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Enhancing Photovoltaic Panel Performance through Hybrid Nanoparticle Cooling – A Study on Zinc Oxide and Aluminum Oxide Nanofluids

Shahnaz Alkhalil[1], Yousef Altork[2], Mustafa Sukkariyh[2], Eman Abdelhafez[2*]

[1] Department of Mechanical Engineering, Faculty of Engineering and Technology, Al-Zaytoonah University of Jordan, PO Box 130, Amman 11733, Jordan

[2] Department of Alternative Energy Technology, Faculty of Engineering and Technology, Al-Zaytoonah University of Jordan, PO Box 130, Amman 11733, Jordan

* Corresponding author's e-mail: eman.abdelhafez@zuj.edu.jo

ABSTRACT

High operating temperatures, particularly under conditions of high solar irradiation have adverse effects on the performance of the photovoltaic (PV) panels. The efficiency of electricity generation decreases with an increase in operating temperature, and therefore, minimizing the operating temperature is essential. Thus, efficient cooling systems are of significant importance, particularly in areas with scorching heat during the day. Hybrid nanoparticles have been identified as one of the most effective methods in utilizing the concept of PV cooling because of their special characteristics that can help improve the efficiency of solar panels in the long run. These nanoparticles offer the best heat dissipation and convective heat transfer alongside better light trapping and stability and are relatively cheaper to produce, thus playing a central role in enhancing the cooling effectiveness in photovoltaic systems. In our view, depending on these combined forces, hybrid nanoparticles can enhance the general effectiveness, dependability, and efficacy of solar panels as a high-potential instrument for solar power extraction. This study sought to determine the most effective ZnO and Al_2O_3 Nanofluids concentrations in improving the performance of PV modules. Five PV modules were placed side by side. One of them was a reference sample; the other four were coated on the backside with a range of hybrid nanofluid concentrations. K-type thermocouples were used to monitor the hourly backside thermal profile of each module to ensure thermal integrity. Moreover, a data logger monitored the current and the voltage of each PV during the experiment. In general, the coated modules had significantly better results compared to the control. The best improvement in the generated output power was obtained when 0.4% Al_2O_3 and 0.2% ZnO reached 28.4% and increased efficiency to 29.6%.

Keywords: hybrid nanoparticles, PV cooling system, zinc oxide, aluminium oxide.

INTRODUCTION

Solar energy, particularly through photovoltaic (PV) technology, is a beacon of hope in the realm of renewable energy sources. It not only helps to alleviate the issues associated with climate change but also paves the way for a transition to green energy. The shift towards renewable energy sources is driven by the understanding that traditional energy sources, by emitting carbon dioxide into the atmosphere, are causing significant harm to our environment. Solar energy, on the other hand, offers a cleaner, readily available, and renewable source of power, thereby reducing the greenhouse gas emissions that contribute to climate change and its impacts [1–2].

Photovoltaic systems using solar energy have the following advantages: Photovoltaic power is the conversion of sunlight into electricity without the need to store it first and so it is sustainable and efficient. They come in a wide range of form factors and are easily scalable, meaning that they can be used in small-scale residential rooftops as well as large commercial plants. Thus, solar power can provide electricity locally, making energy generation less dependent on centralized systems, therefore promoting energy security. This decentralization also eases the electrification of rural regions where standard power infrastructure is difficult to put in place [3–4].

The importance of solar energy is further highlighted by the economic benefits that come with the use of this source of energy. With time, technological development, and large-scale production, photovoltaic systems reduce their cost and become more viable than traditional power sources. It makes solar energy affordable to many people as well as puts pressure on more job creation in the renewable energy sector. Also, solar energy is less dependent on scarce and politically sensitive fossil fuel resources, which leads to energy security and creates a more sustainable global energy mix [5–6].

