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Numerical Study on Enhancing Photovoltaic Panel Efficiency Through Heat Exchanger Cooling with Al_2O_3 Nanofluid

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Photovoltaic panel, cooling, nanofluid, heat exchanger, efficiency

Abstract

This study offers a numerical assessment of the thermal, electrical, and hydraulic performance of a monocrystalline photovoltaic (PV) module featuring a rear-mounted copper heat exchanger and cooled with Al_2O_3 nanofluids at concentrations of 2% and 4% across Reynolds numbers (Re) ranging from 1500 to 2600. The findings indicate that both nanofluids decreased PV surface temperatures relative to the uncooled baseline, resulting in enhanced electrical conversion efficiency. The 2% concentration exhibited consistent thermal reduction from 333.44° C to 326.48°C and constant efficiency improvements from 12.88% to 13.30% alongside predicted friction factor behaviour, reducing from 0.0427 to 0.02888. Conversely, the 4% nanofluid attained enhanced cooling which result in 301.90 °C and optimal efficiency of 14.78% at low Reynolds numbers, yet suffered significant performance decline at elevated flow rates, with temperatures surpassing the baseline and efficiencies plummeting to a mere 3.74%, due to heightened viscosity, nanoparticle agglomeration, and flow instabilities. These findings underscore the necessity of optimizing nanofluid concentration and flow rate to attain a balance of heat dissipation, efficiency improvement, and feasible pumping demands. The 2% concentration proves to be the most dependable choice for continuous PV cooling throughout various operating circumstances, whereas the 4% concentration may only be beneficial in low-flow scenarios. Future research must prioritize experimental validation, the examination of long-term nanoparticle dispersion stability under operational stresses, and an extensive techno-economic analysis to evaluate the viability of incorporating nanofluid-based cooling systems into large-scale solar energy installations.

1. Introduction

The utilization of renewable energy sources, particularly solar energy, is widely promoted in numerous countries globally. The Middle East and North Africa (MENA) possess enormous renewable resources that, if utilized well, may transform the region's economy permanently [1]. This tendency has initiated a transition towards renewable resources, exemplified by the utilization of solar energy for power generation using photovoltaic cells [2]. During the operation of the photovoltaic (PV) solar cell, approximately 20% of the solar irradiance incident on the PV surface is converted into electrical energy, while the remainder is transformed into absorbed heat. Consequently, the electrical conversion efficiency diminishes as the working temperature of the PV module rises [3]-[5]. Every degree increase in the temperature of PV modules lowers the solar electrical efficiency of crystalline and amorphous silicon cells by 0.5% and 0.25%, respectively [6].

Nevertheless, photovoltaic cells often have a limited lifespan and diminished performance under high temperatures, such as those prevalent in the climate of Aswan City in Upper Egypt. Consequently, it is imperative to implement diverse cooling approaches, encompassing both passive and active methods, to lower cell temperature and sustain maximum performance [7]. In several studies, a typical photovoltaic cell temperature was recorded above 80°C, significantly exceeding the standard nominal operating cell temperature (NOCT) of 40°C.

Various studies were conducted to overcome the thermal issue faced by PV panel. A study was conducted by mixing aluminium powder into soil around ground heat exchanger (GHE) to cool the PV panel in Iraq. The result showed promising outcome with 30% aluminium content with a temperature reduction of 44 °C [8]. In this study, the heat exchanger (HE) which is integrated at the rear of PV panel is simulated using ANSYS. This setup is known to reduce the surface temperature of the PV panel and improve the efficiency of the panel simultaneously. The present study is also to investigate the effect of various Reynolds number (Re) of the Aluminium oxide (Al_2O_3) nanofluid which flows through the heat exchanger on the temperature of the PV panel. The monocrystalline PV panel simulated in this study is Vertex TSM-DE19 which is being used in Universiti Tun Hussein Onn Malaysia.

