# Effects of passive cooling on performance of silicon photovoltaic cells

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## Abstract

In this study, an experimental research concerning the effects of passive cooling on performance parameters of silicon solar cells was presented. An aluminum heat sink was used in order to dissipate waste heat from a photovoltaic (PV) cell. Dimensions of the heat sink were determined considering the results of a steady-state heat transfer analysis. The experiments were carried out for different ambient temperatures and various illumination intensities up to 1 sun under solar simulator. Experimental results indicate that energy, exergy and power conversion efficiency of the PV cell considerably increase with the proposed cooling technique. An increase of ~20% in power output of the PV cell is achieved at 800 W/m$^2$ radiation condition. Maximum level of cooling is observed for the intensity level of 600 W/m$^2$. Performance of PV cells both with and without fins increases with decreasing ambient temperature.

*Keywords:* photovoltaic cell; passive cooling; heat sink; performance; efficiency

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## 1 INTRODUCTION

Solar energy is one of the most important renewable energy technologies, since it provides an unlimited, clean and environmentally friendly energy. Conversion of sunlight directly into electricity by photovoltaic (PV) cells is a significant and rapidly developing solar energy application. Intensive efforts are made to reduce the cost per peak power obtained from PV cells. These efforts aim at narrowing the gap between PV and conventional power sources. Besides the importance of developing new manufacturing processes related to PV cells, it is quite significant to provide the most appropriate operating conditions for a PV system.

The present commercial PV cells convert solar energy into electricity with a relatively low efficiency, <20%. More than 80% of the absorbed energy is dumped to the PV cell as waste heat [1]. This heat is generated in two ways. First, there are $I^2R_s$ as a result of the current flowing through the resistance, $R_s$, of the solar cell. Second, there is the thermal energy which represents the difference between the absorbed solar photons and the realized electrical energy of the generated electron–hole pairs [2]. Cell temperature is of vital importance for performance of PV cells. Temperature dependence of performance parameters and energy conversion in PV cells is investigated by many authors [3–10]. It is well known that the efficiency of PV cells decreases with increasing cell temperature. This decrease arises from the drop in voltage parameters of PV cells. Therefore, it is necessary to keep the PV cell temperature and cell reflection as low as possible in order to enhance the efficiency of PV cells. Air-cooled or water-cooled technology for PV cells has been studied for many years. Passive cooling may be considered one of the most effective methods to provide an acceptable level of cooling for PV cells. This technique enables to cool a PV cell by using low-cost extended surfaces via natural convection and requires no additional device such as fan, pump, etc. for heat extraction. Therefore, passive cooling method is quite cheap and practical.

An experimental evaluation of phase change materials for thermal management of PV devices has been presented by Huang *et al.* [11]. The experimental results indicated that the cell temperature of building integrated PVs can be reduced by more than 30°C.

Odeh and Behnia [12] have carried out an experimental study about improving the PV module efficiency using water cooling. Cooling of the PV panel was achieved by introducing water trickling configuration on the upper surface of the PV panel. The experimental results showed that an increase of ~15% in system output was achieved at peak radiation conditions. Abdolzadeh and Ameri have carried out an experimental study about improving the effectiveness of a PV water pumping system by spraying water over the front of PV cells. A 225 W PV water pumping system was used in that study.

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It was shown that, spraying water over the cells increases the PV cell efficiency, subsystem efficiency and total efficiency 3.26, 1.40, 1.35%, respectively [13].

Zhu *et al.* investigated a liquid-immersion cooling method for efficient heat removal from densely packed solar cells in highly concentrating systems. The direct contact heat transfer performance was investigated under different concentration ratios, liquid temperatures and flow velocities. Electrical performance of the immersed module was also measured. Experimental results show that the module temperature can be cooled to lower than 45°C and the convective heat transfer coefficient can be higher than 3000 W/m$^2$ K [14]. Anderson *et al.* have presented an experimental study about heat pipe cooling of concentrating PV cells. A cooling design that uses a copper/water heat pipe with aluminum fins to cool a concentrating PV cell by natural convection was analyzed [15].

The particular temperature characteristics of concentration PV system which is different from the normal PV system are analyzed by Qifen *et al.* [16]. Non-uniformly temperature distribution's influence on PV system's electrical characteristics, which is caused by non-uniformly concentrated solar radiation, was discussed. Cooling of PV cells was considered as one of the main concerns when designing concentration PV systems.

Royne *et al.* [17] have presented an overview of various methods that can be employed for cooling of PV cells. Tonui and Tripanagnostopoulos [18] found that heat extraction from the PV module can be enhanced with fins for better electrical and thermal energy production. Tonui and Tripanagnostopoulos [19] have investigated the performance of two low-cost heat extraction improvement modifications in the channel of a PV/T air system to achieve higher thermal output and PV cooling so as to keep the electrical efficiency at acceptable level.

The goal of this study is to investigate passive cooling effects on performance of silicon PV cells. Effects of passive cooling technique on performance characteristics of silicon solar cells are analyzed for various illumination intensities under the solar simulator. The study also aims at investigating the level of cooling achieved for each intensity level. Enhancement in the efficiency and maximum power output is evaluated.

## 2 EXPERIMENTAL STUDY

### 2.1 Theory and analysis

The current–voltage relation of a PV cell under constant illumination intensity is given by

$$I = I_{ph} - I_{ds}\left[\exp\left(\frac{\xi}{n}(V + IR_s)\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

where $I_{ph}$, $I_{ds}$, $n$, $R_s$ and $R_{sh}$ are the photocurrent, diode saturation current, ideality factor, series resistance and shunt resistance, respectively. $\xi = q'/k'T$ is the usual inverse thermal voltage, where $k'$ is the Boltzmann constant ($1.381 \times 10^{-23}$ J/K), $q'$ the electronic charge ($1.602 \times 10^{-19}$ C) and $T$ the temperature.

