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Investigation of the Thermal Performance of Water and Aluminum Oxide Nanofluid as a Coolant for Solar Panels

Ahmad Fawwaz Irsyaad Ahmad Farhan[1], Nur Atiqah Mohamad Aziz[1,2], Hassan Mohamed[1,2,*], Bidattul Syirat Zainal[2], Hazlina Junoh[2]

1 College of Engineering, Universiti Tenaga Nasional, Jalan Ikram – Uniten, 43000 Kajang, Selangor, Malaysia
2 Institute of Sustainable Energy, Universiti Tenaga Nasional, Jalan Ikram – Uniten, 43000 Kajang, Selangor, Malaysia

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ABSTRACT

A solar panel, also known as a photovoltaic (PV) panel, converts photons from sunlight into usable energy. However, panel warming during the day limits voltage production and results in energy-electricity waste. The efficiency of this PV panel's cooling system utilizing water and aluminum oxide (Al_2O_3) nanofluid was simulated and assessed using Computational Fluid Dynamics (CFD). This research examines the thermal performance of temperature differences between uncooled, water-cooled, and Al_2O_3 nanofluid-cooled solar panels. To find the lowest temperature of the solar panel achieved, the mass flow rates of coolants (16.5, 33, 66, and 99 L/h) and inlet coolant temperatures (20, 25, 30, 35, and 40 °C) were varied. Al2O3 nanofluid-cooled solar panels at the maximum flow rate and the lowest inlet coolant temperature, 99 L/h and 20℃, respectively, promised the minimum solar panel temperature, which is critical for energy storage. Furthermore, the use of nanofluid coolant assisted in the reduction of 41 to 60% of solar panel temperature. These results shed insight into the capabilities of nanofluid in the coolant system.

1. Introduction

The sun provides more than light during the day; each photon of sunlight that reaches Earth carries solar energy that powers our planet. Enough solar radiation reaches the planet's surface every hour to provide our global energy demands for nearly a year. The sun is a massive nuclear reactor that, within a nuclear fusion reaction, it generates enormous amounts of energy, radiating from the sun's surface and into space as light and heat [1]. Solar energy is one of the renewable energy sources suited to Malaysia's climate [1]. Extensive research is currently being conducted to achieve the government's goal of an energy transformation involving 31% renewable energy by 2025 and 40% by 2035.

Photovoltaics (PV) or solar thermal collectors are used to capture, transform, and utilize solar energy. A solar PV system's solar panels convert sunlight directly into power that may be used

* *Corresponding author.*
E-mail address: MHassan@uniten.edu.my

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immediately. The Sustainable Energy Department Authority (Malaysia) encourages consumers to produce and use electricity by mounting solar PV panels on the roof. The PV effect is how solar energy is converted into usable power in solar panels. When sunlight strikes a semiconductor material (usually silicon), electrons are knocked loose, allowing them to travel and generating an electric current that can be stored by wiring. A solar inverter is required to convert direct current (DC) electricity to alternating current (AC) [2].

Electricity efficiency is inversely related to the temperature of the solar panels [3-7]. The efficiency of the voltage output decreases as the temperature rises. Nowzaki [4] reported that every 1℃ increase in solar panel temperature reduces efficiency by 0.5%. The study employed a flow rate range of 3 to 6L/min at constant inlet temperature (20℃). Therefore, cooling systems exist to reduce the solar panel's temperature. Unconverted solar energy is mainly converted to heat [5]. Each method of cooling these solar panels has advantages and disadvantages. Many studies have shown that the water-cooling system has successfully lowered the temperature of the solar panel while directly improving the efficiency of the air-cooling system due to its heat capacity [7].

Saad and Masud *et al.,* [8] used water cooling to enhance the electrical efficiency of the PV panel. Due to the ability of water to transmit heat, the surface of the PV panel improved by roughly 15% of the output system for the peak sun hour. The study was conducted during summer with an average temperature of 58℃ at a water flow rate of 4L/min. Matthew *et al.,* [9] investigated a water-cooling system that used many ice cubes placed into a tank to keep the water temperature as low as possible. Furthermore, by incorporating a water-cooling system, the electrical behavior of the PV panel can be improved by 4.6%. Besides, Fujii *et al.,*[10] suggested utilizing a water-cooling system to prevent the output power of the PV panel from degrading under high-temperature conditions.

Technology is rapidly evolving, especially nanofluid, a fluid in nanometer-sized particles suspended in a base fluid, forming a colloidal solution of nanoparticles in a base fluid. If nanofluid is utilized as the coolant, it has a higher specific surface area, hence more heat transfer between particles and fluids, resulting in an excellent cooling system [11]. Zheng *et al.,* [12] reported that using $CuO-H_2O$ nanofluid as a heat transfer working medium boosted the solar collector's efficiency by approximately 24%, with the improved efficiency varying depending on the size of the nanoparticles. Next, Munzer *et al.,* [13] conducted an outdoor cooling experiment using (TiO_2) nanofluid in a water-polyethylene glycol mixture, (Al_2O_3) nanofluid in water-cetyltrimethylammonium bromide mixture, and water as cooling medium for volume flow rates ranging from 500 to 5000 mL/min at concentrations (0.01 wt.%, 0.05 wt.%, and 0.1 wt.%) under different radiation intensity. However, the temperature range studied was 20 to 30℃. The results showed that the PV cells cooled by the two nanofluids had a more significant decrease in average PV cell temperature than the water-cooled PV cells. The previous research had a distinct temperature range and flow rate range from this study. Therefore, in this study, Computational Fluid Dynamics (CFD) Simulation software was used to investigate the thermal performance of the uncooled solar panel, water-cooled solar panels, and nanofluid-cooled solar panels. The effects of different mass flow rates (16.9 to 99 L/h) and inlet coolant temperatures on reducing the solar panel temperature were examined in accordance with Malaysian weather, with a range of 20 to 40℃, to determine the appropriate coolant for the PV panel.

2. Methodology

This project was divided into two main parts. The first was to study the effect of a different mass flow rate of coolants in reducing the temperature of solar panels. Meanwhile, the second part analyzed the impact of varying inlet coolants' temperatures on lowering the temperature of solar panels. Both objectives were conducted via the Computational Fluid Dynamics (CFD) Simulation Software (ANSYS Simulation).

A three-dimensional geometric model of the PV panel was created using Creo 3D Parametric Software. Both studies have identical geometry (Baranwal *et al.,* [14]). The model was saved as a Step (stp.) and then imported into ANSYS Software for further processing. The "System Coupling" analysis system was used to ensure that the input for calculating temperature difference was completed and ready for computation. Figure 1 depicts the PV Panel, represented by the Steady State Thermal Analysis system, while Figure 2 shows the cooler Fluid Flow (Fluent). PV Panel dimensions were L (length) – 1640 mm, W (width) = 980 mm, and d (depth) = 0.4 mm. Table 1 provides the properties of the PV Panel cells layer in a PV panel.