2. Methodology

2.1 Parameters

This article investigates the effect of various Re of Al_2O_3 nanofluid which is passed through the heat exchanger to cool the PV panel. The Reynolds number used in these simulations are 1500, 1800, 2300 and 2600. The panel used in this simulation is shown in Fig. 1. Based on Eq. (1) the inlet velocity, V_{in} of Al_2O_3 nanofluid is calculated based on the properties shown in Fig. 2 [9].

$$Re = \frac{\rho V D}{\mu} \tag{1}$$

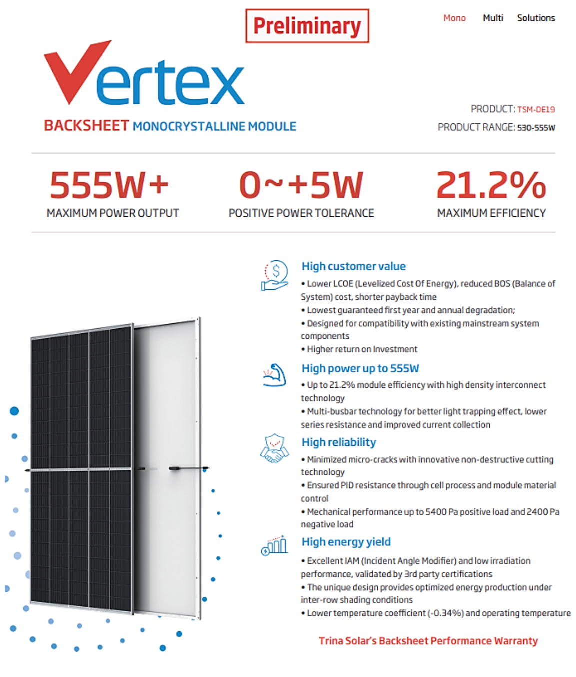


Fig. 1 *Model of PV panel used*

Particle Concentraion	Density, ρ (kg/m³)		Specific heat, C_P (J/kg K)		Thermal conductivity, k (W/m K)		Viscosity, μ (kg/m s)	
	Al_2O_3	CuO	Al_2O_3	CuO	Al_2O_3	CuO	Al_2O_3	CuO
φ = 0%	981.3	981.3	4189	4189	0.643	0.643	0.0006	0.0006
φ = 1%	1007.4	1052.2	4154.7	3966.504	0.765	0.736	0.000612	0.00068
φ = 2%	1033.6	1106.2	4120.5	3736.596	0.782	0.751	0.000627	0.000714
φ = 3%	1059.8	1160.2	4086.2	3528.095	0.798	0.764	0.000642	0.000795
φ = 4%	1086	1214.2	4052	3338.146	0.813	0.777	0.000657	0.00089
φ = 5%	1112.2	1268.2	4017.8	3164.376	0.828	0.79	0.000672	0.001

