Abstract: The efficiency of PV (photovoltaic) modules is highly dependent on the operating temperature. The objective of this work is to enhance the performance of PV by passive cooling using aluminum fins that have been nanocoated (like those on an automobile radiator). A rise in the cell temperature of the module PV leads to a decrease in its performance. As a result, an effective cooling mechanism is required. In this work, the performance of the PV module has been improved using natural convection, which was achieved by placing three similar PV modules next to each other in order to test them simultaneously. The first panel will be the base panel and will be used for comparison purposes. An automotive radiator (with aluminum fins) was firmly fixed onto the rear of the other two PV modules, and the fins of the third PV panel had titanium oxide (TiO$_2$) water-based nanofluid applied to them. The power produced by the PV modules, as well as their rear side temperatures, were recorded every 30 min over four months. A temperature reduction of 4.0 $^\circ$C was attained when TiO$_2$ water-based nanofluid was sprayed onto the panel's finned rear side. This was followed by the scenario where the rear side was only finned, with a temperature drop of 1.0 $^\circ$C. As a result of the temperature reduction, the percentage of power produced by the coated-finned PV and the finned PV increased by 5.8 and 1.5 percent, respectively. This caused an increase in PV efficiency of 1.1 percent for coated-finned panels and 0.4 percent for finned PV.

Keywords: PV; solar energy; finned PV; nanoparticles; titanium oxide

1. Introduction

With volatile fossil fuel prices, a politically-driven energy market, global warming, environmental concerns, and the future availability of fossil fuels against demand, global energy has become a significant problem for governments. All of this has prompted academics to investigate the idea of substituting alternate and sustainable energy sources for a portion of the energy generated by fossil fuels.

Among these sources, solar energy has been discovered to be one of the most promising energy sources. Photovoltaic cells convert solar radiation into electrical power with a maximum efficiency ranging from 15 to 20 percent, depending on the solar cell type. Nearly all of the solar energy that incidents on the PV is either reflected or transformed into thermal energy. This increases the temperature of the cells, which lowers the PV efficiency. Thus to improve the performance of the PV, a cooling method is a must [1,2].

Recently, research has concentrated on methods for cooling down the cell’s dependable temperature in order to improve its performance. Many researchers have used air or water for the active cooling of the PVs in order to improve electrical efficiency [3–5]. However, the additional energy consumption for air or water circulation may diminish the net power production, or even cause the PV power output to be insufficient to cover the energy consumption. Furthermore, research was conducted using PCM as a means to cool down the PV panels [6,7].
According to Sathe and Dhoble [8], researchers have created a novel method to extract the surplus heat from these systems, in order to lower their temperatures and increase electrical efficiency. This method makes use of nanotechnology. The idea behind adding nanoparticles to base fluids is to improve thermal conductivity, which could result in a higher cooling rate as well as higher thermal efficiency.

Hamdan and Kardasi [9] experimented to examine how cooling affected the efficiency of three similar PV modules that were positioned next to each other. The first was employed as a base unit, the second was water-cooled, and the third PV was cooled by nanofluids. The nanofluid was made by adding different amounts of clean water to aluminum oxide (Al$_2$O$_3$) and copper oxide (CuO) nanoparticles. They discovered that the panel’s efficiency increased by 2 percent when 0.4 percent Al$_2$O$_3$ was used to form the water-based nanofluid, while the efficiency increased by 2.34 percent when 0.6 percent CuO was used.

Aberoumand et al. [10] investigated the effectiveness of a photovoltaic/thermal (PV/T) system cooled by a water-based silver nanofluid. Numerous factors were taken into account when evaluating the PV/T system’s performance in order to identify the most effective performance indicators, such as the system’s electrical and thermal energy efficiency and exergy efficiency. They looked at how mass flow—specifically, the various laminar, transient, and turbulent flow regimes—affect efficiency. The findings demonstrated that cooling the PV/T system with nanofluids may greatly improve the system’s energy and exergy efficiency. Additionally, they discovered that raising the flow rate and the nanofluid concentration made this beneficial effect much more noticeable.