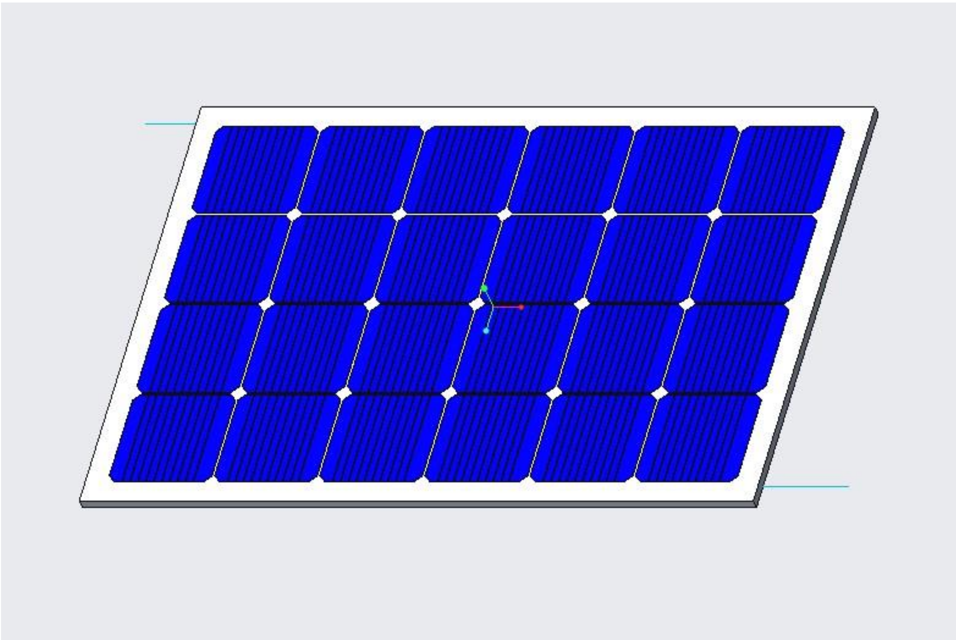


Fig. 1. PV Panel used for simulation (Steady State Thermal)

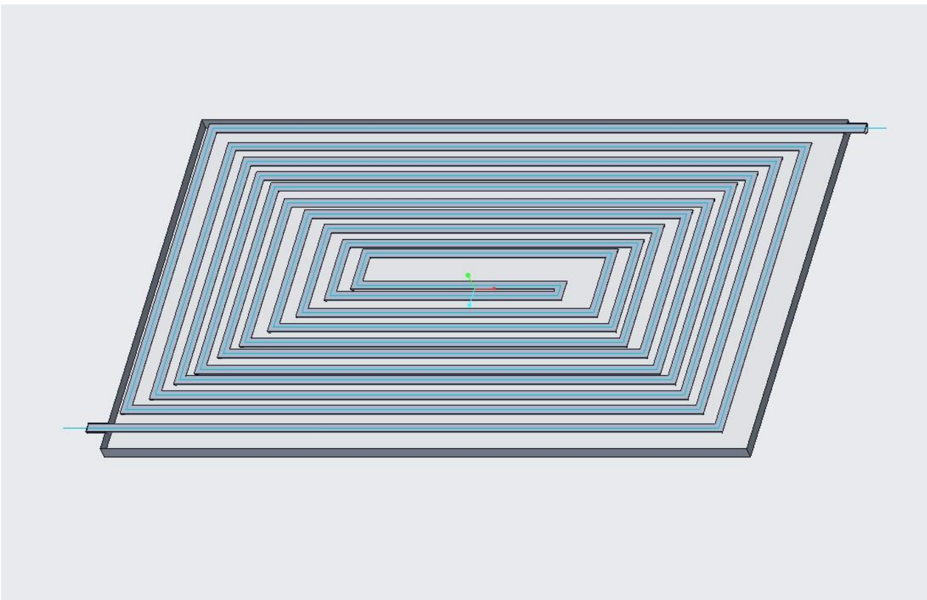


Fig. 2. Cooler used for simulation (Fluid Flow – Fluent)

Table 1
Properties of the PV cells layer in PV panel

Layer	Thickness (mm)	Thermal conductivity (W/m·K)	Density (kg/m3)	Specific heat capacity (J/kg·K)
PV cells	0.4	148	2330	677

Fluid flow (fluent), Steady-state thermal, and system coupling were the three analysis systems used in the modeling. To complete the simulation, each of the three has its role. As mentioned in the modeling of the geometry section, only the PV panel and the cooling area were involved in the simulation. As a result, the simulation was built around the "System Coupling," in which fluid flow (fluent) represented the cooling area and Steady-State thermal denoted the PV panel. Following the required input, the system coupling combined data from the two analyzed systems for computation and distribution profiles.

Steady State Thermal. The simulation started by determining the solar panel's temperature without any coolant. Next, the geometry and the thermophysical properties were updated in steady-state thermal, with the top surface of the PV Panel receiving 900 W·m^2 of heat flux. In contrast, convection was applied on six PV panel surfaces with a film coefficient of 10 W/m^2·K and an ambient temperature of 300.15 K (27℃). Next, the Fluid Solid Interface (FSI) was set to the surface where heat transfer occurred. The bottom part of the PV panel was used in this case since it was in direct contact with the coolant. All the particulars were referred from Baranwal *et al.,* [14]. It was found that the solution of the average PV Panel temperature without cooling is 71.82 °C, closely in line with the reference study. For each experiment with a different mass flow rate, the input temperature was set to 20°C. When the inlet temperature was assessed, a mass flow rate of 66 L/h was used.

Fluid Flow (Fluent). The simulation proceeded by moving on to the Fluid Flow (Fluent), where the coolant setup was constructed this time. The model meshed after it was updated to "Geometry." The system consists of 102273 nodes and 368628 elements. Figure 3 illustrates the meshing of the model.

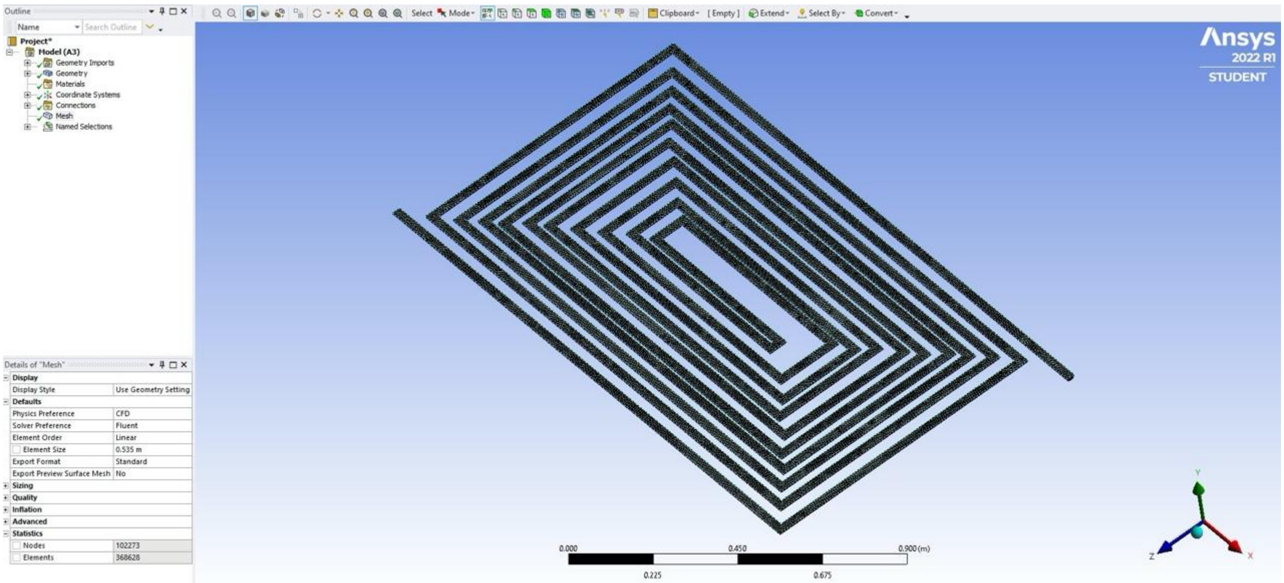


Fig. 3. The meshing of the geometry

2.1 Solver Configuration
2.1.1 Material

The models were then set up in Fluid Flow (Fluent) using the "Set up" tool. All parts of this project used laminar flow, and the energy equation was checked. The Reynolds Number for the simulations was less than 2300, indicating laminar flow. Setting up the materials was one of the most critical aspects of the Solver. The essential thermophysical properties were inserted in "Materials" by following the type of coolant used in this project: water and Aluminum Oxide–Water (Al_2O_3–H_2O) – 1%. Table 2 demonstrates the calculations and the thermophysical properties of these two types of coolants.