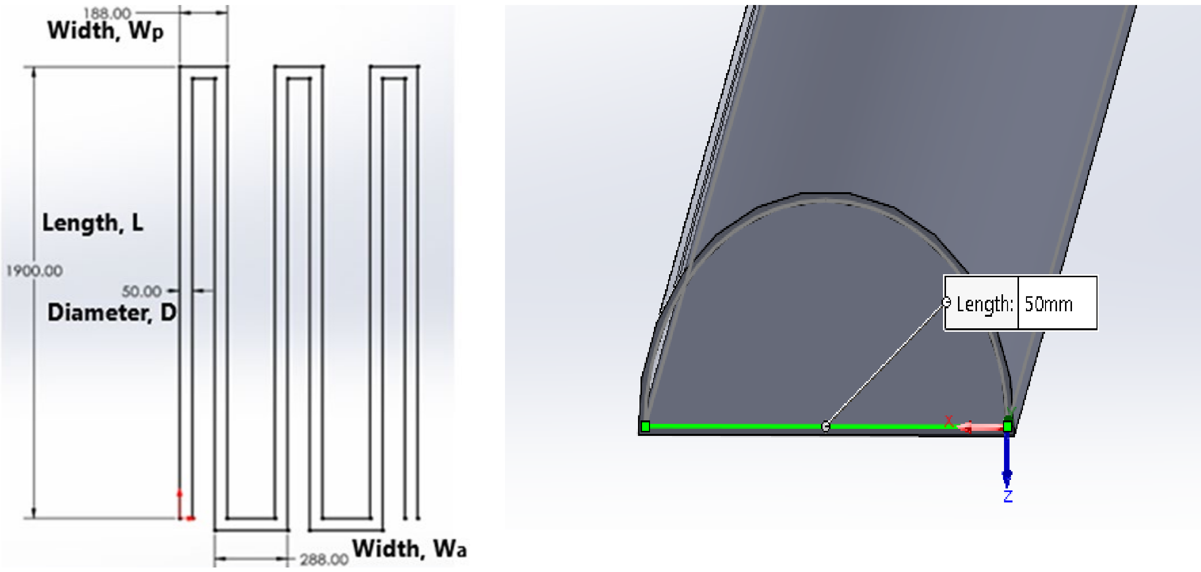
Fig. 2 *Al2O3 nanofluid properties*

A numerical simulation is conducted using Anys Fluent to examine the effect of implementing nanofluid cooling to regular monocrystalline PV panel and to identify the optimum Al_2O_3 nanofluid volume concentration to sustain lower surface temperature of PV panel. The electrical specifications of the PV panel at standard test conditions (STC) are stated in Table 1.

The dimension of PV panel of PV panel is 2384 mm x 1096 mm x 35 mm. The dimension of heat exchanger pipe is shown in Fig. 3. The geometry model of this setup is drawn in SolidWorks as shown in Fig. 4. The length, L of pipe is 1900 mm, Width, Wa is 288 mm and Width Wp is 188 mm. The diameter is 50mm. Material of pipe used is copper as it shown to be a good heat conductive material. Furthermore, the pipe is attached to the rear of PV module to improve its cooling thus lowering the surface temperature as shown in Fig. 4.

Table 1 *Specification of PV panel at STC*

Origin & manufacturer	China, Trina solar
Model number	TSM-DE19
I_{SC} (A)	18.56
Open circuit voltage, V_{OC} (V)	38.1
Voltage at maximum load, V_{MPP} (V)	31.8
Current at maximal load I_{MPP} (A)	17.45



(a) **(b)**

Fig. 3 *Heat exchanger pipe geometry (a) Dimension of pipe; (b) Diameter of pipe*

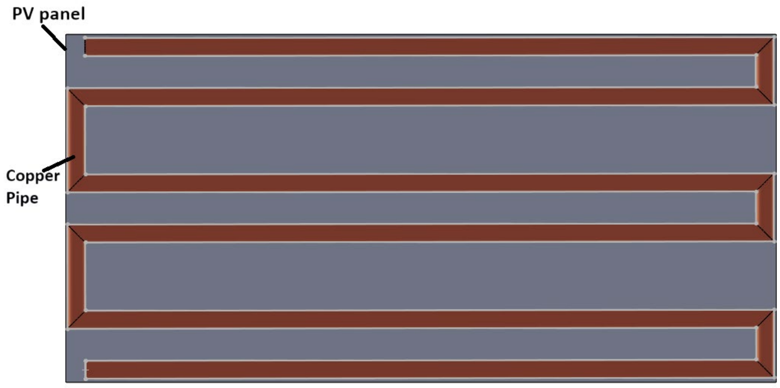
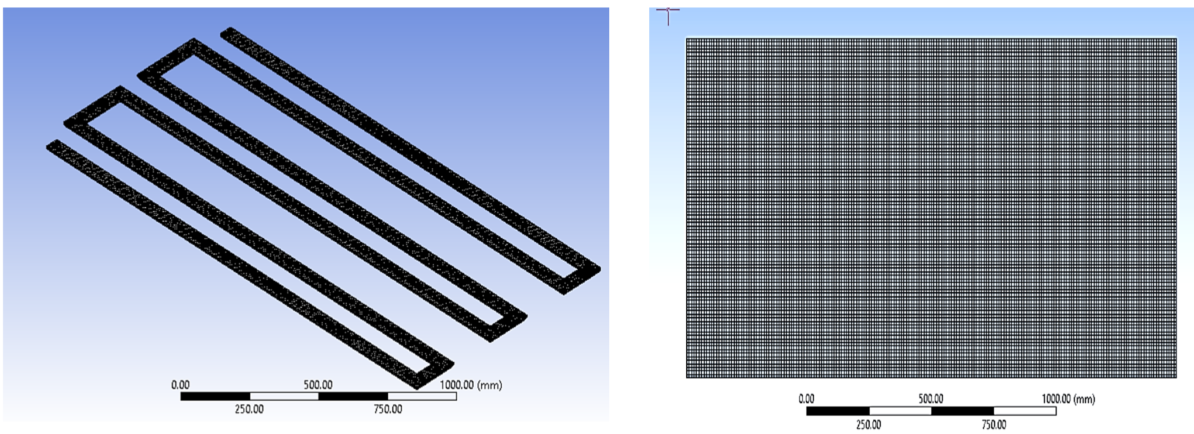