A real PV cell can be characterized by two main parameters which are short-circuit current ($I_{sc}$) and open-circuit voltage ($V_{oc}$). Short-circuit current is the current through the PV cell when the voltage across the cell is zero. Open-circuit voltage reflects the voltage of the cell in the night and it can be mathematically expressed as

$$V_{oc} = \frac{nk'T}{q'}\ln\left(\frac{I_{ph}}{I_{ds}}\right) = V_{th}\ln\left(\frac{I_{ph}}{I_{ds}}\right) \qquad (2)$$

where $n$ is the ideality factor.

It is clear in literature that the open-circuit voltage increases logarithmically with the ambient irradiation, while the short-circuit current is a linear function of the ambient irradiation. The dominant effect with increasing cell's temperature is the linear decrease in the open-circuit voltage, the cell being thus less efficient. The short-circuit current slightly increases with the cell temperature [20].

Efficiency for a PV cell measures the ability to convert radiative energy into electrical energy. There are three main efficiency expressions which characterize the performance evaluation of PV cells. These are called as energy, exergy and power conversion efficiencies. Energy efficiency is determined by the ratio of theoretical electrical power output of a PV cell divided by the input illumination intensity.

$$\eta_e = \frac{I_{sc}\,V_{oc}}{GA} \qquad (3)$$

where $A$ is the surface area of the PV cells (m$^2$).

Power conversion efficiency is determined by the ratio of the area under the current–voltage characteristic curve of a PV cell divided by the input illumination intensity.

$$\eta_{pce} = \frac{\int_0^{V_{oc}} I(V)\,dV}{GA} \qquad (4)$$

Exergy efficiency is calculated as the maximum useful energy produced by a PV cell divided by the input exergy of illumination intensity.

$$\eta_{ex} = \frac{I_m\,V_m}{G_{ex}\,A} \qquad (5)$$

The exergy content of thermal radiation has been presented by Petela [21]. Cuce [22] investigated the performance evaluation of PV systems under various operating conditions. Thermodynamic assessment of PV cells has been proposed in recent studies [23–25].

### 2.2 Experimental setup

The experimental setup consists of a solar simulator, a control room and measurement devices.



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### 2.2.1 *Solar simulator*

A solar simulator was manufactured in order to carry out the experiments under any constant illumination intensity. The solar simulator illustrated in Figure 1a consists of 12 tungsten halogen bulbs. The maximum power of the illumination system is 12 suns. It was placed in a hood and was mounted on the top of the control room. An electronic circuit was manufactured and it was placed in an electrical panel. The illumination intensity could be adjusted to any constant value using a potentiometer which was connected to the electrical panel.

### 2.2.2 *Control room*

A control room with air-conditioning system was constructed to carry out the experiments under constant ambient temperature ($T_{amb} = 25^{\circ}C$). The control room has 1000 mm length, 1500 mm width and 2000 mm height. During the manufacturing of the control room, 10 mm thick glass wool was used between two 20 mm thick plywood plates in order to provide insulation. An air conditioner with 15 000 BTU cooling capacity was assembled on one side of the control room as it is seen in Figure 1b.

### 2.2.3 *Measurement devices*

Kipp & Zonen CMP 11 Pyranometer with high linearity and low tilt error was used to measure illumination intensity. The electrical parameters of the PV cell were evaluated using FLUKE 87V multimeters with a measuring error of 0.2% for DC current and 0.06% for DC voltage. A 1100 Ω, 0.8 A rheostat was used to vary the resistance of the circuit. A LUTRON HT 3006HA humidity–temperature meter was utilized for temperature and humidity measurements of the control room. An EXTECH infrared high-temperature thermometer was used in order to measure the cell temperature. Measurement devices are illustrated in Figure 1c.

Calibration of the solar simulator is very significant in terms of the accuracy of the experimental results. Before starting the experiments, the distance at which the PV cells are positioned from the solar simulator was determined with respect to the electrical characteristics of the PV cell presented by the manufacturer for standard test conditions. The simulation results showed good agreement with the manufacturer's data report. The experiments were carried out in the illumination intensity range 200–800 W/m$^2$. Temperature of the control room was adjusted to

