Effect of water-based cooling on PV performance: case study

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ABSTRACT

Solar energy, especially photovoltaic (PV), is one of the most common renewable energy resources. Panel temperature and dust are the common problems which have a great effect on the conversion performance of PV. These problems can be alleviated by cooling and cleaning in order to improve its efficiency. This paper investigates the effect of PV cooling on the energy harvesting. The study is carried out experimentally using two similar PV panels which are subjected to the same environmental conditions and connected to similar load. The proposed cooling system is applied to one of these panels while the other is left without cooling for comparison. Five cases of water cooling are tested; surface cooling in two ways, back cooling using sprayers with and without cotton net, and hybrid cooling. The effect of cooling can be noticed from the measured load voltage and power. It is found that the surface cooling is the most effective because it achieved the best improvement comparing to others. When the panel temperature decreased from 65 to 42 °C, the load voltage increased from 32.55 to 35.8 V and the load power from 4.57 to 5.37 watts, with an improvement of about 10% and 18%, respectively.

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1. INTRODUCTION

Solar energy will be the largest source of electric power by 2050 [1]. Solar energy is the most common renewable energy source because of its environmental friendliness, sustainability, and absence of expenses of fuel [2]. So, photovoltaic (PV) applications as well as researches are fast increasing. Photovoltaics are semiconductors which convert sunlight into electricity. Temperature is a significant factor influencing the PV output power [3]. Due to the temperature increase, not all of the sunlight gathered by PV cells can be transformed into electric power [4]. In accordance with the law of energy conservation, any remaining solar energy is converted into heat. As an effect of this wasted heat, overall conversion efficiency decreases. PV cooling is a significant aspect to keep in mind while operating photovoltaic systems to enhance efficiency.

Many experiments based on different techniques have been undertaken to cool the PV panel in order to enhance its performance. Most common of these cooling techniques are air, phase change material (PCM), and water. Air-based cooling technology mostly needs few materials and in some cases no. So, air-based cooling is considered as a cost-effective technology. On the contrary, air has weak thermo-physical properties [5]. Other cooling technologies, such as PCMs, heat pipe, and heat sink. are simple and don’t need additional equipment, but they have low rate of heat transfer. On the other hand, water cooling has the largest capability of heat extraction from the photovoltaic panels when compared to other cooling technologies [6].

To enhance PV performance, Elnozahy *et al.* [7] examined surface cooling by water. The back temperature falls by 39% and surface temperature fall by 45.5%. As a consequence, the efficiency of the cooled panel became 11.7%, instead of 9% for the un-cooled panel. In addition, the highest output power produced by the cleaned module reached 89.4 watt, instead of 68.4 watt for the un-cooled panel. Hadipour *et al.* [8] tested an efficient PV cooling system utilizing water pulsed spray (PSWC) and steady spray (SSWC). As SSWC and PSWC with DC (duty cycle) = 1 and 0.2 are used, the maximum output power improves by 33.3 percent, 27.7 percent, and 25.9 percent, respectively, as compared to the un-cooled system. The underside of a PV had been cooled by water sprayer in closed loop cycle, according to Yang *et al.* [9]. That system boosted efficiency by 14.3%. Fakouriyan *et al.* [10] created cooling structure, which increased the efficiency and produced hot water. Electrical and efficiency were enhanced to 12.3% and 61.7%, respectively. Lucas *et al.* [11] main objective is to improve PV efficiency by using flowing water on the surface and a solar chimney on the backside. In addition, that system acts as a radiator for a water chiller, which also serves as a cooling tower. The results with a 500 liter per hour of water flow in sprayers and a 250 liter per hour of sliding rate indicate 15 °C of average temperature reduction and a 10% increase in efficiency. Water was used to cool a PV system mounted a building [12]. A cooling system with an optimized six liter per minute water flow boosts power output by 15% and adds 0.0178 kWh of energy per hour for each panel. Zilli *et al.* [13] also investigated the effect of a water sprayer on polycrystalline PV panels. The mentioned system for cooling was employed at a high degree of irradiation, resulting in a 12.26% increase in power and a 12.17% enhancement in efficiency.