Fig. 4 *Numerical setup*

2.2 Boundary Conditions

The boundary conditions are set in Ansys Fluent and simulation are run. Meshing was carried out and the nodes and elements are 44117 and 142989 respectively as shown in Fig 5. The heat flux used to replicate actual sun irradiation is 900 W/m^2 projected onto the surface of the panel. Configurations for inlet is inlet velocity where velocity is calculated using Reynolds number and the outlet is configured as outflow. Two sets of simulations were conducted where the first simulation is to investigate the effect of variable (Re) on temperature while keeping the volume concentrations constant at 2%, while the second simulation is to investigate the effect of variable volume concentrations while keeping the (Re) constant. First study was carried out with (Re) ranging from 1500 to 2600. The second study was carried out with 2% and 4% volume concentration of Al_2O_3.



(a) **(b)**

Fig. 5 *Meshing (a) Meshing of pipe; (b) Meshing of PV panel*

2.3 Governing Equations

The governing equations used for this numerical simulation of PV panel cooling are listed below [10], [11].

Continuity:

$$\frac{\partial(\rho uj)}{(\partial xj)} = 0 \tag{2}$$

Momentum of conservation:

$$\frac{\rho uiuj}{\partial xj} = \left(-\frac{\partial p}{\partial xi}\right) + \left(\frac{\partial}{\partial xj}\right)[\mu(\frac{\partial \mu i}{\partial xj} + \frac{\partial uj}{\partial xi})] \tag{3}$$

Energy conservation:

$$\frac{\rho uiuj}{\partial xi} = \left(\frac{\partial}{\partial xj}\right)[k(\frac{\partial T}{\partial xj})] \tag{4}$$

K is the thermal diffusivity:

$$\mathrm{k} = \frac{u}{p} \tag{5}$$

The heat transfer rate of the whole system is calculated using [12], [13].

$$\mathrm{Q} = \mathrm{mcp}(T_0 - T_i) \tag{6}$$

Average convective heat transfer coefficient:

$$\mathrm{h} = \mathrm{Q}/[A(T_w - T_b)] \tag{7}$$

T_w is the average wall temperature, meanwhile T_b represent the bulk temperature.

3. Result and Discussion

The results obtained showed an improvement in the temperature of PV panel which is the main objective of the study. Average temperature of PV panel without any sort of cooling reached 345.13K as shown in Fig 6. High temperatures such as this can drastically affect the efficiency of the panel. Thus, cooling with nanofluid is introduced through this numerical study.

