Volume 8, Number 2, 2015. pp. 113-124

Jordan Journal of Physics

ARTICLE

Effect of Dust and Ambient Temperature on PV Panels Performance in Egypt

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Received on: 5/1/2015; Accepted on: 20/5/2015

Abstract: This study investigated the effects of dust deposition and ambient air temperature on the performance of a thin film photovoltaic module under real outdoor conditions in the humid harsh climate of Egypt. The experimental study investigated the effect of dust deposition and the effect of ambient air dry bulb temperature on the performance of the PV module. Theoretical study predicted the temperature of the PV panels at various metrological conditions in different locations inside Egypt. The study experimental results show that dust deposition has a significant effect on I_{sc} current, while is has less effect on V_{oc} voltage. Dust effect becomes more significant on cloudy days more than on sunny days. The PV modules must be cleaned regularly every 4 days and directly after a dusty storm. The ambient air dry bulb temperature has a significant effect on V_{oc} voltage, while it has less effect on I_{sc} current. The theoretical models results were compared with the experimental results, and good agreement were found. The theoretical results show that the Crystalline PV panels are more affected by the ambient air dry bulb temperature rather than the thin film PV panels.
Keywords: PV panels; performance; Dust; Ambient temperature.

Introduction

Performance of photovoltaic (PV) panels in dry harsh environments is influenced by the ability of the glass cover to transmit solar radiation into the collection surface and the ambient air temperature. The dust particles in the ambient air carried by the wind can deposit on the solar photovoltaic devices external surface and obscure the solar radiation, and, therefore reduce their efficiency. However, only a fraction of the incoming sunlight striking the cell is converted into electrical energy; the remainder of the absorbed energy will be converted into thermal energy in the cell and may cause the junction temperature to rise, which leads to a decrease in efficiency unless the heat is efficiently dissipated to the environment [1].

Moharram et al. [2] investigated experimentally the influence of cleaning PV panels using water and a surfactant using a non-pressurized water system on their performance. They reported that the efficiency of the PV panels decreased by 50% after 45 days of cleaning using non-pressurized water, while the efficiency remained constant when a mixture of anionic and cationic surfactants was used for cleaning. In their study, they did not indicate the relation between the weather conditions like wind speed, relative humidity and ambient air temperature and the cleaning process. Kaldellis and Fragos [3] experimentally investigated the side effect of the atmospheric air pollution on the degradation of photovoltaic (PV) cells'

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performance, by using two identical pairs of PV-panels. The first tested cell was clean and the second one was artificially polluted with ash. They carried out a series of systematic measurements of PV panel current intensity, voltage output and incident solar radiation simultaneously for the clean and the polluted PV-panels. They reported that the deterioration of the PV-panels' performance was almost 30% energy reduction per hour or 1.5% efficiency decrease (in absolute terms) for the case when ash deposition on the panels' surface reached up to 0.4 mg/cm^2. In their study, they did not mention the coverage area, particle diameter, dust composition and the relation between weather conditions and dust deposition characterization. Jiang et al. [4] experimentally studied the dust deposition onto different types of solar PV panels and the corresponding efficiency degradation under various conditions. Their experiment was designed and conducted inside the laboratory with a sun simulator and a test chamber. They reported that dust pollution on PV panel surface has a significant impact on PV panel output. However, as dust deposition density increased from 0 to 22 g/m^2, the corresponding reduction of PV panel output efficiency grew from 0 to 26%. The reduction in the PV panel efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious. In their study, they did not take into account the effect of inclination angle, weather conditions, dust coverage area and dust composition.

