Enhancing the Efficiency of Photovoltaic Panel Using Open-Cell Copper Metal Foam Fins

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Abstract- In this experimental study, a passive cooling technique by open-cell copper metal foam fins was performed for a photovoltaic (PV) panel to enhance its performance by reducing the operating temperature of the PV panel. The experiment was carried out in Baghdad-Iraq climatic conditions during February, March, and April 2019. Three polycrystalline PV panels were used, two panels were equipped with the proposed cooling technique and the other without modification for the purposed of comparing. The open-cell copper metal foam fins mounted on the backside of the PV panel by thermal grease. Four longitudinal fins arrangements (4, 6, 8, and 10 fins) were investigated. The porosity of the metal foam helps the penetration of air through the fins to extract more heat from the PV panel. It was found that the adding of ten longitudinal fins can reduce the average PV panel temperature by about 8.4% and improve the power output by an average of 4.9%.

Keywords Photovoltaic panel, Photovoltaic efficiency, Metal foal fins, passive cooling.

1. Introduction

Sun energy is a significant root of all renewable energy since it provides clean and unlimited energy. The solar energy can be turned directly by the photovoltaic (PV) cells into electrical energy. PV panel is rapidly developing, and it represents one of the most significant solar energy applications. Covering 1% of the earth area with 10% efficient PV modules would produce twice the current need for worldwide energy. When the PV cells exposed to sunlight, it uses a small fraction of this radiation to generate electricity. In practical, only (15–20%) of the incident solar radiation can be turned into electricity [1-4]. While the enduring fraction of the absorbed radiation is heating the PV module, which is increasing the operating temperature of the cell. This increment in the operating temperature leads to reduce the electrical efficiency of the cell. The average degradation in the electrical efficiency of the PV panel ranged from (0.25 %/°C to 0.5 %/°C) when it exposed to high operating temperature [5]. This degradation depends on the PV modules manufacturing quality and the specific PV technology. Also, the ambient temperature affected the electrical efficiency of the PV panel, i.e., when the ambient temperature increased, the electrical efficiency decreased [6]. So, it is essential to have efficient cooling methods to enhance the electrical efficiency of PV cells by decreasing PV temperature. Thereby, the lifetime of the PV module can also be prolonged [7-9].

Many researchers aimed to increase the electrical efficiency of the PV panel by using different cooling techniques to remove any excess heat. The cooling techniques can be classified into two groups: passive and active cooling. Unlike the active cooling technique, passive cooling does not consume any power. Generally, it is less complicated and more economical than the active cooling [10-11] but less efficient. There are many techniques used for passive cooling like heat pipe attached to the back surface of the PV panel [12]. A phase change material (PCM) was used in direct contact with the backside of the PV module [13]. The PV module temperature was regulated experimentally through the use of heat spreaders and cotton wicks [14]. Two identical PV modules were used to study the combined effect of fins and evaporative cooling. First PV module used for the cooling system and the other set as a reference for the comparison. The experimental data showed that the reduction by about 12% in the PV module temperature leads to an increase of 14% in electrical efficiency.

The passive cooling technique by the addition of fins on the backside of the PV panel was studied experimentally by [15]. Two different geometry of aluminum fins were investigated. The first configuration was pasted in a parallel positioned on the PV panel back surface. While, the second configuration, consisted of perforated fins were pasted in random positions. It was shown that the second geometry gives better results of performance than the first one. Theoretical and experimental studies were implemented to evaluate the passive cooling by attached fins on the backside of the PV module [16]. It was found that the fins cooling was reduced the module temperature by about (4-5°C). Different ribs configurations were studied numerically to show the reduction in the temperature of the PV panels [17]. Three rib angles were studied in the simulations (45°, 90°, and 135°). In compare to the base case, the increase of the maximum power was from 6.97% to 7.55% for the rib's angles from 90° to 45°, respectively. The effect of using an aluminum heat sink on the performance of silicon solar cells was studied experimentally under indoor conditions by Ref. [18]. An increase in the output power of the PV cell was achieved by 20% at the radiation condition of 800 W/m^2. Chen et al.[19] presented a comparative experimental study to investigate the effect of the solar radiation, wind velocity, PV panel inclination and ambient temperature on the PV panel's electrical performance with and without fin cooling. Under different conditions in their study, the average power output of PV panel with fins was higher than without fins by 1.8~11.8%. Also, the average electrical efficiency for the PV panel with fins was 0.3~1.8% higher than the PV panel without fins. An experimental study under natural convection was carried out for PV panels with and without fins [20]. Nine aluminum perforated fins were used for the passive cooling. The results showed that the cooling by fins reducing the temperature by 4.2% and increasing the output power by 5.5%. A finned plate of aluminum was used as a cooling method on the rear surface of the PV panel to enhance efficiency [21]. The results showed an increase in the output power by 1.87 W and improving in the electrical efficiency by 1.77%. An experimental and theoretical studies were implemented to enhance the performance of the PV panel through the cooling by fins [22]. An aluminum heat sink consists of 52 variable cross-section rectangular fins were attached to the back surface of the PV panel. The results showed that there was a reduction in temperature by about 9.4% for the panel with a finned surface.

