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Performance Analysis of Nanofluid-based Photovoltaic Thermal Collector with Different Convection Cooling Flow

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Abstract

Using solar energy through photovoltaic (PV) panels has excellent potential as an alternative energy source. However, the problem of high operating temperatures causing a reduction in work efficiency needs to be addressed. This study aimed to analyze the development of a cooling system to increase PV panels' electrical and thermal efficiency. The research involved analyzing the use of TiO_2, Al_2O_3, and ZnO working fluids by adding 0.5 vol% to water in an active cooling method. The cooling system involved a rectangular spiral and a rectangular tube behind the PV panel. A solar simulator simulated solar radiation with intensity variations to analyze the cooling system's performance in different working conditions. The results showed that the heat exchanger with a nanofluid configuration reduced the panel temperature by 14 °C, which increased the electrical efficiency by up to 4.7% in the ZnO nanofluid. In the rectangular spiral configuration, the ZnO nanofluid reduced the panel temperature from 60 to 45 °C, increasing the Isc value from 2.16A to 2.9A and the Voc value from 21.5V to 23V. This resulted in a maximum power increase of the panel to 53W.

Keywords: Photovoltaics; Nanofluids Cooling; Temperature; Efficiency; PV Panel.

1. Introduction

The global energy crisis has created a significant demand for developing renewable energy technologies. Among these, solar energy is one of the most promising sources due to its abundance, cleanliness, and accessibility. Solar energy can be harnessed to generate both heat using solar collectors and electricity using photovoltaic (PV) solar cells [1]. PV cells have become increasingly popular for electricity production due to their eco-friendliness and cleanliness [2]. Photovoltaic thermal (PV/T) systems have been widely used in developed countries, particularly for residential and commercial buildings [3]. In China, PV/T systems are employed for hot water production and heat pumps, such as solar-assisted heat pumps. The PV/T module is directly integrated into the heat pump and used as an evaporator [4]. However, the primary challenge hindering the extensive use of PV systems is the increase in panel temperature [5].

In the PV module, every 1°C increase in operating temperature can decrease the output power performance by 0.4-0.5%. In the case of building-integrated photovoltaics/thermal (BIPV/T), the PV module performance will decrease when the operating temperature exceeds 80 °C in the summer [6, 7]. Additionally, only 5 to 25% of solar radiation can be absorbed by PV, with the rest being wasted [8]. This makes the concept of PV cooling an effective way to improve efficiency and reduce the rate of thermal module degradation. Various cooling techniques have been widely applied to improve the efficiency of PV modules.

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Conversely, the PV module absorbs most solar radiation in the form of heat that is difficult to remove with natural convection [9]. Forced convection using water is the most popular cooling technique for PV panels. In addition, nanofluids as working fluids have also been widely used recently. Colloidal suspensions known as nanofluids have more thermal conductivity and heat transfer capabilities than water. Nanoparticles smaller than 100 nm are often dispersed into water, oil, and ethanol to create nanofluids [10, 11]. The cooling technique with forced convection of water using the spraying method on the top surface of the PV can improve overall PV performance, such as current, power, and efficiency [12]. This result is reinforced by Hadipour et al. (2021), who designed an experimental PV cooling system with pulsed-spray water cooling and steady-flow water spray to reduce water consumption during the cooling process [13]. The panel surface temperature was reduced from 57.1 to 24.8 and 26.5 °C using a steady-flow water spray and pulsed-spray water cooling system with DC = 0.2 compared to an uncooled PV system.

Another method Kordzadeh (2010) implemented was covering the PV panel's surface with a thin layer of water to improve the system's operation [14]. In addition, the water used in the cooling process can be collected and reused. Similar research conducted by Jakhar et al. (2017) shows that by adjusting the water inlet on the back of the PV panel, this system can increase the efficiency of the PV panel by 1.02-1.41% [15]. However, Nižetić et al. (2016) revealed that cooling the PV on both sides simultaneously is more efficacious [16]. The test results can increase total efficiency by 7.7%, electric power by 5.9%, and temperature reduction from 54°C to 24°C. In addition, the development of PV cooling by passively controlling the temperature of the PV module using water and cotton wicks can reduce the temperature of the PV module by 12% and increase the electric power by 14% [17]. In addition, PV performance can be improved by combining conventional PV and cooling systems. This combined system provides higher power output and efficiency than conventional systems [18].

The application of nanofluids and modification of geometric configurations have a significant impact on the behavior of photovoltaic/thermal systems. Kahani et al. (2022) describe flowing TiO_2 nanofluid using a serpentine pipe under the panel, which can increase the thermal efficiency of PV panels up to 86.9% with a concentration of 0.5 wt% nanofluid [19, 20]. Ahmed et al. (2021) evaluated the performance of single multi-junction solar cells for high-concentrator photovoltaics using mini-channel heat sinks with nanofluid [21]. The benefits of nanofluid are significant in increasing electrical efficiency, thermal efficiency, and High Concentrating Photovoltaic Thermal Systems (HCPVT), respectively, at 0.47%, 7.83%, and 4.68% at Re 8.25. However, the effect of using nanofluids is significant when the solar irradiation is high and the Reynolds number is low. This is also supported by Bianco et al. (2018), who suggest nanofluid utilization may be more efficient in applications with high heat flux, especially at low Reynolds numbers and in temperature control [22]. In another study using spiral flow with a 0.75 vol% Multi-Walled Carbon Nanotube (MWCNT) working fluid, there was an increase in electrical efficiency numerically and experimentally of 10.72% and 12.25% at a flow rate of 120 lpm. While the temperature of the solar cell decreases by 0.77 numerically and 0.72 experimentally per 10 lpm increase in speed [23]. In addition, a rectangular tube cooling system collector with stainless material filled with three types of water-based nanofluids (SiO_2, TiO_2, and SiC) showed the highest thermal efficiency of 81.73% and 13.52% electrical efficiency in SiC nanofluids [24].

Based on previous literature reviews, it has been found that significant research progress has been dedicated to PVT cooling systems that use forced convection processes. Because the increase in thermal and electrical efficiency values is influenced by the ability of the working fluid to cool the PV panel operating temperature, the PVT system is highly influenced by the properties and characteristics of the working fluid used. Therefore, in this research, it is interesting to discuss the use of nanofluids on metal-oxide/water due to their better cooling ability than water. The high heat transfer capability is obtained from a type of nanofluid with higher thermal conductivity [25]. The nanoparticles considered include Aluminum oxide (Al_2O_3), Titanium oxide (TiO_2), and Zinc oxide (ZnO), which are all dispersed in water as the base fluid at 0.5 vol% [26]. The thermal conductivity value of the nanoparticle solids dispersed in water is expected to increase the thermal conductivity of the working fluid used. In addition, the thermal collector shape factor also plays a crucial role. Generally, the flow path shape of the working fluid is only similar to the heat exchanger in rectangular tube form, so in this research, the use of a spiral tube collector with a rectangular tube model made of stainless steel will be compared. This research aims to experimentally investigate the effect of three types of water-based nanofluids used for cooling on panel temperature, efficiency, and performance of integrated PV solar panels with thermal collectors with rectangular and spiral tube shapes. This experiment was conducted indoors using halogen lamps as a solar simulator to simulate actual working conditions.