Teo et al. [5] designed an experiment to investigate a hybrid photovoltaic/thermal (PV/T) solar system. To actively cool the PV cells, they designed a parallel array of ducts with inlet/outlet manifold for uniform airflow distribution, where it was attached to the back of the PV panel. They performed their experiments with and without active cooling. A linear trend between the efficiency and temperature was found. Without active cooling, the temperature of the panel was high and solar cells could only achieve an efficiency of 8–9%. However, when the panel was operated under active cooling condition, the temperature dropped significantly leading to an increase in the efficiency of solar cells to between 12% and 14%. A heat transfer simulation model was developed to compare to the actual temperature profile of PV panels, and good agreement between the simulation and the experimental results was obtained. Krauter [6] proposed experimentally numerous ideas to reduce cell surface temperature by utilizing a flowing film of water on the panel front. He used water, with a refractive index of 1.3, as a viable intermediary between glass (n_{glass}=1.5) and air (n_{air}=1.0). In addition to help keeping the surface clean, water reduces reflection by 2–3.6%, decreases cell temperature up to 22 ^{0}C and the electrical yield can return a surplus of 10.3%; a net-gain of 8–9% can be achieved even when accounting for power needed to run the pump. Tonui et al. [7] 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 an acceptable level. They suggested the use of a thin flat metal sheet suspended at the middle or finned back wall of an air channel in the PV/T air configuration. In addition, they developed a theoretical model and validated it against experimental data. They concluded that a good agreement between the predicted results and measured data was achieved. After that, they used the validated model to study the effect of the channel depth, channel length and mass flow rate on electrical efficiency, thermal efficiency, PV cooling and pressure drop for both improved and typical PV/T air systems, and their results were compared. They observed from both experimental and theoretical results that the suggested modifications improve the performance of the PV/T air system.

The present study aims to clarify the effect of both dust deposition and ambient air temperature on PV panel performance degradation. Furthermore, this study will provide a recommendation for surface cleaning schedule for the PV panels in Borg El-Aarb Area (Support to EJUST solar power generation). In addition, this study will provide a recommendation for PV system designers regarding which type of PV panels is suitable in a given area according to ambient temperature levels in this area. These aims will be achieved by a methodology of two parts; the first is experimental work to study the effect of both dust deposition and ambient air temperature on the performance of PV panels. The second part is a theoretical work to predict the performance of PV panels at different ambient air temperatures.

Thermal Model

Instead of air as the coolant of the panels, water can be used in order to absorb more heat and to cool the panels more effectively. It transforms the sun's radiation to electrical energy and simultaneously absorbs the heat from the panels. By this way, the panels are working at lower temperatures (higher efficiency). Fig. 1 shows the components of the PV/water cooling circuit. The working fluid is water flowing below the aluminum plate.

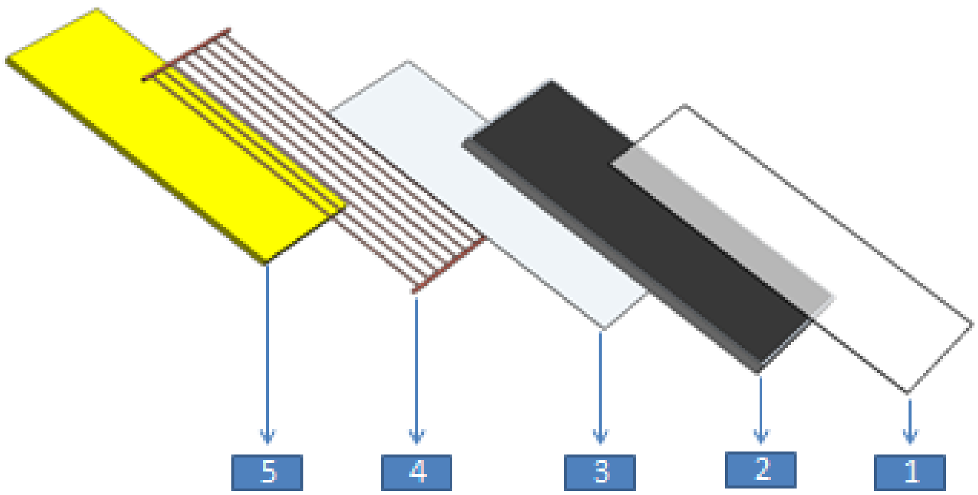


FIG.1. PV/T components (1) Glass cover (2) PV cell with EVA and water proof layer (tedlar) (3) Aluminum absorber plate (4) Copper parallel pipes circuit (5) Wool glass insulation layer.

