Numerical approach of Al$_2$O$_3$-water nanofluid in photovoltaic cooling system using mixture multiphase model

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Abstract. This article aims to numerically analyze the cooling system of photovoltaic device using mixture multiphase model. Aluminum oxide (Al$_2$O$_3$)-water nanofluids at various concentration of 0, 0.5, 1 and 2 vol.% were used as cooling fluid for photovoltaic module. The constant and uniform heat flux of 800 W/m$^2$ was applied on photovoltaic (PV) module and the various cooling fluids flowed under PV module at Reynold number of 200 and 500. The temperature distribution and local heat transfer coefficient of cooling fluid were observed. The results show that increasing concentration of Al$_2$O$_3$ nanoparticle enhances the local heat transfer coefficient and decreases the temperature of PV cell. The significant enhancement of convection heat transfer of Al$_2$O$_3$-water nanofluid occur at entrance region. The operating temperature of PV cell can be decreased till 303 K for 2 vol.% Al$_2$O$_3$-water nanofluid at Reynold number of 500.

1. Introduction
Solar energy is one of the most abundant renewable energy resources. The electrical devices which convert solar energy into electrical energy via photovoltaic mechanism such as silicon have been developed to gain maximum performance. One of the main factor that can decrease the efficiency of photovoltaic cells is temperature [1]. Moreover, the effect of temperature in photovoltaic devices also decrease the life time and stability of PV system. The cooling mechanism is one of the solution which is applied by researcher to decrease the operating temperature of PV panels. The various types of fluids which can be used as PV cooling system are air, water, ethylene glycol and nanofluid. Nanofluid is a fluid which dispersed nanomaterials with size typically of 1 to 100 nm. The use of nanomaterials have attracted the interest for many applications such as semiconductor, solar cells, nanofluid, sensor, and etc [2-5]. The dispersion process of nanoparticle will enhance thermal conductivity and specific heat of fluid [6]. The addition of Al$_2$O$_3$ nanoparticles into water have been reported to increase the performance of convection heat transfer [6]. The heat transfer characteristic of nanofluid had been successfully investigated by single-phase and multi-phase model [7, 8]. However, the multi-phase model produce heat transfer prediction which is more accurate than the single-phase model, because the disorder movement of nanoparticle and its interaction with base fluid also considered. Movareji, et al [8] showed that Al$_2$O$_3$-water nanofluid under heat flux constant in the discrete phase model had enhancement in heat transfer coefficient and a good agreement with experimental results. Thus, this work will investigate the numerical investigation of Al$_2$O$_3$-water nanofluid as cooling fluid for photovoltaic cells by using two-phase mixture model approach. The
laminar flow condition was chosen to show the influence of nanoparticle contribution particularly at low velocity which is easier for engineering application.

2. Methods

2.1. Problem Description

Generally, the intensity of solar radiation which is accepted by PV module is 1000 W/m². The efficiency of PV cell at the market is range from 12 to 17% and the portion of 3 to 10% of solar radiation is reflected by glass [9, 10]. Thus for this study assume that the total of 20% of solar energy is converted into electrical energy and back to surrounding. Meanwhile the portion of solar radiation which is not converted will be changed as heat input to the PV module that is 800 W/m². There are 6 main layers components in the PV module as shown in table 1. The layers are arranged like a sandwich, and the cooling fluid steadily flows under the PVF layer. At this work, the cooling fluids steadily flow in 5 mm channel along 1 m horizontal PV panels. The 0 (pure water), 0.5, 1 and 2 vol.% of Al₂O₃-water nanofluid were chosen due to its high thermal conductivity and minor agglomeration tendency [6, 11].

| Layer      | Thickness (m) | Thermal conductivity (W/m.K) | Density (kg/m³) | Specific heat capacity (J/kg.K) |
|------------|--------------|-----------------------------|-----------------|---------------------------------|
| Glass      | 3 x 10⁻³     | 1.8                         | 3000            | 500                             |
| ARC        | 1 x 10⁻⁷     | 32                          | 2400            | 691                             |
| PV cells   | 2.25 x 10⁻⁴  | 148                         | 2330            | 677                             |
| EVA        | 5 x 10⁻⁴     | 0.35                        | 960             | 2090                            |
| Rear contact | 1 x 10⁻⁵   | 237                         | 2700            | 900                             |
| PVF        | 1 x 10⁻⁴     | 0.2                         | 1200            | 1250                            |

Table 1. Properties of PV panel’s layers [9, 12].

2.2. Nanofluid’s properties

The properties of Al₂O₃ nanoparticle which is used for this study were demonstrated in table 2. The Al₂O₃ nanoparticles were assumed that had perfect ball shape with uniform and constant properties. The density (ρₙaghetti) and specific heat (cₚ,ₙaghetti) of nanofluid in any various volume fraction (φ) can be calculated by equation (1) and (2). The subscript nf, np and bf mean nanofluid, nanoparticle and base fluid, respectively. The viscosity of nanofluid (μₙaghetti) can be evaluated by Bachelor equation as shown in equation (3). The experiment results from Ghanbarpour M, et al [16] also showed that the thermal conductivity of Al₂O₃-water nanofluid (kₙaghetti) can be predicted by equation (4).

\[
\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_{np}
\]

\[
c_{p,nf} = \frac{(1 - \phi)(\rho c_p)_{bf} + \phi(\rho c_p)_{np}}{(1 - \phi)\rho_{bf} + \phi\rho_{np}}
\]

\[
\mu_{nf} = (1 + 2.5\phi + 6.2\phi^2)\mu_{bf}
\]

\[
k_{nf} = (1 + 3.5\phi + 2.5\phi^2)k_{bf}
\]
2.3. Governing Equation
The interaction between Al₂O₃ nanoparticle and water can be modelled in mixture multiphase by Euler-Euler approach using ANSYS-Fluent. Mixture model can be used to analyze multiphase flow with very strong coupling, and phases moving at the same or different velocity. Equation (5), (6) and (7) show the continuity, momentum and energy equation for mixture multiphase flow, respectively.

