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Performance Enhancement of a Photovoltaic Cell Working in Hot Environment Conditions using Al_2O_3 Nanofluids: A CFD Study

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ABSTRACT

The performance of photovoltaic cells is affected by the cell's temperature resulting from the ambient temperature. The solar cell's efficiency decreases significantly in hot regions due to its high temperature. In this work, the effect of cell temperature on the performance and efficiency of a photovoltaic cell consists of three layers is studied using a three-dimensional CFD model. A serpentine circular pipe has been fixed behind the aluminium plate and used as a heat exchanger to transfer the heat from the photovoltaic cell to the pipe fluid and reduces the photovoltaic cell temperature. Alumina nanoparticles (Al_2O_3) has been chosen due to the good chemical stability in the base fluid (water), relatively low cost compared to other nanoparticles, and most importantly, a lot of literature concluded that using Al_2O_3 nanofluid can improve the heat transfer in heat exchangers. Nanoparticles of Al_2O_3 were added to the water at a rate of 4% to improve the thermal performance and efficiency of the heat exchange. The results showed an improvement of approximately 10% in the photovoltaic electrical efficiency when using the water cooling method and about 12% when using the nanofluid. The importance of the results in this study illustrates the possibility of increasing the performance and efficiency of the photovoltaic cell by cooling it in hot environment conditions with water alone and also with nanofluids by using a small percentage of nanoparticles.

Keywords: Photovoltaic Cell, Nanofluids, CFD, Hot Environment.

1. INTRODUCTION

The solar cells are used to receive solar energy and convert the solar energy into electrical energy. There are millions of solar cells in a piece of a solar panel. Each cell consists of P and N semiconductor layers. These P and N layers are susceptible to light. When these P and N semiconductor layers receive the light energy, the electrons in the layers jump into the conduction layer. The external resistance connected across the P and N layers will cause the current conducts. The P and N layers holding the electrons also will form a potential difference across the terminal of the cell. According to the research [1], each cell can contribute to the average voltage of 3.7 mV to 48 mV. A combination of solar cells in series connection is required to increase its voltage level. The cells can be placed in a block with m × n matrix, where m and n are the row and column. The blocks are then combined to get high voltage and high current output. When the solar cells exposed to solar or under receiving solar energy, the heat may introduce on the surface of the solar cells. The heat occurs because of the heating effect by the sun and when the solar cells are in operation (connected to the electrical loads). The heat introduced by solar energy will create thermal noise, and this noise typically proportional to the temperature. The heat produced in the solar cells can be removed by a cooler. The design of a cooler is varieties.

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There are numerous ideas proposed in the past to reduce the temperature and removed the heat in the solar cells.

The primary purpose of removing the heat is to improve the stable operation of the solar cells and hence improve efficiency. In the past, there were many ideas proposed using a heat sink, fan as a cooler device and the structure that can help to remove the heat under the solar cells. All these devices perform great in terms of efficiency, but they tend to make the system bulky, complicated and increase the cost. There are numerous cooling systems for solar PV system being proposed by many engineers and designers around the world. Each of the proposed cooling systems is unique and using a different mechanism. In the reviews, some of them using water to spray [1], using aluminium fins [2], using the electric fan for cooling [3], using heat absorber method [4]. All the suggested methods have advantages and disadvantages. Some of them could be expensive in cost, bulky and occupy many spaces, and some of them are portable and detachable. The heat reduction or cooling system by means of using a radiator is no more recent in the invention. However, to the solar PV system, this could be a new idea. People did not think of using a radiator method for cooling photovoltaic cell mainly because it is very bulky and inconvenient. However, in return, this method tends to give a better cooling system when significant wattage of the photovoltaic cell is employed in the power plant. The radiator comprises of mechanical structure that is designed to remove the heat from the solar panel, especially when the radiator is placed in touch with the bottom of the solar panel. The heat usually absorbed by the solar cells at the surface, but the heat will pass through the solar cells and comes to the bottom part of the panel. The heat is then accumulating if it is not removed. The more heat accumulates, and then this will give rise to the temperature increase and hence introduces the thermal noise in the solar output.