A series of numerical investigations on a new porous cooling channel utilized in photovoltaic thermal (PVT) systems was carried out by Zhang *et al.* [14] carried out to improve the insufficient heat transfer in the standard channel. The findings showed that holes spread irregularly near to the water outflow had a greater cooling impact, with 0.005m hole diameter providing the optimum performance. The efficiency with the new channel proved 4.17% higher than without cooling. The performance of a normal PV (NPV) panel, concentrated PV (CPV), and CPV with water cooling (WCCPV) was examined practically and mathematically [15]. Based on the empirical findings, the maximum NPV, CPV, and WCCPV temperatures are 57.5, 64.1, and 36.5 °C, consecutively. In addition, the WCCPV and CPV power outputs were increased by 24.4% and 10.65%, respectively. Two comparable solar panels were studied concurrently, one with and one without back surface water cooling [16]. The fitted cooling system improved the PV's output power by approximately 14.1%. In addition, the electricity efficiency increased to 19.8%, up from 17.4% without cooling. A PV experimental analysis was studied by Chanphavong *et al.* [17] under front surface water cooling to improve the efficiency. In this investigation, two 50-watt monocrystalline modules are employed for cooled and uncooled instances. The exergy efficiency of cooled and uncooled modules was found to be 12.76% and 2.91%, respectively. Ahmad *et al.* [18] developed a PV cooling system that uses water to reduce the effects of high temperature. It was noticed that utilizing water at room temperature (24 °C) boosted efficiency by 10.35% over the non-cooled panel. Patel *et al.* [19] investigated the PV performance increase of by cooling the front surface with water. Water passed at a consistent rate over the panel. The temperature drop of the back and front surfaces is 2.79 °C and 3.54 °C, respectively, owing mostly to the front water flow over the PV module. On average, front cooling improves efficiency by 9.64%.

According to the previous introduction, water-based cooling is the most fast and effective method in addition to eliminating dust and contaminants from the surface of the PV. Much researches have been conducted on water cooling, some of which were mentioned above. All of these researches have dealt with water cooling of the active type, which requires external equipment such as pumps to perform cooling through a closed loop cycle. The effect of using cotton net from the back on the panel temperature has not been compared in the presence of water cooling. This paper investigates the effect of different water-cooling techniques on the PV performance. The proposed cooling system uses fresh water and doesn't need any external equipment. Five cases of water cooling were used. The cases are as, cooling from the surface in two ways, cooling from the back using sprayers with and without cotton net, and hybrid cooling by combining cooling from the surface and back with the presence of cotton net. The rate of change of the panel temperature over time was studied in each cooling case to determine which case that achieved the highest rate of decrease over time. The paper is presented as: i) Section 2 illustrates temperature impact on PV panel; ii) Section 3 briefly discusses PV cooling; iii) Section 4 illustrates methodology and materials; iv) Section 5 shows the result analysis and discussion; and v) Section 6 includes the conclusion.

2. IMPACT OF TEMPERATURE ON PV PERFORMANCE

The solar panel is affected by a variety of environmental factors [20]. For example, module temperature, solar irradiation, humidity, wind, dust, and shading. Solar irradiance and temperature are significant actors among different factors. The PV surface temperature is crucial in PV conversion process [21]. A typical photovoltaic module converts 6-20% of radiation into electricity, based on the panel type and the ambient circumstances. The leftover solar energy is converted into heat, thereby raising the PV temperature and decreasing its efficiency. So, the PV operating temperature is one of the most critical elements influencing the panel output [22]. The resulting heat could be evacuated by conveying water or air over the PV panel.

In practice, PV transforms a portion of the irradiance into energy, while the remainder is reflected or transformed into heat [18]. Photovoltaic technology uses semiconductors for converting solar radiation into electrical energy. As in Figure 1, each cell contains parallel and series resistances; when temperatures rise, the parallel resistance falls while the series resistance rises. A rise in series resistance causes more voltage decreases, lowering the output voltage, whereas a fall in parallel resistance lets more current pass through it. As a result of the high temperature, the output power decreases, see Figure 2.

V_{oc} (open circuit voltage) and I_{sc} (short circuit current) are two crucial factors of PV' I-V curve [10]. Both parameters are affected by fluctuations in ambient temperature and irradiance. V_{oc} rises somewhat as radiation rises and falls as panel temperature rises, leading to a considerable drop in output power. I_{sc}, on the contrary, grows just slightly as panel temperature goes up. As a consequence, it is clear that changes in cell temperature have an impact on PV efficiency.

