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Research Article

Effect of Using Hybrid Nanofluid in Thermal Management of Photovoltaic Panel in Hot Climates

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Photovoltaic (PV) cells have been applied for direct conversion of solar radiation into electricity. Their performance is significantly affected by the working temperature. Due to the higher efficiency of the cells in lower temperatures, several thermal management approaches have been applied in recent years. Employing liquids as coolant is one of the efficient approaches in cooling down the PV cells. Using fluids with enhanced heat transfer properties would lead to further improvement in the output of the cells. In this paper, utilization of a hybrid nanofluid, with improved thermophysical characteristics, is numerically investigated by applying Computational Fluid Dynamics (CFD). Results revealed that by employing the low concentration hybrid nanofluid instead of water, higher efficiency and consequently electrical output are achievable. The maximum enhancement in the efficiency of the cell compared with the reference case without cooling is around 35.66% which is obtained in case of using the nanofluid with mass flow rate of 0.0002 kg/s and solar irradiation of 1000 W/m^2.

1. Introduction

Industrialization progress and the population growth have caused remarkable increment in world total electricity consumption in recent years. According to the data provided by International Energy Agency (IEA) [1], world electricity consumption has increased from around 14157 TWh in 2000 to more than 24738 TWh in 2018. Along with the growth in energy and particularly electricity consumption, carbon dioxide emission has increased from about 23241 Mt in 2000 to around 33513 Mt in 2018. These data reveal the necessity of utilizing more efficient and cleaner energy technologies to both supply the energy demand of the world and decrease the corresponding environmental issues. In this regard, different types of renewable energy technologies have been evolved in recent decades [2]. These technologies can be used for wide variety of applications from power generation to desalination [3–5]. Among the renewable energy sources, solar is one of the most attractive ones due to its high amount and wide availability. This source of energy is applicable for electricity generation both in direct and indirect ways. For direct electricity generation, PV cells are employed while there are several configurations that are applicable for indirect electricity generation from solar energy.

Compared with the solar thermal systems, there are some benefits in utilizing PV cells for power generation. For instance, PV cells can be applied in small-scale and portable utilization. In addition, these cells can be easily integrated with other renewable sources to provide hybrid technologies with higher reliability. According to the data of IEA, as shown in Figure 1, solar PV electricity generation has increased from 800 GWh in 2000 to about 554382 GWh in 2018 [1]. The output of the PV cells is mainly dependent on the received solar irradiation, area of the cell, and its efficiency. Higher solar irradiance means higher received energy, which leads to increase in the output of the cell at constant efficiency. The efficiency of the cells depends on

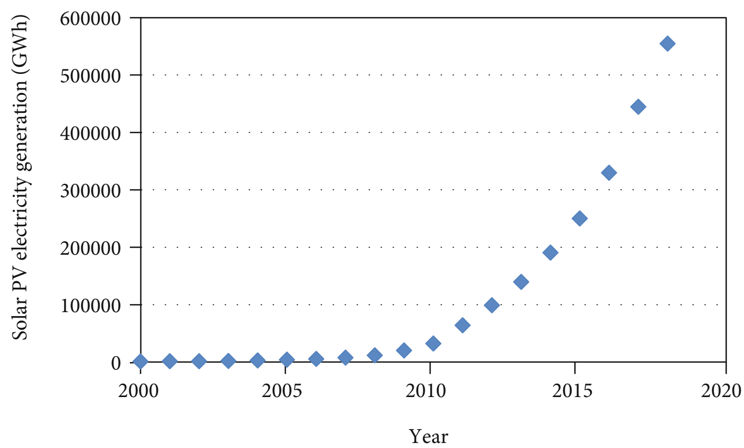
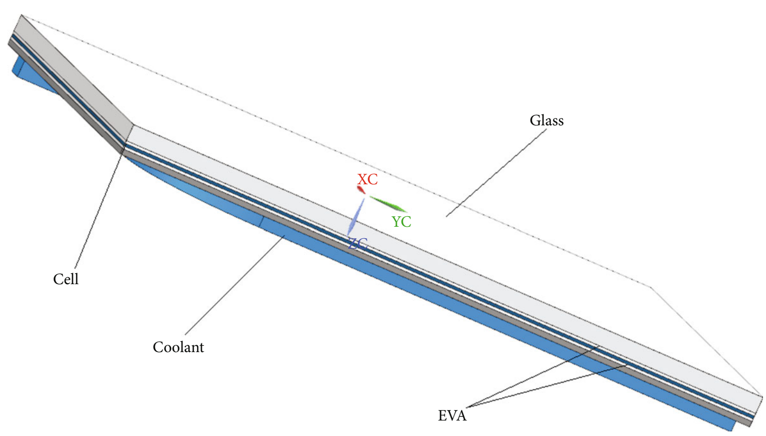