In order to derive the energy balance equation for each component of the PV/water cooling system, the following assumptions are made:

1. Heat capacity of solar cell materials, tedlar and insulation (wool) is neglected.
2. Heat transfer through aluminum plate is neglected.
3. Transmittivity of ethyl vinyl acetate (EVA) is approximately 100%.
4. Temperature variation along the thickness is negligible.
5. Water flow between the tedlar and insulation material is uniform.
6. The system is in quasi-steady-state condition.
7. Contact surface resistance is neglected.
8. Heat conduction is one-dimensional.

The thermal model will be used to evaluate the parameters such as cell temperature, thermal gain, outlet water temperature and thermal efficiency. Energy balance equations for the components in the integrated PV/T system; namely, PV panels, back surface of the tedlar and water flow below the tedlar, are written as derived by Breu et al. [8]. Applying energy balance equation on PV cell:

$$\left.\begin{aligned} &A\tau_g\left[\alpha_C I\beta_C + (1-\beta_C)\alpha_T I\right] = \\ &\quad AU_T(T_C - T_a) + A_T h_T (T_C - T_{bs}) \\ &\quad + dA\eta_C \tau_g I \beta_C \alpha_C \end{aligned}\right\} \quad (1)$$

Applying energy balance equation on back surface of the tedlar:

$$A_T h_T\left(T_C - T_{bs}\right) = A h_W\left(T_{bs} - T_W\right) \quad (2)$$

Applying energy balance equation on flowing water element:

$$\left.\begin{aligned} &h_W\left(T_{bs} - T_W\right) b dx = \\ &\quad \dot{m}_W C_W\left(\frac{dT_W}{dx}\right) dx + b dx U_b\left(T_W - T_a\right) \end{aligned}\right\} \quad (3)$$

The software package used to code the model is MATLAB version R2011a. The power simulation (PSIM) software is used to identify and predict the electrical performance of the photovoltaic panels working under different weather conditions.

Experimental Set-up

To study the effect of dust deposition and ambient air temperature on thin film photovoltaic panels performance, the test rig shown in Fig. 2 is used. Two statistically checked identical pairs of PV-panels (located at the same area) both being south oriented and adjusted at the same inclination 30^0 with the horizontal (latitude of Borg Al-Arab) are used. The experimental measurements are carried out at the roof of the Laboratories of Energy Resources Engineering Department located at the campus of the Egypt-Japan University of Science and Technology (E-JUST) in New Borg Al-Arab, Alexandria, Egypt (longitude/latitude: E 29° 42' /N 30° 55').

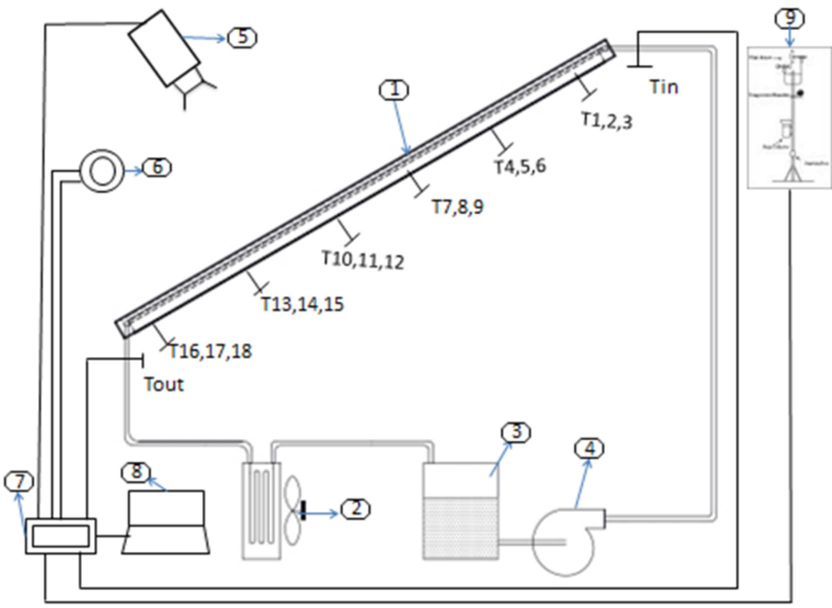


FIG. 2. Schematic diagram of experimental setup consisting of: (1) Two identical thin film PV-panels and 20 thermocouples type (T), (2) Heat exchanger and DC fan, (3) 10 liter tank, (4) Peristaltic pump, with the following measuring instruments, (5) Infrared camera, (6) Pyranometer, (7) Data logger, (8) Laptop (9) Weather station.