Different forms of energy are fundamental in our daily lives and none is as important as the renewable energy, specifically the solar energy installed through photovoltaic technology. Therefore, acceptance of solar power is critical in managing environmental policy, combating global warming, improving energy independence, and encouraging economic growth. With the daily advancements in energy technologies and as governments, enterprises, and citizens more and more emphasize environmental protection, the further global-scale implementation of solar energy systems will form the basis of the transition to a cleaner, adaptive, and sustainable economy [7–8].

Besides, the usage of nanofluids as a cooling method has received increased attention in the PV industry in the recent past. This concept provides a good potential to address the problem of overheating of the cells in PV modules and the improvement of the efficiency of the system. A literature review of existing cooler technologies for solar PV systems has been widely explored in the literature as described in [9–11]. Thus, more attention has been paid to the investigation of new types of coolants that can be obtained using hybrid nanofluids. The unique benefits of hybrid nanofluids are that they have more flexible characteristics as compared to basic nanofluids. The addition of new filler material or using two or even three nanofluids enables the obtaining of a new fluid that has the desired properties, which extends the field of applications in different industries.

Nanotechnology has recently come out as one of the best recommendations for cooling PV systems [12]. The size of nanoparticles and thickness of the nanoparticle layer directly influence many parameters within a photovoltaic system [13]. They argue that the narrow size distribution allows the particles to be tuned for a desired light wavelength absorption. Generally, small-sized nanoparticles bathe in high-energy photons while large nanoparticles sit well with low-energy photons. The adjustment of the nanoparticles' size increases the capability of capturing a wider solar spectrum, hence improving light trapping. When embedded in the active layer, nanoparticles affect the radiation incidence and reflection, which increases the optical path length and the probability of the interaction between light and medium. Interestingly, this scattering effect causes the photons to be more inclined to be absorbed, which in turn increases the efficiency. The concentration of nanoparticles in the layer has a direct influence on the performance of the PV panel [14]. It is also observed that with an increase in the layer's thickness, the transition from absorption to scattering within the PV improves. Particle density and surface coverage of the adjacent layers determine the ability to trap light, promote charge transport, and minimize inter-particle separation to allow for charge extraction.

Aluminum oxide (Al_2O_3) nanoparticles, which are also referred to as alumina nanoparticles, have been considered for use in PV cooling systems because of the following attributes: high thermal conductivity, large surface area, stability, compatibility, relatively cheap prices, and easy incorporation in the PV systems [15]. Thus, the high thermal conductivity of Al_2O_3 nanoparticles actively participates in heat dissipation and determines the efficiency and service life of PV systems. Likewise, zinc oxide (ZnO) nanoparticles are widely used in PV cooling since they possess desirable properties of high thermal conductivity, a large number of functional sites, chemical inertia, and low cost [16]. Further, ZnO nanoparticles have a large band gap, which can effectively absorb and hence scatter a large portion of the UV radiation. This property negates the possibility of heat originating from UV radiation compromising higher temperatures within the PV cells.

The active cooling algorithm, namely DN-NFC, was proposed by Manasrah et al. [17] using five fans connected with the PV model, where two fans were working at the same time. An ANN was also trained through backpropagation in order to predict the best fan pattern with respect to time. The performances of the algorithm were evaluated using indoor and outdoor image databases to obtain an accuracy greater than 97% and the mean square error was estimated to be 0.02.

Nasrin et al. [18] numerically simulated thermal collector systems, recommending nanofluid-based photovoltaic thermal (PVT) systems as compared to water-based systems. Employing COMSOL Multiphysics, a typical collector system is installed with different baffle structures, various nanofluids, and a range of parameters. This was hoped after numerical outcomes were computed and showed that two percent volume percentage of solid was ideal for use in nanofluids. The result of the comparative analysis pointed out that PVT with nanofluids (Ag, Cu, Al) as the cooling medium had higher thermal efficiency compared to water, with maximum enhancement at 7.49%. In addition, there are variations in thermal energy extraction from the inlet temperature and the rate of heat transfer in a PVT system that uses nanofluid.