Al-Waeli et al. [11] tested the effectiveness and features of a PV panel using a nanofluid and nano-PCM (paraffin wax) -based PV/T hybrid. They concluded that the collector achieved a maximum PV efficiency of 13.7 percent while operating, which is acceptable compared to the efficiency of 14 percent for normal testing settings for conventional PV modules, which reached a 7.1 percent efficiency.

Al$_2$O$_3$ and TiO$_2$ water-based mixtures were used in experiments by Ebaid et al. [12] to cool PV panels at varying volume flow rates and concentrations (0.01 percent, 0.05 percent, and 0.1 percent) by weight. Additionally, three PV panels were simultaneously cooled with nanofluids, water, and fresh air. The results indicated that nanofluids for cooling significantly improved heat transfer rate compared to water and ambient air. TiO$_2$ nanofluids produced the best outcomes when used at 0.1 wt percent concentration.

Firoozzadeh et al. [13] evaluated a concentration range of 0–0.4 wt percent carbon black water-based nanofluid to cool down a PV panel. They concluded that carbon black/water nanofluid’s cooling behavior was surprising, with the optimum concentration of carbon black nanoparticles being 0.21 weight percent. Furthermore, by concentrating the energy, 7 percent more output power was produced compared to using water as a coolant, and 54 percent more output power was produced compared to using a traditional photovoltaic module.

Hamdan and Abdelhafez [14], looked into the impact of using the optical liquid filter to cool down PV modules by allowing the beneficial part of the spectrum to pass through while obstructing the unfavorable part of the spectrum, with copper sulfate solution (CuSO$_4$·5H$_2$O) and purified water being utilized as absorption filters. The average power generated by the PV when using pure water as an optical filter was 31.3 percent, whereas it was 11.3 percent when using copper sulfate solution, compared to the base unit. With an average PV temperature drop of 15 percent as opposed to 7.5 percent when (CuSO$_4$·5H$_2$O) is employed, pure water had a more effective cooling effect on the PV than copper sulfate solution.

As indicated above, almost all research work so far on PV cooling with nanotechnology has been conducted using nanofluid flowing within a heat exchanger fixed to the rear side. In the present work, the PV panel was cooled down by the passive method, using nanofluid-coated fins (automotive radiator) firmly attached to its rear side. This method of passive cooling represents the main novelty of this work, and has not been used previously.
To accomplish the work, three similar PV modules are put next to each other. The first panel will be the baseline for comparison; fins will be linked onto the rear side of the second panel; and the fins and rear side of the third panel will be coated with titanium oxide (TiO$_2$) nanoparticles, which was selected due to its higher thermal conductivity compared with other nanoparticles such as Al$_2$O$_3$ [15]. It is very important to conduct experimental work on all PV panels simultaneously, so that they are subject to the same meteorological conditions, including, ambient temperature, humidity, and wind speed. Consequently, the effect of these parameters on the obtained results will be the same, and hence the effect of nanofluids on the performance of the PV will be investigated. It is to be noted that the experimental work was conducted for several weeks, and only the results of 18 April are presented and discussed here. It is to be noted that 18 April was selected at random.

2. Materials and Procedure

2.1. Experimental Setup

The instrumentations and devices used in the present study are depicted in Figure 1. It is to be noted that although four identical PV panels are shown in this figure, only three were used in this study. The fourth is an existing panel that may be used in future work.

Figure 1. Experimental Setup.
The devices and instrumentation include the following elements:

2.1.1. Photovoltaic PV Modules

Three similar PV modules are mounted adjacent to each other, as shown in Figure 1, to execute work on all of them at the same time. The first panel is used as a reference.

On the rear sides of the other two panels, fins are connected, and on the third one, the fins and the rear side of the panel are coated with nanoparticles. The specification of the PV module is presented in Table 1.