Table 2
Thermophysical properties

Material	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)	Viscosity (kg/m·s)
Water (H_2O)	998.2	4182	0.6	0.001003
Aluminum Oxide-Water (Al_2O_3-H_2O)	1026.63	4046.301	0.6187	0.00093175

2.1.2 Boundary conditions

The coolant's flow rate varied in terms of mass flow rate for the effect of coolants' mass flow rates on solar panel temperature. Therefore, a few conversions were needed to obtain the value of the mass flow rate. The flow rates of coolants used were 16.5, 33, 66, and 99 L/h. Table 3 displays the conversion tables from the coolant's flow rate to its mass flow rate for the boundary conditions. For the effect of inlet coolants temperatures on solar panel temperature, the impact of different inlet coolants temperature was analyzed, with inlet velocity ranging from 20 to 40 ℃, with a 5℃ gap.

Table 3
Conversion of coolant flow rate to mass flow rate

Water flow rate (L/h)	Water flow rate (m^3/s)	Mass flow rate (kg/s)
16.5	4.58333×10^{-6}	0.004570042
33	9.16667×10^{-6}	0.009140083
66	1.83333×10^{-5}	0.018280167
99	2.75000×10^{-5}	0.02742025
Nanofluid flow rate (L/h)	Nanofluid flow rate (m^3/s)	Mass flow rate (kg/s)
16.5	4.58333×10^{-6}	0.005246748
33	9.16667×10^{-6}	0.010493496
66	1.83333×10^{-5}	0.020986992
99	2.75000×10^{-5}	0.031480488

System Coupling. After both the Fluid Flow (Fluent) and Steady-State Thermal systems were configured correctly, both systems were merged to get the desired outcomes. After system coupling was established on the Steady–State Thermal, the computation began. The temperature of the PV Panel after being cooled under the circumstances was achieved.

Based on the evaluation of various grid conditions, a grid-independent test was performed to determine the optimal grid condition with the fewest number of grids without incurring a difference in the numerical results. As a result, the optimum number of element sizes in this simulation is 368,268. Furthermore, verification with earlier research was attempted, and the percentage difference in values was less than 10%.

3. Results

3.1 The Effect of Coolants Mass Flow Rates on Solar Panel Temperature

The simulation was initially performed on a PV panel without a cooling system to determine the initial temperature before the coolant was supplied to study the influence of mass flow rate for each type of coolant (water and nanofluid). The simulation then continued by providing water as a coolant to the solar panel but with different mass flow rates to find how much it could reduce its temperature. Later, the material was replaced with nanofluid, with various mass flow rates of 16.5, 33, 66, and 99 L/h.

Figure 4 depicts the temperature of the PV Panel without a cooling system throughout the simulation with the maximum and minimum temperatures of 72°C (345.15 K) and 71.82°C (344.82 K), respectively, and an average temperature was 71.91°C (344.99 K). Meanwhile, Figure 5 and 6 show the temperature distribution of the PV Panel after cooling with water and nanofluid, with a flow rate of 66 L/h as an example. Finally, the results are presented in Figure 7.

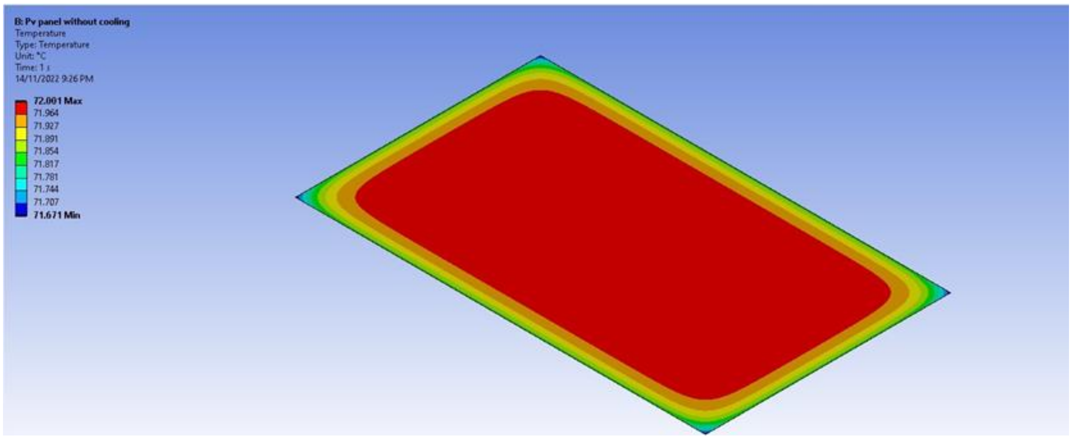


Fig. 4. Average temperature distribution of PV panel without cooling

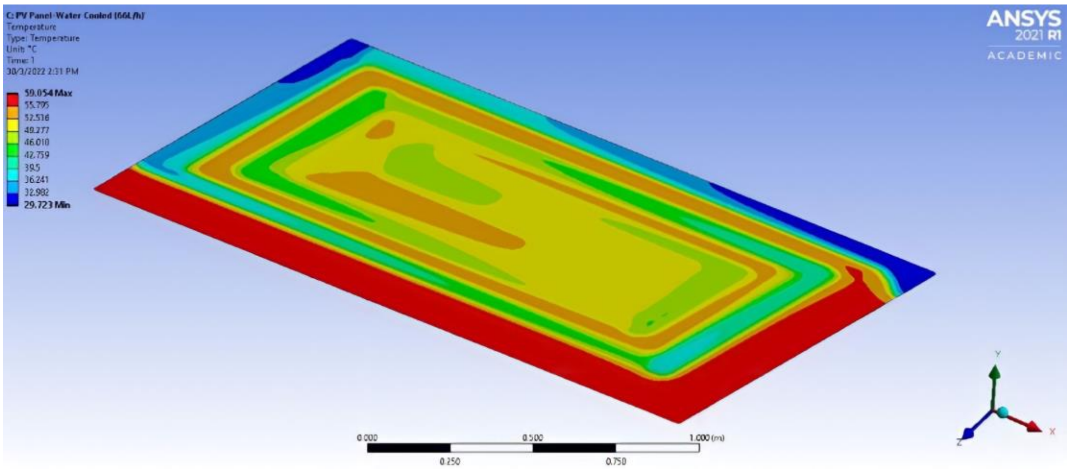


Fig. 5. Average temperature distribution of water-cooled PV panel for a mass flow rate of 66 L/h

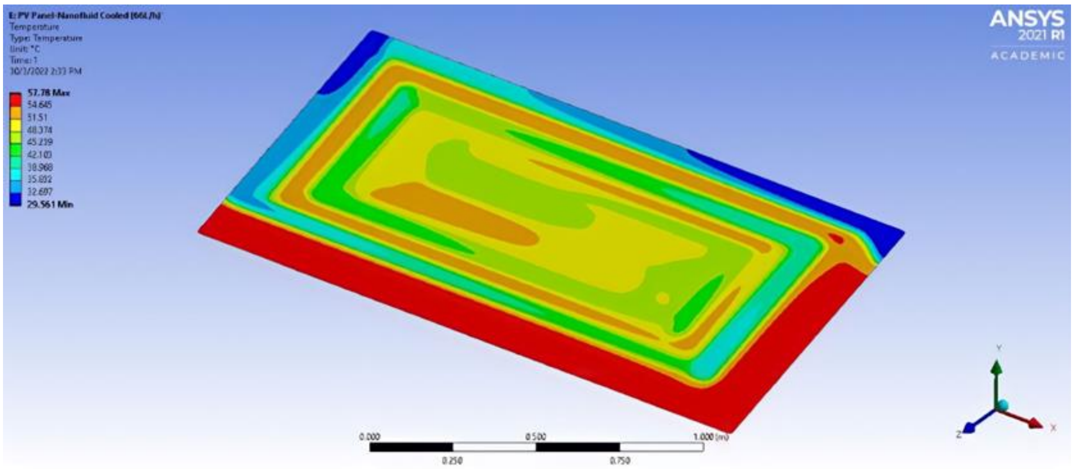


Fig. 6. Average temperature distribution of nanofluid-cooled PV panel for a mass flow rate of 66 L/h