2. Method

The study used several variations in applying a thermal collector integrated with nanofluids with simplification, as shown in Figure 1.

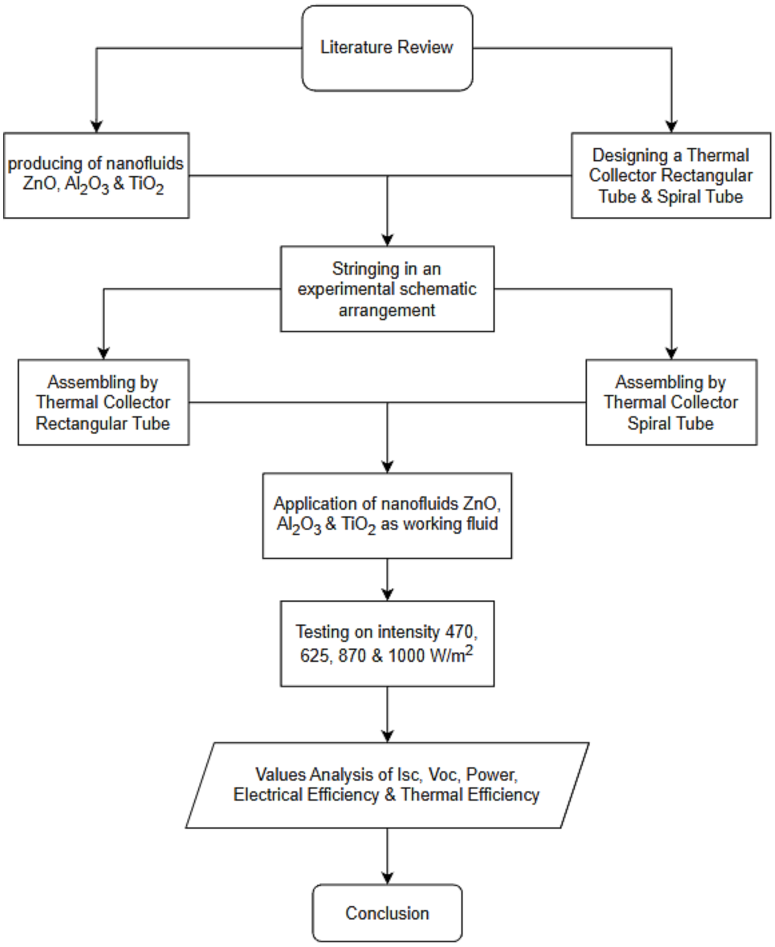


Figure 1. Research flowchart

2.1. Tools and Materials

The nanofluids used in this study are Al_2O_3, TiO_2, and ZnO, used as cooling media for PV solar panels and circulated in heat exchanger pipes. The characteristics of the nanofluid used in this study are shown in Table 1.

Table 1. Properties of the nanofluids

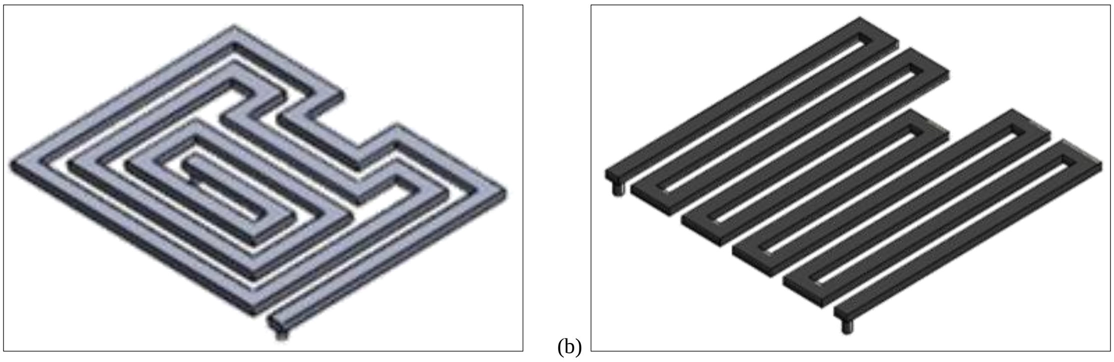
Parameters	ZnO	Al_2O_3	TiO_2
Nanoparticle's size	250nm	382nm	640nm
Concentrations in the water (%vol)	0.5	0.5	0.5
Density (kg/m^3)	1014	1030	1035
Thermal Conductivity (W/mK)	0.6356	0.64	0.6363
Specific Heat (J/kgK)	4164.42	4164.95	4111.81

In this research, the photovoltaic panel is a 50Wp polycrystalline panel produced by Sunwatt Aust. Pty. Ltd with specifications as shown in Table 2.

Table 2. Specifications for Sunwatt 50Wp photovoltaic panels

Specification	Score
Solar panels	Polycrystalline
Open-circuit voltage (Voc)	18.0V
Short-circuit current (Isc)	2.77 A
Maximum power (Pmpp)	50 Wp
Efficiency	17.6%
Operating module temperature	-40 to 85 °C
Dimensions	670 × 530 × 30 mm
Irradiance and Cell	1000 W/m^2

As seen in Figure 2, the pipe employed in the designed cooling system has a rectangular spiral and rectangular tube structure. The cooling pipe is composed of stainless steel and is 4.61 m long, 0.03 m by 0.015 m in cross-section and 0.001 m in thickness.



(a) (b)

Figure 2. Cooling pipe (a) rectangular spiral and (b) rectangular tube

The nanoparticles used in this study are TiO_2, Al_2O_3, and ZnO. The manufacture of nanofluid in this study uses a two-step process method [27]. This process disperses TiO_2, Al_2O_3, and ZnO nanoparticle powders with a concentration of 0.5% vol. into the primary fluid (water). Mixing nanoparticles and essential fluids uses a Wird Hotplate MSH-20A magnetic stirrer. After that, the sonication process was continued for 2 hours using Digital Ultrasonic Cleaner Krisbow 303363 [28]. The sonication process provides better dispersion, thereby helping the suspension to be more homogeneous, and the possibility of agglomeration is minimal [29].