In this study, three-dimensional modelling of a photovoltaic cell consists of three layers was performed. The serpentine circular pipe has been fixed behind the aluminium plate and used as a heat exchanger to transfer the heat from the photovoltaic cell to the pipe fluid and reduces the photovoltaic cell temperature. A lot of literature concluded that using nanofluid can improve the heat transfer in heat exchangers [5, 6]. Therefore, nanofluid was used in this research as a cooling fluid in a system of tubes for a solar cell that acts as a heat exchanger to study the resulting improvement in reducing its temperature and increasing its efficiency. An Alumina nanoparticle (Al_2O_3) has been chosen due to the good chemical stability in the base fluid (water), relatively low cost compared to other nanoparticles, and widespread and familiarity in the industry. Nanoparticles of Al_2O_3 were added to water at a rate of 4% to improve the thermal performance and efficiency of the heat exchange. To the author's knowledge, this work is the first to employ nanofluid as a coolant in solar cells with three-dimensional effect using CFD technology.

2. COMPUTATIONAL FLUID DYNAMICS (CFD) SIMULATION MODEL

CFD simulation used the branch of fluid mechanics to calculates numerical results. CFD utilized a finite element method to simulate an engineering problem. So, the numerical technique can be used to calculate the results for significant engineering problems, and its results were in agreement when compare with experimental and analytical results [7-11].

2.1 Computational Domain and Solution Method

The computational domains of the photovoltaic cell structure in this work are prepared from three layers with a total area of $90\ \text{cm} \times 60\ \text{cm}$. The first layer is glass, then the solar cell (crystalline cells), and the last layer is an aluminium plate. Water/Nanofluid flows through a fixed serpentine circular pipe behind the aluminium plate with 1 cm diameter. The mesh type of quadratic elements has been used in the current three-dimensional model (Figure 1). The finite-volume method has been applied to discretizing and solving the governing equations using the multi-physics computational fluid dynamics code of COMSOL. A mesh independence study was considered in this work to ensure that the solution is independent of the mesh size. The analysis begins with a mathematical model of the heat transfer and fluid flow equations, where the conservation of matter, momentum, and energy have satisfied throughout the region of this domain. Physical properties have been specified with high precision to all part of this model such as viscosity, thermal conductivity, specific heat, and density to define a problem. The thermal performance characteristics of the solar cell cooling based on a certain parameter can be obtained by varying that parameter (type of coolant - water or nanofluid) while keeping all other parameters constant at the base case. Therefore, for the base case study, the inlet coolant temperature was considered to be 25 ^{o}C, and the ambient temperature was 40 ^{o}C. A constant solar radiation intensity of 800 W/m^2 was applied to this photovoltaic cell panel. The inlet coolant temperature was considered to be 25 ^{o}C, and the ambient temperature was 40 ^{o}C. A constant solar radiation intensity of 800 W/m^2 was applied to this photovoltaic cell panel. The velocities of the coolant were assumed uniform at the inlet of the flow field, while the pressures of each of them ware assumed uniform at the outlet. The coupled equations were solved using an iterative solution. A criterion of error less than or equal to 1.0×10^{-6} was assumed adequate to achieve the solution convergence [12].