Equations, representing the solar cell, used to compute the PV electrical efficiency, output power, and fill factor (FF). The IV curve squareness is measured by the fill factor. It demonstrates the formation of a junction and the formation of low series resistance. The PV electrical efficiency and fill factor drop as the cell temperature rises, increasing the cost per unit watt [24]. The panel efficiency is affected by the output power from the panel at any moment [3]. This power is determined by the measured values of Imp and V_{mp}. The PV output power can be calculated as (1).

$$P_{mp} = V_{mp}\ x\ I_{mp} = FF \times V_{oc} \times I_{sc} \quad (1)$$

Where, P_{mp} is the maximum PV output power. V_{mp} and Imp are the voltage and the current at the maximum power, respectively. FF is the panel fill factor under consideration, while V_{oc} is the PV no-load voltage and I_{sc} is the current of the panel when the output is short-circuited. The panel power improvement is determined using (2).

$$\%\ \text{power improvement} = \frac{\text{average power with cooling} - \text{average power without cooling}}{\text{average power without cooling}} * 100 \quad (2)$$

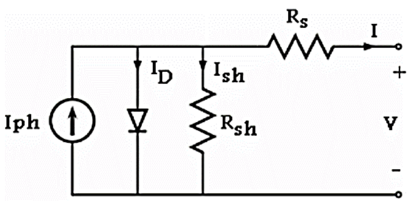

Figure 1. PV cell equivalent circuit [5]

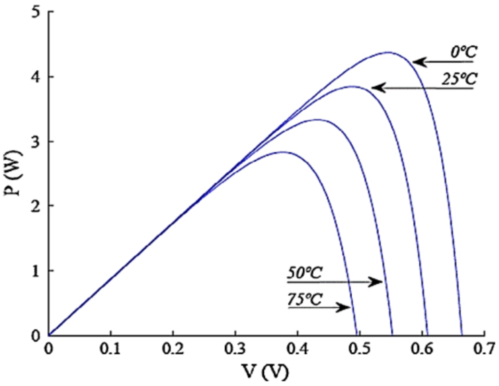

Figure 2. PV curve under variable temperatures [23]

3. PV COOLING

The basic goal of PV cooling is to eliminate the heat from PV panels [25]. It can be achieved by passive or active cooling [26], [27]. The system that uses external source (mechanical or electrical) to manage heat absorption, such as fans, pumps, or blowers, is called active cooling [28], [29]. In active cooling, thermal energy storage can be used for storing the energy gathered. This stored energy can eventually be utilized to heat buildings or generate power. Passive cooling systems, on the contrary, don't require any external heat extraction equipment. It absorbs heat and transfers it to the environment completely on its own and through thermodynamics.

Active approaches (air, water, and hybrid) have been demonstrated to be effective in dispersing heat created by sunlight into water, air, or some other fluids. PV active cooling is extremely simple and has an extensive number of possible applications. Water is being suggested for cooling due to its heat carrying capacity and its availability. Cooling by water is not cost-effective in comparison to cooling by air. However, it has the capacity to extract heat, offering a dual-sided advantage when output water is used for heating uses. Heat removal in air cooling is accomplished by convection. Air cooling doesn't require many materials, making it a cost-effective option, but it suffers from poor thermo-physical properties.

Passive cooling as microchannel, PCMs, thermoelectric, heat pipe, evaporative, heat sink, wick, and hybrid achieves the cooling in photovoltaic cells without external power. Nonetheless, various problems have occurred as a consequence of passive cooling [12]. These problems may be summarized as follows: minimal cooling impact, materials that may have a negative effect on the environment, expensive system cost, which increase produced electricity cost, bulky system for usage in a residential area, and temperature profile that is not symmetrical. Active cooling, on the other hand, has inherent losses from water pump or fan, while obtaining better performance increases than the other. Finally, water cooling is the finest active cooling method used on the PV front surface as it delivers a homogeneous temperature profile dispersed over the surface as well as a cleaning [30]. Further details about PV cooling techniques can be found in [5].

4. METHODOLOGY AND MATERIALS

The proposed experimental cooling setup was carried out on two symmetrical poly-crystalline PV panels located on rooftop of National Research Centre at Dokki, Giza, Egypt. In the summer, in Egypt, the ambient temperature is 35 °C in average with around 9 sun hours versus 19 °C in the winter with around 6 sun hours. As a result, in Egypt, PV panels must be cooled in the summer rather than the winter. So, the study was conducted in the summer, when there are little fluctuations in climatic conditions. Other environmental factors such as humidity and wind were not taken into consideration for the purposes of this study. The tests were done in the midday with water cooling. The experiment setup was established to investigate the effect of the suggested cooling system on the panel performance. As shown from Figures 3 and 4, the main components of the experimental setup are two PV panels (cooled and reference), source of water, valves, feeding pipes, thermocouples to measure the panel temperature, data logger to storing data, and control unit to control the opening and closing of valves. Also, two PV analyzers were used in order o draw the IV and power curve for the panels.