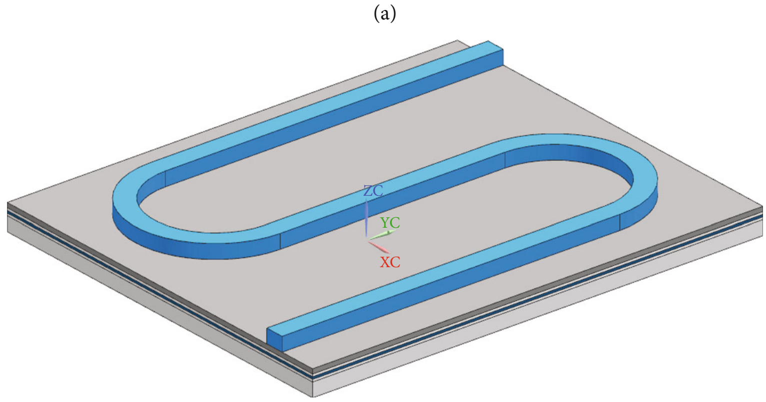
Figure 1: Solar PV electricity generation in the world between 2000 and 2018 [1].

Table 1: Properties of the layers.

	Thickness (mm)	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
Glass (CFX library)	3	2500	750	1.4
EVA [16]	0.5	960	2090	0.35
Cell [9]	0.5	2330	677	148
Tedlar [16]	1	1200	1250	0.2



(a)



(b)

Figure 2: Schematic of the model.

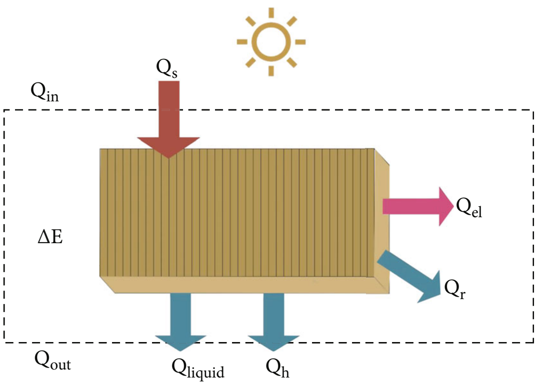


Figure 3: Conservation of energy in solar panel (q_h, q_r, q_{el}, q_{liquid}, and q_s are the convective and radiative heat transfer, generated electricity, heat removal from the cell by coolant, and the absorbed heat from the solar radiation, respectively).

Table 2: Thermophysical properties of coolants at 20°C [15].

	Density (kg/m^3)	Dynamic viscosity (m Pa.s)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)
Water	998.5	0.79	0.602	4182
MWCNT-Fe_3O_4/water (0.3%)	1055	1.01	0.6856	4131

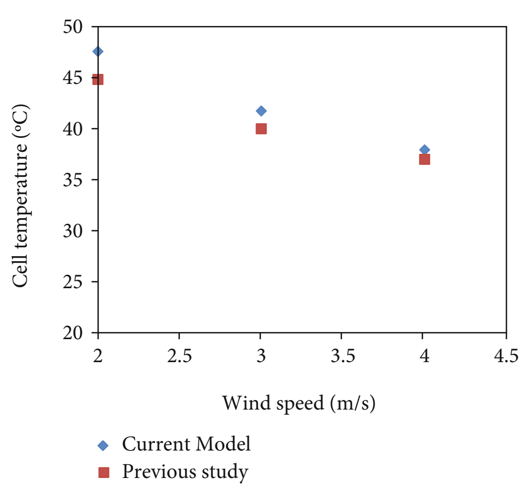


Figure 4: Comparison of the results of the current model with previous study at $q_s = 1000\,\mathrm{W/m^2}$ [17].

some factors such as their material and temperature. Since the cells produce higher electricity at lower temperatures, several cooling approaches have been tested for their thermal management.