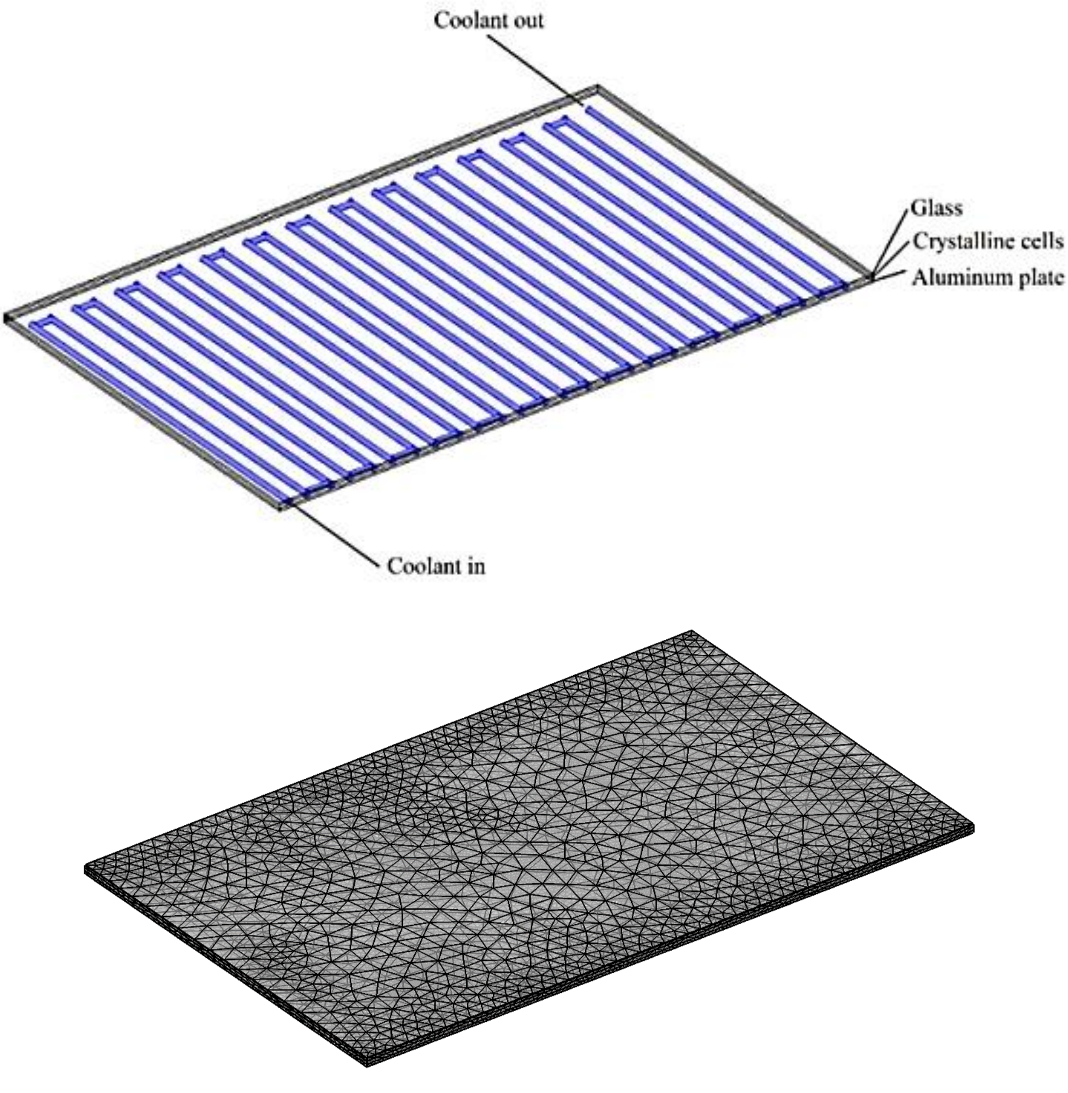

Figure 1. Computational domain and mesh of the photovoltaic cell panel

2.2 Conservation Equations

Reynolds-averaged Navier–Stokes equations (RANS) for the momentum conservation, and also the continuity equations for the turbulence flow model, are expressed as [13, 14],

$$\rho\frac{\partial U}{\partial t}+\rho U.\nabla U+\nabla.\overline{(\rho u' \otimes u')}=-\nabla P+\nabla.\mu\left(\nabla U+(\nabla U)^{T}\right)+F \quad (1)$$

$$\rho\nabla.U=0 \quad (2)$$

where, U is defined as the average of the fluid velocity, while $\otimes$ stands for the outer vector product. k-ω model for flows involving strong streamline curvature where preparation of this turbulence model is as follows [13, 15],

$$\rho\frac{\partial k}{\partial t}+\rho u\ .\nabla k=\ P_k-\rho\beta^{*}k\omega+\ \nabla.\left((\mu+\ \sigma^{*}\mu_T)\nabla k\right) \quad (3)$$

$$\rho\frac{\partial \omega}{\partial t}+\rho u\ .\nabla \omega=\ \alpha\frac{\omega}{k}P_k-\rho\beta\omega^{2}+\ \nabla.\left((\mu+\ \sigma\mu_T)\nabla \omega\right) \quad (4)$$

where,

$$\mu_T=\rho\frac{k}{\omega} \quad (5)$$

$$\alpha=\frac{13}{25},\beta=\beta_o f_\beta,\ \beta^{*}=\ \beta_o^{*}f_\beta,\ \sigma=\frac{1}{2}\ ,\ \sigma^{*}=\frac{1}{2} \quad (6)$$

$$\beta_o=\frac{13}{125}\ ,f_\beta=\frac{1+70X_\omega}{1+80X_\omega},\ X_\omega=\left|\frac{\Omega_{ij}\ \ \Omega_{jk}\ \ S_{ki}}{(\beta_o^{*}\omega)^{3}}\right| \quad (7)$$

$$\beta_o^{*}=\frac{9}{100}f_\beta^{*}=\begin{cases}1 & \text{for}\ \ X_k\le 0\\ \frac{1+680X_k^2}{1+400X_k^2} & \text{for}\ \ X_k>0\end{cases},X_k=\frac{1}{\omega^{3}}(\nabla k.\nabla\omega) \quad (8)$$