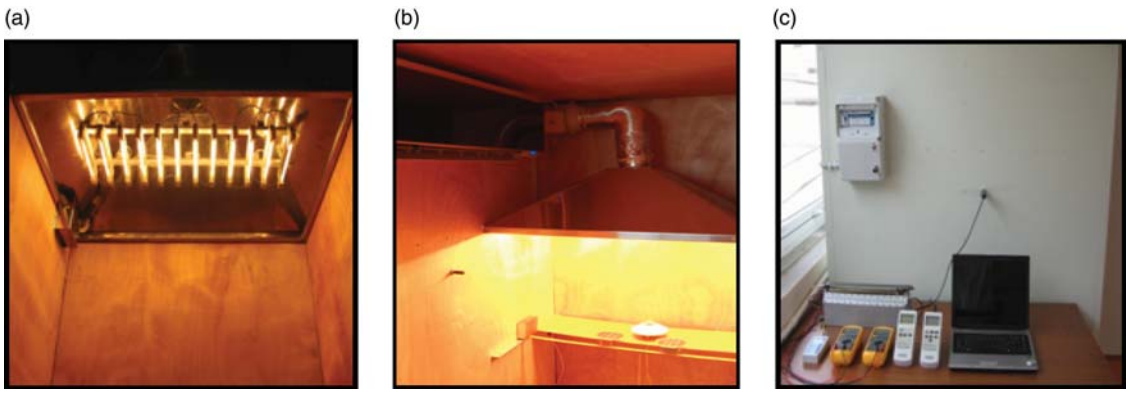



**Figure 1.** *Solar simulator (a), control room (b) and measurement devices (c).*

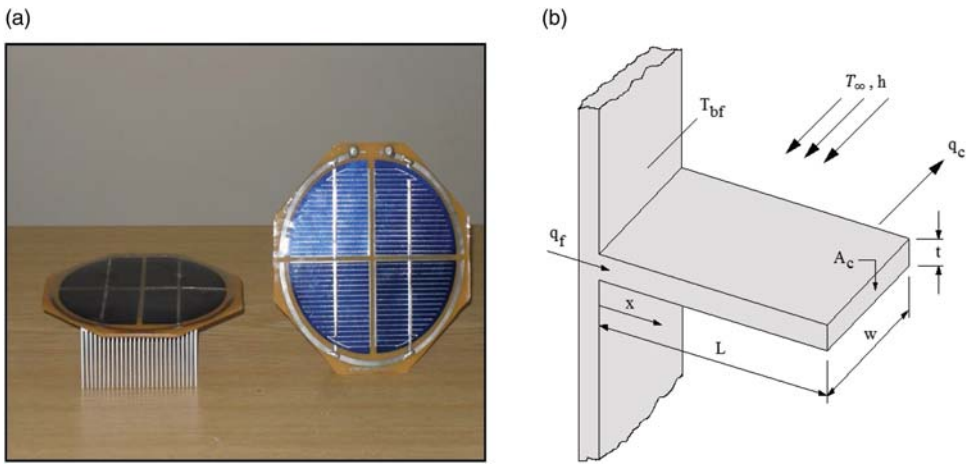



**Figure 2.** *Photovoltaic cells equipped with fins and without fins (a) and straight fins of uniform cross section (b).*

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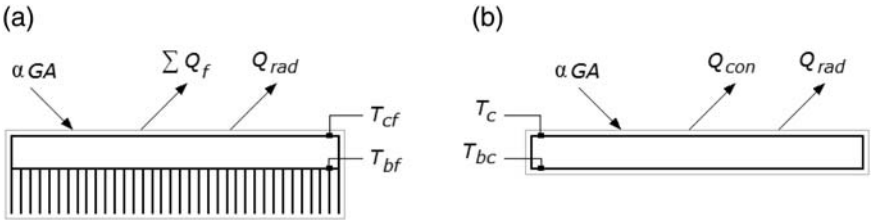