The effect of closed-cell metal foam fins on the backside of the PV module was studied by Ref. [23]. A comparison between PV panels with and without pours metal foam fins was held. This study showed that the adding of fins result in a higher PV output power when compared to the panel without fins. The effect of the PCM and rectangular fins was investigated numerically to reduce the temperature of the PV panel [24-25]. The PCM was directly in contact with the backside of the PV module and the effect of fins length was examined with different values. The results confirmed that the combined effect of the fins and the PCM could reduce the temperature of the PV panel significantly.

Metal foam is a cellular structure that consists of a solid metal (frequently copper, aluminum and nickel). This structure is containing a large volume fraction of pores. The pores either consisting of ligaments that form an interconnected network, so it is called open-cell metal foam. Alternatively, the pores can be sealed with metal; then it is called closed-cell metal foam [26-27]. In compare to the solid material, metal foams have various attractive characteristics. Metal foams have a great combination of physical and mechanical properties such as high fluid permeability, high thermal conductivity, and high stiffness in conjuring with its very lightweight. So they are used in different applications that range from mechanical to thermal [28]. Metal foam enhances the heat transfer rate through increasing the contact of the surface area between the working fluid and the absorber plate and provide a better mixing between them [29].

In this work, an experimental study was implemented to investigate the effect of metal foam fins on the performance of the PV panel. Open-cell copper metal foam fins with 15 PPI were used. Fins were attached on the backside of the PV panel. Four different cases of longitudinal fins arrangements were studied; (I) four fins, (II) six fins, (III) eight fins, (IV) ten fins.

2. Experimental Setup

The experimental setup was tested on the roof building of the Technical Engineering College in Baghdad. The outdoor experiments were carried out in Baghdad-Iraq climatic conditions located at (latitude 33.26˚ North and longitude 44.49˚ East) during February, March, and April 2019. Three polycrystalline PV modules have been used, two of them was attached with longitudinal metal foam fins (5 mm thickness) for the purpose of passive cooling. Whereas, the third one served as the reference panel (without cooling) for the investigation of the performance difference. Each panel has a width of 67 cm, a length of 54 cm and peak power of 50W. More data about the module specifications were available in Table (1).

Table 1. Modules specifications at standard test conditions.

Peak voltage	18 V	Peak power	50 W
Peak current	2.8 A	Module efficiency	14.54 %
Short circuit current	3.17 A	Fill factor	75.39
Open circuit voltage	22 V	Module area	3589.74 cm^2

A base frame was used to carry the three panels with a variable inclination angle from (0°-90°). The PV panels are oriented for south facing and the tilt angle is changed to the optimal value of each month in Baghdad to receive the maximum amount of solar radiation [30], the values of the optimal tilt angles were shown in Table (2).

Table 2. Monthly optimal tilt angle in Baghdad city. [30]

Month	Feb.	Mar.	Apr.
Optimal tilt angle	45	35	25

The open-cell copper metal foam fins with a height of 10 cm and (0.9) porosity were attached on the rear surface of the PV panels. Fins were attached on the backside of the PV panel with a thermal grease to eliminate the air gap and provide good contact between the fins and the PV panel. Thermal grease provided a good heat transfer from the panel to the fins. The open-cell metal foam was shown in **Fig. 1**.