where, ω_{ij} denotes the mean tensor of rotation rate,

$$\Omega_{ij}=\frac{1}{2}\left(\frac{\overline{\partial u_i}}{\partial x_j}-\frac{\overline{\partial u_j}}{\partial x_i}\right) \quad (9)$$

and, S_{ij} is the mean strain rate tensor,

$$S_{ij}=\frac{1}{2}\left(\frac{\overline{\partial u_i}}{\partial x_j}-\frac{\overline{\partial u_j}}{\partial x_i}\right) \quad (10)$$

$$P_k=\mu_T\left(\nabla u:\left(\nabla u+(\nabla u)^{T}\right)-\frac{2}{3}(\nabla.u)^{2}\right)-\frac{2}{3}\rho k\nabla.u \quad (11)$$

2.3 Cooling Fluid Thermophysical Properties

Water is the base fluid for the coolant ("bf"), and the thermophysical properties for water that depend on its temperature can be calculated from the following equations [5],

$$\rho_{bf}=\frac{\begin{matrix}999.84+18.225(T+273.15)-7.92\times10^{-3}(T+273.15)^{2}-5.545\times10^{-5}(T+273.15)^{3}+\\1.498\times10^{-7}(T+273.15)^{4}-3.933\times10^{-10}(T+273.15)^{5}\end{matrix}}{1+1.816^{-2}(T+273.15)}\left(\frac{kg}{m^{3}}\right) \quad (12)$$

$$\mu_{bf} = 2.414 \times 10^{-5} \times 10^{\left(\frac{247.8}{T-140}\right)} \quad \left(\frac{kg.m}{s}\right) \tag{13}$$

$$Cp_{bf} = (8958.9 - 40.535T + 0.11243T^2 - 1.014 \times 10^{-4}T^3) \quad (J/kg.K) \tag{14}$$

$$k_{bf} = (-0.58166 + 6.3556 \times 10^{-3}T - 7.964 \times 10^{-6}T^2) \quad (W/m.K) \tag{15}$$

The nanoparticles Alumina (Al_2O_3) is used to prepare the nanofluid with water and used in the coolant pipe. Alumina is chosen because it is characterized by excellent chemical stability in water and its low cost and safety compared to other types of nanoparticles. The nanofluids' thermophysical properties "nf" depends on the volume fraction $\emptyset$ of the nanoparticles "np" in the suspension and can be calculated through the following equations [16, 17],

$$\rho_{nf} = (1-\emptyset).\rho_{bf} + \emptyset\rho_{np} \tag{16}$$

$$\rho_{nf}Cp_{nf} = (1-\emptyset).\rho_{bf}Cp_{bf} + \emptyset\,\rho_{np}Cp_{np} \tag{17}$$

Based on the Brownian motion of nanoparticles, the thermal conductivity is calculated as,

$$k_{eff} = k_{static} + k_{Brownian} \tag{18}$$

The static thermal conductivity is calculated as,

$$k_{static} = k_{bf}\left(\frac{k_{np}+2k_{bf}-2(k_{bf}-k_{np})\emptyset}{k_{np}+2k_{bf}+(k_{bf}-k_{np})\emptyset}\right) \tag{19}$$

The Brownian thermal conductivity values for the nanofluid coolant are calculated as,

$$k_{Brownian} = 5 \times 10^4\beta.\emptyset.\rho_{bf}.Cp_{bf}\sqrt{\frac{\sigma_B.T}{\rho_{np}\cdot d_{np}}}.f(T,\emptyset) \tag{20}$$

The dynamic viscosity is given as,

$$\mu_{eff} = \mu_{static} + \mu_{Brownian} \tag{21}$$

$$\mu_{static} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}} \tag{22}$$

$$\mu_{Brownian} = 5 \times 10^4\beta.\emptyset.\rho_{bf}.\sqrt{\frac{\sigma_B.T}{\rho_{np}\cdot d_{np}}}.f(T,\emptyset) \tag{23}$$

$$f(T,\emptyset) = (2.8217 \times 10^{-2}\emptyset + 3.917 \times 10^{-3})\left(\frac{T}{T_o}\right) + (-3.0699 \times 10^{-2}\emptyset - 3.91123 \times 10^{-3}) \tag{24}$$

β is defined as the fraction of the liquid volume moving with the nanoparticles and are listed in Table 1. σ_B is the Boltzmann constant. Finally, d_{np} is the diameter of the Alumina's particles suspended in the nanofluids [nm]. The thermophysical properties of the Al_2O_3 nanoparticles calculated at the reference temperature of 300 K are listed in Table 2.