Fig. 7 illustrates the fluctuation in surface temperature of the PV panel under three specific cooling conditions: absence of cooling, cooling with 2% nanofluid, and cooling with 4% nanofluid. The analysis was performed at various Re ranging from 1500-2600. The findings unequivocally indicate that nanofluid-based cooling markedly lowers the surface temperature relative to the uncooled baseline, with the degree of cooling affected by nanoparticle concentration and flow rate. In the absence of cooling, the surface temperature attained a peak of 345.13 °C, signifying significant thermal accumulation without active heat dispersion. Upon the introduction of a 2% nanofluid, the surface temperature diminished to 333.44 °C at Re = 1500 and further reduced to 326.48 °C at Re = 2600.

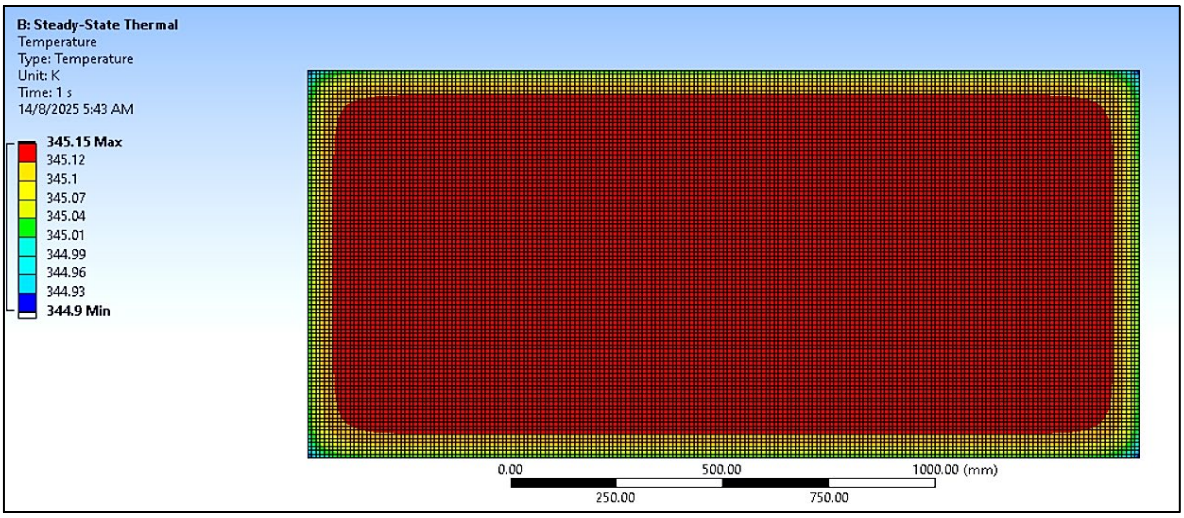


Fig. 6 *Temperature contour of uncooled PV panel*

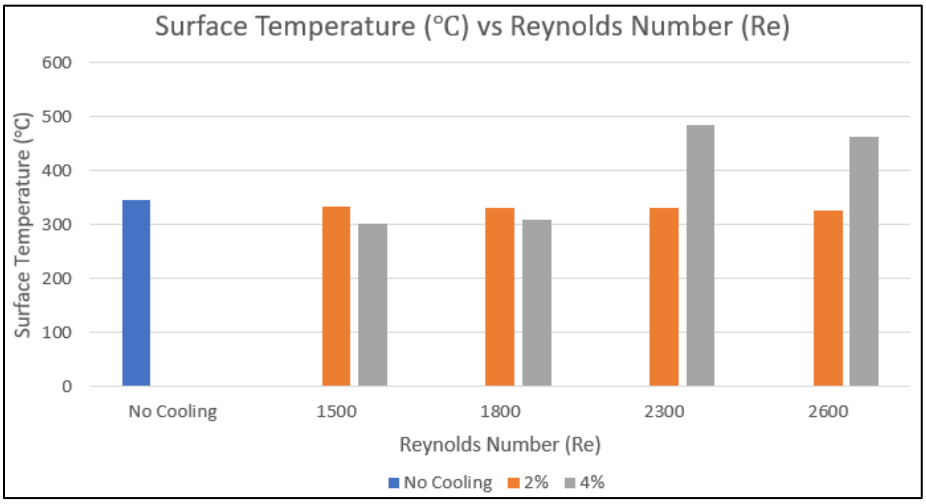


Fig. 7 *Surface temperature of panel for various Re*

This persistent decrease underscores the improved convective heat transfer attained with elevated flow rates, as increased Re facilitate more efficient fluid movement and thermal exchange. Conversely, the 4% nanofluid demonstrated a more intricate behaviour. At Re = 1500, the surface temperature was markedly reduced to 301.9 °C, indicating enhanced thermal efficiency at flow rates. Nevertheless, as the Reynolds number escalated, the surface temperature suddenly soared to 485.78 °C at Re = 2300 and 462.98 °C at Re = 2600. This paradoxical trend may be ascribed to many variables, such as nanoparticle agglomeration, which can diminish the effective thermal conductivity of the fluid, or the emergence of turbulent flow regimes that hinder uniform heat transmission. Moreover, simulation artifacts or constraints within the numerical model may have led to these abnormalities and require validation through experimental comparison.

The findings emphasize the necessity of controlling nanofluid concentration and flow rate for effective cooling of photovoltaic panels. Increased nanoparticle concentrations can improve thermal conductivity, but they may also complicate fluid dynamics, adversely affecting performance at high flow rates. Reduced surface temperatures are directly associated with enhanced