As illustrated in Figure 3, two poly-crystalline PV panels were employed. The reference panel is on the bottom, and the cooled panel is on the top. The two PV panels are exactly the same and have the same specifications as shown in Table 1 (at actual irradiation G = 1000 W/m^2 and T = 25 °C). One is used as a reference panel and the other is used to be combined with the proposed cooling system. A similar DC load (3 small computer fans) is connected in series to the two panels. As shown in Figure 4, K-type temperature sensor was installed behind each panel to measure the panel temperature, in addition to another temperature sensor to measure the ambient temperature. Data measuring and control unit was installed to measure and record current, voltage, and panel temperature as well as controlling the two solenoid valves. The reference panel is always connected to the load without cooling and works in parallel with the cooled panel.

Figure 3. Experimental PV panel setup

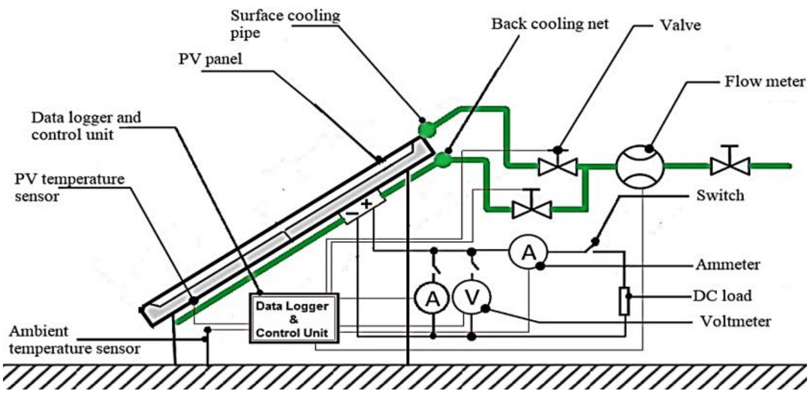

Figure 4. Experimental setup schematic diagram

The proposed cooling technique included five case studies using water cooling; surface cooling in two ways, back cooling using sprayers with and without cotton net, and hybrid cooling by combining both surface and back cooling. All cases were carried out at noon, where there is almost constant solar radiation and temperature. Each case was applied sequentially. So, the first case was applied, the results were recorded, then waiting without cooling until the panel temperature rises again to apply the second case, and so on. The rate of change of the panel temperature over time was studied in each cooling case to determine which case that achieved the highest rate of decrease over time. In each case; the panel temperature, PV current, and PV voltage were measured.

Table 1. Technical specifications for PV panel

PV panel specification parameters			
Panel maximum power	260 W	Open circuit voltage	38.1 V
Voltage at maximum power	30.78 V	Short circuit current	8.91 A
Current at maximum power	8.42 A	Filling factor	0.763

4.1. Timing surface cooling (case 1)

Cooling is by passing water over the surface of the panel which uses a thin layer of water, as in Figure 5(a). A water pipe is placed at the highest point of the panel surface to allow water to flow over it from top to bottom. The pipe is 0.5 inch in diameter and 150 cm long so that it covers the entire length of the panel. Holes with a diameter of 1 mm were made along the length of the pipe, with each hole separated by a distance of 1.5 cm to ensure that the entire board was covered with water. An electric solenoid valve is installed to control the opening and closing of water. The water is opened automatically every three minutes by passing one liter of water within 10 seconds.

4.2. Automatic surface cooling (case 2)

Automatic surface cooling is as in case one typically except water opening and closing method. As in Figure 5(a), thin layer of water was passed over the surface of the panel. The difference between this case and the previous case is that here the water is opened continuously until the panel temperature remains at the lowest possible value. Then the water valve is automatically closed and does not open until panel temperature increased by 2 degrees.

4.3. Back cooling (case 3)

In this case as in Figure 5(b), water sprayers were used through a network of pipes under the PV panel and covering all back. The back cooling system consists of a network of 10 pipes with a diameter of 0.5 inches each. The pipes are distributed evenly under the panel, every 15 cm, so that they cover the entire panel from the back. Each pipe has holes with a diameter of 1 mm with one hole every 10 cm, pointing upwards to allow the water to rush into the back of the panel. The system was operated for only one minute to study how this method effects on the panel temperature.