2.2. Experiment Set Up

The rectangular spiral and rectangular tube-shaped thermal collector are mounted at the base of the PV panel. In this instance, fieldwork circumstances are simulated using a solar simulator [30]. The solar simulator is built for panels with a 50 Wp capacity, 16% effective area, and 2.61% non-uniformity [31]. Using a data logger (Labjack-U6, US), a K-type thermocouple is used to measure and record panel temperature data. The intake and exit channels of the heat exchanger, as well as the top and bottom of the panel, are all equipped with sensors. Install a Dwyer 490 digital manometer at the intake and outflow channels to measure the pressure differential. On the pipe's input channel, the flowmeter is mounted. A Lutron SPM-1116SD solar power meter was used to measure the amount of solar irradiation. Figure 3 shows the experimental setup used in this investigation.

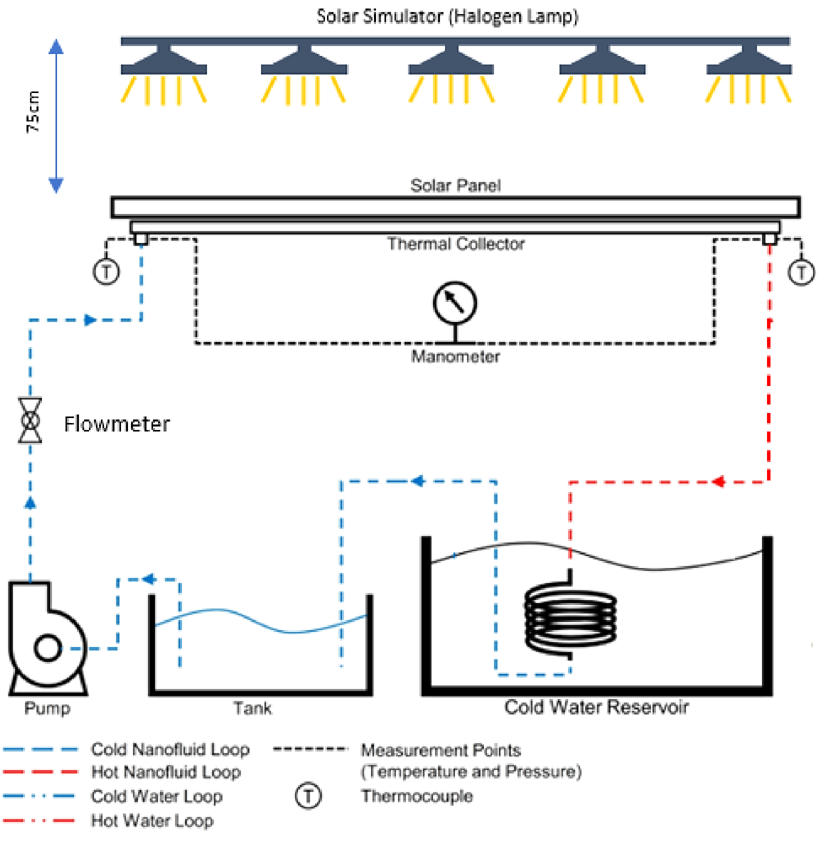


Figure 3. Experimental schematic arrangement

2.3. Thermal Analysis, Energy, and Efficiency

The thermal conductivity of TiO_2 and ZnO nanofluids can be predicted based on Equations 1 and 2, respectively [32-34]. At the same time, the conductivity value of Al_2O_3 is obtained from Apmann et al. (2021) [35].

Calculation of TiO_2 thermal conductivity:

$$k_{nf}(T) = k_{bf}(T), (a + b\emptyset) \tag{1}$$

ZnO conductivity calculations:

$$\frac{k_{np}+2\,k_{bf}+2\,(k_{np}-k_{bf})(1+\beta)^3\emptyset}{k_{np}+2\,k_{bf}-2\,(k_{np}-k_{bf})(1+\beta)^3\emptyset} K_{bf} \tag{2}$$

In this case, the density properties of the Al_2O_3 and TiO_2 nanofluids were obtained from Hussein et al. (2013) [36]. While the density of nano ZnO fluid is obtained from Sapphire et al. (2019) [34]. On the other hand, the specific heat of Al_2O_3 and ZnO nanofluids is based on the volume concentration of nanoparticles which can be found using Equation 3 [37]:

$$C_{Pnf} = \emptyset(C_{P_{nP}}) + (1-\emptyset)(C_{P_{bf}}) \tag{3}$$

C_p is the specific heat value of the TiO_2 nano fluid obtained from Hussein et al. (2013) [36]. Without the influence of external forces, the conservation of energy, in general, can be expressed as Equation 4:

$$\dot{Q} = \dot{m}, C_p, (T_e - T_i) \tag{4}$$

where T_i and T_e are the average fluid temperatures at the inlet and outlet of the pipe, $\dot{m}$ is the mass flow rate, and $\dot{Q}$ is the rate of heat transfer to or from the fluid. In an active cooling system, heat transfer occurs by forced convection which can be defined as Equation 5:

$$\dot{Q} = h, A_s, (\Delta Tlmtd) \tag{5}$$

where h is the heat transfer coefficient, A_s is the surface area of the pipe, and $\Delta Tlmtd$ is the surface temperature of the pipe and the average temperature of the working fluid In finding the value of the heat transfer coefficient (h), you can use Equation 6 [38]:

$$h, A_s, (\Delta Tlmtd) = \dot{m}, C_p, (T_e - T_i) \tag{6}$$

The temperature at the inlet and outlet must be carefully calculated. In the flow in the heat exchanger, $\Delta Tlmtd$ can be calculated from Equation 7:

$$\Delta Tlmtd = \frac{Ti-Te}{\ln[(Ts-Te)/(Ts-Ti)]} = \frac{\Delta Te-\Delta Ti}{\ln\left(\frac{\Delta Te}{\Delta Ti}\right)} \tag{7}$$