**Figure 3.** *Convection and radiation losses from the surface of photovoltaic cell (a) with and (b) without fins.*

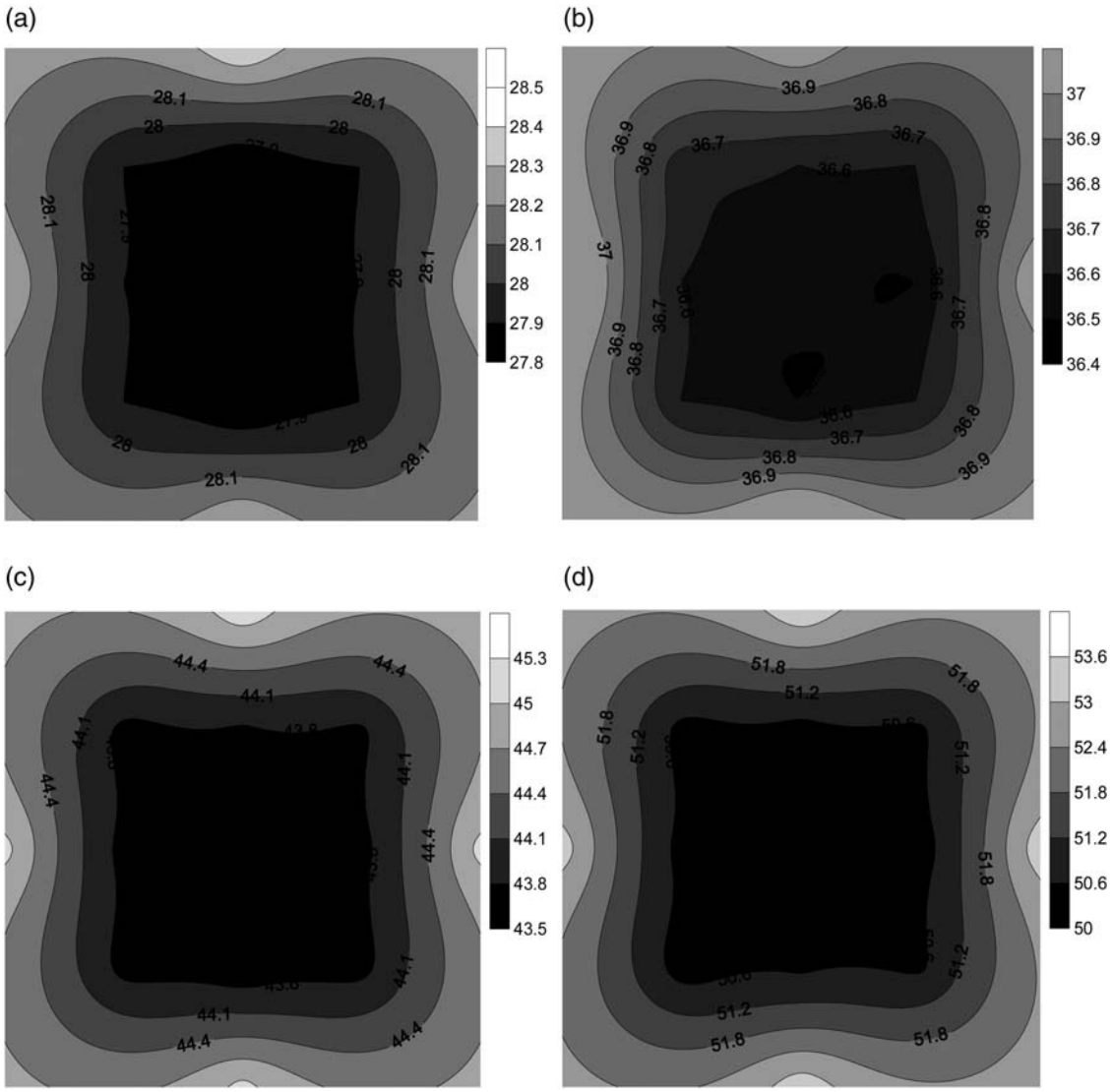



**Figure 4.** *Surface temperature profiles of photovoltaic cell with fins for (a) 200, (b) 400, (c) 600 and (d) 800 W/m$^2$.*

25°C. Two identical polycrystalline silicon PV cells were analyzed in the experimental study. One of the PV cells was equipped with an aluminum heat sink while the other was not as it is shown in Figure 2a. Thermal grease was used between the heat sink and the back surface of the PV cell. Thermal grease is a fluid substance which increases the thermal conductivity of a thermal interface by compensating for the irregular surfaces of the components. The heat sink was attached at the back of the PV cell from the corner points using adhesive.

The heat sink used in the experimental study is a high efficient heat dissipation device, especially preferred in electronics. Dimensions of the heat sink were determined considering the results of a steady-state heat transfer analysis. Thickness of the fins varies from bottom to top, but the variation of



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cross-sectional area can be neglected. Bottom thickness of the fins is 1 mm. Before starting the experiments, cell temperatures of PV cells were adjusted to 20°C. Steady-state temperatures of PV cells were measured by an infrared high-temperature thermometer. Energy, exergy and power conversion efficiencies of PV cells were calculated for each operating condition. In addition, maximum power outputs of PV cells were determined for various radiation conditions and the results were compared.

## 2.3 Heat transfer analysis

Heat transfer analysis is based on the assumption that the fins have uniform cross-sectional area as shown in Figure 2b. For the prescribed fins,

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0 \tag{6}$$

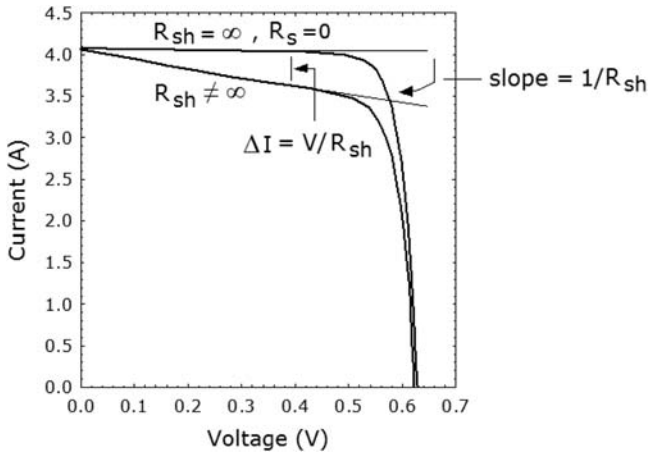



**Figure 5.** *Effect of shunt resistance on current-voltage characteristic of a photovoltaic cell.*

where

$\theta(x) = T(x) - T_\infty$ and $m^2 = hP/kA_c'$.

The general solution of Equation (6) is

$$\theta(x) = C_1 e^{mx} + C_2 e^{-mx} \tag{7}$$

$$\theta_{bf} = T_{bf} - T_\infty \tag{8}$$

where the subscript bf denotes the base of fins.

The first tip condition considers that the rate at which energy is transferred to the fluid by convection from the tip must equal the rate at which energy reaches the tip by conduction through the fin [26].

$$h\theta(L) = -k\left.\frac{d\theta}{dx}\right|_{x=L} \tag{9}$$

where $L$ is the length of fins and $k$ the thermal conductivity.

Substituting Equation (7) into Equations (8 and 9), temperature distribution is obtained as follows:

$$\frac{\theta}{\theta_{bf}} = \frac{\cosh m(L-x) + (h/mk)\sinh m(L-x)}{\cosh mL + (h/mk)\sinh mL} \tag{10}$$

The amount of heat transferred from the entire fin is determined by applying Fourier's law at the fin base.

$$q_f = -kA_c'\left.\frac{d\theta}{dx}\right|_{x=0} \tag{11}$$

$$q_f = \sqrt{hPkA_c'}\,\theta_{bf}\frac{\sinh mL + (h/mk)\cosh mL}{\cosh mL + (h/mk)\sinh mL} \tag{12}$$