Karaaslan et al. [19] discussed the application of both single and hybrid nanofluids to enhance the efficiency of photovoltaic thermal systems where sheet and tube structures were used and contrasted with water-based systems. Based on the results, they found that at larger inlet fluid velocity the thermal efficiency was enhanced while the pressure drops experienced a similar improvement but not as much in the electrical efficiency. According to the outcomes highlighted above, the authors agreed that the integration of hybrid Nanofluids can be used to improve the efficiency of the PVT systems.

Al-Oran et al. [20] assessed the thermal performance of two similar parabolic trough solar collector fields in Amman, Jordan. The first system incorporates MWCNTs, Y_2O_3 nanoparticles, and soluble gum Arabic as the nanofluid at four distinct concentrations (0.01, 0.025, 0.05, and 0.1) % and utilizes distilled water as the heat transfer fluid. To evaluate the nanofluid's thermal performance, the preparation and stability of the nanofluids were tested and compared to distilled water. The results revealed that the heat transfer enhancement occurred for the hybrid nanofluid more than the single nanoparticles, and the optimum concentration ratio of the nanofluid was 0.1% concentration reached the highest thermal efficiency of 44% due to the reason that the Clausius clapeyron curve shows that the highest efficiency. Water had a considerably lower figure of thermal efficiency with 19% while oil recorded 24%, far better than water. 32%. Furthermore, the enhancement of nanofluid concentration led to a higher value of maximum optical efficiency at r = 0.1% volume. The experimental data were finally confirmed through studies made with the help of the solid work simulation model developed for determining the outlet temperature and the thermal efficiency of the collectors that demonstrated a great level of accuracy with an average variation of 0.03% and a thermal efficiency variation of 0.9%.

This research aims to determine the optimum concentration of aluminum oxide (Al_2O_3) and zinc oxide (ZnO) water-based nanofluid for cooling photovoltaic in the specific climatic conditions of Amman, Jordan. The overall research aim is thus to assess the effect of different water-based nanofluid solutions where the concentrations of both Al_2O_3 and ZnO nanoparticles could be different on the cooling of PV. To address this concern, simple and effective techniques of using nanofluid coatings on the rear side of PV panels will be employed.

EXPERIMENTAL SETUP AND PROCEDURE

Experiment setup

The experimental setup in Figure 1 comprises several key components. First, five Poly-Crystalline PV panels with a rating of 155 W each are affixed to iron structures, including one standard panel for reference at a 27° tilt angle. Secondly, zinc oxide and aluminum oxide nanoparticles are combined as water dispersions, obtained from US Research Nanomaterials. These white powder nanoparticles have a high surface area, with particle sizes of 30 nm for Al_2O_3 and 30 nm to 40 nm for ZnO. Thirdly, a DATAQ Instruments Furthermore, a GL 220 midi logger is employed to continuously record voltage and temperature data. Three type K thermocouples attached to each PV module provide hourly average backside temperature measurements, which are further analyzed within the data logger software. Finally, a Nano spray gun for spraying the prepared water-based nanofluid to the PV backside. This provides even dispersion of the solution from the internal tanks.

Procedure

Five photovoltaic panels, positioned adjacent to each other, were subjected to the same meteorological conditions for temperature analysis. K-type thermocouples were attached to the backside

Figure 1. Experiment setup

of each panel to measure the temperature. A GL220 midi logger continuously records and stores temperature, current, voltage, and power data. Ambient temperature and wind speed were monitored using a GRWS100 weather station. To investigate the influence of nanofluids on backside cooling, four panels received spray applications of a hybrid Al_2O_3 and ZnO nanofluid mixture via a Nano spray gun. The applied mixtures varied in composition, with concentrations of 0.4% Al_2O_3 + 0.2% ZnO, 0.2% Al_2O_3 + 0.4% ZnO, 0.3% Al_2O_3 + 0.1% ZnO, and 0.1% Al_2O_3 + 0.3% ZnO.