Figure 7 illustrates the average temperatures of the PV panel's surface after cooling with water and nanofluid with the coolants' flow rate. The primary purpose of this section was to investigate the impact of mass flow rate on solar panel temperature reduction. The higher the mass flow rate, the lower the solar panel's temperature. The heat transfer theory was used to explain this event. Heat transfer is the process through which the internal energy of one substance is transferred to another. When two objects have a temperature difference, heat transfer occurs in the direction of decreasing temperature, that is, from a hot object to a cold item. On that note, when the solar panel cooled with the coolants, the heat was transferred from a higher to a lower temperature, and heat transfer occurred.

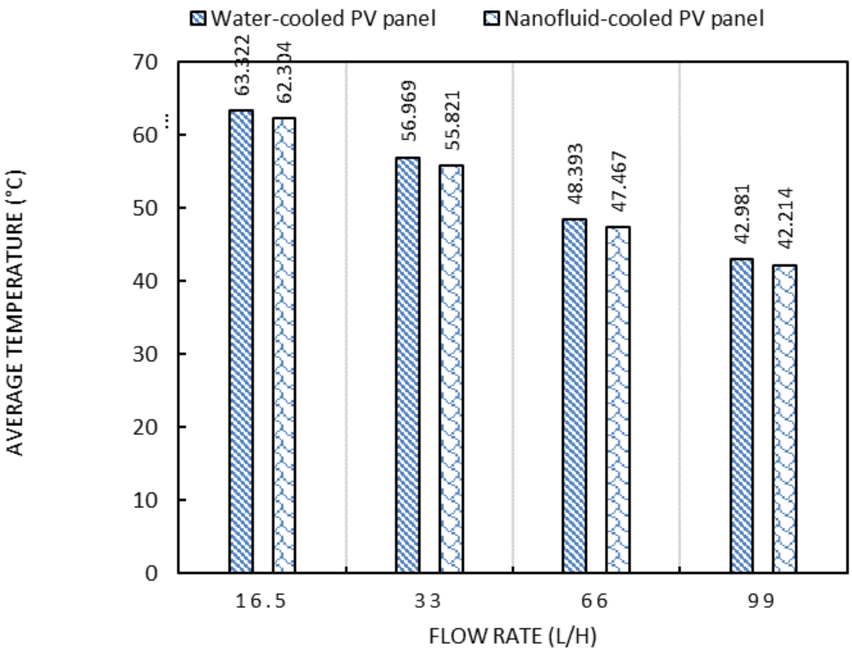


Fig. 7. Effect of coolants mass flow rates on the average temperature reduction of PV panel

To put it in context, heat transfer is affected by various factors such as temperature difference, material heat capacity, and mass flow rate. Because the heat transfer rate is proportional to the mass flow rate, as the mass flow rate increases, so does the heat transfer. The reducing temperature of the solar panel increases as heat transfer increases, proving the theory that the higher the mass flow rate, the lower the temperature of the solar panel. The heat capacity of water indicates the required heat per unit mass in raising the temperature of the solar panel. There was a synergistic effect for the Al_2O_3 nanofluid that enhanced the coolant's ability to store more heat per unit mass [7].

3.2 The Effect of Inlet Coolants Temperatures on Solar Panel Temperature

In this simulation, the inlet temperatures were 20, 25, 30, 35, and 40 °C. The steps for studying the impact of inlet temperature on every type of coolant (water and nanofluid) were the same as in the previous section. The simulation was executed on a PV panel without any cooling system, followed by the application of coolants. After that, the material was changed to nanofluid. Figure 8 presents the average temperature of the surface of the PV panel after cooling, with the inlet temperature rising from 20 to 40°C with a 5 °C interval. The average temperature of the PV panel increased as well, indicating that the inlet temperature of coolants was directly related to the average temperature of the PV panel. This pattern means that the lower the coolant inlet temperature, the better the cooling system. As a result, the PV Panel will have a lower average temperature on the surface, allowing it to generate more electricity.

This condition occurred because when the temperature of the inlet coolants rises, less heat is transferred from the PV Panel through the coolants, causing the solar panel's temperature to climb. Heat dissipation is a type of heat transfer that occurs when a hotter object is placed in an environment where the heat is transferred to the cooler objects and the surrounding environment. Convection dissipates heat in this cooling system since the fluid is used as a heat transfer medium. As a result, the lower the inlet temperature, the better the cooling system is since it may increase the heat dissipation rate, resulting in a lower solar panel temperature.

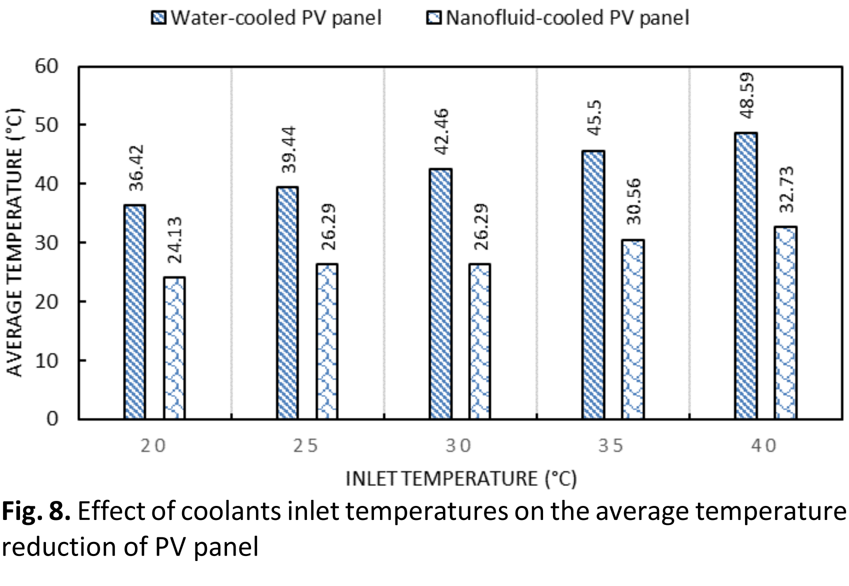


Fig. 8. Effect of coolants inlet temperatures on the average temperature reduction of PV panel

According to the simulation study, the uncooled solar panel temperature was 71.82 °C. The average solar panel temperature was 63.32 °C, at the lowest water flow rate of 16.5 L/h. Meanwhile, the temperature for the Al_2O_3 nanofluid was 62.3 °C. At the highest flow rate of 99L/h, water and Al_2O_3 nanofluid reduced temperatures to 42.98 and 42.21°C, respectively. In investigating the effect of various flow rates (from 16.5 to 99 L/h) on solar panel temperature, water coolant reduced the temperature by 12 to 40%. When Al_2O_3 nanofluid was used as a coolant, the temperature was decreased by 13 to 41%, as tabulated in Table 4. A higher flow rate indicates a shorter retention time for the coolant to store heat and a larger medium volume to retain the existing heat. This discovery was consistent with earlier nanofluid coolant studies [6,15].