Alizadeh et al. [6] conducted numerical simulation on thermal management of a PV cell by using pulsating heat pipe. They found that by employing the heat pipes, output of the cell can be increased by up to 18%. In another work [7], array of ducts were applied at the back of a cell for cooling it by using airflow. It was found that employing airflow as coolant increased efficiency of cell in range of 12-14%, while its efficiency without cooling was in range of 8-9%. Hasan et al. [8] applied a passive thermal management unit by using phase change material for this purpose. They found that using this approach in hot climate condition can lead to annual enhancement of 5.9% in electrical output. Among different approaches, using liquids as coolant is one of the most attractive ones that is investigated in several papers. For instance, Alizadeh et al. [9] compared the performance of water flow cooling and heat pipe-assisted thermal management approach and found that using water leads to higher decrease in the temperature of the cell. In another work, Maleki et al. [10] investigated cooling of a PV cell by using water as coolant and found that thermal management of the cell is more useful at higher ambient temperatures and solar irradiances.

The effectiveness of liquid cooling approach can be modified by employing fluids with improved thermophysical characteristics. Nanofluids, composed of suspended solid structures and a base fluid [11, 12], are attractive alternatives for heat transfer improvement [13, 14]. In this regard, these fluids can be applied for thermal management of solar systems such as PV cells. In this work, numerical simulation is applied to investigate impact of using a hybrid nanofluid (MWCNT-Fe_3O4/water) in 0.3% vol concentration for thermal management of a PV cell for the first time by considering the thermophysical properties obtained in another experimental work [15]. Furthermore, different parameters such as mass flow rate of the coolants, solar irradiance, and concentration of the nanofluid are considered to gain deeper insight. The procedure of simulation and the results are presented in the following sections.

2. Method

In order to numerically simulate the current problem, a PV cell with length and width of 120 mm and 1000 mm, respectively, is considered as case study. In addition, a meandering channel is considered at the back of cell with width and depth of 5 mm and 3 mm, respectively. The considered cell is composed of five layers including glass, first EVA, silicon cell (monocrystalline), second EVA, and tedlar. The properties of each layer are provided in Table 1. The schematic of the model is shown in Figure 2.

To obtain the temperature of the cell, energy equation is used. As shown in Figure 3, absorbed solar irradiation by the cell is converted into electricity, increasing its internal energy, and the remained part is dissipated via convection and radiative heat transfer as shown in Figure 3. To simplify the simulation, generated power by the cell is assumed as heat dissipation.

In order to determine the solar cell surface temperature, energy equation has been used. The considered cell in the current study is monocrystalline type, and its specifications are represented in Ref [6] and Table 1. According to Figure 3, part of the absorbed radiation by the solar cell is dissipated to environment via radiation and convection heat transfer. Part of the remaining energy is converted into electricity, and the other part is used to increase the internal energy of solar cell.