Table 1. Solar Panel Module Specification.

| Specification               | Value       |
|-----------------------------|-------------|
| Maximum Power at STC Pmax   | 150 W       |
| Operating voltage (Vmp)     | 18.10 V     |
| Operating current (Imp)     | 8.29 A      |
| Operating circuit voltage (Voc) | 22.06 V |
| Short circuit current (ISC) | 8.73 A      |
| Weight                      | 11.5 kg     |
| Dimension (mm)              | 1495 × 670 × 40 mm |

2.1.2. Titanium Oxide (TiO$_2$) Nanoparticles Dispersion

Nanoparticle dispersion may be used right away or diluted using the right solvents, it is a fine, white powder made up of 10–30 nm-sized titanium oxide particles. It is made by US Research Nanomaterials out of high-surface-area nanocrystals or nanodots.

2.1.3. Power Resistors

Four power resistors with a dissipated power of 50 W and 10 ohms apiece. The four resistors’ combined equivalent resistance and power are 2.5 Ohms and 200 W, respectively. They are used to measure the voltage and are connected in parallel; the current and power were estimated using Ohm’s law.

2.1.4. Data Logger

DATAQ Instruments makes the midi logger GL 220, which measures voltages and temperatures. Ten analog measuring channels are available. The logger additionally supports four alarm outputs and one external trigger input. A 2 GB inbuilt flash memory is included that allows for quick data capture, and its built-in USB connector lets you attach any regular USB flash drive to add more capacity.

2.1.5. Thermocouples

The average temperature of the PV rear side was monitored hourly using copper constantan (type K) thermocouples. For further investigation, these temperature readings were captured and kept in a data logger. To measure the average temperature value, thermocouples were inserted in three different places on the rear side of each PV.

2.1.6. A Radiator

The radiator is made up of tubes, fins, and headers. The radiator matrix is made up of tubes and fins. With the installation of titles and side supports, the radiator block is completed. The side supports hold the radiator in place inside the sleeves on the rear of the PV and provide extra support.

2.2. Procedure

Figure 1 shows how the three PV panels were mounted next to each other for simultaneous testing. The second and third PV panels are passively cooled using an aluminum-fin radiator that serves as a heat sink. Each corner-located aluminum clamp securely fastens the radiator to the backside of each PV panel, ensuring it is in touch with the PV. By doing
so, the air layer between the radiator and the PV is kept from forming, while the contact resistance is ignored. Furthermore, the third panel is coated with water-based titanium oxide nanofluid, which covers the radiator on the rear side of the PV.

Each panel has three k-type thermocouples mounted on its rear side to record temperature values from three different points to estimate the module’s average temperature.

A GL220 data logger saves and stores the measured temperature values for later study. Each PV’s generated power was recorded and saved. It is to be noted that the site’s GRWS100 meteorological station was used to read both the ambient temperature and the solar radiation.

The trials were run from 9:00 a.m. to 5:00 p.m., with data collected every 30 min both with and without a heat sink. To corroborate the results, the experiment was performed several times on different days. All of the gadgets were calibrated previously. Total insolation was measured using a CMP11-L Pyranometer with a range of 0–4000 W/m² and a reading uncertainty of <±2 percent.

3. Results and Discussion

The average daily maximum ambient temperature and the average daily incident solar radiation recorded in Amman during the four months are shown in Figure 2a–d. As indicated, the ambient temperature ranges from a minimum value of 22 °C on 12 April to a maximum value of 42 °C on 19 July; meanwhile, the solar intensity ranges from a minimum value of 600 W/m² on 8 April to a maximum value of 1070 W/m² on 17 June. Furthermore, and as may be noticed in these figures, the ambient temperature increased continuously during the experimental work from April to July. The average daily ambient temperature in April was 30.3 °C, while in July it was 38.2 °C. Such behavior in ambient temperature is normal this time of year. Furthermore, the average daily incident solar radiation is expected to increase with time in the summer season, as indicated during April, May, and June; while it decreased slightly in July compared with June, this may be caused by dusty days during this month, since Amman is usually subjected to dusty days in the summer seasons [16].