1- Photovoltaic Panels

For dust deposition experiment, two CIS (copper, indium and selenium) PV panels are used in the measurements; the first is used to investigate the effect of dust deposition on the output power, while the second is always kept clean by regular daily manual cleaning with surfactant and water mixture, where its output power is used as a reference. For investigating the effect of ambient air temperature on the panel performance, one PV panel is cooled while the other kept without cooling. The main specifications of the panels are listed in Table (1).

TABLE 1. PV panel specifications used in this study.

Model	*SF80-A*
Power-generating element	CIS (thin-film)
(P_m) nominal maximum output	80W
Nominal operating voltage maximum output (VP_m)	41.0V
Nominal maximum power current (I_{pm})	1.95A
Nominal open-circuit voltage (V_{oc})	56.5V
Nominal short-circuit current (I_{sc})	2.26A
Gross weight	12.4kg
Overall dimensions, in mm (W × L × D)	641 × 1,235 × 35

2- Dust Deposition Measurement Method

To measure the rate of dust deposition on the solar cell surface as a function of time, 75x22 mm glass slides are fixed side by side with the panels at the same level. Therefore, the deposition dust on the solar cell PV surface is almost the same as deposited on the glass slide surface, where both have the same environmental conditions.

3- Cooling System Set-up

To study the effect of ambient air temperature on the performance of thin film photovoltaic panels, one panel is cooled by an active closed loop water cooling circuit. The circuit consists of an aluminum absorber plate, parallel copper tube heat exchanger, a pump, 10 liter water tank and air cooled heat exchanger with DC fan as shown in Fig. 2. The cooling circuit consists of 8 tubes and 2 headers made of copper with a tube spacing of 5 cm and a diameter of 0.5 inch, while the absorber which is made of red copper (or aluminum plate) has a diameter of0.25 inch. The parallel copper tubes are fastened on the surface of the aluminum plate by means of ligament sheets. In order to increase the contact surface area and enhance the heat transfer process, thermal conductive silicon past has been used between the copper tubes and the aluminum plate. In addition, two types of thermal insulation have been used; insulation foam and glass wool insulation of 5 cm thickness in order to decrease the heat losses from the copper tubes to the atmosphere.

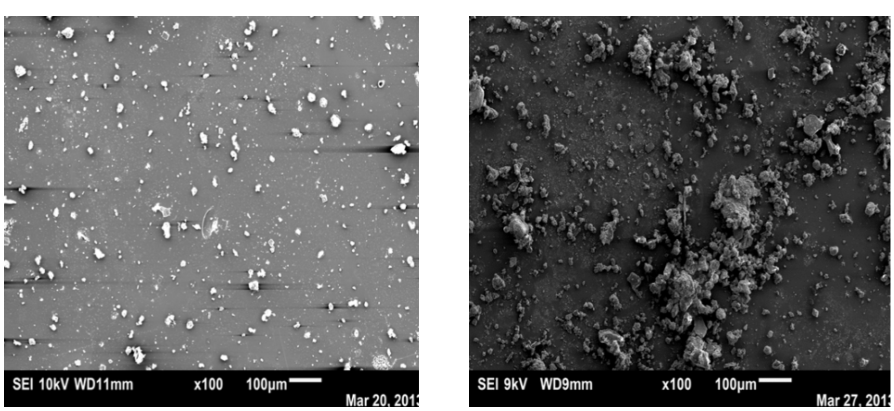
Results and Discussion

a- Effect of Dust Deposition on PV Panel Performance

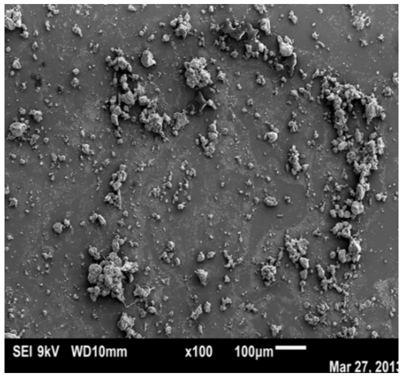
(1) Characterization of the Deposited Dust