Table 4
Percentage decrease of PV panel temperature at various coolant flow rates

Flow rate (L/h)	Average temperature of a solar panel (°C)			Percentage decrease in PV panel temperature after coolants are applied (%)	
	Uncooled	Water	Nanofluid	Water	Nanofluid
16.5	71.82	63.32	62.3	11.83	13.25
33		56.97	55.82	20.68	22.28
66		48.39	47.47	32.62	33.91
99		42.98	42.21	40.15	41.22

In Table 5, water coolant reduced solar panel temperature from 71.82 to 48.59°C at the highest coolant inlet temperature (40 °C). The temperature reduced by Al_2O_3 nanofluid was considerably lower, at 32.73°C. At the minimum inlet temperature, a similar improvement trend was observed for water and Al_2O_3 nanofluid. Both had higher reduction temperatures of 36.42 and 24.13°C, respectively. Overall, 32 to 49% of temperature reduction was observed for water coolant while evaluating the effect of varying inlet temperatures (from 40 to 20 °C) on solar panel temperature. However, when using Al_2O_3 nanofluid as a coolant, temperatures were decreased by 54 to 66%, as shown in Table 5. This finding is because nanofluid has different thermophysical characteristics than water.

Table 5
Percentage decrease of PV panel temperature at various coolant inlet temperatures

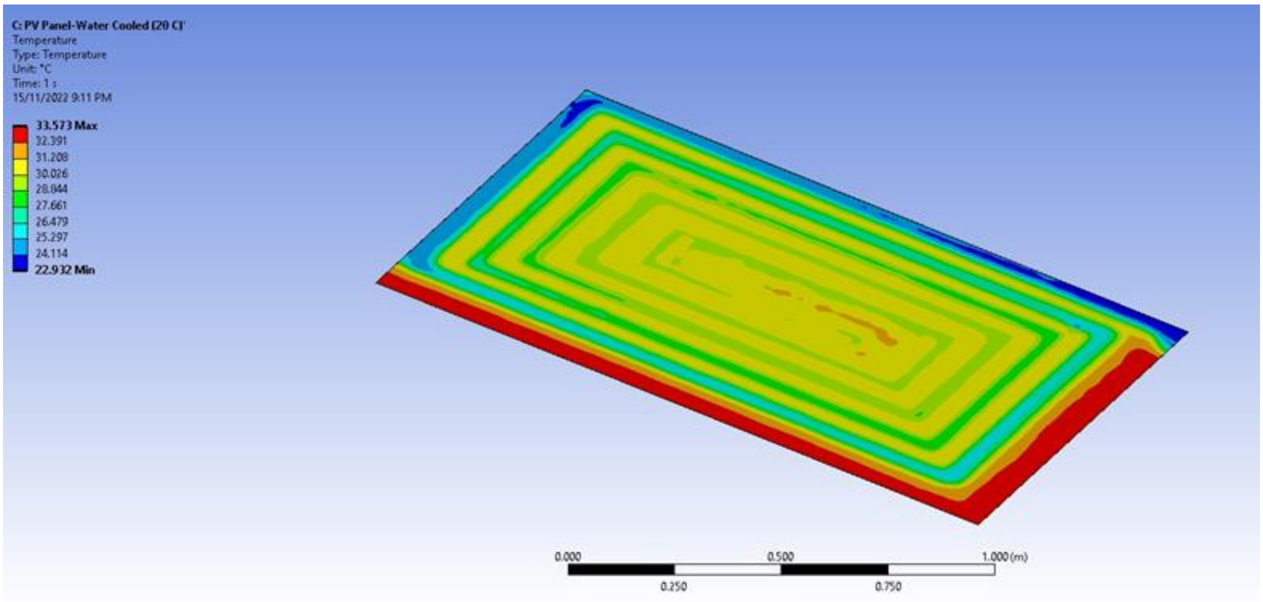
Inlet temperature (°C)	Average temperature of a solar panel (°C)			Percentage decrease in PV panel temperature after coolants are applied (%)	
	Uncooled	Water	Nanofluid	Water	Nanofluid
20	71.82	36.42	24.13	49.28	66.4
25		39.44	26.29	45.08	63.39
30		42.46	26.29	40.88	63.39
35		45.5	30.56	36.65	57.45
40		48.59	32.73	32.34	54.42

Aluminum Oxide nanofluid has a higher density of 1026.63 kg/m^3 than water, with a thickness of 998.2 kg/m^3. The higher the density of a fluid, the more stable the solution. The stability of a nanofluid is related to Electrical Double Layer Repulsive Force (ELDRF) and Van Der Walls attractive force, with the ELDRF having to be greater than the Van der Walls attractive force to produce a stable nanofluid [16]. A nanofluid must be stable since it substantially affects thermal conductivity. Stability is related to nanoparticle dispersion in the base fluid, with more nanoparticle dispersibility corresponding to the higher thermal conductivity of the nanofluid [17]. In short, the higher a solution's stability, the greater its thermal conductivity, which leads to another explanation of why nanofluid is superior to water.

Thermal conductivity (known as k, λ, or κ) is a material's intrinsic ability to transport or conduct heat. The thermal conductivity of nanofluid is higher at 0.6187 W/m·K than that of water, which is slightly lower at 0.6 W/m·K. As a result, the higher the thermal conductivity values, the faster heat will be transferred through that material, resulting in better cooling performance. On top of that, the viscosity of nanofluid is lower than that of water. Viscosity affects heat transfer due to its properties;

the lower the viscosity, the more stable the solution [18]. The more stable the solution, the better the heat transfer. As a result, the nanofluid has a more excellent cooling performance than water.

It was postulated that comparing factors which are flow rate and inlet temperature for coolants, the reduction of PV panel temperature across faster flow rates only has a marginal effect. This is because the coolant and PV panel had less contact time at a high flow rate. Therefore, heat absorption was ineffective [4]. However, the ability to absorb more heat at low temperatures was more pronounced at a constant flow rate. The temperature distribution profiles of water-cooled and nanofluid-cooled PV panel at temperatures 20 – 40 °C were presented as follow. The cool region was displayed in blue, while the warmer part was shown in yellowish to red. Figure 9 and 10 show the temperature distribution on water-cooled and nanofluid PV panel for inlet temperature respectively



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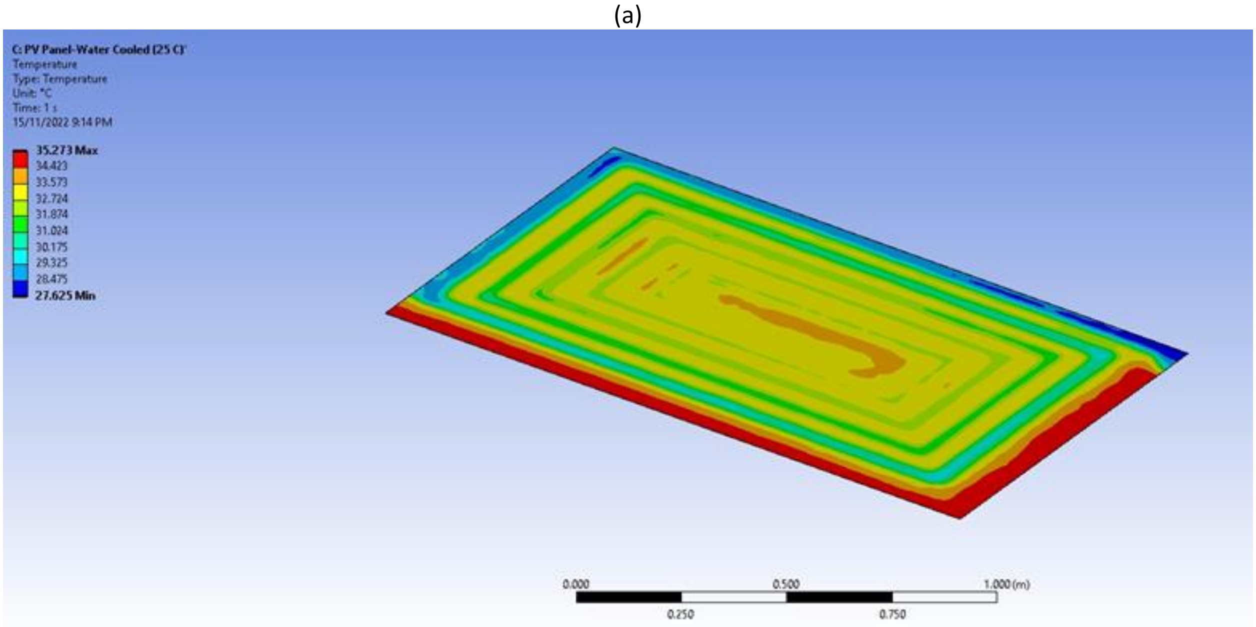

