased by (4.8%) at non-
cooling case to (9.05%) at cooling with volume fraction (5%) as shown in figure 9b. The results have been compared with other data available in the literature with good agreement.

![Figure 9. Thermal and electrical energies of PV/T.](image)

Figure 10 illustrated the effect of nanofluid concentration on the efficiency of the system under climatic conditions of Sherqat-Iraq. It can be seen that the thermal efficiency is increased from 15% to 33.9% with increasing of nanofluid volume concentration from 0.2% to 1% respectively. Likewise, the electrical and overall efficiency are increased from 7% and 42.9% to 19.5% and 55.45% respectively as increased of nanofluid volume concentrations form 0.2% to 1%.

![Figure 10. Thermal, electric and overall efficiency with nanofluid volume fraction.](image)
The behaviour of the system efficiency against nano fluid volume concentrations is agreed to the experimental investigation [19] under same climatic conditions and the values have deviations not more than 5% due to deferent area and season.

5. Conclusion
Numerical analysis of cooling PV solar cell of (50W) was carried out using water and different concentration (0.25%, 0.5%, 0.75% and 1%) of Ferrofluid (Fe$_3$O$_4$) in addition to non-cooling PV cell. All cases of PV/T worked under laminar flow regime at a constant flow rate (450mL/min) under solar radiation (830 w/m$^2$), the inlet and ambient temperature was (32.6 °C and 32.1 °C) respectively under climate condition of Sherqat-Iraq during March. The study concluded computing thermophysical properties of the nanofluid and evaluated thermal and electrical performance of the PV cell. The study concluded the optimum efficiencies achieved at 1% volume fraction, where the thermal and electrical efficiencies achieved (68.22034% and 7.287797%) and the highest heat transfer coefficient was (543.34 W/m$^2$.K) at the same concentration. The temperature of PV solar cell decreased from (53.4 °C) at non-cooling case to (41.15706˚C) at 1% volume fraction of nanofluid. Finally, this study proved that using (Fe$_3$O$_4$/Water) nanofluid achieved significant performance of PV solar cell compared with water-cooling and non-cooling cases. The numerical results have been validated with other previous data.

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Nomenclatures

- $\mu_{\text{eff}}$: Viscosity of nanofluid.
- $m_p$: Mass of nanoparticles.
- $\mu_{\text{p}}$: Viscosity of nanoparticle.
- $m_b$: Mass of base fluid.
- $\phi$: Concentration of nanoparticle (volume fraction).
- $v_p$: Volume of nanoparticles.
- $\phi_{\text{p}}$: Concentration of nanoparticle.
- $v_b$: Volume of base fluid.
- $\rho_{\text{eff}}$: Density of nanofluid.
- $c_{\text{p},\text{eff}}$: Specific heat of nanofluid.
- $\rho_p$: Density of nanoparticles.
- $c_{\text{p},\text{p}}$: Specific heat of base fluid.
- $\rho_b$: Density of base fluid.
- $c_{\text{p},b}$: Specific heat of base fluid.
- $k_{\text{eff}}$: Thermal conductivity of nanofluid.
- $Pe_{\text{p}}$: Particle Peclet number of nanofluid.
- $K_p$: Thermal conductivity of nanoparticles.
- $Re$: Renold number of nanofluid.
- $k_b$: Thermal conductivity of the base fluid.
- $Pr$: Prandtl number of nanofluids.
- $\delta$: Declination angle.
- $\phi$: Latitude angle.
- $\omega$: Hour angle.

- $G_H$: Global radiation on Horizontal earth surface.
- $G$: Total radiation on tilt surface.
- $I_{\text{SC}}$: Short circuit current.
- $V_{\text{OC}}$: Open voltage circuit.
- $P_{\text{MAX}}$: Maximum power of PV.

- $\alpha_s$: Absorptivity of silicon layer.
- $\tau_g$: Transmissivity of glass layer.
- $\eta_e$: Electrical efficiency of PV.
- $T_e$: Surface temperature of PV.
- $T_a$: Ambient temperature.
- $T_{\text{BS}}$: Backside temperature of absorber plate.
- $T_f$: Average temperature of work fluid.
- $F'$: Collector efficiency factor.
- $F$: Fin efficiency.
- $F_{\text{RM}}$: Heat removal factor.
- $T_{\text{fo}}$: Outlet temperature.
- $T_{\text{in}}$: Inlet temperature.
- $Q_u$: Useful heat energy.
- $A_m$: Surface area of PV.
- $m$: Mass flow rate.
- $FF$: Fill factor.
- $\eta_{\text{PV/T}}$: Overall efficiency of PV/T.
- $T_s$: Sky temperature.
$\theta$: Incident angle.  
$\theta_z$: Zenith angle.  
$\beta$: tilt angle.  
$G_{bb}$: Direct radiation for tilt surface.  
$G_{d\beta}$: diffuse radiation for tilt surface.  
$G_{DN}$: Normal radiation.  
$G_r$: reflect radiation.

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