![Figure 2](image_url)

Figure 2. Cont.
Figure 2. Average daily ambient temperature and solar intensity during the four months of experimental work. (a) April (b) May (c) June (d) July.
Figure 3 represents the average daily maximum temperature of the three panels and the average daily maximum ambient temperature during the four months. As indicated, the temperatures of the panels exceed that of the ambient, with the temperature of the nanocoated finned panel being the lowest, followed by that of the finned panel, while the base unit had the maximum average temperature. It is to be noted that, the temperatures shown in these figures are recorded simultaneously under the same meteorological conditions (wind speed, cloudy periods, humidity, etc.), which means their values are similarly affected by any variation in weather conditions: this is why they behave in similar trends as shown in Figure 3.

Figure 3. Cont.
Figure 3. Average daily maximum temperature of the three PV panels and the ambient during the four months of experimental work. (a) April (b) May (c) June (d) July.

The average daily maximum produced power by the three PVs during the four months is shown in Figure 4, from which it may be noticed that the produced power of the nanocoated PV has maximum value during all the experimental work period, while the power produced by the finned PV comes in at second place and always exceeds the power produced by the base PV. This behavior is expected since the power produced is associated with the temperature of the PV, which is presented in Figure 3.

As illustrated in Figure 4, the maximum power produced increased continuously during April, May, and June, while it decreased slightly in July compared with June. This is due to the formation of rather dusty conditions in Amman during this month; this behavior is in full agreement with the variation of incident solar radiation shown in Figure 2, since produced power increases with the incident solar radiation on the PV surface.
As may be noticed from Figure 4a, a sudden power drop occurred on 3, 8, 17, and 18 April, and on 11, 14, 16 and 21 May. This may be attributed to the sudden drop in the incident solar radiation presented in Figure 2 during these days. Furthermore, and as depicted in Figure 4d, there is a systematic drop in the power produced during July, this is because the power produced increases with the quantity of solar radiation. Unfortunately, during this month the weather conditions in Amman were dusty, which is shown in Figure 2. This lead to a systematic drop in the solar insolation and, hence, a drop in the power produced during this month, as shown in Figure 4d.
Figure 4. Average daily maximum power produced by the three PV panels during the four months of experimental work. (a) April (b) May (c) June (d) July.

Figure 5 illustrates the average daily maximum efficiency of the three panels during the four months. As noticed, the coated and finned PV has the highest performance among the three panels, followed by the finned PV, with the base unit being the least efficient one. It is clear from Figure 5 that, the maximum efficiency strongly follows the maximum power produced; this is very clear from Equation (1).

$$\text{Efficiency (\%)} = \frac{\text{produced power out}}{\text{incident solar radiation} \times \text{PV Panel Area}} \times 100\%$$ (1)

Consequently, it is expected that both maximum efficiency and maximum power produced follow each other very clearly, as shown in Figures 4 and 5, respectively.
Experimental results were taken over the four months of experimental work. In the remaining part of this section, the results from 18 April will be presented and discussed in Figures 6–9.

Figure 6 shows the hourly solar incident radiation during a typical working day as recorded by the power station and stored in the data logger. As shown in this figure, solar intensity increases steadily in the morning until it reaches a maximum value of 720 W/m² at noon, beyond which it decreases to a minimum value late in the afternoon. Also shown in the figure, the ambient temperature increases from a low value in the morning to a maximum value of 28 °C at 15:00, before it starts to decrease to a low value late in the afternoon.

Figure 6 shows the hourly solar incident radiation during a typical working day as recorded by the power station and stored in the data logger. As shown in this figure, solar intensity increases steadily in the morning until it reaches a maximum value of 720 W/m² at noon, beyond which it decreases to a minimum value late in the afternoon. Also shown in the figure, the ambient temperature increases from a low value in the morning to a maximum value of 28 °C at 15:00, before it starts to decrease to a low value late in the afternoon.