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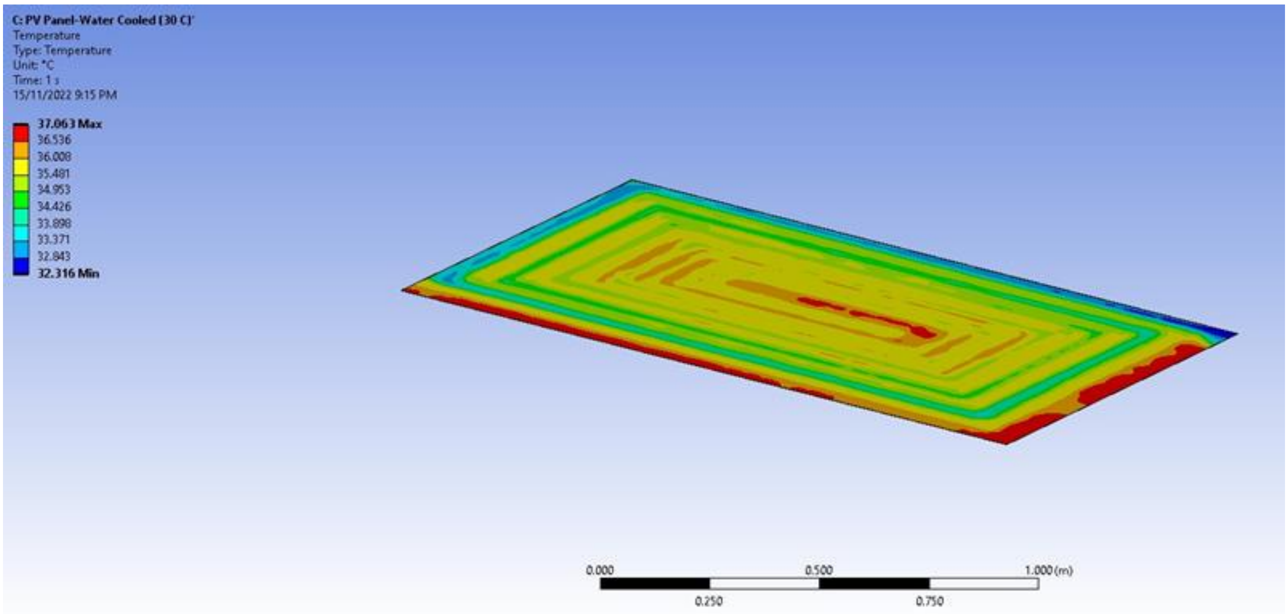
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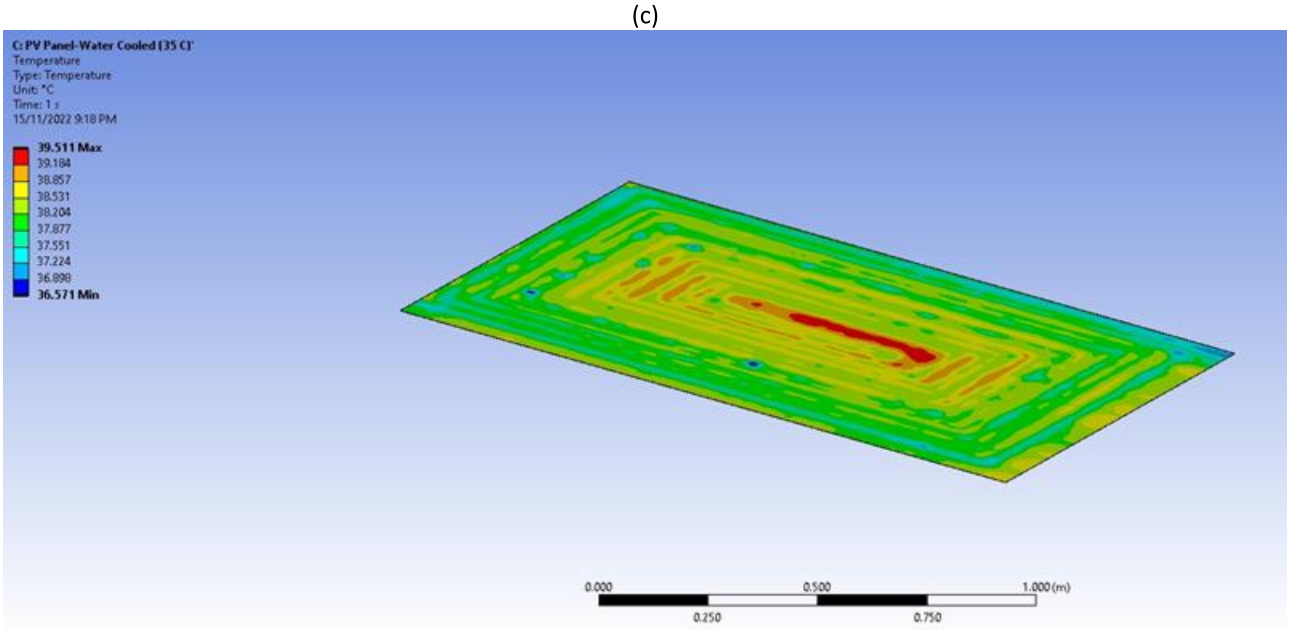
(c)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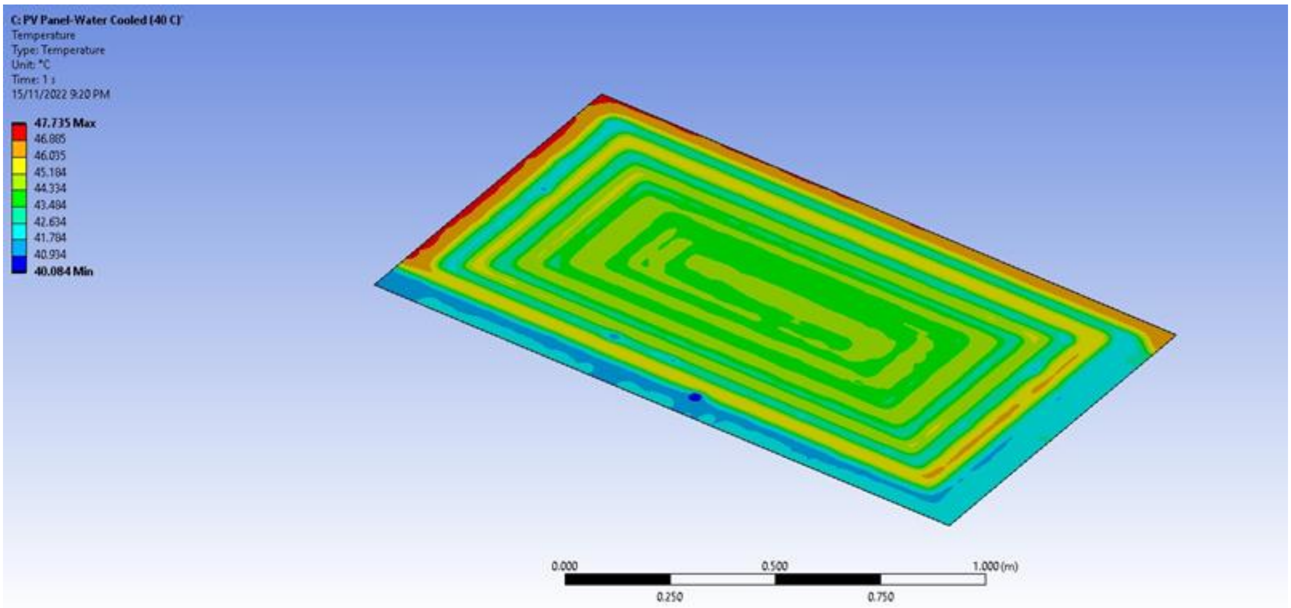
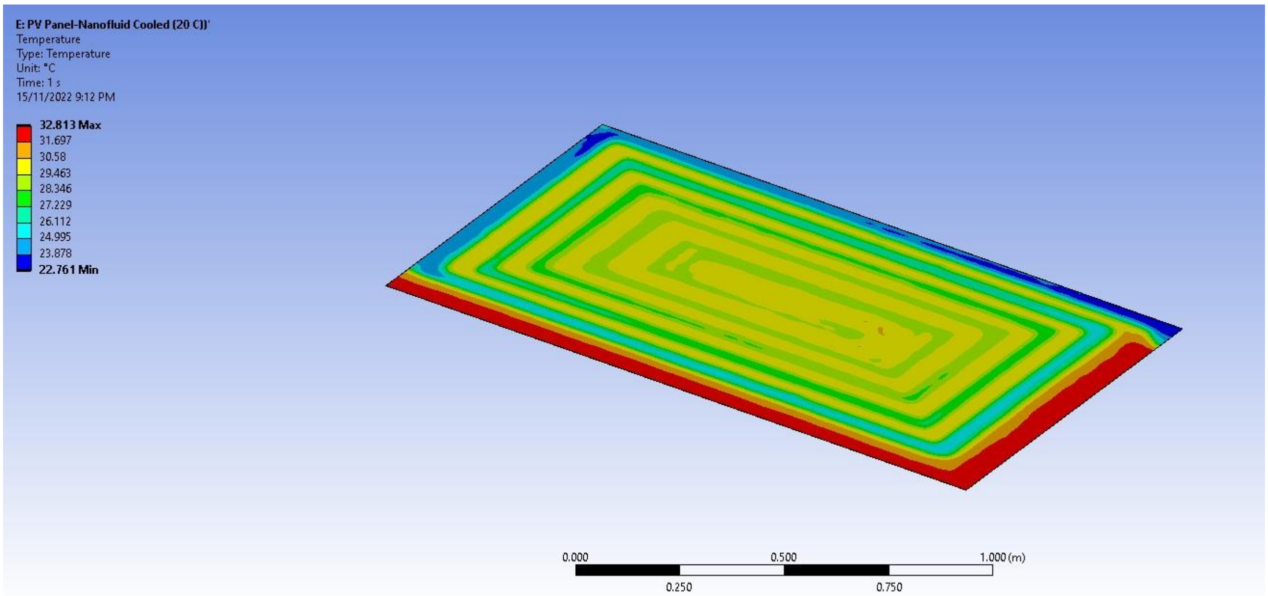
0.500
0.750
1.000 (m)