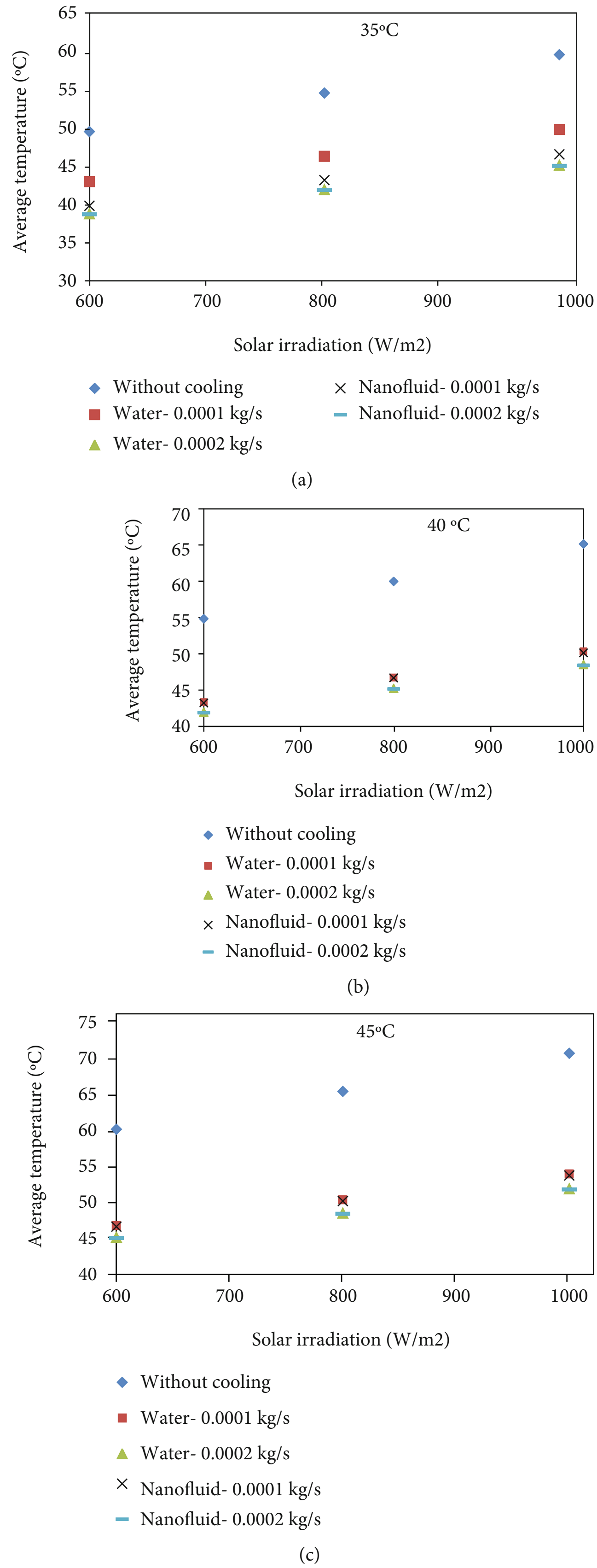


FIGURE 5: Average temperature of cell vs. solar irradiation at ambient temperatures of (a) 35°C, (b) 40°C, and (c) 45°C.

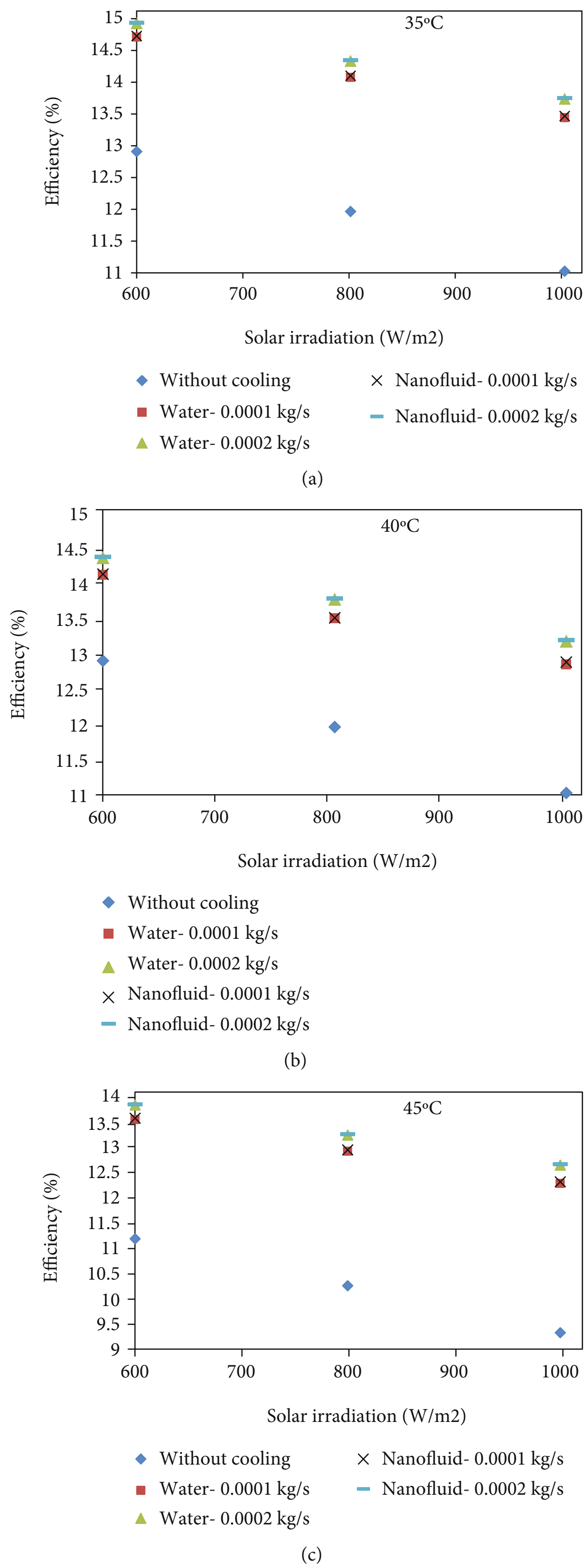


Figure 6: Efficiency of cell vs. solar irradiation at ambient temperatures of (a) 35°C, (b) 40°C, and (c) 45°C.