4.4. Back cooling with cotton net (case 4)

Here as illustrated in Figure 5(c), a piece of cotton net is attached to the panel from the back in the presence of back cooling network. Cotton net is a piece of burlap that covers the entire back of the panel. The cooling system is running for two minutes to study how this method effects on the panel temperature.

(a) (b) (c)

Figure 5. PV cooling system: (a) surface cooling, (b) back cooling, and (c) back cooling with cotton net

4.5. Hybrid cooling (case 5)

In hybrid cooling, more than one cooling method was used at the same time on the same panel. Here surface cooling, back cooling, and cotton net were used as a hybrid cooling. All cooling systems were operated simultaneously, and the back cooling was stopped firstly after two minutes, and then the surface cooling was stopped automatically when the panel temperature remained at the lowest possible value.

5. RESULT AND DISCUSSION

The study was carried out on a single photovoltaic panel in addition to the reference panel. The proposed cooling system includes five cases of water cooling. The cases are as, cooling from the surface in two ways, cooling from the back using sprayers with and without cotton net, and hybrid cooling by combining cooling from the surface and back with the presence of cotton net. In each case, the panel temperature, load current, and load voltage are measured.

5.1. Timing surface cooling (case 1)

Figure 6 shows the effect of temperature on I_{sc} and V_{oc}. The first case was carried out without load to study the effect of temperature on the basic parameters of the solar panel (I_{sc} and V_{oc}). The panel temperature was 54 °C before cooling. The Isc and V_{oc} are measured at 7.56 A and 33.2 V respectively for the panel without cooling. As shown in Figure 6, after the first cooling, the temperature decreased by 7 ^{o}C. As a result, the voltage increased significantly, reaching 34.3 V, but the current decreased by a small amount of about 0.03 A. The panel was cooled to a temperature of 44 °C with a voltage of 34.9 V and a current of 7.7 A to achieve an output power of 205 W, an increase of 7% over the output power of the panel without cooling.

It's observed from Figure 6 that, the current rises at the beginning of cooling then decreases with the decreasing of temperature. The reason for this is that the water sliding on the panel surface acts as a lens, which leads to focusing solar rays on the cells and thus increasing the short circuit current until the effect of the panel temperature appears, leading to decreasing of short circuit current.

5.2. Automatic surface cooling (case 2)

In case two, the system includes surface cooling by opening the water continuously until the temperature remains at the lowest possible value. As shown in Figure 7, it is found that the panel temperature decreased from 65 to 42 °C within a period of about six minutes operation of the cooling system. During this period, the load voltage increased from 32.55 to 35.8 volts, which led to an increase in the load power from 4.57 to 5.37 watts, with an improvement of about 10% and 18%, respectively. It's observed that, the load current suddenly increased by 7% when the panel temperature is less than 48 ^{o}C.

5.3. Back cooling (case 3)

In the case of cooling from the back using sprayers, it turns out that in a period of about six minutes. The panel temperature decreased from 56 to 51 ^{o}C. As a result, the load voltage increased from 33.92 to 34.66 volts, which led to an increase in the power load by the load from 4.75 to 4.85 watts, with an improvement of approximately 2% for both. It is noticed from Figure 8 that a slight decrease in temperature and thus a slight improvement in load voltage and power with higher water consumption. The reason for this is that the water does not stay enough on the panel, unlike the surface cooling.

5.4. Back cooling with cotton net (case 4)

Case four is cooling from the back in the presence of cotton net. In this case, the temperature decreased from 65 to 54 °C in a cooling period of about six minutes, as is clear from Figure 9. This resulted in an improvement in the load voltage from 32.95 to 34.38 volts and thus the load power from 4.6 to 4.8 watts, with an improvement of 4% approximately for both. It is noted that this system solved the problem of the third case slightly by forcing the water to remain behind the panel and maintaining the panel temperature for a relatively longer period. But the improvement was not significant compared to surface cooling as in cases 1 or 2.