(d)



(e)

Fig. 9. Temperature distribution on water-cooled PV panel for inlet temperature of (a) 20℃ (b) 25℃ (c) 30℃ (d) 35℃ and (e) 40℃



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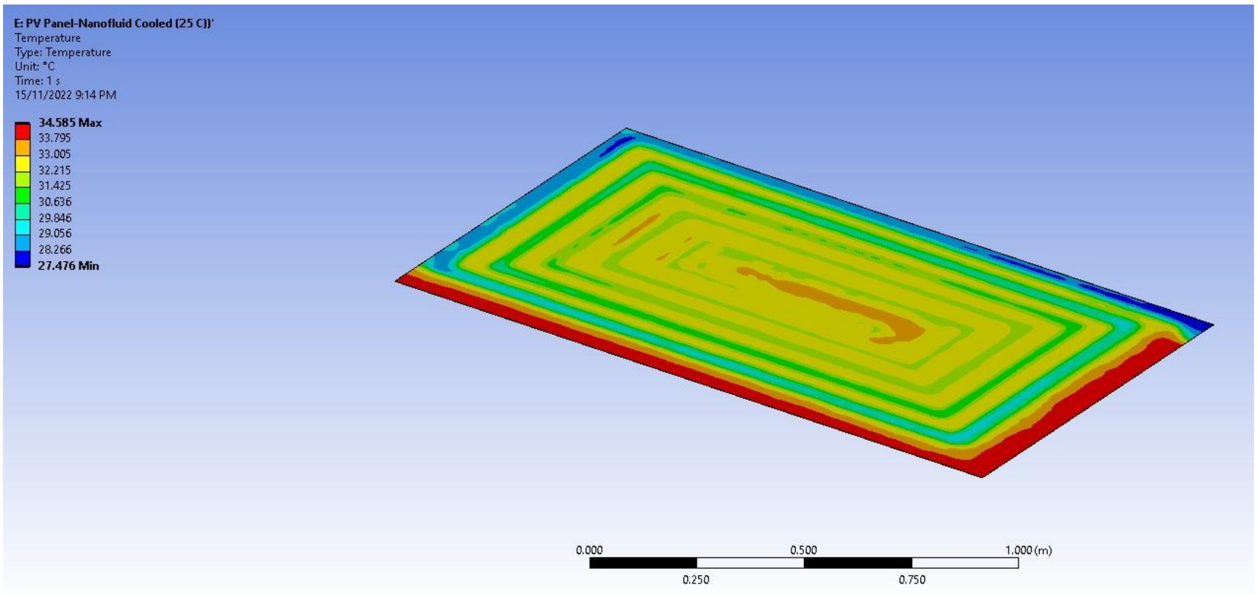
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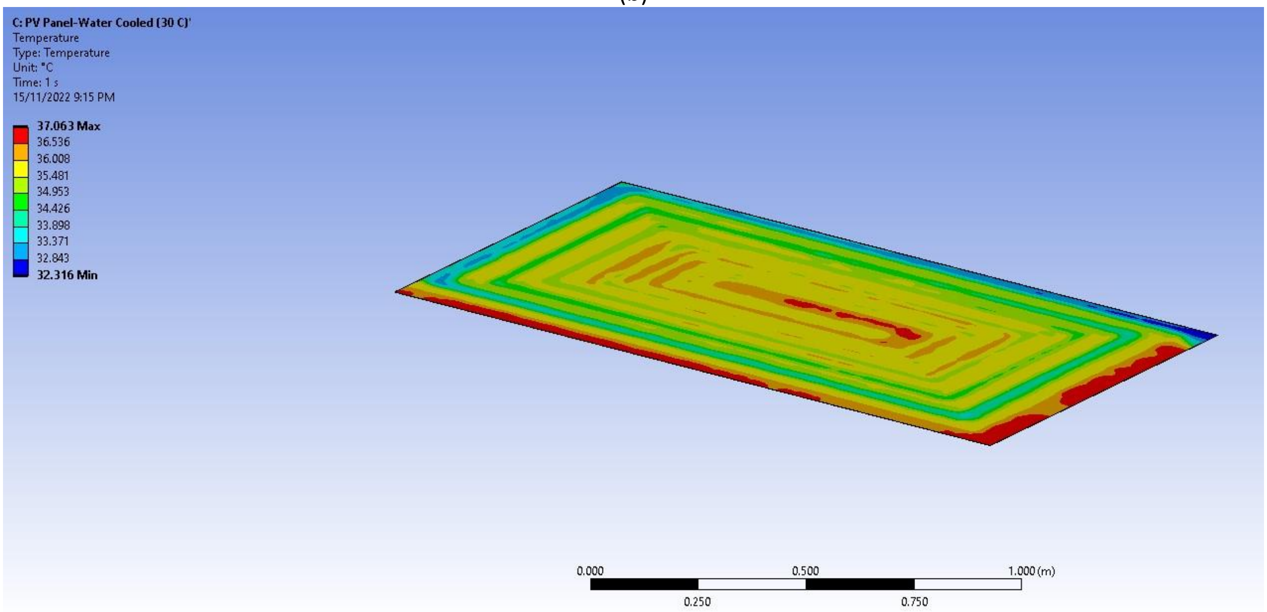
0.750