electrical efficiency and prolonged longevity of photovoltaic modules, rendering nanofluid-cooled heat exchangers a viable alternative for thermal control in solar energy systems. Additional research is advised to examine the stability and dispersion properties of nanofluids under diverse flow circumstances to guarantee constant and dependable cooling efficacy.

Fig. 8 depicts the fluctuation in PV panel efficiency as a function of Reynolds number under two cooling scenarios 2% nanofluid Fig. 9 shows for 4% volume concentrations. The data, displayed in both graphical and tabular formats, demonstrate clear trends in thermal performance and energy conversion efficiency at the evaluated flow rates. The panel efficiency of the 2% nanofluid exhibits a steady and progressive enhancement as the Reynolds number increases. The efficiency begins at 12.88% at Re = 1500 and rises to 13.3% at Re = 2600. This pattern indicates that increased convective heat transfer at elevated flow rates significantly lowers panel temperature, thereby enhancing electrical production. The curve's stability across all Reynolds numbers signifies dependable thermal behaviour and effective dispersion of nanoparticles inside the fluid.

Conversely, the 4% nanofluid demonstrates a more inconsistent performance. The efficiency starts at a notable 14.78% at Re = 1500 and stays robust at 14.25% at Re = 1800; however, a significant reduction occurs at Re = 2300, where efficiency plummets to 3.74%. Despite a modest rebound to 5.11% at Re = 2600, the overarching pattern indicates a substantial decline in cooling efficacy at elevated flow rates. This anomaly may result from nanoparticle aggregation, elevated viscosity, or flow instability, which can impede heat transfer and negatively impact panel performance. These findings underscore the significance of controlling nanofluid concentration and flow parameters. A greater concentration (4%) may initially improve thermal conductivity and efficiency; however, it can also lead to issues such as sedimentation or turbulent flow behaviour that undermine performance at increased Re. Conversely, the 2% nanofluid exhibits more regular and predictable behaviour, rendering it a potentially more dependable option for photovoltaic panel cooling applications.