Table 1 Values of β for Al_2O_3 nanoparticles

Nano particles	β	Volume fraction [%]	Temperature [K]
Al_2O_3	$8.4407(100\emptyset)^{-1.07304}$	$1\% \le \emptyset \le 10\%$	$298 \le T \le 363$ K

Table 2 The thermophysical properties of Al_2O_3 nanoparticles at T=300K, [16].

Thermophysical properties	Al_2O_3
Density ρ (kg/m³)	3970
Thermal conductivity k (W/m.K)	40
Specific heat Cp (J/kg.K)	765

2.4 Data Acquisition

The equivalent coefficient of the heat transfer (h) is calculated as,

$$h = \frac{Q}{A.(T_{hot} - T_{cold})} \tag{25}$$

where Q is the total heat transmission [W], A is the total surface area [m^2], and T is the fluid temperature [K]. A solar cell's efficiency is very much affected by its temperature. The energy of solar radiation that falls on the solar cell turns into two parts. The cell converts part of this radiation energy into electrical energy while absorbing the other part of this energy. This last part will be responsible for heating the solar cell and raising its temperature. While the electrical energy is removed from the cell through the external circuit, the thermal energy is dissipated by a combination of heat transfer mechanisms. The heat dissipation from the bottom surface of the solar cell is critical to the performance of the solar cell, where the most significant possible amount of thermal energy must be dissipated from the solar cell so that the cell operates at the lowest possible temperature; thus, obtaining the highest efficiency from it. Using the energy balance, the solar cell temperature's in working mode can be determined. The electrical efficiency of the solar cell panel, as a function of temperature, is given by,

$$\eta_{el} = \eta_o\left(1 - \beta_o(T_c - 298.15)\right) \tag{26}$$

where, η_o is the efficiency of PV module at Standard Testing Conditions at the temperature of 298.15 K, β_o silicon efficiency temperature coefficient (0.004 K^{-1}, [18]), and Tc average cell temperature [K].

3. RESULTS AND DISCUSSION

In this study, three-dimensional modelling of a photovoltaic cell consists of three layers was performed. The serpentine circular pipe has been fixed behind the aluminium plate and used as a heat exchanger to transfer the heat from the photovoltaic cell to the pipe fluid and reduces the photovoltaic cell temperature. Nanoparticles of Al_2O_3 were added to water at a rate of 4% to improve the thermal performance and efficiency of the heat exchange. The results showed an improvement of approximately 10% in the photovoltaic electrical efficiency when using the water cooling method and about 12% when using the nanofluid. The importance of the results in this study illustrates the possibility of increasing the efficiency of the photovoltaic cell by cooling it with water using a small percentage of nanoparticles. The temperature distribution in the photovoltaic cell structure with a range of Reynolds numbers are presented well in this section, as shown in Figures 2 to 6.

Figure 2 shows the temperature distribution in the photovoltaic cell structure as a result of exposure to solar radiation without cooling. The results show that the maximum temperature (56 ^oC) occurs at the top glass layer of the cell, exposed to the highest solar radiation. The arrival of the photovoltaic cell to a high temperature negatively affects its performance, and its efficiency decreases significantly. To maintain the nominal efficiency, the photovoltaic cell must be cooled. Figure 3 shows the temperature distribution in the photovoltaic cell structure when cooling using water for a range of Reynolds numbers. The results show a significant decrease in temperature inside the photovoltaic cell when it is cooled by water, and the temperature decreases more with the increase in the flow velocity of the water (Reynolds numbers). Figure 4 shows the temperature distribution in the photovoltaic cell structure when using Al_2O_3 nanofluid as a cooling, for a range of Reynolds numbers. The results show a very important decrease in the temperature of the cell when it is cooled using nanofluids than when using water only, and the temperature decreases further with the increase in the speed of the water flow (Reynolds numbers). This result demonstrates the increase of cooling efficiency when using Al_2O_3 nanofluid, which leads to the possibility of minimizing the volume of the heat exchanger used and raise its efficiency. In addition, Figures 2 and 3 show that for the coolant flow, the photovoltaic cell temperature values are less low through the flow direction, and the maximum value of the temperature takes place at the exit of the coolant through the pipe channel. Figure 5 shows the photovoltaic average cell temperature as a function of Reynolds numbers. The results show that an increase in the velocity of the cooling fluid flow (Reynolds numbers) leads to a decrease in the average temperature of the cell, which leads to an improvement in its performance, but in return, increasing in pumping power cost. Figure 5 also shows the effectiveness of Al_2O_3 nanofluid in increasing with decrease in cell temperature. Figure 6 shows the photovoltaic electrical efficiency reduction as a function of Reynolds numbers. The results show the effectiveness of the cooling method especially when using Al_2O_3 nanofluids. The results show that there is an improvement of approximately 10% in the photovoltaic electrical efficiency when using the water cooling method and about 12% when using the Al_2O_3 nanofluid.