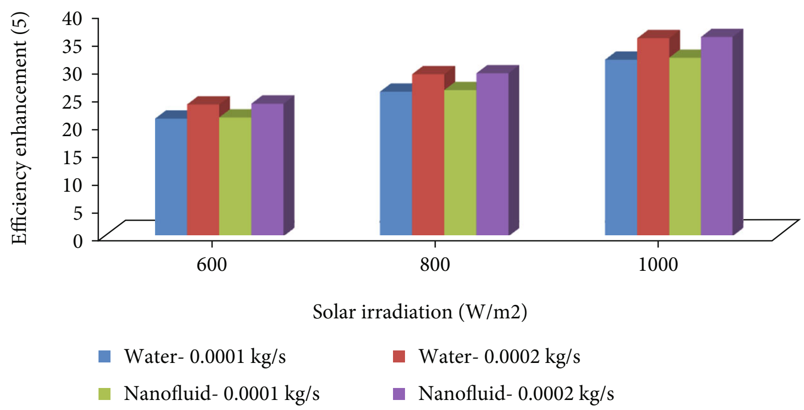


FIGURE 7: Efficiency enhancement of the cell in different cooling conditions.

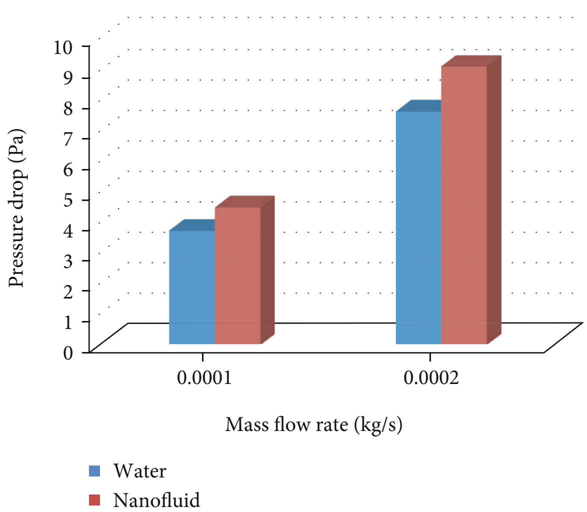


FIGURE 8: Pressure drop vs. mass flow rates of coolants.

Solar cell energy conversion can be expressed as follows:

$$\rho C_p \delta \frac{dT_s}{dt} = q_s - q_{\mathrm{el}} - q_h - q_r - q_{\mathrm{liquid}}. \quad (1)$$

In Equation (1), q_h, q_r, q_{el}, q_{liquid}, and q_s refer to the convective and radiative heat transfer, generated electricity, dissipated heat by the fluid flow, and the absorbed heat from the solar irradiation, respectively. The absorbed heat by the cell is obtained as follows:

$$q_s = \varepsilon_0 Q_s. \quad (2)$$

In the above equation, Q_s refers to the normal solar irradiation and ε_0 is absorption coefficient that is assumed equal to 0.9 here.

As mentioned, generated electricity is considered as heat sink, which can be determined as follows:

$$q_{\mathrm{el}} = \beta Q_s. \quad (3)$$

In Equation (3), β refer to the efficiency of the cell in converting the solar irradiation to electricity which is temperature dependent and determined as follows [6]:

$$\beta = -0.1757\, T_s + 21.737, \quad (4)$$

where T_s is the temperature of the cell. To determine the convective and radiative heat transfers, Equations (5) and (6) are used, respectively [6]:

$$q_h = h_h \left(T_s - T_a\right), \quad (5)$$

$$q_r = \varepsilon_1 \sigma_{\mathrm{sb}} \left(T_s^4 - T_a^4\right). \quad (6)$$

In Equation (5), T_a and h_h are ambient temperature and convective heat transfer coefficient, respectively. In Equation (6), ε_1 and σ_{sb} are emissivity and Stefan Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{W/m^2K^4}$), respectively. Radiative heat transfer is applied on both upper and lower sides of the cell.

Convection heat transfer is considered on the walls of cell components. In order to simplify the simulation, Equation (7) is used to obtain convective heat transfer coefficient [6].

$$h_h = 2.8 + 3.8 u_w \left(\mathrm{W/m^2K}\right). \quad (7)$$

In Equation (7), u_w refers to the wind speed in m/s. Here, the speed of wind is considered equal to 2 m/s in all of the simulations. In the current work, two coolants including water and MWCNT-Fe_3O4/water in 0.3% concentration are used in the simulation. The inlet temperature of the coolant in all simulation is considered equal to 20°C. The properties of these fluids are provided in Table 2. Since the variations of the temperatures of the coolants are very low, lower than 5°C, it is assumed that the thermophysical properties of the coolants are constant.