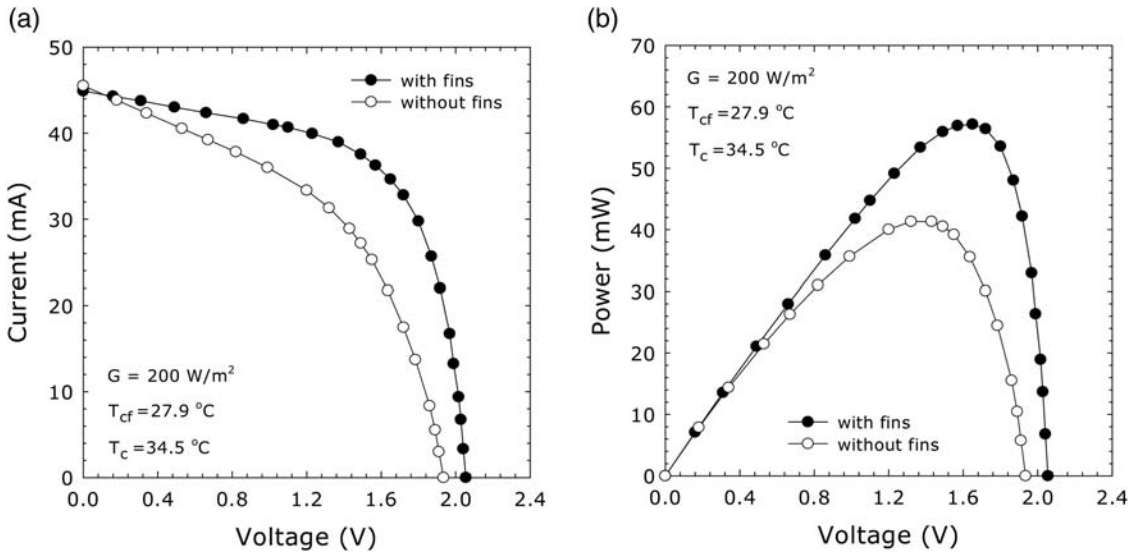



**Figure 6.** *Current-voltage (a) and power-voltage characteristics (b) of photovoltaic cells with/without fins for 200 W/m².*

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**Table 1.** *Measured and calculated parameters in the experimental study.*

| | $G$ (W/m$^2$), with fins | | | | $G$ (W/m$^2$), without fins | | | |
|---|---|---|---|---|---|---|---|---|
| | 200 | 400 | 600 | 800 | 200 | 400 | 600 | 800 |
| $T_c$ (°C) | 27.9 | 36.6 | 43.7 | 50.4 | 34.5 | 46.2 | 56.6 | 67.9 |
| $I_{sc}$ (mA) | 44.90 | 134.42 | 241.46 | 366.60 | 45.51 | 136.50 | 247.00 | 368.00 |
| $V_{oc}$ (V) | 2.05 | 2.12 | 2.11 | 2.10 | 1.93 | 2.01 | 1.99 | 1.91 |
| $\eta_e$ | 3.47 | 5.35 | 6.38 | 7.23 | 3.31 | 5.17 | 6.16 | 6.61 |
| $\eta_{pce}$ | 2.93 | 4.50 | 5.34 | 6.03 | 2.41 | 4.07 | 5.04 | 5.34 |
| $\eta_{ex}$ | 2.31 | 3.66 | 4.30 | 4.76 | 1.67 | 3.13 | 3.96 | 3.96 |
| $W_m$ (mW) | 50.18 | 188.06 | 325.94 | 463.82 | 42.01 | 160.99 | 279.97 | 398.95 |

Total amount of heat transferred from the fins is determined for each illumination intensity as follows:

$$\sum q_f = N\, q_f \tag{13}$$

where $N$ is the number of fins.

Radiation heat transfer rate from the surface of the PV cell is determined as follows:

$$q_{rad} = \varepsilon\, \sigma A_c\, (T_c^4 - T_{amb}^4) \tag{14}$$

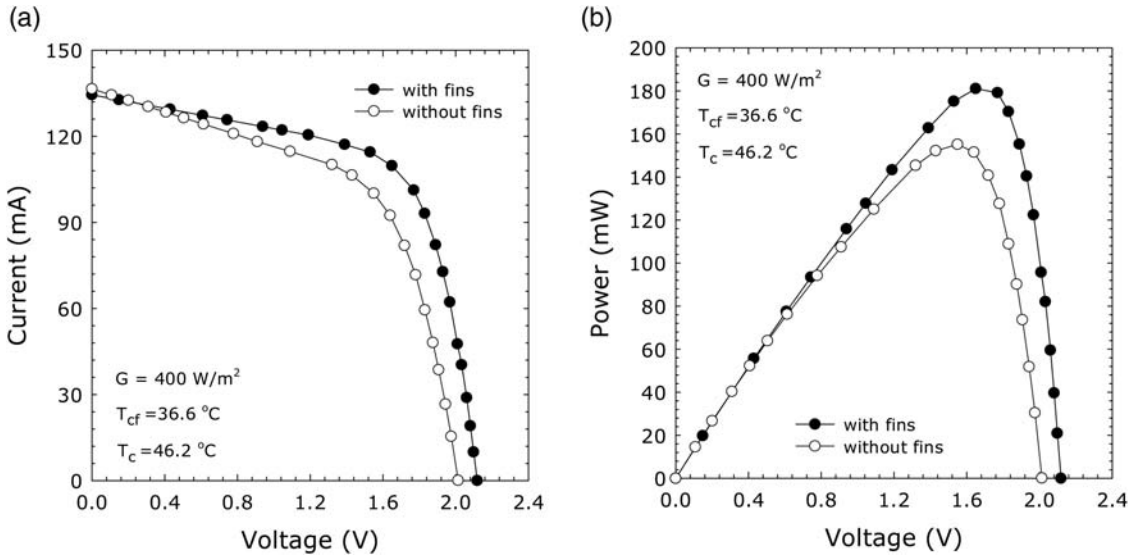



**Figure 7.** *Current-voltage (a) and power-voltage characteristics (b) of photovoltaic cells with/without fins for 400 W/m$^2$.*