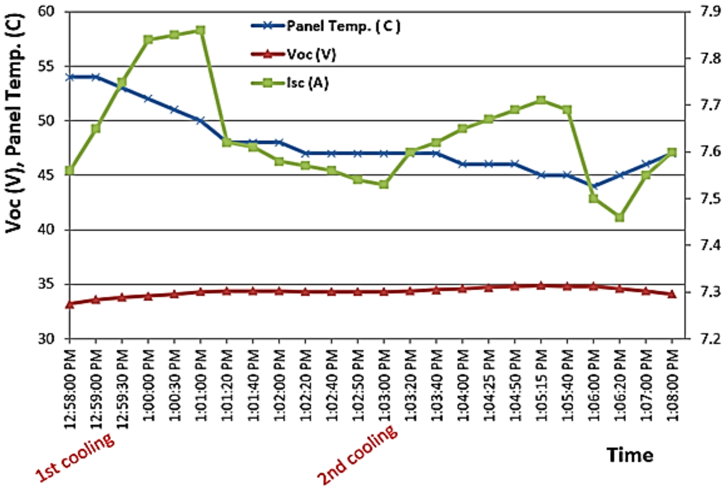

Figure 6. Panel temperature effect on Voc and Isc, surface cooling (case 1)

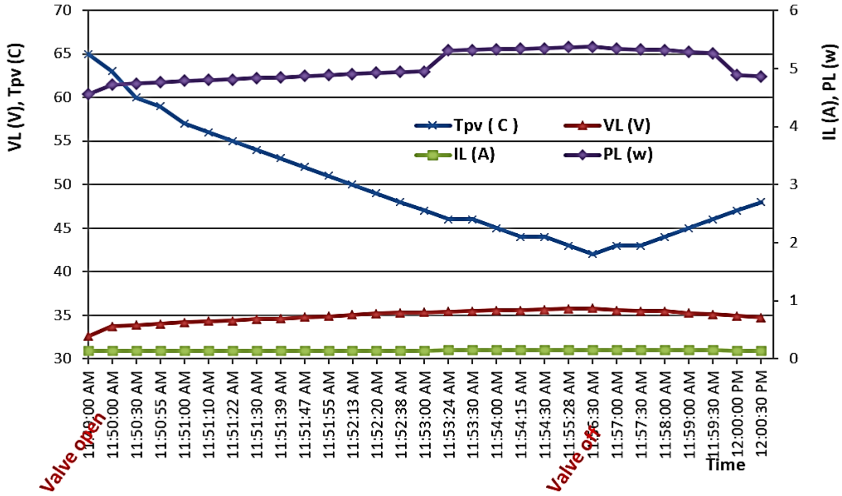

Figure 7. Panel temperature effect on VL, IL, and PL, surface cooling (case 2)

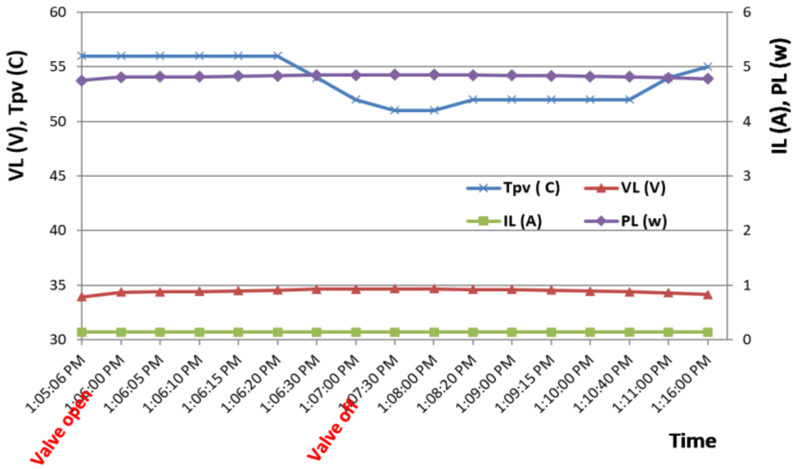

Figure 8. Panel temperature effect on VL, IL, and PL, back cooling without cotton net (case 3)

5.5. Hybrid cooling (case 5)

Case five is hybrid cooling. In this case, surface cooling is used along with back cooling in the presence of cotton net. As shown in Figure 10, the panel temperature decreased from 61 to 44 °C within a cooling period of about six minutes as well. This resulted in an improvement in the load voltage from 33.75 to 36.29 volts and thus the load power from 4.7 to 5.4 watts, with an improvement of 7.5% and 15%, respectively.