The main factor affecting dust deposition rate on a surface is the weather data and conditions that are wind speed and direction, relative humidity and dew point. In this study, the dust deposition density is determined by measuring the weight of a glass slide before and after dust deposition. The picked glass slides from the experimental set-up are prepared and scanned by the Scanning Electronic Microscope (SEM) before being coated with golden film to obtain images as shown in Fig. 3. The presented images of the glass slide are picked up every four day intervals except for the period from 3 to 9 of April which was 6 days [the image of Fig. 3(a) is after 4 days, (b) after 8 days from the start of the experiment and so on]. From the experiment… conducted at the period from 14/3/2013 to 22/3/2013 (after 8 days), there was a significant increase in dust coverage area fraction. It reached 20.45% of the total photovoltaic surface area with a dust deposition density of 0.15 mg/cm^2.

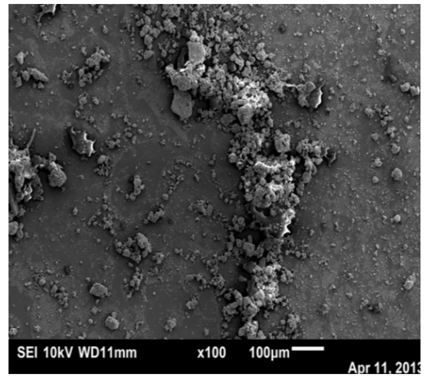
This is due to the remarkable activity in the movement of dust-laden wind during this period, as the wind speed reached 8.27 m/s, relative humidity (RH) reached 74%, with an average solar radiation intensity of 604.84 W/m^2. This result is based on the fact that dust promotes dust, and the higher relative humidity (close to the sea conditions) leads to facile the dust coagulation. After that date, the dust coverage area fraction is decreased to reach about 10.27%, while the dust deposition density increased to 0.27 mg/cm^2 (after 12 days) due to lower relative humidity that reached 57.29% and moderate high wind speed that reached 5.38m/s. As the time passed, the dust coverage area fraction and dust deposition density increased again to reach 24.40% and 0.37 mg/cm^2 (after 16 days) as the weather condition of high RH reached 72.15% at a relatively low wind speed of 3.14m/s. With progress of the time, the dust coverage area fraction increased slightly and reached 25.23% (after 20 days), while dust deposition density decreased to 0.33 mg/cm^2.



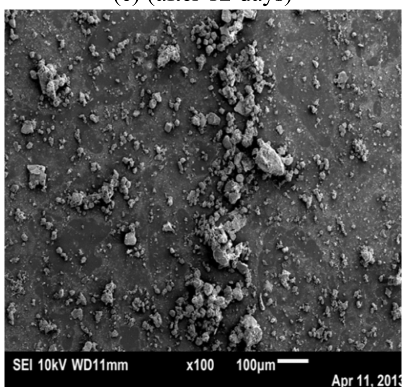
(a) (after 4 days) (b) (after 8 days)



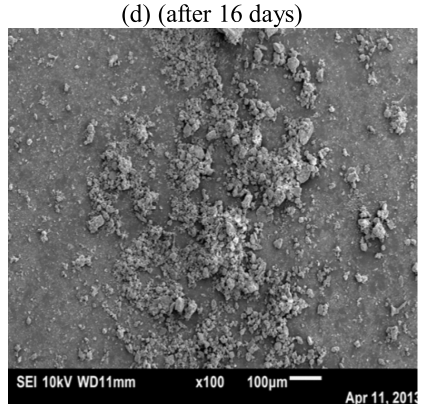
(c) (after 12 days)



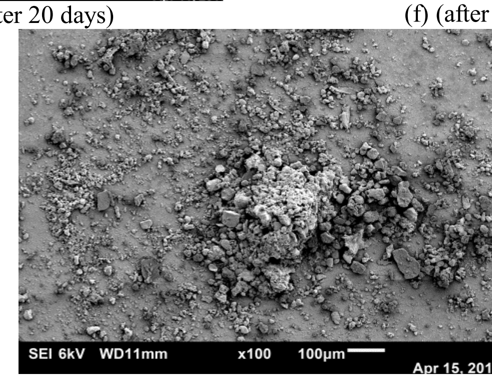
(d) (after 16 days)



(e) (after 20 days)



(f) (after 26 days)



(g) (after 30 days)

FIG.3. SEM pictures for deposition on PV panel outer surface.