(b)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Temperature
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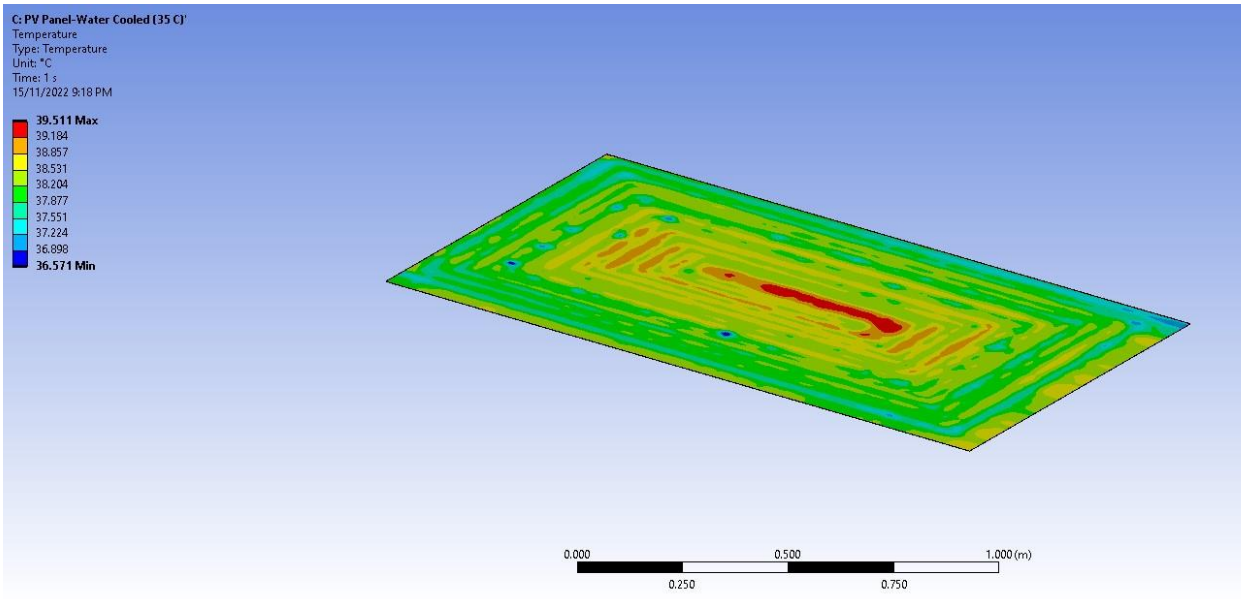

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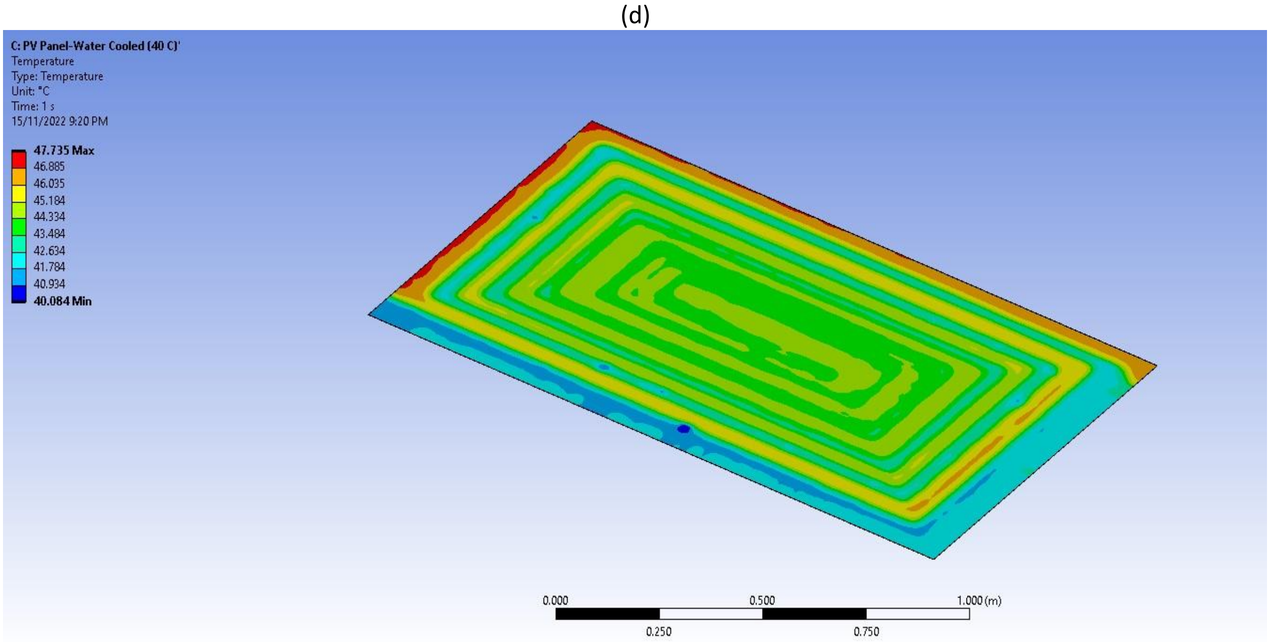

(e)

Fig. 10. Temperature distribution on nanofluid-cooled PV panel for inlet temperature of (a) 20°C (b) 25°C (c) 30°C (d) 35°C and (e) 40°C

4. Conclusions

This study examined the thermal performance of temperature differences between uncooled, water-cooled, and Al_2O_3 nanofluid-cooled solar panels. The findings revealed no significant effect on the PV panel between water and Al_2O_3 nanofluid coolant at various flow rates. For Al_2O_3 nanofluid coolant, the average percentage of solar panels displayed a 13 to 41% temperature decrease compared to 12 to 40% when using water. Nonetheless, when Al_2O_3 nanofluid coolant was employed at various inlet temperatures, the solar panel temperature was reduced by more than 10% (54 to 66%), whereas water resulted in a 32 to 49% temperature reduction. In contrast, the Al_2O_3 nanofluid coolant outperformed water in thermal performance. Using Al_2O_3 nanofluid coolant at the minimum solar panel temperature might reduce electrical efficiency lost during solar energy capture. Future research should focus on the electrical and thermal efficiency of the system, as well as the active ingredient in coolants derived from renewable sources.

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