Energy efficiency (η) is the ratio between the maximum power (P_{MPP}) to the power from the solar radiation received by the solar cell (I_{light}). Meanwhile, solar radiation power (I_{light}) is obtained from the multiplication of the intensity of sunlight (I_{rad}) and the active area of the solar cell (A). The value of the electrical efficiency of photovoltaic cells is inversely proportional to the significant increase in cell operating temperature during the absorption of solar radiation [39]. In this case, energy efficiency is written by Equations 8 and 9 as follows [40]:

$$\eta_{elctrical} = \frac{P_{MPP}}{I_{light}} = \frac{I_{SC}\times V_{OC}\times FF}{I_{rad}\times A} \tag{8}$$

$$\eta_{thermal} = \frac{m\times C_p\times \Delta T}{I_{rad}\times A} \tag{9}$$

3. Result and Discussion

3.1. The Effect of Nano Fluid Variations on Solar Panel Temperature Reduction

In actual conditions, the performance of solar panels is affected by the weather conditions outside and the solar panel production process. In this case, an increase in the working temperature of the solar panel can reduce the open circuit voltage (Voc) and cause a decrease in power (P) [41]. The increase in temperature can be minimized by an active cooling system using nanofluids. In this study, the initial temperature of the panel and fluid was conditioned at 28°C. This follows the average temperature of the test room. Other test conditions were limited to using nanoparticles at a concentration of 0.5% vol and a flow rate of 5 lpm, while the tests were carried out with a solar simulator. In this case, the flow rate used affects the heat transfer rate of the fluid [42]. The higher flow rate of the fluid used can increase the convection heat transfer rate from the heat exchanger to the fluid [43]. The test results shown in Figure 4 show the temperature drop in each nanofluid variation.

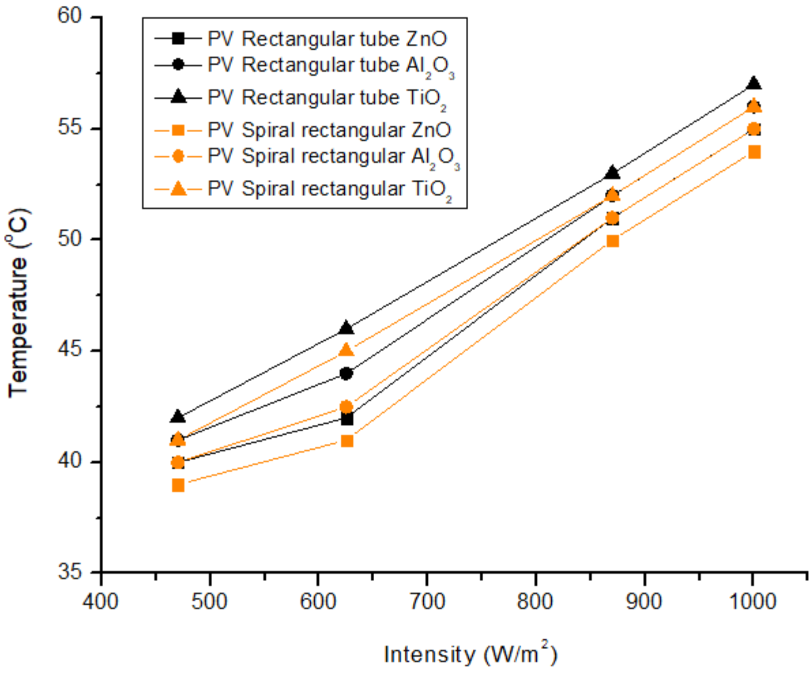


Figure 4. Variation of nanofluid and heat exchanger configurations with temperature

In a variation of the test at an intensity of 1000 W/m^2, the temperature of the panel that has been cooled by the addition of ZnO, Al_2O_3, and TiO_2 nanofluids in a rectangular tube configuration is 55, 56 and 57 ℃ respectively. In comparison, the rectangular spiral configuration is 54, 55 and 56 ℃, respectively. This decrease in solar panel temperature is due to an increase in thermal conductivity value due to the addition of nanoparticles to the working fluid (water). Increasing the concentration and size of nanoparticles causes an increase in thermal conductivity. Most studies that used smaller nanoparticles also revealed more significant thermal conductivity numbers. Due to a reduction in Brownian motion and a reduced surface area-to-volume ratio, the thermal conductivity decreases as nanoparticle size rises. Since heat transmission is a function of surface area, larger particles have a lower surface area to volume-ratio, which lowers thermal conductivity [44].

Additionally, as fewer agglomerates form as nanoparticle sizes grow, the viscosity of the nanofluid also decreases. Placing particles near one another during particle agglomeration contributes to the viscosity of the nanofluid, regarding the rise in thermal conductivity brought on by particle thermophoresis and Brownian motion [35]. The nearby liquid molecules shift somewhat due to Brownian motion, which increases heat conductivity. The thermal conductivity rises due to the amplified Brownian motion because additional routes for heat transmission are created. Thermophoresis, on the other hand, is a phenomenon that moves lighter molecules into hotter regions and heavier molecules towards more excellent parts. This phenomenon increases particle collisions, which eventually promotes heat transfer.

Based on the data shown in Figure 5, using ZnO nanofluids provides the highest cooling of solar panels due to several factors, such as thermal conductivity, particle size, and the convection heat transfer coefficient. In this case, Figure 5 shows the results of testing the nanofluid convection heat transfer coefficient at an intensity of 1000W/m^2. Based on these results, it can be seen that ZnO has the highest convection heat transfer coefficient in both types of heat exchangers. The increase in the heat transfer coefficient is a better indicator than the increase in thermal conductivity for the nanofluids used in the design of heat exchange equipment. The physical properties of nanofluids in the form of density, specific heat, and viscosity can affect the increase in the heat transfer coefficient [45].

In the results obtained, the configuration of a rectangular spiral heat exchanger provides a better reduction in panel temperature than a rectangular tube. This is because the flow rate in the rectangular spiral configuration is lower than the flow rate in the rectangular configuration, allowing the heat transfer of the square spiral to absorb more heat from the PV. This flow rate is directly related to pressure. Therefore, the flow rate will also be lower if the pressure is lower. This is shown in research [46], which varies in three heat exchanger configurations (web, direct, and spiral configurations). The spiral configuration has the best temperature reduction of the three configuration variations. However, using a rectangular tube and rectangular spiral configurations has the same material price but different fabrication difficulties.