Figure 5. Cont.
Figure 5. Average daily maximum efficiency of the three PV panels over the four months of experimental work. (a) April (b) May (c) June (d) July.

Figure 7 displays the three panels’ average rear side temperatures on an hourly basis throughout 18 April. As shown, the surface temperature of the coated and finned PV panel is the lowest at 45 °C, followed by that of the finned PV with a value of 47 °C, and the highest is that of the base with a value of 49 °C. The cooling system of the finned and coated PVs is, therefore, more effective than that of the finned and base PVs. This is because the fins enhance the amount of heat that is lost to the environment as they increase the surface area of the PV’s rear side. In addition, TiO₂ coating increases the emissivity of the backside, leading to a further increase in heat loss and, hence, more efficient cooling.
Figure 5. Average daily maximum efficiency of the three PV panels over the four months of experimental work. (a) April (b) May (c) June (d) July.

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Figure 6. Hourly solar radiation and ambient temperature during a typical experimental day.

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Figure 7. Variation of the module rear side temperature with time during a typical experimental day (Monday, 18 April).

Figure 8 compares the average hourly output power of the modified panels to that produced by the base PV over the course of 18 April. The base PV panel produced the least amount of electricity with an average daily maximum value of 77 W, while the coated-finned PV panels produced an average daily maximum power of 83 W, and that produced by the finned PV was 78 W. It is to be noted that the average hourly output power calculation was based on the measured value each hour between 09:00 and 17:00 of each day.

Figure 8. The average hourly output power during a typical experimental day (Monday, 18 April).
Figure 8. The average hourly output power during a typical experimental day (Monday, 18 April).

Figure 9. The average hourly efficiency during a typical experimental day (Monday, April 18).

Figure 9 shows that the coated-finned panel had the maximum average hourly efficiency of 13.5%, followed by the finned PV with a value of 12.5%, while the base PV had the lowest value of 11.9%. This is in complete agreement with Figure 7, which shows that the finned and coated PV produced the maximum hourly power, followed by the finned PV. It is to be noted that the efficiency data in this figure represents actual data by using the line with markers chart type and not the best curve fitting: this might cause fluctuation in the efficiency values from 09:30 to 11:00 in the morning.

The temperature drop achieved in this work was compared to previously published research that used different heat sinks. The results in Table 2 show that the method proposed in this study is compelling.
Table 2. The temperature drops using different cooling methods.

| Reference | Cooling Technique                          | Temperature Reduction (°C) |
|-----------|--------------------------------------------|----------------------------|
| [17]      | Multi-way forced convective                | 14.4                       |
| [18]      | Aluminum fin                               | 1                          |
| [19]      | U-shaped fins cooling                      | 2                          |
| [20]      | Aluminum with perforated ribs              | 10                         |
| [21]      | Finned heat sinks                          | 11                         |
| Present study | TiO$_2$ water-based nanofluid coated Al automobile radiator | 4                          |

4. Conclusions

The effect of enhancing natural cooling on the performance of a solar panel was explored in this study. This was accomplished by lining up three identical photovoltaic modules side by side and performing operations on all of them simultaneously. The first panel will serve as the baseline for comparison, while aluminum fins in the shape of an automotive radiator were fastened to the rear of the second and third modules. Titanium oxide (TiO$_2$) was also applied to the fins (automotive radiator) mounted on the third module.

It may be concluded that, when the finned rear side of the panel was sprayed with TiO$_2$ water-based nanofluid, an average temperature reduction of 4.0 °C was obtained over the four months of experimental work, and hence the cooling mechanism of the panel was improved. This is followed by the case when the rear side is only finned, with a temperature reduction of 1.0 °C. The percentage of power produced by the finned and coated PV and by the finned PV increased by 5.8 percent and 1.5 percent, respectively, as a result of the reduction in temperature. This translates to a 1.1 percent increase in finned and coated PV efficiency, and a 0.4 percent increase in finned PV efficiency.

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