(2) Effect of deposited dust on the PV Panel Performance

Time variations of measured values for panels efficiency, output daily energy, daily solar energy intensity, normalized short circuit current (I_{sc} dusty/I_{sc} clean) and normalized open circuit voltage (V_{oc} dusty/V_{oc} clean) of the two panels are shown in Figs. 4 and 5. The presented data clearly shows that dust has a significant effect on the PV panel short circuit current and the output power. As can be seen from the figure, as the dust deposition density increased from 0 to 0.28 mg/cm^2 after 26 days without cleaning, the value of I_{sc} decreased from 100% to 83.39 % compared with clean panel value, and, the power degradation (or decrease) reached 12.11 %. This degradation is due to the effect of dust coverage area fraction which reached 26 % during this period. Moreover, the voltage degradation (decrease) due to deposited dust is also clear in the presented results as shown in Fig. 5. However, the reduction in V_{oc} from 100% to 99.7% is slight when compared with that in I_{sc} value. One can conclude that dust deposition has a significant effect on I_{sc} and less effect on V_{oc}. In addition, dust effect is more significant on cloudy days than on sunny days. Finally, PV panels must be cleaned regularly every 4 days and directly after a dusty storm.

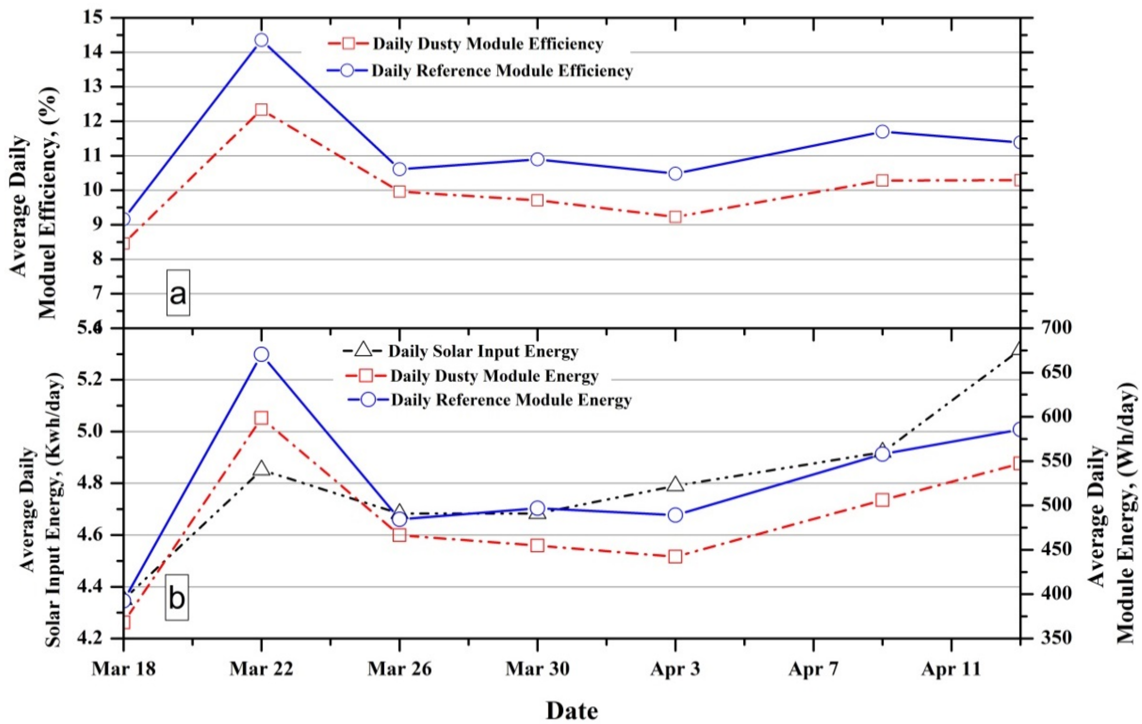


FIG.4. Comparison of panel performance with date variation.