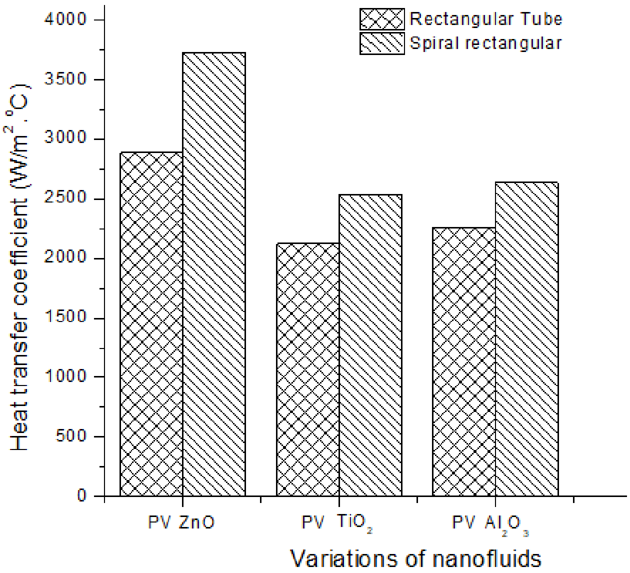


Figure 5. Convective heat transfer coefficient for nanofluids at intensity 1000W/m²

3.2. Electrical and Thermal Efficiency

The electrical efficiency of a photovoltaic-thermal (PV/T) system is usually used to determine the overall electrical performance. Electrical efficiency is calculated from the ratio of the output obtained compared to the input given. The inputs given for both efficiencies are the same, namely the received solar irradiation and the surface area of the PV. Even so, the output in the form of power in each variation obtained is not the same. Data from the calculation of electrical efficiency can be seen in Figure 6.

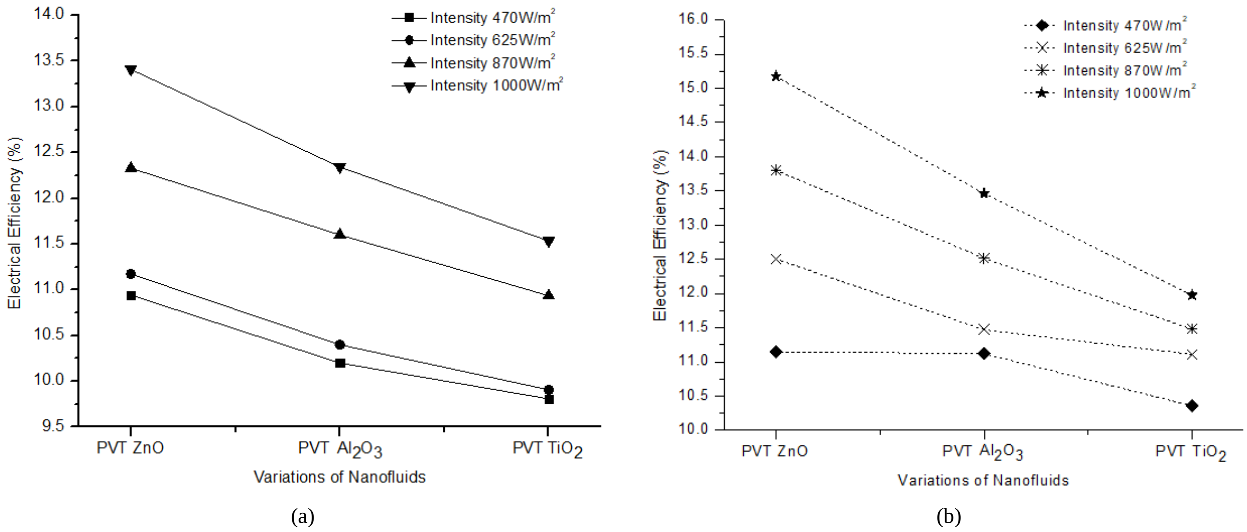
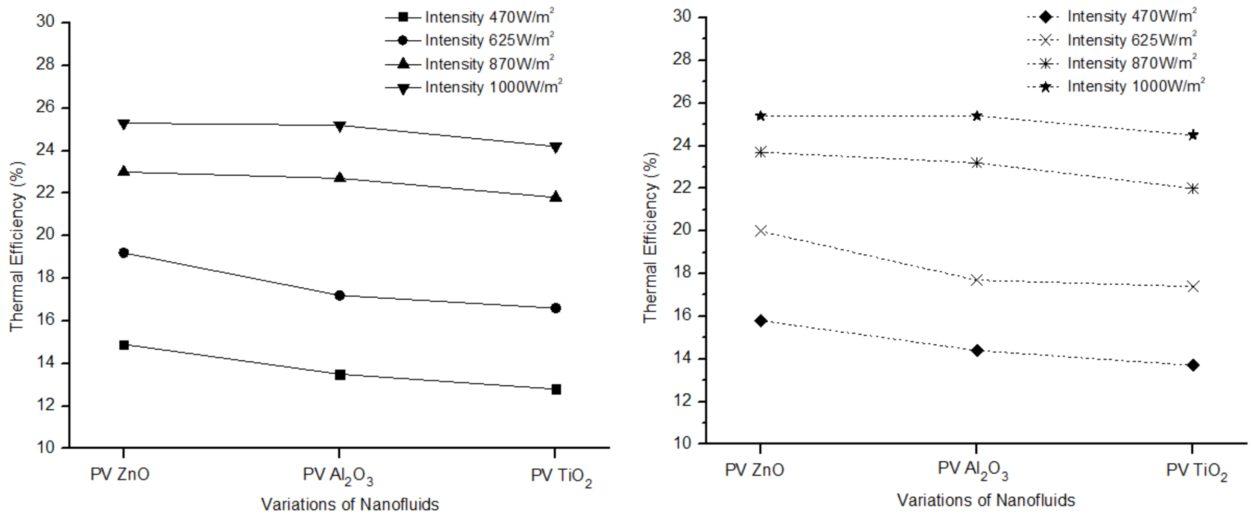


Figure 6. Electrical Efficiency of (a) Rectangular and (b) Spiral Rectangular Tubes

Figure 6-a shows a graph of the relationship between irradiation intensity and the electrical efficiency of solar panels with heat exchanger configurations rectangular tubes. In this graph, increasing irradiation will increase the electrical efficiency of solar panels. The electrical efficiency of solar panels with ZnO, Al_2O_3, and TiO_2 nanofluid cooling at a test intensity of 470 W/m^2 with a rectangular tube heat exchanger has an electrical efficiency of 10.9, 10.2, and 9.8%. While the electrical efficiency of solar panels at a test intensity of 1000 W/m^2 with ZnO, Al_2O_3, and TiO_2 nanofluid cooling increased to 13.4, 12.3, and 11.5%. Figure 6-b is a graph of the relationship between solar irradiation intensity and solar panels' electrical efficiency with a heat exchanger configuration rectangular spiral. Adding ZnO, Al_2O_3, and TiO_2 nanofluids at an intensity of 470 W/m^2 resulted in an electrical efficiency of 11.14, 11.12, and 10.3%, respectively. Meanwhile, at a test intensity of 1000 W/m^2, the electrical efficiency increased by 15.1, 13.46, and 11.9%, respectively.