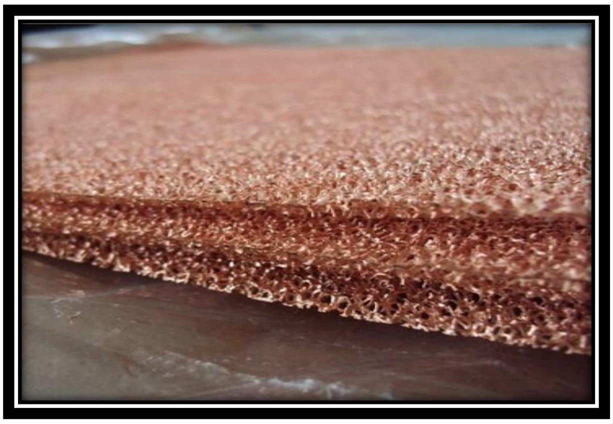
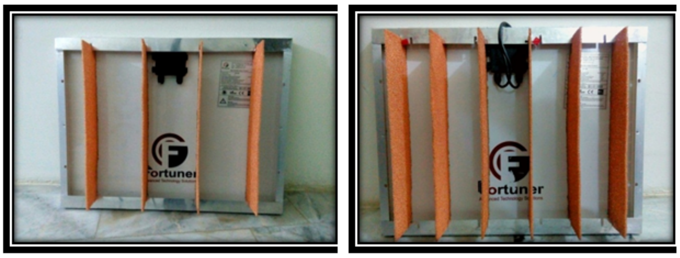


Fig. 1. Open-cell metal foam.

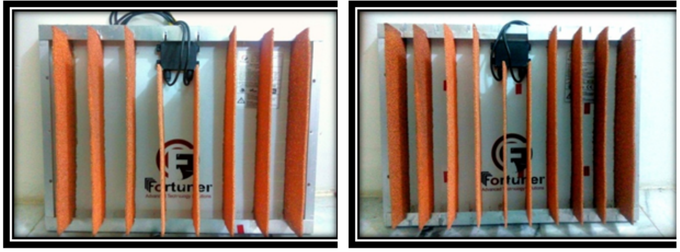
Four longitudinal fins arrangements were attached to the backside of the PV panel were investigated experimentally. The number of longitudinal open-cell copper metal foam fins for each arrangement were 4, 6, 8, and 10, respectively. The lateral spacing between each consecutive fin were 15.5, 10.3, 7.7, and 6.2 cm, respectively. An equal lateral distance was made between each consecutive fin. All fins arrangements were shown in **Fig. 2**.

The measured variables from the experimental work were; front and back surfaces of the PV panels temperatures, ambient temperature, voltage, current, maximum power, wind speed, and solar radiation. The data were recorded every 30 minutes from 9:00 am to 2:00 pm. The wind velocity was measured about 15 cm above the PV panels by a multi-function measuring instrument. The temperatures were measured by K-type thermocouples. Twenty-eight thermocouples were used in this work. Six thermocouples were placed evenly on the backside of each PV panel and three on the front surface. The distribution of the thermocouples on the front and back surfaces was shown in **Fig. 3**. One thermocouple was left free in approximately 15 cm under the PV panel to measure the ambient temperature in shade.

Four selector switches were used to connect the thermocouples to the data logger. The data logger (Whilst Pico data logger Tc-08) with eight channels was used to record the output of the thermocouples. The data logger plugged into the PC through a USB port. Solar Survey 200R was used to measure solar radiation. Also, it measures the inclination and the orientation of the PV panel by a built-in inclinometer and compass. The solar irradiance meter is mounted parallel to the PV modules surface. Solar module analyzer PV200 is used to test the short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), and maximum power (P_m). The measuring devices with the PV panels were shown in **Fig. 4.**

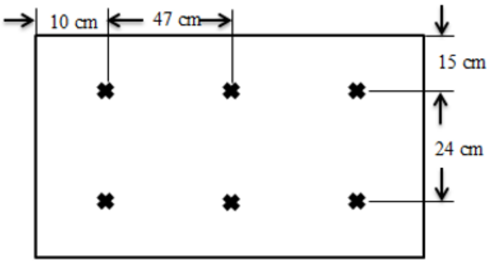


(a) Case I, four fins arrangement. (b) Case II, six fins arrangement.