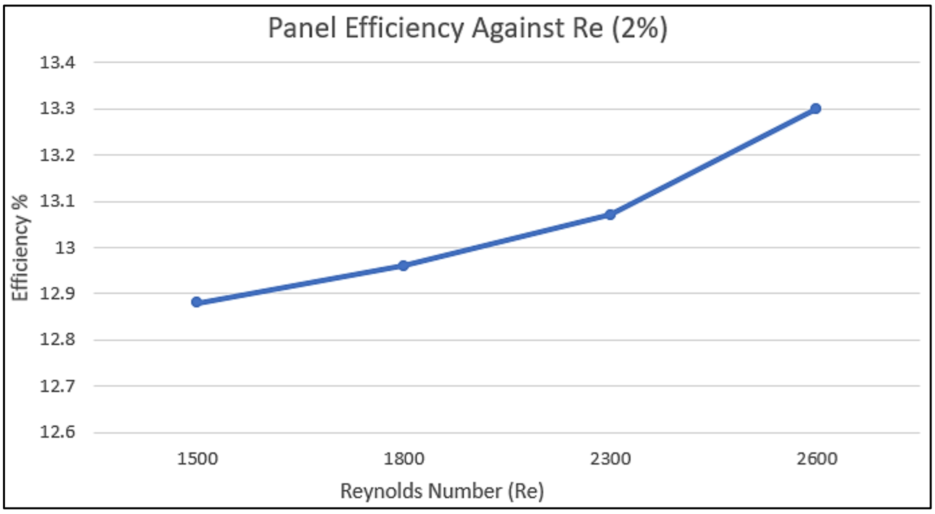


Fig. 8 *Efficiency against Re for 2% volume concentration*

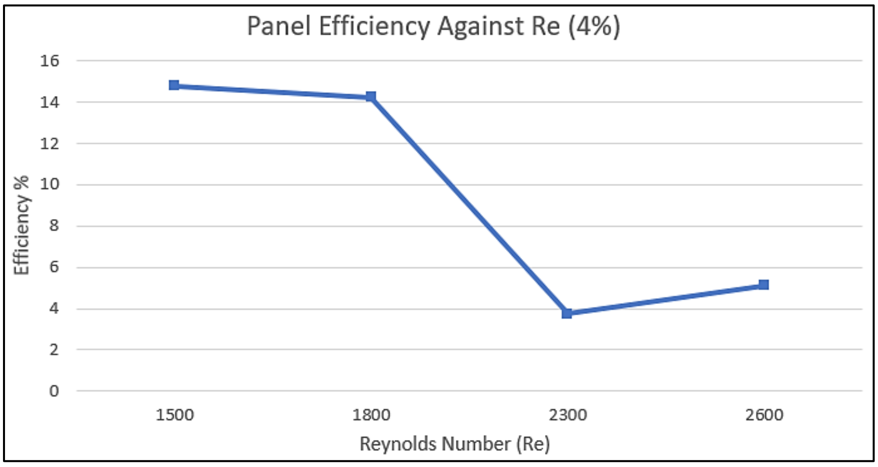


Fig. 9 *Efficiency against Re for 4% volume concentration*

Fig. 10 illustrates the relationship between the friction factor and the Reynolds number for the 2% Al_2O_3 nanofluid. The friction factor constantly diminishes from 0.0427 at Re = 1500 to 0.02888 at Re = 2600. This tendency corresponds with conventional fluid dynamics theory, wherein the friction factor inversely correlates with the Reynolds number in laminar and transitional regimes. For Re < 2300, the flow remains laminar, and the friction factor adheres to the theoretical relationship as shown in Eq. (8) signifying steady and predictable viscous behaviour. As the flow approaches turbulence Re ≥ 2300, the reduction in friction factor diminishes, indicating the emergence of inertial effects and improved mixing. The gradual decrease over the examined range indicates that the 2% nanofluid preserves uniform flow properties without notable irregularities like particle agglomeration or viscosity surges. This consistency benefits solar panel cooling by ensuring dependable thermal performance and controllable pumping demands.

