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Efficiency Enhancement of Photovoltaic Panels Using an Optimised Air Cooled Heat Sink

Wisam K. Hussam, Ali Alfeeli, Gregory J. Sheard

Abstract—Solar panels that use photovoltaic (PV) cells are popular for converting solar radiation into electricity. One of the major problems impacting the performance of PV panels is the overheating caused by excessive solar radiation and high ambient temperatures, which degrades the efficiency of the PV panels remarkably. To overcome this issue, an aluminum heat sink was used to dissipate unwanted heat from PV cells. The dimensions of the heat sink were determined considering the optimal fin spacing that fulfils hot climatic conditions. In this study, the effects of cooling on the efficiency and power output of a PV panel were studied experimentally. Two PV modules were used: one without and one with a heat sink. The experiments ran for 11 hours from 6:00 a.m. to 5:30 p.m. where temperature readings in the rear and front of both PV modules were recorded at an interval of 15 minutes using sensors and an Arduino microprocessor. Results are recorded for both panels simultaneously for analysis, temperate comparison, and for power and efficiency calculations. A maximum increase in the solar to electrical conversion efficiency of 35% and almost 55% in the power output were achieved with the use of a heat sink, while temperatures at the front and back of the panel were reduced by 9% and 11%, respectively.

Keywords—Photovoltaic cell, natural convection, heat sink, efficiency.

I. Introduction

THE overall power generation in Kuwait is totally relying on fossil fuel such as oil or natural gas which is depleting non-renewable resources and damaging the environment. The total consumption of electricity in Kuwait has increased significantly over the last five decades. Between 1960 and 2008, total consumption of electricity increased from 380 million kWh to 45234 million kWh. The rise in consumption was mostly due to increases in both per capita consumption and population. In particular, over the period 2000-2009, annual per capita consumption of electricity increased at an annual rate of 6.8%, surpassing the population average growth rate of 3.9% per year [1]. Therefore, there is an essential need to diversify away from these sources and pursue alternatives such as solar and wind energy.

Due to the abundance of sunlight throughout the year, the power generation from solar energy is the more likely candidate than wind energy in the near future. Kuwait is exposed to a high rate of solar radiation with annual average of 3.5-8.0 kWh/day [2]. The maximum average hourly radiation is attained in summer during the months May–September at $12:00$ a.m. with the highest average value in June, while the minimum average hourly radiation occurs in winter during November, December, and January with a lowest average value in January [3]. The daily average temperature in the winter season is $14.4°\mathrm{C}$ while it often exceeds $48°\mathrm{C}$ in the summer season.

Photovoltaic (PV) solar cells directly converts sunlight into electrical energy. When solar radiation passes through a PV panel, part of the energy is converted into electrical energy, while the rest is converted into heat that is dissipated to the surroundings by convection and radiation via the front and back surface of the panel. Due to the fact that the energy extracted from the solar radiation is only limited to a small waveband of $0.4 - 1.1nm$, the portion of energy absorbed by the photoelectric phenomenon is limited to a maximum of less than 20% efficiency [4].

Temperature is a vital factor that affects the performance and the power output of PV cells. It is increased by the absorbed solar radiation that is not converted into useful energy resulting in a decrease in their conversion efficiency and hence the power output [5]–[10]. Thus, it is essential to keep the PV cell temperature as low as possible to enhance the efficiency and increase the life of the cell by a proper cooling system such as passive and active cooling techniques [11], [12]. Passive cooling may be considered one of the most effective, cheap and practical cooling approaches that provides an acceptable level of cooling for PV cells. In this approach extended surfaces are used to cool PV cells via natural convection, i.e. the buoyancy difference between the hot and cold air. Comprehensive reviews of experimental and numerical work pertaining to photovoltaic cooling systems are given in [13] and [14].