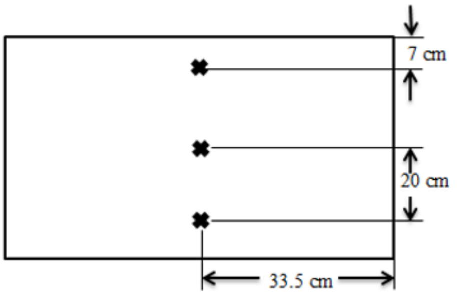


(c) Case III, eight fins arrangement. (d) Case IV, ten fins arrangement.

Fig. 2. Fins arrangements.



(a) Distribution of thermocouples on the back surface



(b) Distribution of thermocouples on the front surface

Fig. 3. Distribution of thermocouples on the PV panels.

The electrical efficiency of the PV module (η) is calculated from the ratio of (P_m) divided by the solar module surface area (A_m) and the input solar radiation (G)

$$\eta = \frac{P_m}{G A_m} \tag{1}$$

3. Uncertainty Analysis

The uncertainties in any parameter of the measured data caused by the human error reading and the instrumentation accuracy. In this study, the uncertainties in the short circuit current δI were calculated as follows:

$$\boldsymbol{\delta I} = \sqrt{\left(\frac{\partial I}{\partial V}\boldsymbol{\delta V}\right)^2 + \left(\frac{\partial I}{\partial R}\boldsymbol{\delta R}\right)^2} \tag{2}$$

Fig. 4. The experimental test rigs.

Where, I is a function of (R, V).

In the same manner, the relating uncertainties in the output power $\boldsymbol{\delta}$P of the PV panels were obtained as follows:

$$\boldsymbol{\delta P} = \sqrt{\left(\frac{\partial P}{\partial I}\boldsymbol{\delta I}\right)^2 + \left(\frac{\partial P}{\partial V}\boldsymbol{\delta V}\right)^2} \tag{3}$$

Where, P is a function of (V, I).

The values of the uncertainty for different parameters were listed in Table (3).

Table 3. Values of uncertainty analysis connected with measured values.

Parameters	Range	Resolution	Accuracy
Thermocouple K-type	-200-1370 °C	1 °C	± 0.19 °C
Solar meter	100-1500 W/m^2	1 W/m^2	± 5 W/m^2
Thermal anemometer	0.2 m/s	0.01 m/s	± 0.03 m/s
Uncertainty in measurement		Uncertainty (%)	
Temperature, T (°C)		± 0.19	
Solar intensity, G (W/m^2)		± 5	
Wind velocity, v (m/s)		± 0.03	
Current, I (A)		± 0.342	
Power, P (W)		± 2.11	

4. Results and Discussion

In the present study, the effect of open-cell copper metal foam fins on the electrical efficiency and the operating temperature of the PV panel was investigated experimentally. PV panel without fins was called panel A, whereas the two PV panels with fins were called panel B. **Fig. 5** depicts the average back surface temperature difference between panel A and panel B for all arrangements. The maximum and minimum temperature reduction recorded for the case (IV) with ten fins arrangement were 5.25 and 2.5 °C, respectively. It was concluded that the increase in fins number leads to more reduction in PV panel temperature, i.e., when the lateral spacing between fins reduced, it will help the air velocity to increase underside the PV panel. Besides, the fin porosity lets wind velocity pass underneath the PV panel from different directions, unlike the solid fin, as reported by Ref. [31]. Thereby, the natural convection removes more heat from the PV panel. Also, **Fig. 6** shows the power difference between panel A and panel B for all cases. The maximum power difference was recorded for ten fins arrangement with an average of 4.9%. This power improvement is due to the fins (extended surface) effect, which improves the conductive heat transfer from the back surface of the PV panel and dissipate this heat to the surrounding by natural convective.