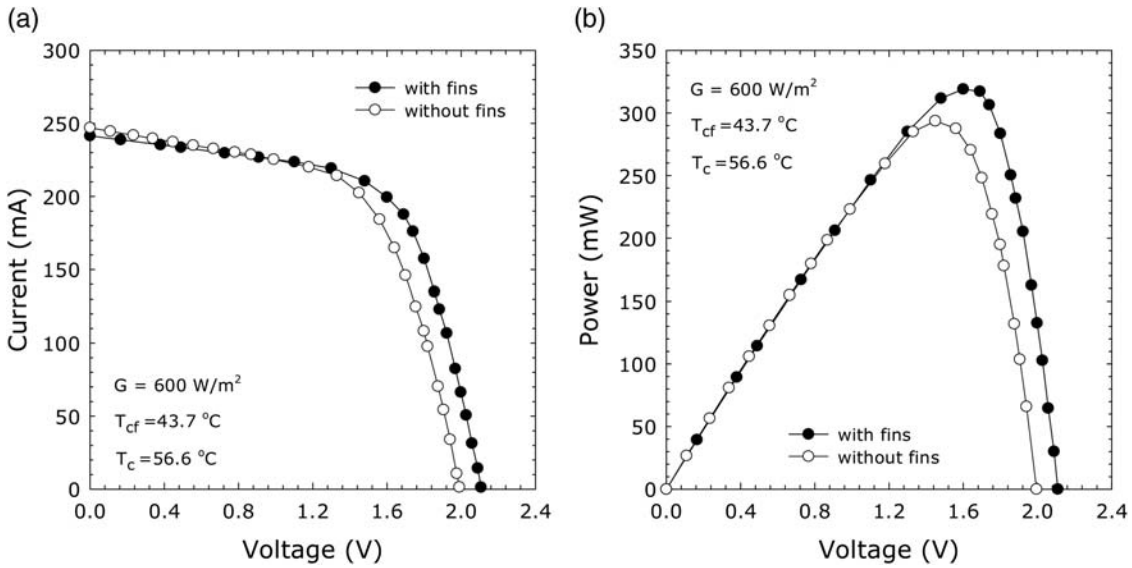



**Figure 8.** *Current-voltage (a) and power-voltage characteristics (b) of photovoltaic cells with/without fins for 600 W/m$^2$.*



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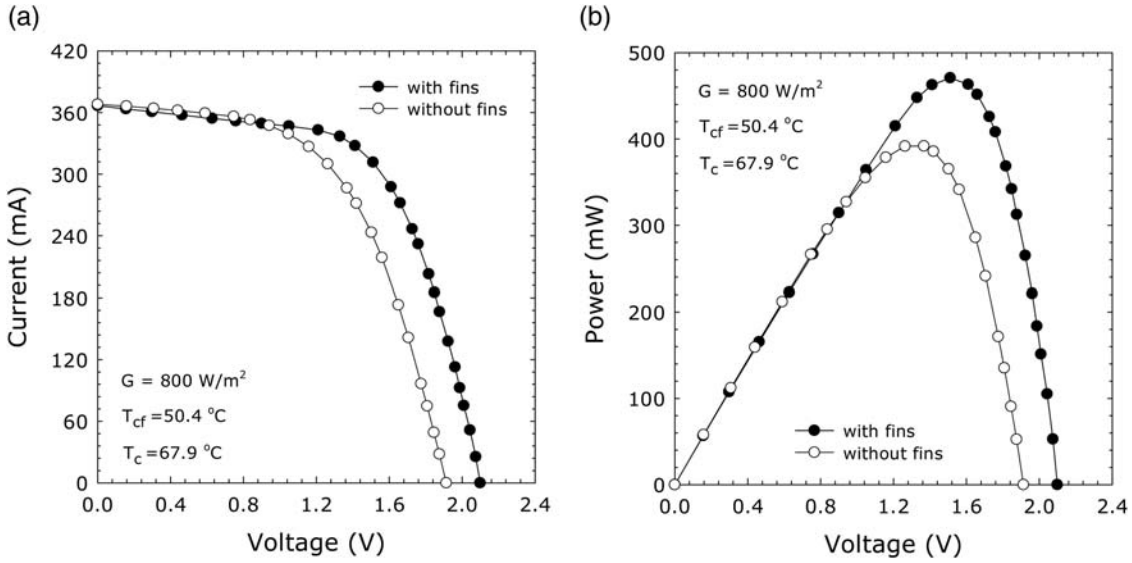



**Figure 9.** *Current-voltage (a) and power-voltage characteristics (b) of photovoltaic cells with/without fins for 800 W/m$^2$.*