The power output of a PV module decreases by approximately 0.5% per degree ($°\mathrm{C}$) of cell temperature rise (i.e. $0.5\%/°\mathrm{C}$) [15]. Previous studies conducted by [16] and [17] revealed that the temperature effect on the efficiency of a PV module is more significant for c-Si modules than for other types (e.g. amorphous silicon soalr cells [18] and thin film of cadmium telluride [19], [20]). It is found that when the solar irradiance is greater than $\simeq 950\ \mathrm{W/m^2}$, cell temperatures will rise to above $60°\mathrm{C}$ while the efficiency will drop to $\approx 9\%$ [10].

The effect of passive cooling on the performance parameters of polycrystalline PV cells under indoor conditions was investigated experimentally by Cuce et al. [11]. Their results demonstrated that passive cooling increased the conversion efficiency and exergy efficiency by 13% and 20%, respectively.

Chen et al. [21] experimentally investigated the performance of polycrystalline PV cells under natural ventilation. They proposed four testing modes to examine the effect of parameters such as PV panel inclination, ambient temperature,

W.K. Hussam is an Assistant Professor in the Department of Mechanical Engineering, School of Engineering, Australian College Kuwait, Safat, Kuwait (e-mail: w.alsaadi@ack.edu.kw).

G.J. Sheard is a Professor in the Department of Mechanical and Aerospace Engineering, Monash University, VIC 3800, Australia.

wind velocity and solar radiation on the efficiency parameters. Their results concluded that the performance of PV cells mainly depends on the heat transfer area and the wind velocity.

Active cooling by spraying water over the front surface of PV panels were studied experimentally by many researchers [22]–[26]. The experimental results showed that due to heat losses by convection from the upper surface of the cells, the operating temperature of the panel was reduced up to 26°C and the performance was improved to near the value of nominal parameters.

The effect of temperature on the efficiency and power output of a PV module was studied experimentally by Teo et al. [27], who developed a hybrid PV/T solar system to investigate the performance of the PV module with and without active cooling. An array of air ducts were attached to the back of the PV panel to increase the heat transfer from the panel to the moving air inside the duct. They found that without active cooling, the efficiency was degraded to 8.6% and a maximum temperature of 68°C was recorded. However, the efficiency and temperature were respectively 12.5% and 38°C with active cooling.

Tarabsheh et al. [28] examined the performance of PV modules whose PV cells operate under different temperatures and proposed cooling pipe layouts underneath the PV module to improve the conversion efficiency of the module. Their results showed that the active cooling increased the efficiency by approximately 17%.

Bahaidarah et al. [29] numerically and experimentally investigated the performance of a PV hybrid water cooled system. The results showed a reduction in operating temperature of 20% and an increase of 9% in the electrical efficiency with active cooling. In addition, the output power of the PV system with cooling at an irradiance of 900 $\mathrm{W/m^2}$ was 211 W compared to 190 W without cooling.

Tonui and Tripanagnostopoulos [30] studied the performance of two low-cost modifications in the channel of a PV/T air system to achieve higher thermal output and PV cooling in order to keep the electrical efficiency at acceptable level during energy conversion. Both experimental and theoretical results showed that the suggested modifications improved the efficiency of PV/T system. A maximum increase in the conversion efficiency of 6% was achieved for the fin system compared to the reference system.

More recently, Idoko et al. [31] employed a multi-concept cooling technique to increase the PV efficiency and power output. The process of cooling was achieved by spraying of water over the front of the panel and attaching a heat sink to the back of the panel. A power output of approximately 21% and an efficiency gain of not less than 3% were reordered.

The aim of this study is to investigate passive cooling effects on the performance of the PV module for hot climate conditions such as that of Kuwait. An optimised passive cooling heat sink is attached to the back of the panel in order to dissipate unwanted heat, lowering the operating temperature, and resulting in higher efficiency and power output. Passive cooling with no extra energy consumption may be considered one of the most effective but cheap and practical techniques that provides an acceptable level cooling for PV panels.