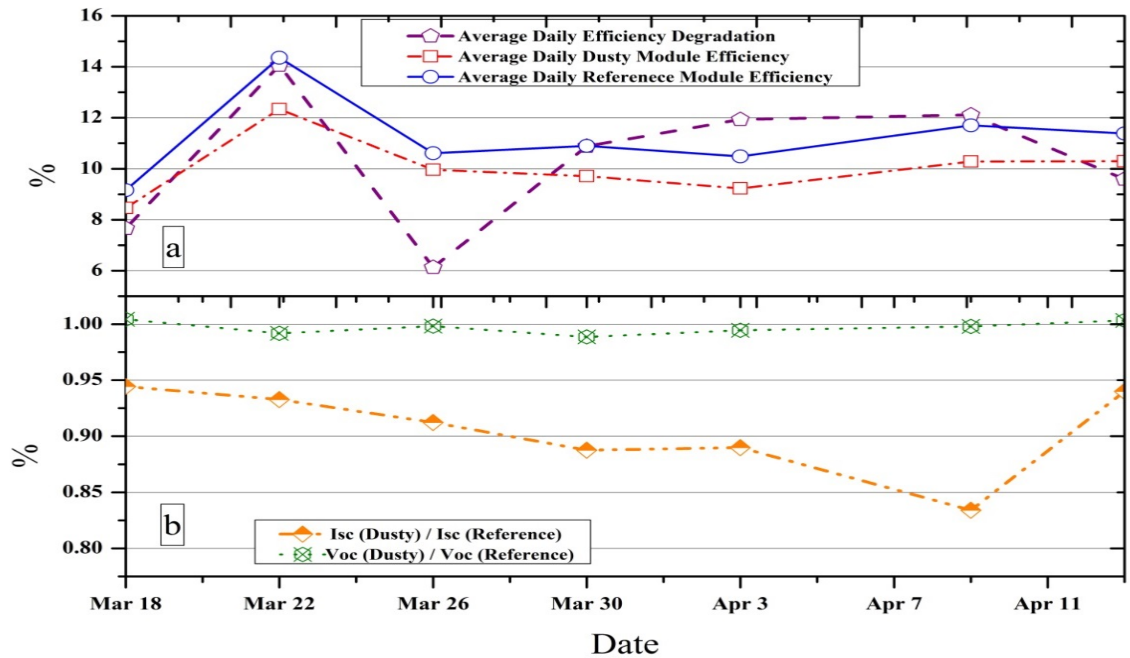
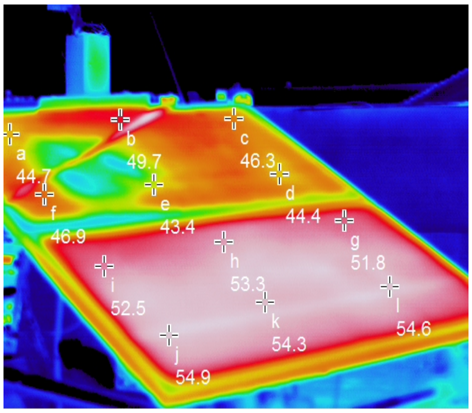


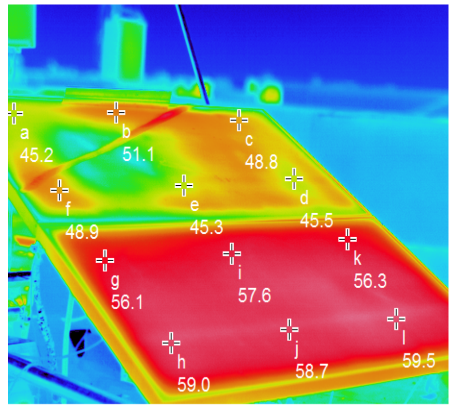
FIG.5. Time variation of experimental values for the panels' efficiency.