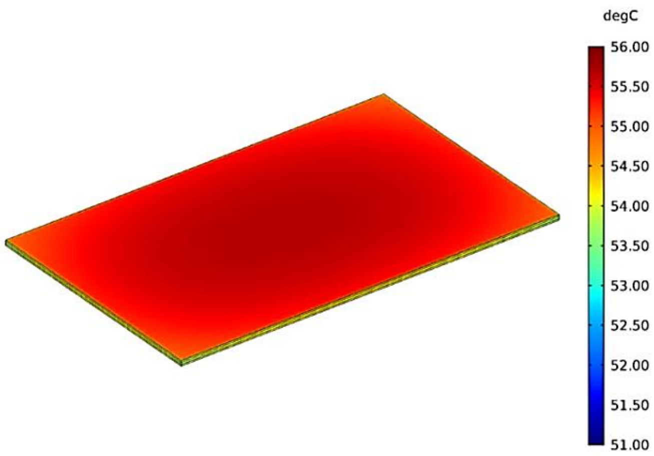

Figure 2. Temperature distribution in the photovoltaic cell structure without cooling (°C)

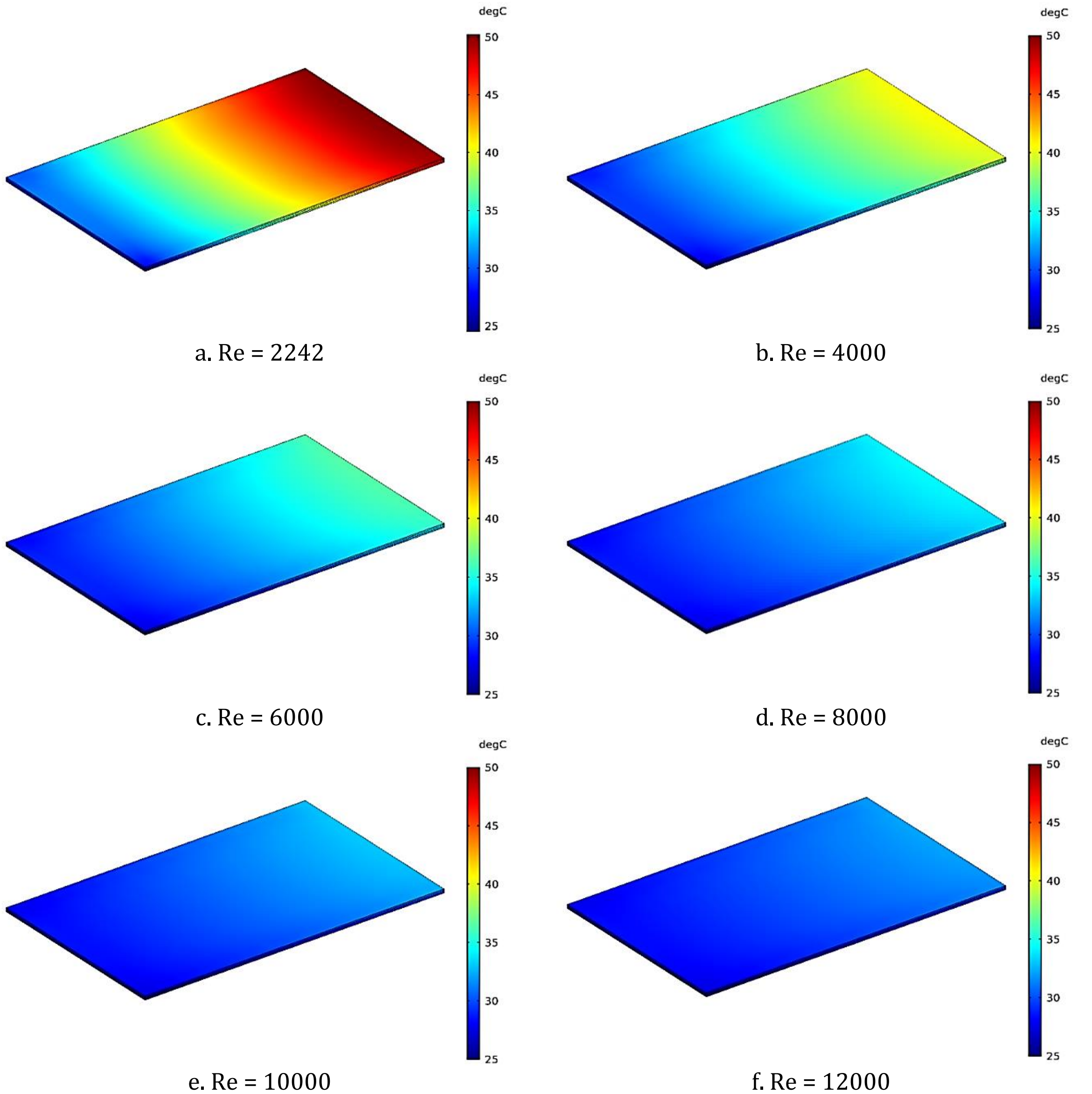

Figure 3. Temperature distribution in the photovoltaic cell structure with water cooling (°C) for a range of Reynolds numbers