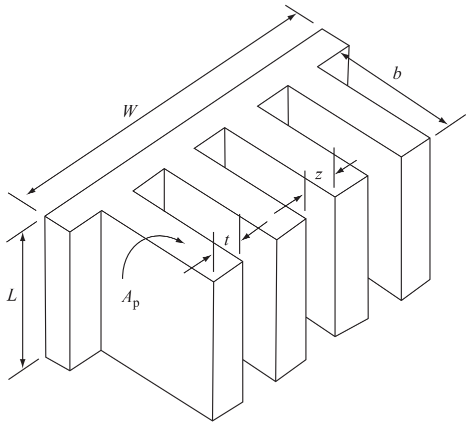

Fig. 1 Schematic diagram of the plate-fin heat sink geometry with the dimensions: spacing z, thickness t, profile length b, profile are A_P, base plate length L, base plate width W [32]

A. Optimization of the Heat Sink

A heat sink is a thermal conductive heat exchanger that is attached to a device to effectively dissipate the unwanted heat to the surroundings. A wide range of applications that require an efficient heat transfer employ heat sinks. Examples include refrigeration, heat engines, and cooling of electronic devices [32]. The performance of a heat sink is enhanced by increasing either the thermal conductivity of the fins, the surface area of the fins, or the heat transfer coefficient. The profile of fins include rectangular, triangular, and parabolic fins. The rectangular plate fins are the simplest solution that used widely in natural convection cooling systems both in terms of cost and reliability [33] and have been considered in this work, as shown in Fig. 1. In a typical heat sink design, it is desired to maximize the heat transfer rate from the fin array and to minimize the mass, volume and cost. Therefore, the material used in heat sink fabrication is aluminum as it offers a good tradeoff between the weight and thermal performance.

For a high performance heat sink, it is necessary to determine the fin spacing or the number of fins for a given plate area $L \times W$ where the thickness of fins is much smaller than the fin spacing [34]. The optimal spacing between fins can be found as [33]

$$z_{\mathrm{opt}} = 2.714 L {Ra_L}^{-0.25}, \tag{1}$$

where Ra_L is the Rayleigh number for a flow over a flat plate of length L, which is defined as

$$Ra_L = \frac{g\beta(T_{\mathrm{base}} - T_\infty)L^3}{\nu\alpha}, \tag{2}$$

where β is the volumetric expansion coefficient, α is the thermal diffusivity, ν is the kinematic viscosity, L is the height of base plate and g is gravity. T_{base} and T_∞ are, respectively, the base plate temperature and ambient air temperature.

Following the work of [34], the optimum profile length b_o is a function of optimum fin thickness t_o,

$$b_o = \frac{1.4192\left(\frac{K_f t_o}{2h_z}\right)^{\frac{1}{2}}}{\left[1 - 1.125\left(\frac{K_f t_o}{2h_z}\right)^{\frac{1}{2}} \frac{h_z}{K_f}\right]}, \tag{3}$$

where K_f is the thermal conductivity of fin material and h_z is the heat transfer coefficient for a vertical parallel flow between two fins which can be found as

$$h_z = \frac{K_a}{z_{\text{opt}}}\left(\frac{576}{El^2} + \frac{2.873}{El^{\frac{1}{2}}}\right)^{-\frac{1}{2}}, \tag{4}$$

where El and Ra_z are, respectively, the Elenbaas number and Rayleigh number based on the spacing between the fins,

$$El = Ra_z \frac{z_{\text{opt}}}{L}, \tag{5}$$

$$Ra_z = \frac{g\beta(T_{\text{base}} - T_\infty){z_{\text{opt}}}^3}{\nu\alpha}. \tag{6}$$

The number of fins is also a function of fin thickness,

$$n_f = \frac{W}{z_{\text{opt}} + t_o}. \tag{7}$$

The total mass of the material as a function of t_o can be written as

$$m_t = n_f \rho_f V_f, \tag{8}$$

where V_f is the volume of a single fin

$$V_f = L b_o t_o. \tag{9}$$

The single-fin efficiency, effectiveness and heat transfer are given, respectively, as

$$\eta_f = \frac{\tanh\left(b_o\sqrt{\frac{h_z(L+t_o)}{K_f L t_o}}\right)}{b_o\sqrt{\frac{h_z(L+t_o)}{K_f L t_o}}}, \tag{10}$$