When added to the base fluid, nanoparticles disperse throughout the entire heat exchanger, leading to an increased heat transfer rate. Due to its superior cooling ability, using a rectangular spiral heat exchanger configuration in this system can further enhance its electrical efficiency compared to the rectangular tube configuration. These results align with research researchers conducted earlier by Zainal et al. in 2022 that investigated the use of TiO_2 nanofluid in a rectangular tube configuration. It was reported that a better electrical efficiency improvement of up to 13.04% was achieved due to the study being conducted outdoors and using direct sunlight irradiation [46].

In this case, Figure 7 shows the change in thermal efficiency for each intensity variation and the working fluid for solar panel cooling. Thermal efficiency is a dimensional performance measure of equipment that uses heat energy. Thermal efficiency is calculated from the temperature difference between the outlet and inlet heat exchanger channels. In conditions of irradiation intensity of 1000W/m^2, adding ZnO, Al_2O_3, and TiO_2 nanofluids with the rectangular configuration tube has a thermal efficiency value of 25.3, 25.2, and 24.2%, respectively. At the same irradiation intensity, the thermal efficiency of nanofluid flowing in a rectangular spiral heat exchanger is 25.4, 25.4, and 24.5%, respectively. This is in line with research conducted by Sardarabadi et al. (2017), which shows that nanofluids' active cooling systems can increase thermal efficiency and reduce panel temperature more effectively [47]. When added to the base fluid, nanoparticles disperse throughout the entire heat exchanger, leading to an increased heat transfer rate. Using a rectangular spiral heat exchanger configuration in this system can further enhance its electrical efficiency compared to the rectangular tube configuration.



(a) (b)

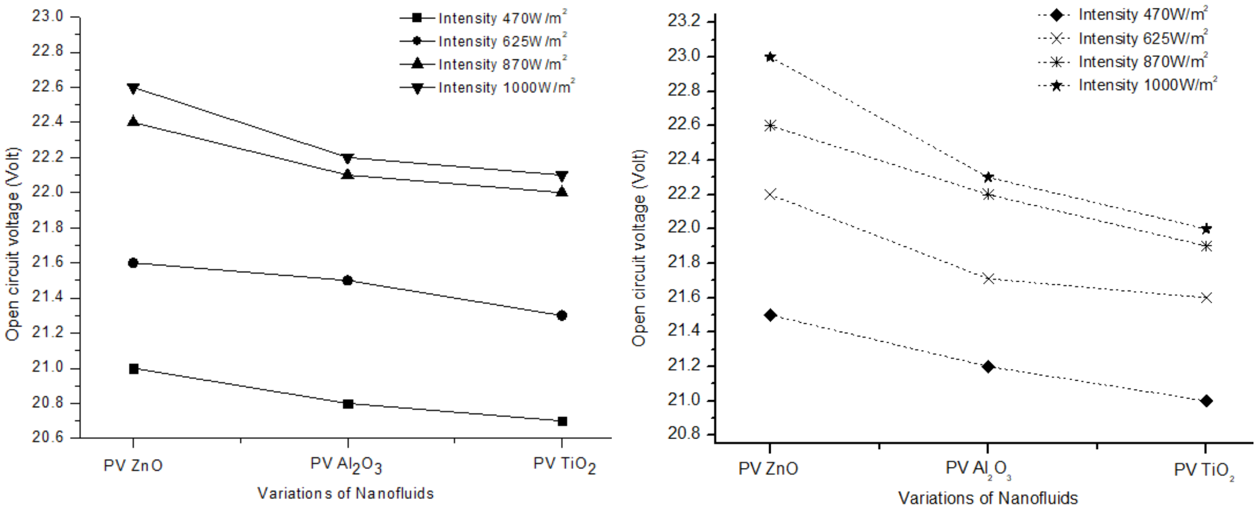
Figure 7. Thermal Efficiency of (a) Rectangular and (b) Spiral Rectangular Tube

Nanofluids have been proven to be more effective in improving the thermal efficiency of PVT systems. According to a study by Gang et al. (2011) on applying PV/T systems, the thermal efficiency of water-based active cooling systems can increase by around 25-75% [48]. Ekramian et al. (2014) also show that nanofluids' thermal efficiency is higher than water, as water has a lower specific heat value that can affect thermal efficiency [49]. The thermal conductivity and mass flow rate of the working fluid in the solar collector is essential in improving thermal efficiency [50]. With higher thermal conductivity values, using nanofluids can increase solar panels' efficiency.

3.3. Solar Panel Performance Characteristics

Photons absorbed by solar panels result in pairs of negatively charged electrons and positively charged holes. At the junction, electrons and holes separate when a load is connected. Due to the separation of these two charges, a voltage is produced between the cell terminals due to an electric potential difference [51, 52]. Therefore the essential characteristics of solar cells include open circuit voltage (Voc), short circuit current (Isc), power, and solar energy conversion efficiency (η).

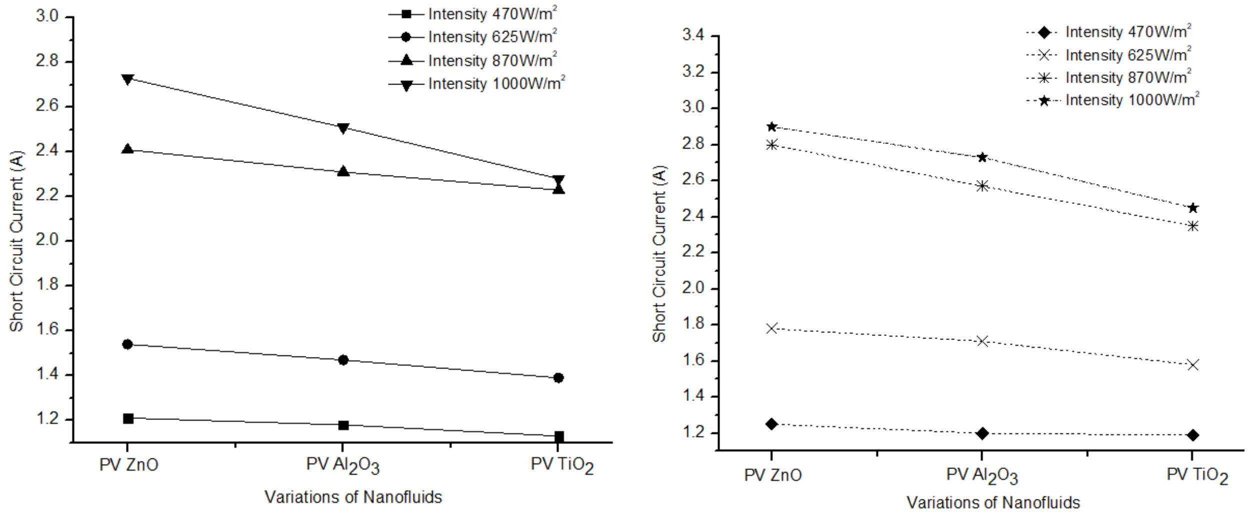
When a maximum voltage but no current flows through the circuit, this is known as open-circuit voltage (Voc). The PV panel's operating temperature and solar radiation intensity both have an impact on the Voc value. If the panel temperature rises, Voc will fall. While irradiation increases along with the value of Voc [53, 54]. Figure 8 shows the relationship between the increase in irradiation intensity and the Voc on the solar panel. The graph shows an increase in all test variations. At the intensity of 870W/m^2, there is the most significant increase in the value of Voc. Value of Voc PV by cooling ZnO, Al_2O_3, and TiO_2 using a heat exchanger rectangular tube Voc respectively 22.6V, 22.2 V, and 22.1 V. In cooling the panel using a rectangular spiral heat exchanger, the addition of fluid in the form of ZnO, Al_2O_3, and TiO_2, respectively, 23 V, 22.3 V, and 22 V. Adding nanofluid as a PV coolant can lower the panel temperature, thereby increasing the Voc value, especially with ZnO nanofluid. Using ZnO nanofluid can increase the Voc value by 1.2V and improve electrical efficiency, as reported by Bazzari et al. (2019) [55]. Similar results were also shown in the study by Sathyamurthy et al. (2021), where the decrease in surface temperature was caused by a cooling medium under the panel, increasing the panel's Voc. The Voc values of PVT systems using nanofluid and water as the working fluid are 26% and 22%, respectively [56].