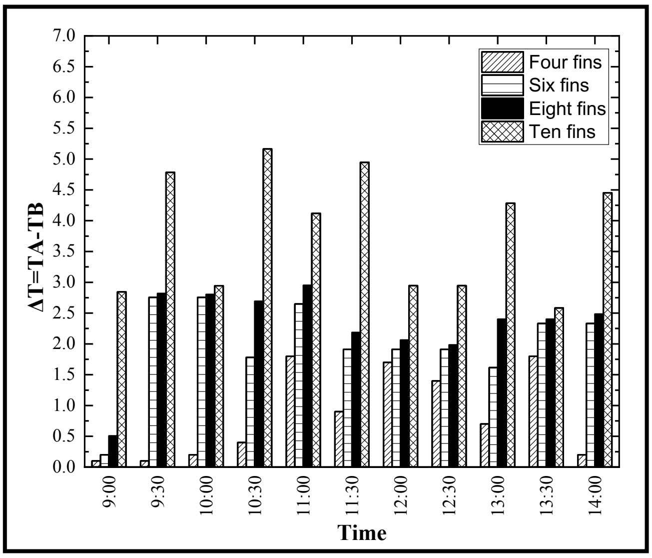


Fig. 5. Variation of the temperature difference of the PV panels with time.

The variation of the ambient temperature and the PV panel's rear surface temperature for the fourth arrangement with the recorded wind velocity was shown in **Fig. 7**. The average rear surface temperature with fins was 44.8°C whereas, it was 48.6°C for the reference panel. Cooling the PV panel was reduced the rear surface temperature by 8.4%, which leads to a noticeable improvement in the power output. When the velocity of the wind increases, backside temperature decreases due to an increase in the convection loss effect. At the first measurement, the average temperature difference between the panels A and B was 2.8°C while it was 4.49°C at 11:30 am. This is due to increase in the wind velocity from 1.027 m/s at 9:00 am and became 3.637 m/s at 11:30 am. It was found that panel B operates on a lower temperature than panel A. therefore, the lifetime of panel B will be prolonged due to the fins cooling technique as mentioned by Ref. [14].

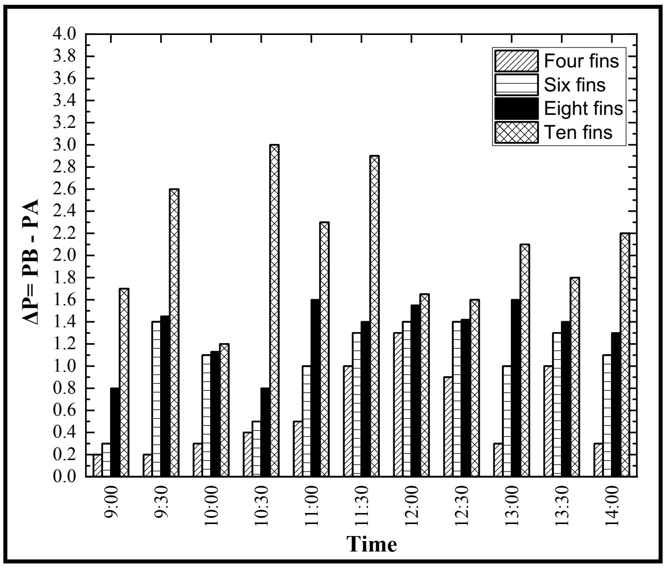


Fig. 6. Variation of the power difference of the PV panel with time.

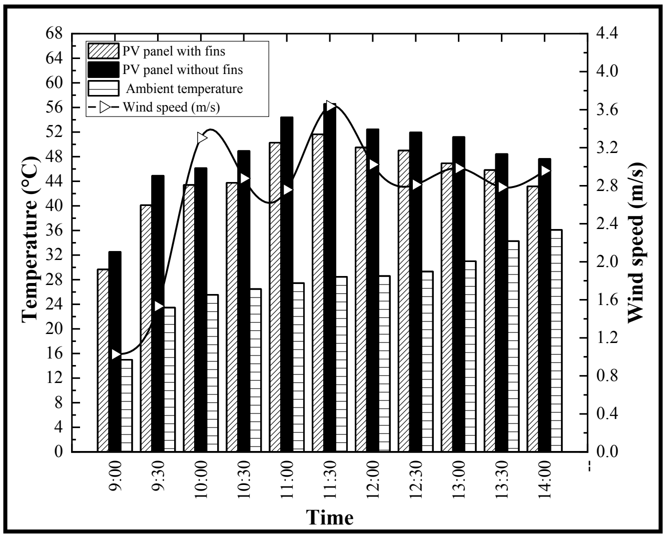


Fig. 7. Variation of the PV panels rear surface temperature with and without fins under the wind velocity and ambient temperature.