$$q_f = \eta_f h_z 2(L + t_o) b_o (T_{\text{base}} - T_\infty), \tag{11}$$

$$\varepsilon_f = \frac{q_f}{h_z L t_o (T_{\text{base}} - T_\infty)}. \tag{12}$$

The final equations for the overall efficiency η_o, total heat transfer q_t rate and overall thermal resistance R_{th} are given in [34] as

$$\eta_o = 1 - n_f \frac{A_f}{A_t}(1 - n_f), \tag{13}$$

with

$$A_f = 2(L + t_o) b_o, \tag{14}$$

$$A_t = \eta_f \left[2(L + t_o) b_o + L z_{\text{opt}}\right], \tag{15}$$

where A_f and A_t are, respectively, the single-fin surface area and the total fins surface area.

$$q_t = \eta_o h_z A_t (T_{\text{base}} - T_\infty), \tag{16}$$

$$R_{th} = \frac{1}{\eta_o h_z A_t}. \tag{17}$$

B. PV Cell Efficiency

The efficiency of a PV cell is the ratio of power output P_{el} obtained from the PV cell divided by the product of the irradiance G and area of the panel A_{pv} [31]

$$\eta_{pv} = \frac{P_{el}}{G A_{pv}}. \tag{18}$$

The electrical power and thus the efficiency depend on the PV cell's working temperature and ambient temperature. This is due to the dependance of the module voltage and current on temperature. The maximum power of the PV module can be expressed as [35], [36]

$$P_{\max} = V_m \cdot I_m = V_{ov} \cdot I_{sc} \cdot FF, \tag{19}$$

where $P_{\max}$, V_m and I_m are the module maximum power, maximum voltage and maximum current respectively. V_{ov} is the open circuit voltage and I_{sc} is the short circuit current. FF is the fill factor. Substituting equations (8) and (18) gives

$$\eta_{pv} = \frac{P_{\max}}{G A_{pv}}. \tag{20}$$

C. Temperature Effect on PV Cell Efficiency

For the most common crystalline silicon c-Si-based applications, the effect of temperature on PV cell efficiency can be expressed using the equation suggested by [37].

$$\eta_{pv} = \eta_R \left[1 - \beta_R(T_C - T_R) - \gamma \log_{10} G)\right], \tag{21}$$

where η_R is the module electrical efficiency at reference temperature T_{ref} ($25°C$), β_R is the temperature coefficient which is mainly depends on the cell material and T_{ref} typically ($0.004 - 0.005/°C$) [17], [38], T_C is the cell operating temperature, γ is a radiation intensity coefficient, and G is the irradiation incident on the PV module. By adding and subtracting the ambient temperature T_a to and from the temperature terms and setting $\gamma = 0$, 21 reduces to [17]

$$\eta_{pv} = \eta_R \left[1 - \frac{G}{G_{NT}}(T_C - T_R)\beta_R(T_{C,NT} - T_{R,NT})\right], \tag{22}$$

where G_{NT}, $T_{C,NT}$, and $T_{R,NT}$ are the solar irradiation, cell temperature and reference temperature at nominal operating temperature, respectively.

II. Experimental Setup

The experimental setup consists of two identical PV modules with specifications given in Table I. The two modules are mounted as shown in Fig. 2 where one module is attached with an aluminum heat sink while the other is not. Thermal grease is applied to the base of the heat sink to eliminate the air gaps, thus increasing thermal conductivity. The heat sink is fabricated in the mechanical workshop of Australian College of Kuwait-ACK, and photographs of the fabricated heat sink is shown in Fig. 3. The dimensions of the heat sink used in this work are given in Table. II.