(a) (b)

Figure 8. Open Circuit Voltage of (a) Rectangular tube and (b) Spiral Rectangular

Based on Figure 9, cooling solar panels using nanofluid can affect increasing Voc. Configuration using a rectangular spiral is also better than the rectangular tube configuration. As the irradiation intensity increases, the Voc also increases. However, if the increase in irradiation intensity causes an increase in the panel's temperature, the Voc will decrease. When there is a difference in electric potential, the voltage drives the current in the circuit. Isc is a condition that occurs at maximum current with minimal resistance on the PV panel. Isc will increase as the intensity of solar irradiation increases [57]. The results of testing the effect of irradiation intensity on Isc are presented in Figure 9. In the graph, it can be seen that Isc has increased along with increasing irradiation in each variable. The most significant increase in Isc occurred at an intensity of 870W/m^2, equal to 0.78 A. This increase also occurs in all types of nanofluids used. This shows that the excited photons on the solar panel also increase at each increase in the irradiation value. These results are like research conducted by Nur Razali et al. (2020), where there is an increase in the Isc value for each increase in the irradiation value [58].

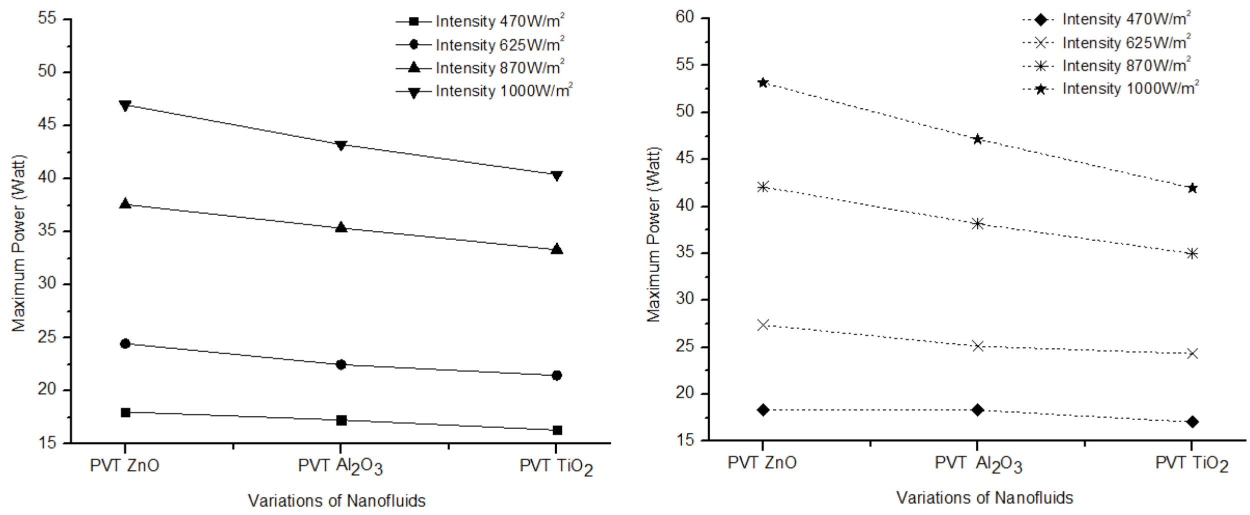


(a) (b)

Figure 9. Short Circuit Current of (a) Rectangular tube and (b) Spiral Rectangular

The Isc values for a PVT system that employs ZnO, Al_2O_3, and TiO_2 as working fluids in a heat exchanger configuration with a square tube are 1.52 A, 1.33 A, and 1.15 A at an irradiation intensity ranging from 470 W/m2 to 1000 W/ m^2. In the rectangular spiral heat exchanger configuration in Figure 9 (b), the Isc increment for each PV variation with ZnO, Al_2O_3, and TiO_2 as working fluids are 1.65A, 1.02A, and 1.26A, respectively. The highest Isc value is achieved at the maximum intensity of 1000 W/m^2 in both heat exchanger configurations. In addition to intensity, the heat exchanger configuration significantly impacts Isc performance. In ZnO, using fluid flow with a square spiral configuration can increase the Isc panel by 1.65 A at the maximum intensity, while a square tube flow increases Isc by 1.09 A under the same conditions. The Isc value decreases when the working temperature of the solar panel rises, which is triggered by photons that surpass the limit for excitation, leading to a drop in the Isc value.

Maximum power (PMPP) is the amount of energy per unit of time obtained from the measured Isc and Voc values. Li et al. (2021) reported that an increase in solar irradiance affects the addition of maximum power points produced by the PV panel [54]. Figure 10 shows the influence of irradiation intensity on maximum power by adding a heat exchanger. At variations of irradiation intensity from 470W/m^2 to 1000W/m^2, there is an increase in the power generated by the PV module. In the square tube heat exchanger tested at an intensity of 470W/m^2, the generated power can increase by 4.41 Watts, 3.66 Watts, and 2.71 Watts for each ZnO, Al_2O_3, and TiO_2 nanofluid, respectively. It is reported that the highest increase in the addition of a heat exchanger occurs with ZnO nanofluid. This is similar to Hussain, Lee, & Kim (2021) research, which reported that adding nanofluids to solar panels could increase panel power by up to 20 watts [59].