Referring to all the previous cases, and as is evident from the recorded measurements, we find that automatic surface cooling (case 2) is the best case, which achieves the best reduction in panel temperature, corresponding to the best improvement in voltage and power compared to other cases. At the same time under the same conditions, the five cases were tested on the cooled panel and compared with the reference panel. All cooling cases were applied again under the same conditions at noon. Each case was started when the solar panel reached a temperature of 65 °C for a similar period (seven minutes) in all cases. The panel temperature and load voltage were recorded over time and the cooling effect on them was recorded in all cases. Figure 11 shows the temperature change during the cooling period for all cases simultaneously, in addition to the reference panel. As a result, Figure 12 shows the increase in panel voltage during the cooling period for all cases as well, in addition to the reference panel.

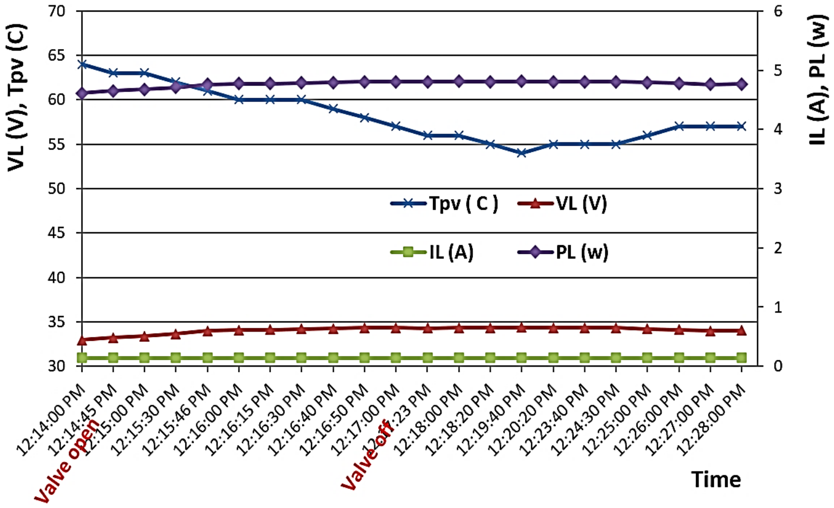

Figure 9. Panel temperature effect on VL, IL, and PL, back cooling with cotton net (case 4)

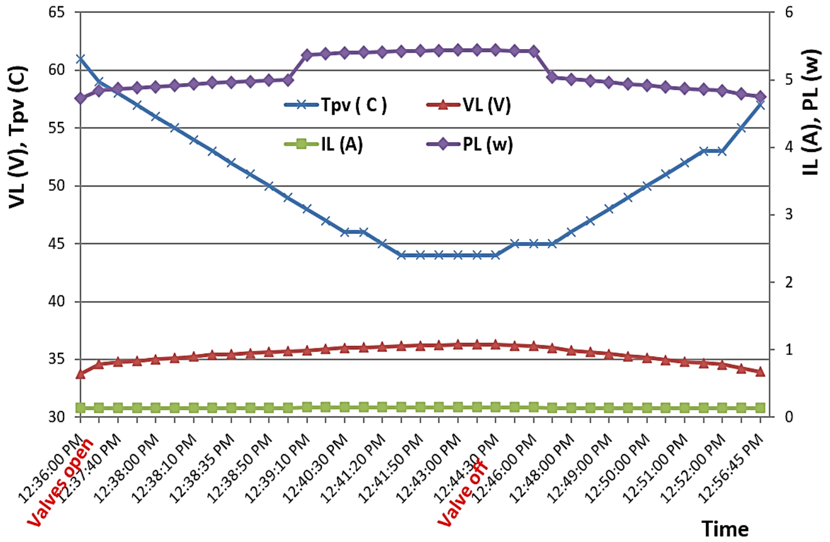

Figure 10. Panel temperature effect on VL, IL, and PL, hybrid cooling (case 5)