The experiments were conducted during the month of April, 2019 in ACK, Mishref, within latitude 29.2761°N and longitude 48.0654°E. The experiments run for 11 hours

TABLE I
SPECIFICATIONS OF THE PV MODULE

Parameter	Value
Module type	FL-M-50W
Maximum power, $P_{\rm mp}$	50 W
Maximum power voltage, $V_{\rm mp}$	18.0 V
Maximum power current, $I_{\rm mp}$	2.77 A
Open circuit voltage, $V_{\rm oc}$	21.60 V
Short circuit current, $I_{\rm sc}$	2.94 A
Cell technology	Monocrystaline silicon
Module dimension	$71 \times 54 \times 3$ cm
Module weight	3.60 kg

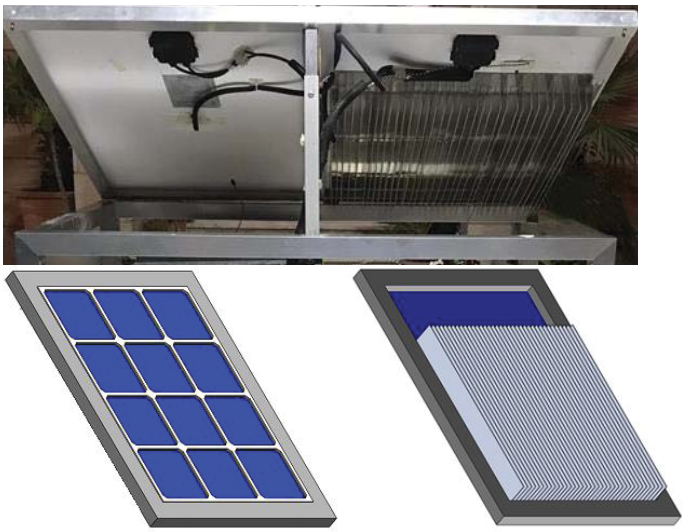

Fig. 2 Experimental setup with PV modules with and without heat sink

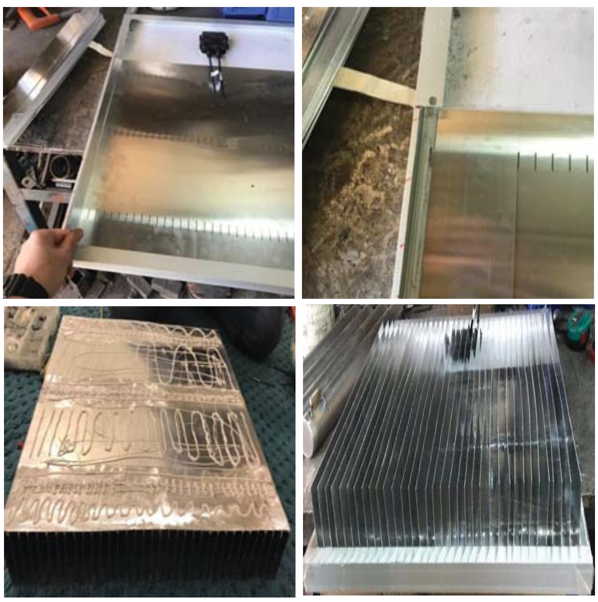

Fig. 3 Photographs of the fabrication process of the aluminum heat sink used in this study

TABLE II
OPTIMISED HEAT SINK DIMENSIONS

Parameter	Dimension
Fin thickness, t (mm)	0.8
Profile length, b (cm)	7.5
Fins spacing, z (mm)	13.6
Number of fins, n_f $(-)$	35.0
Mass of fins, m_f (kg)	3.98
Length of heat sink, L (cm)	84.0
Width of heat sink, W (cm)	49.5

from 6 : 00 a.m. to 5 : 30 p.m. where temperature readings in the rear and the front of both PV modules are recorded at an interval of 15 minutes using sensors and an Arduino microprocessor. Results are recorded for both panels simultaneously for analysis, temperate comparison, and for power and efficiency calculations. The instrument devices used include: thermocouple Omega-k type, voltage sensor, current sensor ACS721, solar meter TES, rheostat, and Arduino Mega R3 (High Quality Clone) with multi pins.

The solar radiation was measured using a pyranometer located at the top of the PV modules. The temperatures in the rear and on the surface of the PV modules were obtained using six-channel data logger. The temperature probes were attached to the rear and front of the panels using tape to aid the accuracy of temperature measurements. The current and voltage were obtained using current and voltage sensors and the Arduino microprocessor while variable resistors were used to reach the PV panels, peak load.