\[
\frac{\partial}{\partial t}(\rho_m \mathbf{V}_m) + \nabla \cdot (\rho_m \mathbf{V}_m \mathbf{V}_m) = 0 \tag{5}
\]

\[
\frac{\partial}{\partial t}(\rho_m \mathbf{V}_m) + \nabla \cdot (\rho_m \mathbf{V}_m \mathbf{V}_m) = -\nabla p + \nabla \left[ \mu_m (\nabla \mathbf{V}_m + \nabla \mathbf{V}_m^T) \right] + \rho_m \mathbf{g} + \dot{F} + \nabla \left[ \sum_{k=1}^{n} \phi_k \rho_k \mathbf{V}_{dr,k} \mathbf{V}_{dr,k} \right] \tag{6}
\]

\[
\frac{\partial}{\partial t} \sum_{k=1}^{n} \phi_k \mathbf{V}_k + \nabla \left[ \sum_{k=1}^{n} \phi_k \mathbf{V}_k (\rho_k \mathbf{V}_k + p) \right] = \nabla \left( k_{eff} \nabla T \right) + S_e \text{ with } E_k = h_k - \frac{p}{\rho_m} + \frac{V_k^2}{2} \tag{7}
\]

3. Results and Discussion

3.1. Verification and Validation
The computational fluid dynamic (CFD) tool, ANSYS Fluent 14.5 was used to analysis this studied models. The Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) procedure was used to solve the velocity-pressure coupling algebraic equations. The validation was conducted by analyzing the heat transfer coefficient (h) of Al₂O₃-water nanofluid which had been experimentally analyzed by Wen and Ding [11]. Figure 1 shows the experiment result that conducted by Wen and Ding (2004) and the numerical simulation by mixture multiphase model at Re = 1050±50. The simulation has good fit prediction with experimental results with errors less than 15%. The work by Wen and Ding had mentioned before that the deviation under their conditions of experiment setup was 6.2% due to heat losses and errors of apparatus.

![Figure 1. Local heat transfer coefficient analysed by Wen and Ding (2004) and mixture multiphase model for water and 0.6 vol.% Al₂O₃-water nanofluid at Re = 1050±50.](image)

3.2. Thermal Distribution
Figure 2 shows the thermal distribution of PV module and cooling fluid under Reynold number of 200 and 500. It reveals that increasing of Reynold number will decrease the temperature of PV module. The fluid temperature increases and develops from entrance region till outlet section. At the entrance region, the PV cell has the lowest temperature and then increase along axial direction. The distribution of PV cell temperature is highly affected by the amount of heat removal from it. The 2 vol.% Al₂O₃-water nanofluid at Reynold number of 500 can decrease the maximum operating temperature of PV cell till 303 K. This result has important role to efficiency of PV module [1]. The local heat transfer coefficient (h(x)) was defined by equation (8). The \( q'' \), \( T_{wall} \) and \( T_{mean} \) are the heat flux, the wall temperature and the mean temperature, respectively.
\[
h(x) = \frac{q^*}{T_{wall}(x) - T_{mean}(x)} \quad \text{with} \quad T_{mean}(x) = \frac{\int u.T.y.dy}{\int u.y.dy}
\] (8)

**Figure 2.** Thermal distribution in PV panels at Reynold number of (a) 200, and (b) 500 of 2 vol\% Al\(_2\)O\(_3\)-water nanofluid

**Figure 3.** Local heat transfer coefficient at Reynold number of (a) 200, and (b) 500 of nanofluid

**Table 3.** Pressure drop of various cooling fluid

| Cooling fluid         | Pressure drop (Pa) |
|-----------------------|--------------------|
|                       | Re = 200           | Re = 500           |
| Water                 | 18.94              | 50.65              |
| 0.5 vol.% Al\(_2\)O\(_3\)-water | 21.50              | 50.82              |
| 1 vol.% Al\(_2\)O\(_3\)-water | 22.00              | 52.10              |
| 2 vol.% Al\(_2\)O\(_3\)-water | 22.05              | 55.44              |

Figure 3 shows the local heat transfer coefficient along axial direction of fluid. At the entrance region, the heat transfer coefficient has high value, then decreases along axial direction. This phenomena is strongly influenced by the temperature gradient at the PVF surface. The heat transfer coefficient of 2 vol\% Al\(_2\)O\(_3\)-water is higher than other cooling fluid types. That is caused by the
thermal conductivity and specific heat of nanofluid which is proportional with volume fraction of nanoparticles in base fluid [7, 11]. At the Reynold number of 500 has higher local heat transfer coefficient for all variation of volume fraction in nanofluid than that of Reynold number of 200. That is related with mass flow rate of cooling fluid. Table 3 shows the pressure drop in various cooling fluid of photovoltaic system. The increasing volume fraction of nanoparticles and Reynold number have linear effect on the pressure drop. However, the increasing of pressure drop due to addition of nanoparticles into base fluid has minor consideration if compared with enhancement of heat transfer coefficient.

4. Conclusions
The numerical approaches of PV cooling system using Al₂O₃-water nanofluid at laminar flow under constant heat flux have been carried out by mixture multiphase model. The various volume fraction of Al₂O₃-water nanofluid at Reynold numbers of 200 and 500 have been numerically investigated to observe their influence on heat transfer coefficient and temperature of PV cell. The results show that nanofluids have significant enhancement of heat transfer coefficient and decreasing of the temperature of PV cells.

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