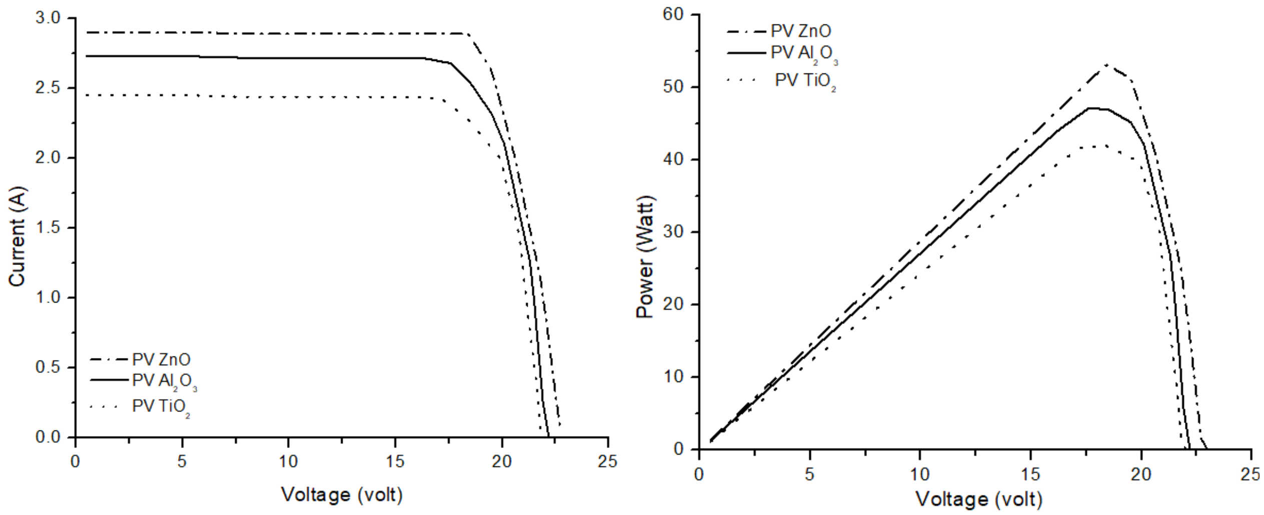


(a) (b)

Figure 10. Maximum Power of (a) Rectangular and (b) Spiral Rectangular Tube

Additional heat exchanger configuration rectangular spiral also increases the panel's maximum power. Testing at an intensity of 470W/m^2 with each of the working fluids ZnO, Al_2O_3, and TiO_2 increased the maximum power of 4.74 Watt, 4.7 Watt, and 3.44 Watt, respectively, compared to non cooling PV. Compared with the cooling results of solar panels using a rectangular tube heat exchanger configuration, the maximum power generated is lower than that of a spiral configuration.

The performance and characteristics of solar cells can generally be determined from the values obtained through the IV and PV graphs. Figure 11 above shows both graphs under test conditions of 1000 W/m^2 intensity with a rectangular spiral configuration, which was the best condition in this test. The values of voltage and current generated by the solar panel are highly influenced by the panel operating temperature, so the cooling system plays a crucial role. Different nanofluids can reduce the panel's temperature with varying cooling effectiveness [60]. Furthermore, the current and voltage values generated by the panel also vary for each configuration [59]. Therefore, the power generated by the PV panel increases when an appropriate cooling system is applied.



(a) (b)

Figure 11. (a) IV and (b) PV Diagram of Spiral Rectangular Tube at Intensity 1000 W/m^2

4. Conclusion

Several cooling methods have been developed for solar PV modules to enhance their efficiency, among which the use of nanofluid media for forced convection is widely accepted. This is due to nanofluids' superior thermal conductivity and heat transfer properties compared to water, which is the base fluid. In this study, the thermal and electrical efficiency of PV solar panels were found to be affected by the heat transfer capability of the working fluid. A nanofluid with higher thermal conductivity results in more excellent heat transfer capability, as the solid particles have a higher thermal conductivity than the liquid base fluid. Aluminum-oxide, Titanium-oxide, and Zinc-oxide were the three types of nanofluids tested in this experiment, and they were dispersed in water with a concentration of 0.5 vol%. The working fluid was made to flow through a rectangular heat exchanger and a stainless steel tube with a rectangular cross-section. According to the experiment's findings, adding ZnO nanofluid with a rectangular spiral heat exchanger configuration produced the lowest temperature of 45°C and the highest increase in electrical efficiency and thermal efficiency of 4.7% and 6%, respectively, at an irradiation intensity of 1000 W/ m^2. This led to a significant increase in the panel's maximum power, which reached 53 watts. The results indicated that the concentration of nanoparticles contributes to increased thermal conductivity caused by Brownian motion and particle thermophoresis. An increase in Brownian motion leads to more paths for heat transfer. At the same time, thermophoresis causes light molecules to move toward hot areas and heavy molecules toward cold areas, resulting in more collisions and an enhanced heat transfer process.

Additionally, the size of the nanoparticles also influences thermal conductivity, with smaller particles having a higher thermal conductivity. As the nanoparticles become more extensive, the thermal conductivity of the nanofluid decreases due to reduced Brownian motion and a smaller surface area-to-volume ratio. Moreover, the larger size of the nanoparticles reduces the viscosity of the nanofluid because there is less tendency for them to clump together. On the other hand, thermophoresis enhances the heat transfer process by causing the lighter molecules to move toward hotter regions and the heavier molecules toward colder regions, thereby increasing the likelihood of particle collisions. The size of the nanoparticles also plays a role in determining the thermal conductivity of the nanofluid, with smaller nanoparticles exhibiting higher thermal conductivity.

5. Declarations

5.1. Author Contributions

Conceptualization, N.H. and Z.A.; methodology, N.H. and Z.A.; validation, B.K., S.D.P., and Z.A.; formal analysis, N.H. and S.D.P.; investigation, N.H.; resources, N.H. and B.K.; data curation, N.H., S.D.P., W.B.B., and B.K.; writing—original draft preparation, N.H. and S.D.P.; writing—review and editing, S.D.P., B.K., and Z.A.; visualization, N.H., W.B.B., and B.K.; supervision, Z.A.; project administration, S.D.P.; funding acquisition, Z.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The corresponding author may provide the data described in this research upon request.

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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