III. RESULTS AND DISCUSSIONS

Results are presented in three subsections. Firstly, dimensions of the passive cooling heat sink are determined with respect to the optimization parameters such as the total heat dissipation and fin effectiveness. This is followed by considering the effect of passive cooling on the performance parameters of the PV modules such as the front and back temperatures, and maximum power. Finally, the increment in performance parameters are presented.

To optimize the heat sink, equations given in § I-A are solved analytically using Matlab. Figs. 4 and 5 show the results of the optimization. For the optimization, the total heat dissipation rate is maximized for a given base to ambient temperature difference when the thermal resistance is minimized. This implies that the heat sink is capable of dissipating unwanted heat, lowering the operating temperature, which in turn increases the efficiency and power output.

Fig. 4 shows the variation of total heat dissipation rate with the fin thickness at different fin profile lengths. It can be noted that there is a significant increase in heat dissipation where a progressive increase in the peak heat dissipation is generated with increasing the fin profile length. It is found that the maximum heat dissipation occurs at small fin thickness which slightly increases as the profile length increases.

The use of fins cannot be justified unless the effectiveness, which is defined as the ratio of heat transfer rate with fins to that heat transfer without fins, is sufficiently large, i.e. $\varepsilon_f \gg 1$. The dependance of the heat sink effectiveness on the fin thickness at different profiles length is shown in Fig. 5.

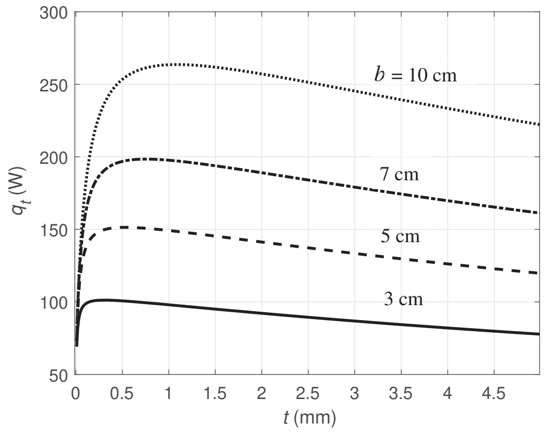

Fig. 4 Optimization of the total heat dissipation of the heat sink at different fin profile lengths at $z = 13.615$ cm and $\triangle T = 20\ K$

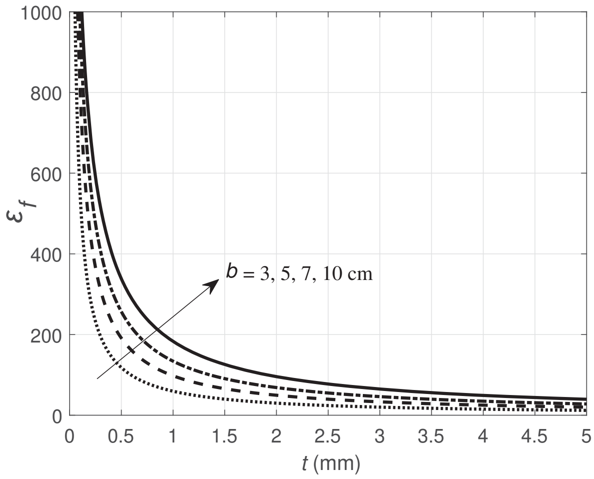

Fig. 5 Optimization of the effectiveness of the heat sink at different fin profile lengths at $z = 13.615$ cm

An effectiveness $\varepsilon_f \gg 1$ is observed at small fin thickness for all b which implies that the current heat sink is capable of increasing the heat transfer rate and hence dissipating the unwanted heat at a given temperature difference.

Now the effect of using a heat sink on the PV module temperatures (front and back) and maximum power output will be considered. The variation of the module front and back surface temperatures with and without heat sink along with solar irradiation is depicted respectively in Figs. 6 and 7. The maximum value of solar irradiation received is $1085\ \mathrm{W/m^2}$ at $12{:}21$ p.m. whereas the average throughout the day was $685\ \mathrm{W/m^2}$. The surface temperature of the PV module experiences the main effect of sun intensity which makes it higher than the rear temperature.