Fig. 8 presents the measured values of the solar intensity and output power for the panels A and B (for case IV). The behavior of solar radiation tends to increase and reaches the maximum value at noon then begins to decrease again. Higher values of solar radiation result in higher power output for both cases. The average power output developed by the PV panel with ten fins was 42.8W whereas it was 40.7W for the reference panel. The improvement in the output power was by 4.9%.

Fig. 9 depicts the variation of electrical efficiency for the panels A and B with the solar intensity. The electrical efficiency of the PV panels decreases with the increase of solar radiation. As the solar radiation was increased from 770 W/m^2 to 855 W/m^2 the electrical efficiency was decreased from 16.8 % to 16.4 % for PV panel without fins, while from 17.5 % to 16.9 % for PV panel with fins. The average electrical efficiency for the PV panel with fins was 18.08 % while it was 17.1% for the PV panel without fins. It can be concluded that the operating temperature of the cell was increased when the value of solar intensity was high. Thereby, the electrical efficiency was decreased. But, for panel B, part of the electrical efficiency was regained by fins cooling. The behavior of the electrical efficiency curve was similar to the result found by Ref. [15].

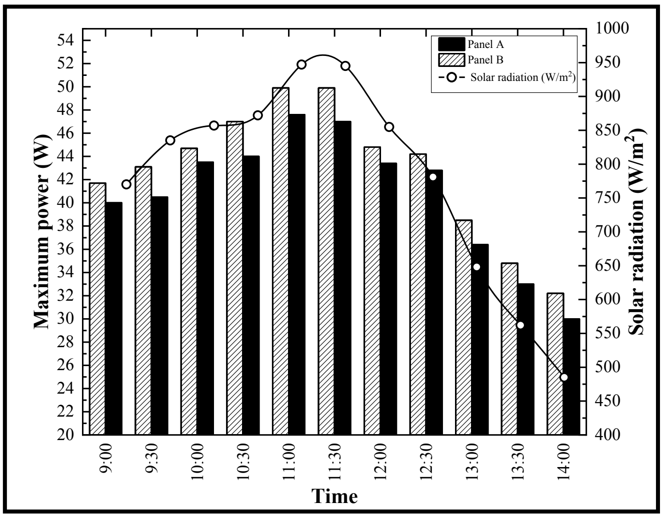


Fig. 8. Variation of the solar intensity and the power output for the PV panel with and without fins.

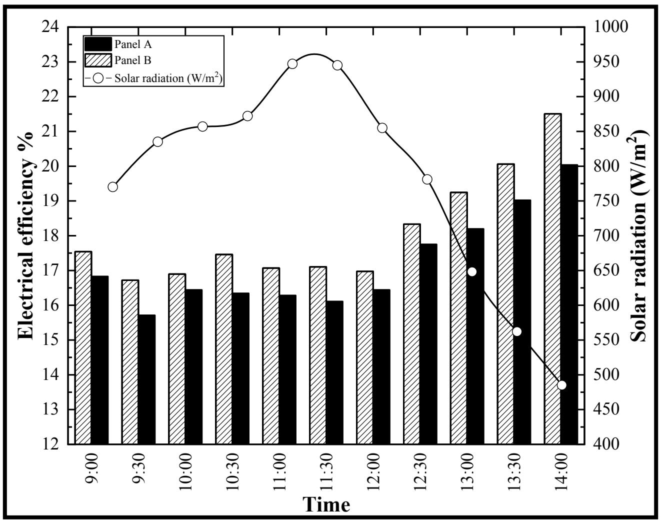


Fig. 9. Variation of the solar intensity and the electrical efficiency for the PV panel with and without fins.