RESULTS AND DISCUSSION

Hourly solar irradiance on a typical day (May 2nd, 2023) in Amman, Jordan, is presented in Figure 2. As anticipated, solar intensity exhibits a characteristic diurnal pattern. It starts low in the morning, gradually increasing until reaching a peak of approximately 720 W/m² around midday. Following this maximum, solar irradiance steadily declines throughout the afternoon, eventually reaching its minimum level in the late evening. This pattern reflects the natural variation in solar angle throughout the day, with the highest irradiance occurring when the sun is directly overhead. It is important to note that the data presented in Figure 2 is specific to May 2023 and may not be representative of other seasons or locations.

Zinc oxide-aluminum oxide hybrid nanofluids prepared with different concentration ratios

Figure 3 presents the hourly temperatures on the backside of five PV panels. It shows that the panel using a 0.4% Al_2O_3 and 0.2% ZnO water-based nanofluid mixture records the lowest temperature. This is followed by the panels with 0.1%

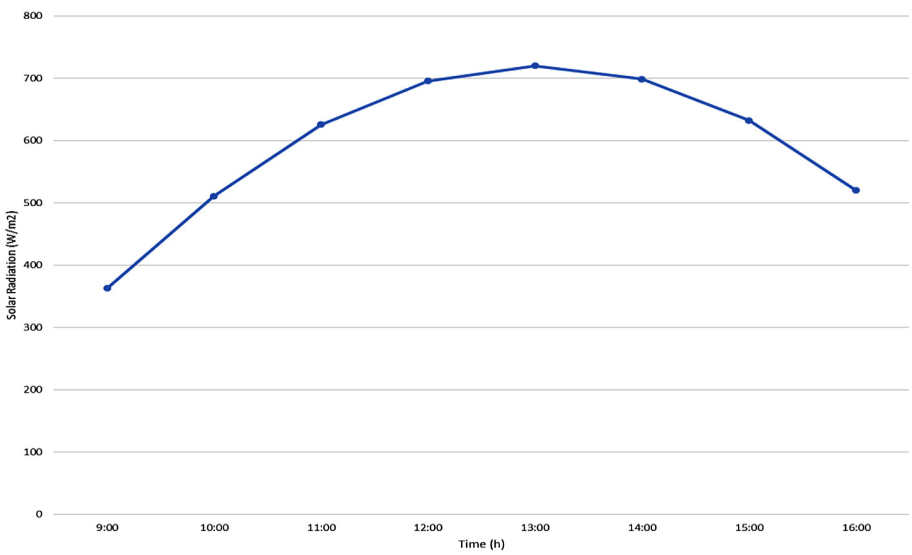

Figure 2. Hourly variations in solar radiation as a function of time on May 2nd, 2023

Al_2O_3 and 0.3% ZnO, and 0.3% Al_2O_3 and 0.1% ZnO coatings, each showing slightly higher temperatures in that order. Panels with 0.2% Al_2O_3 and 0.4% ZnO coatings, along with the uncoated base panel, display the highest temperatures at the back. Notably, the combination of 0.4% Al_2O_3 and 0.2% ZnO is most effective, leading to a significant average temperature reduction of 10.1% on the backside of the panel.

The decrease in temperature on the backside of the panel, as depicted in Figure 3, is primarily due to two factors: the increase in the thermal conductivity of the base fluid due to the addition of nanoparticles and heat transfer by radiation and convection which the nanoparticles allow. Thus, enhancement of the nanoparticle concentration leads to better heat transfer to the cooling medium. However, it becomes a question of concern when concentrations increase, primarily due to aggregation and sedimentation impact on stability and effectiveness. Therefore, the determination of the appropriate concentration of nanoparticles is the most critical step. In experimental research, this study revealed that a solution made of 0.4% Al_2O_3 and 0.2% ZnO. It is evident that the enhancement of the heat transfer coefficient is optimum for a water-based nanofluid. Figure 4 displays the average hourly output power of the panels, allowing