At the start of the experiment, the temperature of both modules was almost the same, after which, there was a progressive difference between the temperature of the two modules as shown in Figs. 6 and 7. For the case without the heat sink, a maximum module surface temperature of $\simeq 48°\mathrm{C}$ was recorded while a maximum temperature of $44°\mathrm{C}$

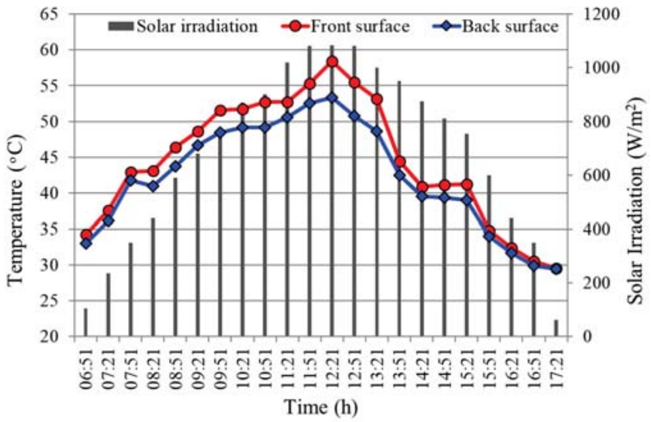

Fig. 6 Front and rear temperatures of the PV panel with heat sink during the day. The bar chart shows the variation of solar irradiance during the day is overlaid in this graph

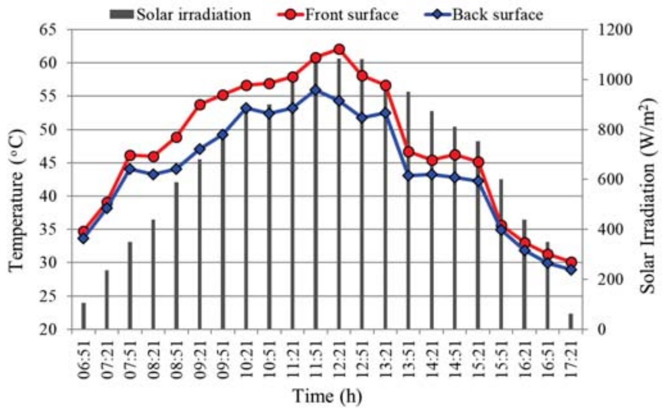

Fig. 7 Front and rear temperatures of the PV panel without heat sink during the day. The bar chart shows the variation of solar irradiance during the day is overlaid in this graph

was recorded for the back surface. In contrast, when the heat sink is attached to the back of the PV module, the respective maximum temperatures were $44.5°\mathrm{C}$ and $42.3°\mathrm{C}$. Cooling the module with the heat sink resulted in an average reduction of the front and back surface temperatures respectively by 4% and 6.5%. The temperature reduction resulted in a remarkable improvement in the efficiency and power output of the PV module as shown in Figs. 8 and 9.

The comparison of the maximum electrical power output of the module for the two cases during the test day is shown in Fig. 8. As discussed in § I-B and § I-C, the maximum power output of the module changes with the intensity of solar irradiance and the surface temperature of the cell. It is also affected by the number of cells in the module, the type of cells, and the total surface area of cells. The peak power of a module is rated by manufacturers under standard test conditions of $1000\ \mathrm{W/m^2}$ solar irradiance and $25°\mathrm{C}$ cell temperature. Therefore, the maximum power output produced by the module is always less than that of the rated peak power under real conditions. The maximum value of the power output for the case without a heat sink was 8.52 W at 2:51 p.m. whereas the maximum power output with the heat sink was