Open-circuit voltage of the PV panels A and B over the period hours was shown in **Fig. 10**. The open-circuit voltage depends on the solar irradiation and the ambient temperature [32]. The measured open-circuit voltage values of the panel B were slightly higher than the panel A. The decrease of the open-circuit voltage with the increase of ambient temperature is more pronounced when comparing its increase with the increase of solar radiation. This explain the variation of the open-circuit voltage in **Fig. 10** which is determined by the change of the ambient temperature as shown in **Fig. 7**.

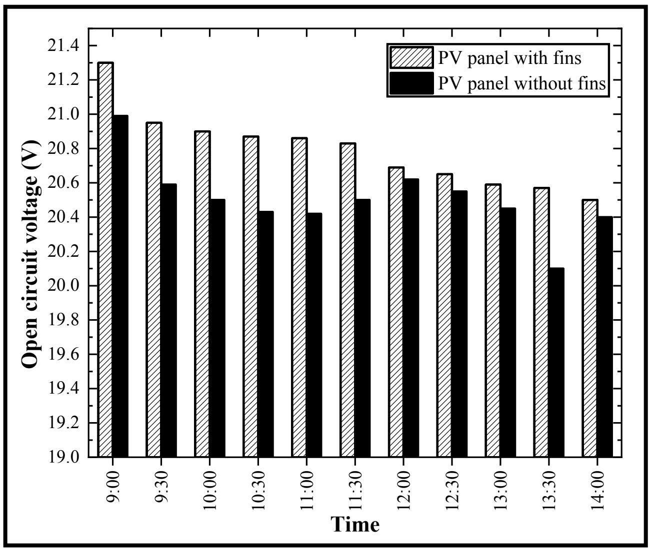


Fig. 10. Variation of the open-circuit voltage for the PV panels with and without fins.

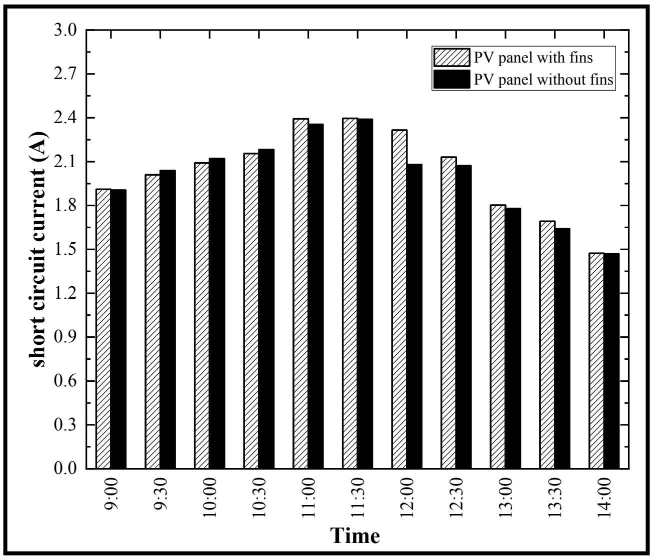


Fig. 11. Variation of the short-circuit current for the PV panels with and without fins.

Fig. 11 shows the variation of the short-circuit current of the PV panels A and B with time of day. The measured short-circuit current values of the panel with fins were slightly higher than the panel without fins. The short-circuit current depends on the solar irradiation and the ambient temperature [32]. The increase of the short-circuit current with the increase of ambient temperature is so small but it is linearly related to the solar intensity. This explains the variation of the short-circuit current in **Fig. 11** which is determined by the change of the solar radiation.

5. Conclusions

In this experimental approach, a simple passive cooling technique was used to reduce the operating temperature of the PV panel. In addition, measured the enhancement occurs in the PV panel efficiency. The cooling technique was fabricated by longitudinal open-cell copper metal foam fins fixed underneath of a 50W PV panel by conductive glue. Four different arrangements of fins were studied to check the reduction in PV panel temperature and the increasing in the PV panel efficiency. The proposed technique of cooling was testing on a single PV panel and compare with the reference one where 8.4% average reduction in the rear surface temperature was found for the ten fins arrangement. This temperature reduction results in an improvement in the power output by an average of 4.9%. The proposed cooling technique has shown to be more efficient in windy periods. The experimental results showed the possibility of enhancing the power output with a simple constructional modification and prolong the PV panel lifetime.

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