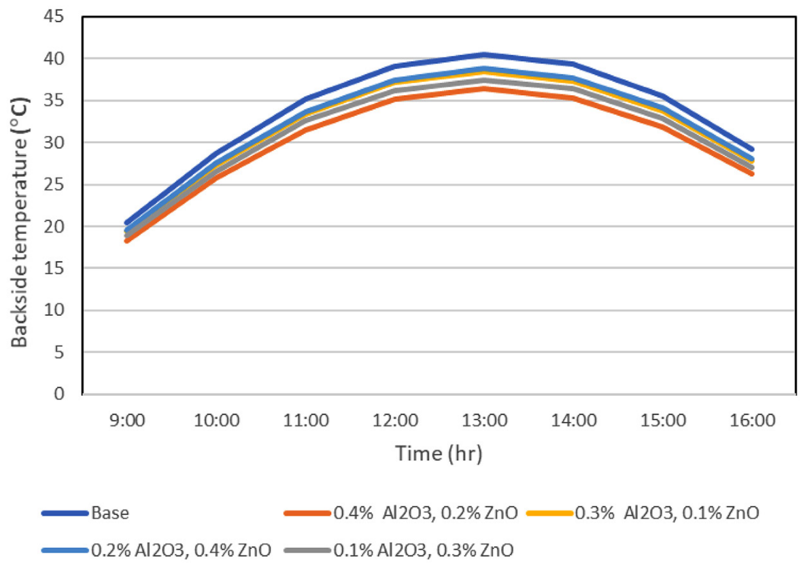

Figure 3. Hourly backside temperature of PV with a hybrid mixture of ZnO and Al_2O_3 on May 2nd, 2023

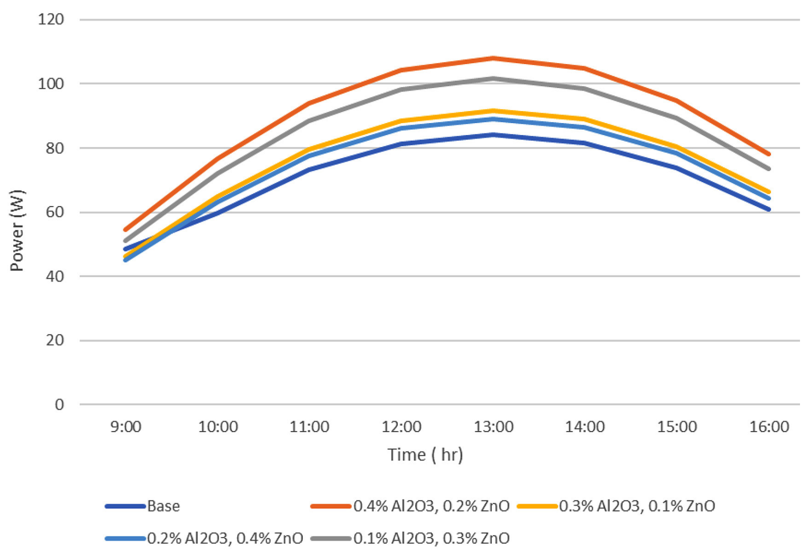

Figure 4. Hourly photovoltaic (PV) power generation (W) was observed on May 2nd, 2023, for a hybrid mixture of ZnO and Al_2O_3

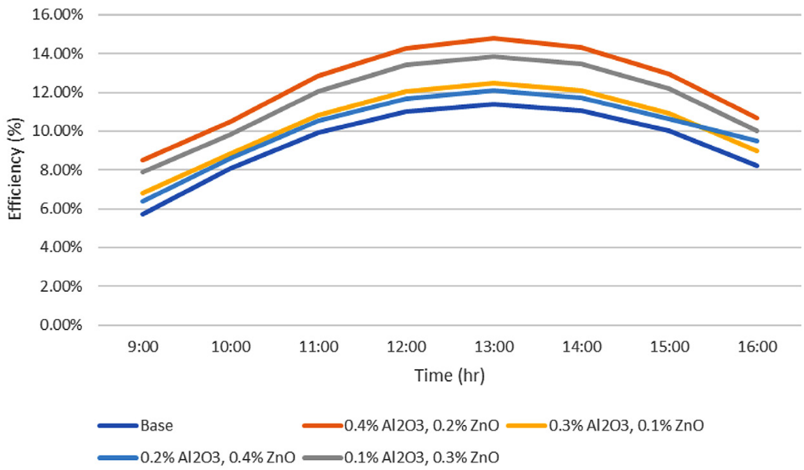

Figure 5. Hourly efficiency of PV panels with for a hybrid mixture of ZnO and Al_2O_3 on May 2nd, 2023