$$f = \frac{64}{Re} \tag{8}$$

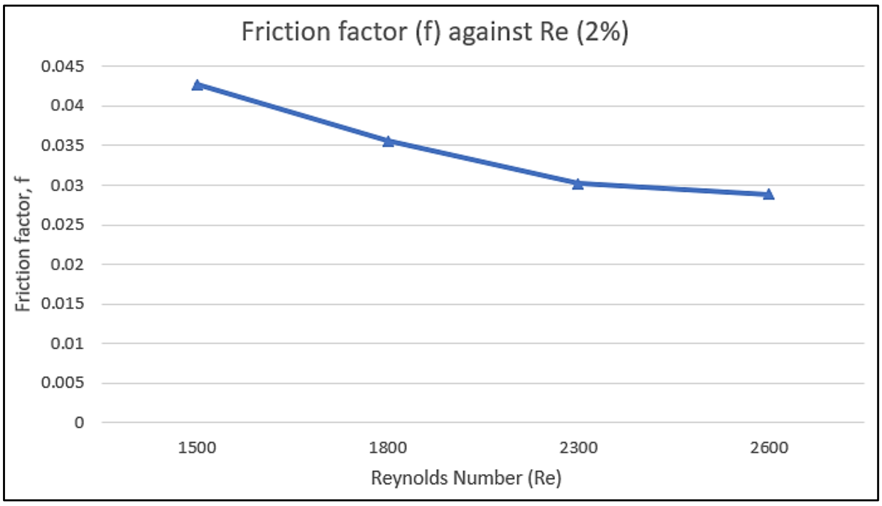


Fig. 10 *Friction factor against Reynolds number for 2% volume concentration*

4. Conclusions

The computational investigation of the cooling performance of PV modules utilizing Al_2O_3 nanofluids at varied Re ranging from 1500–2600 and concentrations of 2% and 4% demonstrates distinct correlations among thermal behavior, electrical efficiency, and hydraulic properties. Fig. 7 illustrates that both nanofluid concentrations decreased the PV surface temperature compared to the uncooled baseline of 345.13 °C. The 2% concentration demonstrated a steady and uniform decrease in temperature from 333.44 °C at Re = 1500 to 326.48 °C at Re = 2600, indicating improved convective heat transfer with rising flow rate. Conversely, although the 4% nanofluid demonstrated enhanced cooling at low Reynolds numbers 301.90 °C at Re = 1500, its thermal efficacy significantly diminished at elevated Reynolds numbers, with temperatures escalating to 485.78 °C at Re = 2300 and 462.98 °C at Re = 2600, an occurrence likely attributable to nanoparticle agglomeration, heightened viscosity, and potential flow instabilities.

The efficiency trends depicted in Figs. 8 and 9 corresponded with these temperature patterns. The 2% nanofluid demonstrated a consistent increase in efficiency from 12.88% to 13.30% within the analyzed Reynolds number range, signifying reliable and stable heat dissipation. In contrast, the 4% concentration, after an initial peak of 14.78% at Re = 1500, had a sharp decline to 3.74% at Re = 2300, with a minor recovery to merely 5.11% at Re = 2600, highlighting its instability at elevated flow rates. The hydraulic performance illustrated in Fig. 10 demonstrated a reduction in the friction factor for the 2% nanofluid, decreasing from 0.0427 at Re = 1500 to 0.02888 at Re = 2600, aligning with theoretical predictions and suggesting stable, predictable flow regimes.

These findings indicate that the 2% Al_2O_3 nanofluid provides a more dependable cooling solution for PV panels, optimizing temperature reduction, efficiency improvements, and acceptable pressure losses. The 4% concentration may excel at low Reynolds numbers, but its operational instability at elevated flow rates restricts its practical use. Subsequent research should empirically confirm these findings, examine long-term dispersion stability under operational pressures, and optimize nanofluid-flow parameter combinations for scaled implementation in high-irradiance settings.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Yamunan, Abdulhafid M A Elfaghi;* ***data collection:*** *Yamunan;* ***analysis and interpretation of results:*** *Yamunan;* ***draft manuscript preparation:*** *Yamunan, Abdulhafid M A Elfaghi. All authors reviewed the results and approved the final version of the manuscript. The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.*

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