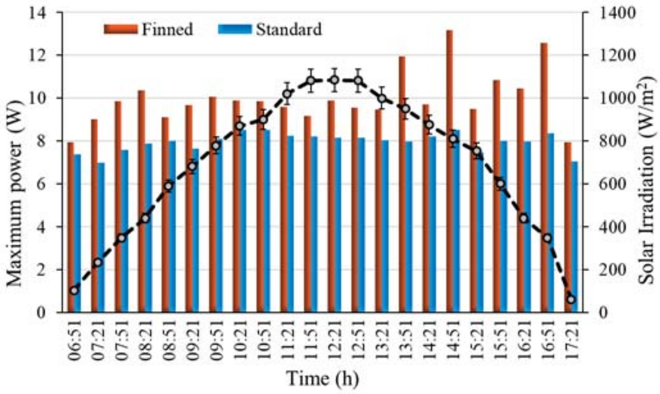

Fig. 8 Comparison of maximum power output of the module $P_{\max}$ during the day with and without heat sink. The dashed-line curve shows the variation of irradiance during the day

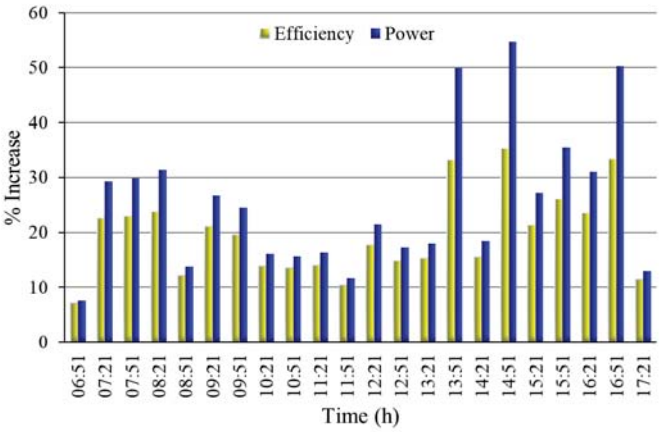

Fig. 9 Percentage increment of the maximum efficiency and maximum power output obtained by adding the heat sink to the of the PV module during the day

13.2 W.

In order to characterize the effect on the maximum power output and maximum efficiency due to the addition of the heat sink, the percentage increment of the power output and efficiency are presented in Fig. 9. A maximum increase in the solar to electrical conversion efficiency of 35% and 55% in the power output were achieved with the use of a heat sink while the respective average increase in the power and efficiency were almost 26% and 20%.

IV. Conclusion

In this study, effects of passive cooling on the performance parameters of PV module are investigated experimentally using an optimized plate fins heat sink. The dimensions of the heat sink are determined with respect to parameters such as the total heat dissipation and fin effectiveness using Matlab $\mathrm{R2019a}$. The effect of incorporating a heat sink with the PV module is investigated experimentally. Efficiency and maximum power output with and without heat sink are determined and the results are compared. The PV surface temperature was observed to significantly alter the conversion efficiency and the maximum power output. It was found that cooling the module with the heat sink resulted in an average reduction of the front and back temperature by respectively 4% and 6.5 which interns lead to a remarkable improvement in the efficiency and power output of the PV panel. A maximum increase in the solar to electrical conversion efficiency of 35% and $\sim 55\%$ in the power output were achieved with the use of a heat sink.

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Wisam K. Hussam is an Assistant Professor in the Mechanical Engineering Department at the Australian College of Kuwait (ACK) since September 2016. He received his PhD in Mechanical Engineering, in the field of Fluid dynamics and Heat Transfer, in 2012 from Monash University, Australia. Prior to joining ACK, he worked as a Research Associate and teaching associate in the Mechanical and Aerospace Engineering Department, Monash University. His research interests include computational fluid dynamics and heat transfer, energy saving, heat transfer enhancement for industrial and solar energy systems, natural convection for Geophysical flow and Nanofluids.

Gergory J. Sheard is Professor of Mechanical and Aerospace Engineering, and Director of The Sheard Lab at Monash University, Australia. Prof. Sheard has secured more than $2.2-million in Nationally Competitive grant funding, and has secured continuous extensive time allocations on Australia's major high-performance computing facilities worth more than 100k per year. He is the author of over 150 research publications, editorials and patents.