ANSYS meshing is applied in this study to generate mesh on the model. After grid independency investigation, sizes of the meshes were selected for each domain. In this condition, the total number of nodes was around 2,600,000. To solve the mentioned equations in the considered domains, ANSYS CFX 16.0 is employed. Here, two mass flow rates of coolant including 0.0001 kg/s and 0.0002 kg/s are considered in simulation. In addition, three ambient temperatures including 35°C, 40°C, and 45°C are applied in the model. According to the values of Reynolds number, the coolant flow is laminar. The convergence criterion for the simulation is RMS of 10^{-5}. The maximum numbers of iteration in each case were set to 150, which was appropriate number according to the monitored values of cell temperature. The obtained results are provided in the upcoming section.

3. Results and Discussion

The results of the present simulation are compared with another study to validate the model. As shown in Figure 4, the temperatures of the cell without employment of any cooling medium are compared in ambient temperature of 18°C and different wind speeds in range of 2-4 m/s and $q_s = 1000\,\mathrm{W/m^2}$. As it can be noticed, the results are very close which demonstrates the validity of the present simulation. The maximum relative difference between the results of the present model and the previous one is around 6.1%.

In this study, PV cell is numerically simulated under different operating conditions to investigate the effective parameters. In this regard, the performance of cell in cases of using liquid cooling and without applying any thermal management is investigated. In Figure 5, the temperatures of the cell in cases of using different coolants at ambient temperatures of 35°C, 40°C, and 45°C are compared. According to these data, it is concluded that by applying thermal management, the temperature of the cell could be remained in more favorable ranges which leads to higher electrical output. Furthermore, it is understood that using the nanofluid as coolant is preferred compared with water, which is attributed to higher heat transfer rate due to the modified effective thermal conductivity. In addition, it can be seen that increase in mass flow rate leads to more reduction in the temperature of the cell; however, it should be mentioned that high mass flow rates of the coolant mean more required pumping energy which causes increment in the investment cost of the system. In this regard, low mass flow rates are considered here to avoid the corresponding issues.

To achieve deeper insight into the effect of applying thermal management on the efficiency enhancement of the cell, the efficiency is compared in different conditions of simulation. As shown in Figure 6, applying the thermal management approach leads to higher efficiency of the cell. Similar to temperature, variations in the efficiency in comparison with the reference case (without cooling) are more remarkable in higher concentrations of nanofluid and mass flow rate of the coolant. In these conditions, employing cooling is more effective; consequently, higher efficiency would be achieved. In addition, it can be concluded that by increase in the solar irradiation, the efficiency of the cell is increased which is due to increment in its temperature owing to higher energy input. Finally, in Figure 7, efficiency enhancement compared with the reference case (without any thermal management) is compared. As shown in this figure, using nanofluid results in higher efficiency enhancement in comparison with water due to its more efficient heat transfer. The maximum enhancement in the cell efficiency is around 35.66% in case of using the nanofluid in 0.0002 kg/s mass flow rate, solar irradiation of $1000\,\mathrm{W/m^2}$, and ambient temperature of 45°C. Finally, the pressure drops of the investigated cases are compared in Figure 8. As shown in this figure, the pressure drops for the considered cases are low. By multiplying the volume flow rate in the obtained values of pressure drop, the maximum determined pumping power is around 1.72×10^{-6}, indicating the feasibility of this cooling approach in terms of energy output.

4. Conclusion

In the present work, effect of using water and MWCNT-Fe_3O4/water in two concentrations as coolant on the thermal management of a PV cell is numerically investigated. In this regard, CFD is used for simulation under different operating conditions by changing the mass flow rate of coolant, ambient temperature, and solar irradiation. According to the determined values by CFD, using this cooling technique leads to significant reduction in the operating temperature of the cell and consequently the efficiency and electrical output. Moreover, it is found that increasing the mass flow rate of the coolants results in more efficient thermal management. Enhancement in the cell cooling by employing the nanofluid is mainly attributed to the increased thermal conductivity of the coolant. To sum up the results, it is reasonable to use the nanofluid in thermal management of PV cells, especially in hot climate conditions. By using this approach, it is possible to increase the efficiency of electricity generation by more than 35% in solar irradiation of $1000\,\mathrm{w/m^2}$ and ambient temperature of 45°C.

Data Availability

Data are available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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