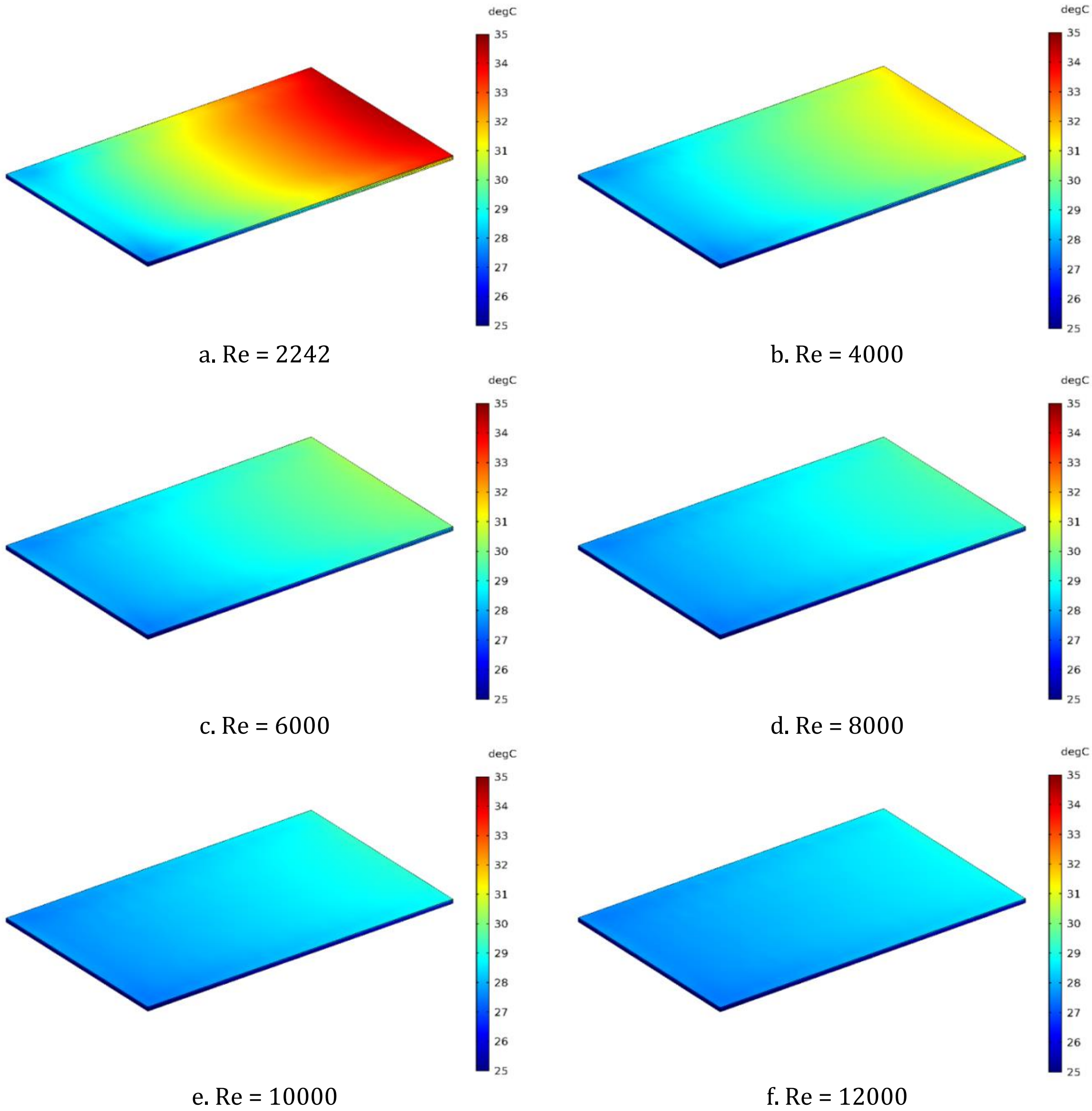

Figure 4. Temperature distribution in the photovoltaic cell structure with nanofluid Al_2O_3 cooling (°C) for a range of Reynolds numbers

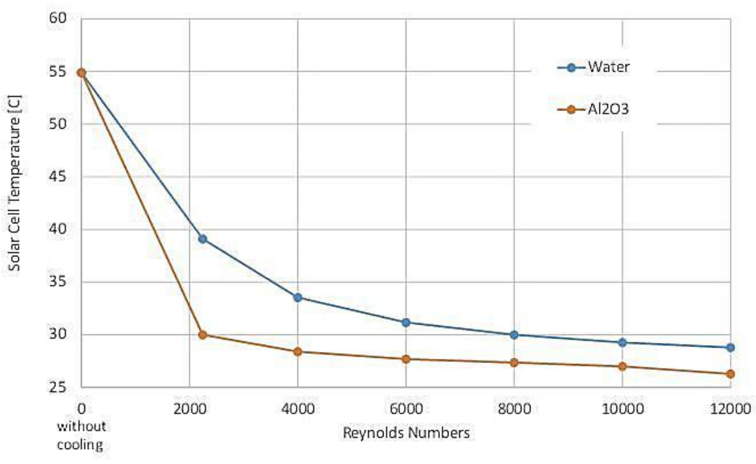

Figure 5. Photovoltaic average cell temperature as a function of Reynolds numbers

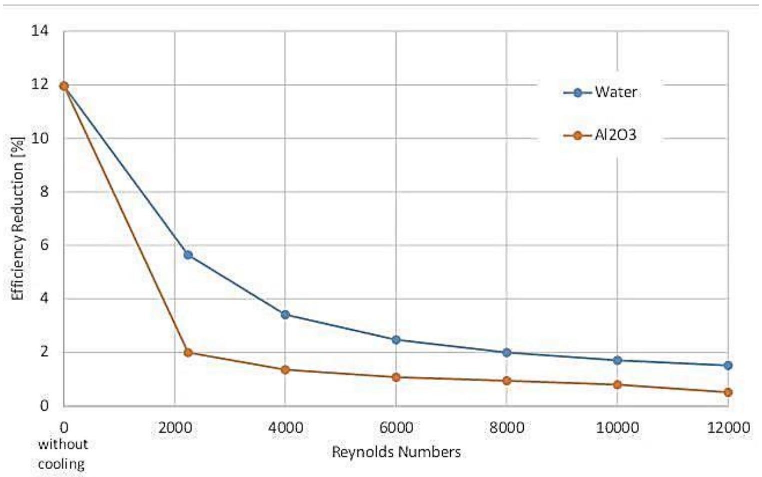

Figure 6. Photovoltaic electrical efficiency reduction as a function of Reynolds numbers

4. CONCLUSION

Three-dimensional CFD simulation model through the finite volume method was used to study the effect of cell temperature on the performance and efficiency of a photovoltaic cell panel. The cooling technique used is a serpentine circular pipe fixed behind an aluminium plate and used as a heat exchanger to transfer the heat from the photovoltaic cell to the pipe fluid and reduces the photovoltaic cell temperature. Nanoparticles of Al_2O_3 were added to water at a rate of 4% to improve the thermal performance and efficiency of the heat exchange. The results showed an improvement of approximately 10% in the photovoltaic electrical efficiency when using the water cooling method and about 12% when using the nanofluid. In addition, to enhance efficiency, the heat transferred from the photovoltaic cell can be utilized in many practical applications. The importance of the results in this study illustrates the cooling techniques for the photovoltaic cell is essential in hot environment regions, and the nanofluids coolant are very helpful to support this technique.

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