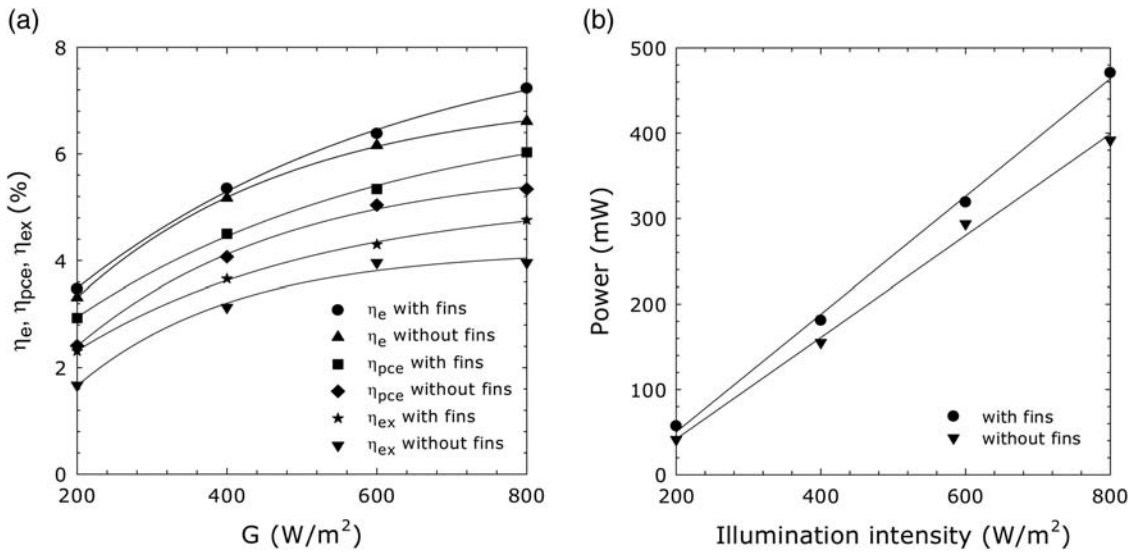



**Figure 10.** *Efficiencies (a) and maximum power output (b) of photovoltaic cells for various illumination intensities.*

where $\varepsilon$ is the emission coefficient, $\sigma$ the Stefan–Boltzmann constant ($5.67 \times 10^{-18}$ W/m$^2$ K$^4$) and the subscript rad and amb denote radiation loss and ambient, respectively.

Total amount of heat transferred from the entire PV cell with and without fins is determined considering the convection and radiation losses as shown in Figure 3. The level of cooling achieved for each illumination intensity level is calculated as follows:

$$\text{level of cooling} = \frac{|q_t - q_{tf}|}{q_t} \tag{15}$$

## 3 RESULTS AND DISCUSSION

In this experimental study, effects of passive cooling on performance parameters of silicon PV cells were investigated. First of all, dimensions of the passive cooling device were determined with respect to the results of a steady-state heat transfer analysis. Then, the surfaces of PV cells with and without fins were scanned by a highly sensitive infrared thermometer in order to observe the temperature distribution for each illumination intensity level. Current–voltage and power–voltage characteristics were determined for various insolation levels and enhancement in the efficiency and maximum power

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output was calculated. Finally, maximum level of cooling achieved was presented.

An almost homogenous temperature distribution is observed on the surface of the PV cell with fins as shown in Figure 4a–d. The temperature distribution is completely homogenous on the surface of the PV cell without fins as expected.

The shunt resistance, $R_{sh}$, represents any parallel high-conductivity paths (shunts) across the solar cell p–n junction or on the cell edges [27]. Shunt resistance notably affects the current–voltage characteristic of a PV cell as it is shown in Figure 5 [28]. Shunt resistance of a PV cell decreases with increasing cell temperature. As a result of that, energy content of the PV cell decreases, especially in low-intensity levels [29, 30]. Comparison of current–voltage characteristics of PV cells under 200 W/m$^2$ illumination intensity is shown in Figure 6a. The effect of a decreasing shunt resistance on the current–voltage characteristic of PV cell without fins is clear.

Figure 6b shows the power–voltage characteristics of PV cells under 200 W/m$^2$ intensity level. Power output of PV cells decreases with increasing cell temperature. This decrease arises from the drop in voltage parameters of PV cells [31]. The PV cell equipped with fins provides more electrical energy than without fins because of the lower cell temperature. An increase of ~8 mW in power output is achieved compared with without fins using the passive cooling technique under 200 W/m$^2$ illumination intensity. Increases in power output are 27, 46 and 65 mW for 400, 600 and 800 W/m$^2$, respectively, as it is illustrated in Table 1.

Dominant effect of shunt resistance on the current–voltage characteristic of PV cell without fins decreases with increasing intensity levels as shown in Figures 7a, 8a and 9a. Although current parameters of the PV cell equipped with fins are lower than without fins, power output is higher because of the lower cell temperatures. Comparison of maximum electrical power output of PV cells is shown in Figures 7b, 8b and 9b.

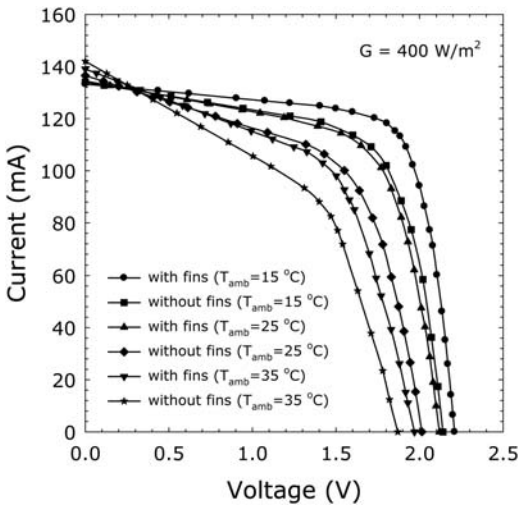



**Figure 11.** *Current-voltage characteristics of photovoltaic cells with/without fins for different ambient temperatures.*

Energy, exergy and power conversion efficiencies of PV cells increase exponentially with increasing intensity levels as it is clear in Figure 10a. Using the passive cooling technique, an increase of ~9, 13 and 20% is achieved in energy, power conversion and exergy efficiency, respectively.