for a comparison with the generated power of the base PV. The coated panel with a hybrid of 0.4% Al_2O_3 + 0.2% ZnO water-based nanofluid exhibits the highest generated power, then the panel which was coated by a hybrid of 0.1% Al_2O_3 + 0.3% ZnO water-based nanofluid, then a combination of 0.3% Al_2O_3 + 0.1% ZnO water-based nanofluid, a mixture of 0.2% Al_2O_3 + 0.4% ZnO water-based nanofluid, and finally, the base PV. This variation in power output is attributed to the reduction in power output as the backside temperature of the PV increases. This figure highlight that the panels coated with a mixture of 0.4% Al_2O_3 + 0.2% ZnO water-based nanofluid experienced a notable increase in output power, amounting to 28.4%. The rise in the power output correlates with the decrease in the operating temperature as a result of this. Cooler temperatures limit the thermal losses in PV cells then leading to better conversion efficiency of light into electrical energy. The increased efficiency of the 0.4% Al_2O_3 + 02% ZnO. This agrees with the lower backside temperature shown for coating in Figure 3. This result again highlights the need to identify the correct nanofluid material to enhance the conversion ability of the PV panels.

The average hourly efficiency of the altered photovoltaic panels, as well as the base panel, is shown in Figure 5. The efficiency in all altered panels shows improvement where the coating has 00.4% Al_2O_3 and 0.2% ZnO water-based nanofluid. Among the selected nanofluids showed the highest enhancement of about 29.6%. This is in concordance with the previous work done to show that this particular coating has a better cooling ability than the regular ones. The remaining modified panels follow in terms of efficiency: 0. whose major motivation is: 0.1% Al_2O_3 + 0.3% ZnO, 0.3% Al_2O_3 + 0.1% ZnO, 0.2% Al_2O_3 + 0.4% ZnO, and a base panel followed it.

The increase in the panels' efficiency through the application of nanofluid coatings evidently originates from a better cooling effect. The 0.4% Al_2O_3 + 0.2% ZnO. Among the selected coatings, the coating can effectively lower the thermal load on the PV cells and minimize the energy losses that result from it. This results in the easy harnessing of the available solar energy, which in return gives better performance efficiency. The findings also demonstrate the possibility of applying hybrid nanofluids for enhancing heat transfer in PV systems, which is a crucial issue in determining the stability and durability of utility-scale PV plants.

Overall, the results from Figures 3, 4, and 5 suggest that the combined nanofluid of 0.4% Al_2O_3 + 0.2% ZnO. Out of all the concentrations of nanoparticles tested, it proved to be the best in managing backside temperatures, enhancing power production, and increasing the efficiency of the PV panels. This optimum solution proved the possibility of improving the efficiency and durability of photovoltaic facilities based on nanofluid coatings in areas with intensive solar activity.

CONCLUSIONS

This study investigates the effectiveness of hybrid water-based Al_2O_3 and ZnO nanofluids in improving photovoltaic system performance. The results demonstrate enhanced heat transfer through lower panel temperatures and improved thermal performance compared to conventional coolants. This superior cooling increases power output, mitigating temperature-induced power losses and boosting overall system efficiency.

The study identifies the optimal hybrid nanofluid composition for maximizing PV performance. A 0.4% Al_2O_3 and 0.2% ZnO mixture delivers the best results, with a remarkable 28.4% increase in power output and a 29.6% efficiency gain. Conversely, a 0.2% Al_2O_3 and 0.4% ZnO mixture show the least favorable performance (excluding the base panel), with a 5.94% power increase and a 6.19% efficiency improvement.

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