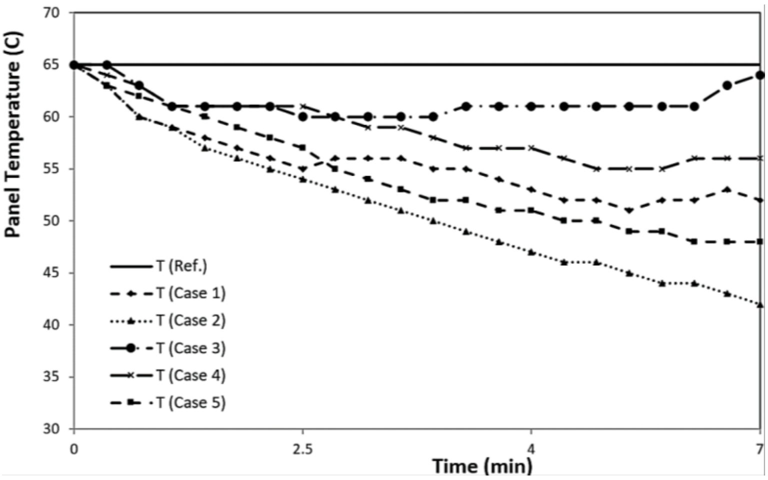

Figure 11. Cooling Effect on the panel temperature

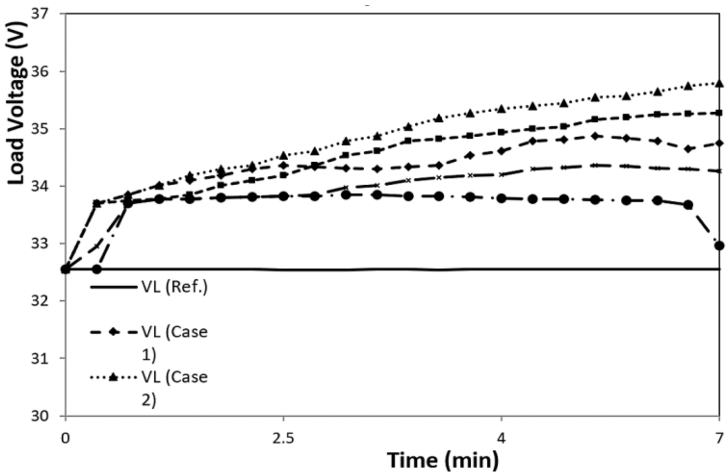

Figure 12. Cooling effect on the load voltage

It is clear from Figures 11 and 12 that the second case achieved the best rate of temperature decrease with time and thus the best rate of voltage increase. The fifth case comes in second place, then the first case. The third and fourth cases (cooling from the back) achieved the lowest rate of decrease in panel temperature over time. It is noted from this that cooling from the surface is better than cooling from the back, in addition to the fact that the presence of the cotton net unfortunately did not improve the performance of the cooling system. It is also noted that the amount of improvement in the hybrid case was not higher than all previous cases, as expected, because it combines more than one cooling system. But the reason for this is that the presence of cotton net, as previously mentioned, works to maintain the temperature of the panel for a longer period depending on the air temperature.

6. CONCLUSION

The temperature of the PV surface is one of the most important elements influencing the PV efficiency. This study emphasis the effect of cooling of PV panels on the energy harvesting. For this purpose, an experiment setup is carried out to investigate the effect of different cooling techniques on the PV performance. The cooling system included five cases of water cooling. The cases are as, cooling from the surface in two ways, cooling from the back using sprayers with and without cotton net, and hybrid cooling by combining cooling from the surface and back with the presence of cotton net.

In case one, the panel was cooled to a temperature of 44 °C with a voltage of 34.9 V to achieve an output power of 205W, an increase of 7% over the output power of the panel without cooling. In case two, it is found that the panel temperature decreased from 65 to 42 °C within a period of about six minutes operation of the cooling system. During this period, the load voltage increased from 32.55 to 35.8 V, which led to an increase in the load power from 4.57 to 5.37 W, with an improvement in voltage and power of about 10% and 18%, respectively. In case three, the panel temperature decreased from 56 to 51 °C. As a result, the load voltage increased from 33.92 to 34.66 V, which led to an increase in the power load by the load from 4.75 to 4.85 W, with an improvement of approximately 2% for both. It was noticed that a slight decrease in temperature and thus a slight improvement in load voltage and power with higher water consumption. In case four, the improvement is of 4% approximately for both. In case five, the improvement in the load voltage and load power is of 7.5% and 15%, respectively. It was noted from this that cooling from the surface is better than cooling from the back, in addition to the fact that the presence of the cotton net unfortunately did not improve the performance of the cooling system. It is also noted that the amount of improvement in this case was not higher than all previous cases, as expected, because it combines more than one cooling system. But the reason for this is that the presence of cotton net, as previously mentioned, works to maintain the temperature of the panel for a longer period depending on the air temperature. It was found that the surface cooling in case two is the most effective because it achieved the best improvement comparing to others.

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