Figure 10b shows that the difference of the electrical power outputs of PV cells increases with increasing illumination intensity levels. Therefore, the passive cooling technique is suitable for concentrated applications of PVs if sufficient cooling is provided.

**Table 2.** *Results for different ambient temperatures.*

| | $T_{amb}$ (°C), with fins | | | $T_{amb}$ (°C), without fins | | |
|---|---|---|---|---|---|---|
| | 15 | 25 | 35 | 15 | 25 | 35 |
| $T_c$ (°C) | 22.2 | 36.6 | 50.1 | 30.4 | 46.2 | 62.3 |
| $I_{sc}$ (mA) | 133.20 | 134.42 | 139.10 | 134.00 | 136.51 | 142.11 |
| $V_{oc}$ (V) | 2.21 | 2.12 | 1.97 | 2.14 | 2.01 | 1.87 |
| $\eta_e$ | 5.53 | 5.35 | 5.15 | 5.39 | 5.17 | 4.99 |
| $\eta_{pce}$ | 4.95 | 4.50 | 3.91 | 4.59 | 4.07 | 3.51 |
| $\eta_{ex}$ | 4.32 | 3.66 | 2.98 | 3.77 | 3.13 | 2.49 |
| $W_m$ (mW) | 213.69 | 188.06 | 147.19 | 186.73 | 160.99 | 123.34 |

**Table 3.** *Heat dissipation from photovoltaic cell with and without fins.*

| | $G$ (W/m$^2$) | | | |
|---|---|---|---|---|
| | 200 | 400 | 600 | 800 |
| $q_{tf}$ (W) | — | 5.49 | 9.06 | 12.03 |
| $q_t$ (W) | — | 4.54 | 6.91 | 9.61 |
| $T_c$ (°C) | 34.5 | 46.2 | 56.6 | 67.9 |
| $T_{bc}$ (°C) | 33.3 | 43.8 | 52.8 | 62.9 |
| $T_{cf}$ (°C) | 27.9 | 36.6 | 43.7 | 50.4 |
| $T_{bf}$ (°C) | 26.1 | 30.3 | 33.7 | 36.4 |

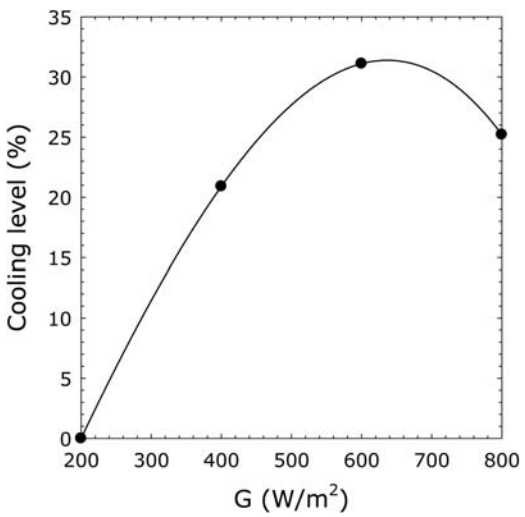



**Figure 12.** *Level of cooling achieved for each illumination intensity level.*

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The experiments were also carried out for different ambient temperatures. As shown in Figure 11, the effect of shunt resistance on the current–voltage characteristic becomes dominant with increasing ambient temperature. Maximum power output of the PV cells both with and without fins increases with decreasing ambient temperature as shown in Table 2. For the ambient temperature of 15°C, the PV cell with fins produces 14.4% more energy than the one without fins.

## 4 CONCLUSION

In this study, effects of passive cooling on performance parameters of silicon PV cells are investigated for various radiation conditions. Efficiency and maximum power output of PV cells with and without fins are determined for each illumination intensity and the results are compared. The specific findings of the study can be summarized below.

(1) Energy, exergy and power conversion efficiencies of PV cells with and without fins increase exponentially with increasing intensity levels. When the PV cells are exposed to 800 W/m$^2$ illumination intensity, an increase of ~9, 13 and 20% is achieved in energy, power conversion and exergy efficiency, respectively.
(2) Maximum power output of PV cells decreases with increasing cell temperature. This decrease arises from the drop in voltage parameters of PV cells. Experimental results show that the PV cell equipped with fins provides more electrical energy than without fins for each illumination intensity level because of its lower cell temperature. Increases in power output are ~8, 27, 46 and 65 for 200, 400, 600 and 800 W/m$^2$, respectively.
(3) Shunt resistance notably affects the current–voltage characteristic of a PV cell. It is observed from experimental results that the dominant effect of shunt resistance on the current–voltage characteristic of the PV cell without fins decreases with increasing intensity levels.
(4) The results of heat transfer analysis show that the amount of heat dissipated from the PV cell with fins is 5.49, 9.06 and 12.03 W for 400, 600 and 800 W/m$^2$, respectively. On the other hand, the PV cell without fins only dissipates 4.54, 6.91 and 9.61 W of heat for the intensity levels investigated as shown in Table 3.
(5) Because the temperature difference is only 1.1°C between fins and the surrounding air, the passive cooling technique is inefficient for the intensity level of 200 W/m$^2$. The level of cooling achieved for the intensity levels of 400, 600 and 800 W/m$^2$ is 20.09, 31.1 and 25.2%, respectively, as shown in Figure 12.
(6) In future studies, performance of silicon PV cells will be investigated under the solar simulator for various velocities of the surrounding air.

## FUNDING

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