b- Effect of PV Panel Temperature on Its Performance Parameters

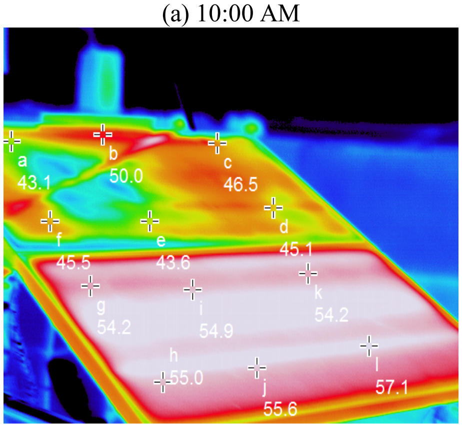
To investigate the effect of ambient air temperature on the performance of thin film photovoltaic panels, two identical panels were used; one had a cooling system and the other was without cooling. Forced water cooling is more effective than passive or active air cooling; thus, cooling is carried out using a closed loop water cooling circuit with volume flow rate of 0.06 l/sec/m^2.The outputs from the two PV panels are measured simultaneously and compared to illustrate the degradation in power and efficiency. Fig. 6 shows infrared images of PV outer surface temperature. An infrared camera was used to take a thermal image of the two panels simultaneously every one hour between 10:00 AM and 02:00 PM. This was followed by using an infrared analyzer software package to determine temperature distribution of the image of the outer surface of the panels and quantitative values for both panels with cooling and without cooling. From the thermal images quantitative values, the average and local temperature values are shown in Fig. 6. From this figure, it is clear that the surface temperature decreases with time. From these thermal images, it is clearly seen that there is a poor uniformity of temperature distribution on the surface of the cooled panel; this may be attributed to poor contact (high thermal contact resistance) between the absorber plate and the back of the panel.



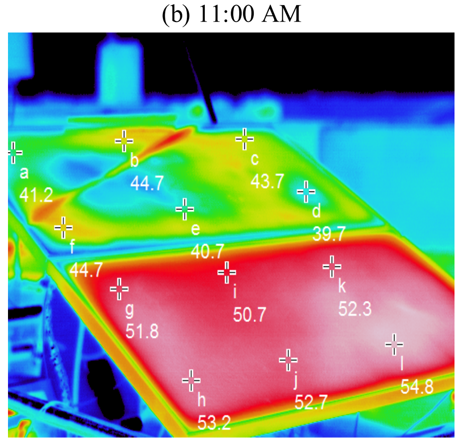
(a) 10:00 AM



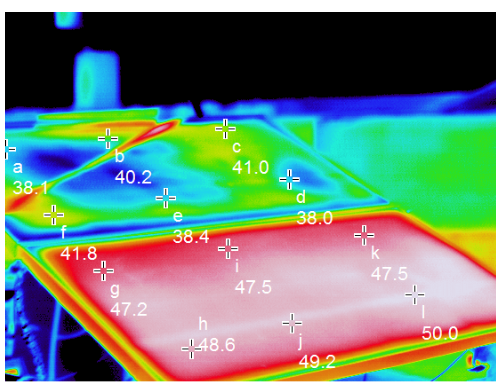
(b) 11:00 AM



(c) 12:00 PM



(d) 01:00 PM



(e) 02:00 PM

FIG. 6. Infrared camera photos of 0.06 $l/sec/m^2$ flow rate taken every hour starting at 10:00 AM.

To investigate the effect of PV panel cooling on panel voltage, current time variation curves for both panels are shown in Fig. 7 and 8. From presented results, one can see that the PV panel cooling process has a significant effect on V_{oc}, while it has less effect on I_{sc}. In quantitative values, for a water volume flow rate of 0.03 l/sec/m^2, the ratios of (Isc(without cooling)/Isc (with cooling) and (Vcc (with out cooling)/Voc (with cooling)) are 100% and 96%, respectively, so there is no degradation in I_{sc}, but there is a 4% increase in V_{oc}. Similar to the previous flow rate, for the other two flow rates (0.04, 0.06 l/sec/m^2), the ratio values of I_{sc} and V_{oc} are (100% and 94.8%) and (100% and 94.7%) with 5.2% and 5.3 % increase in V_{oc}, respectively. As the volume flow rate increases V_{oc} increases. It can be concluded that ambient air temperature has a significant effect on V_{oc} while it has a less effect on I_{sc}.

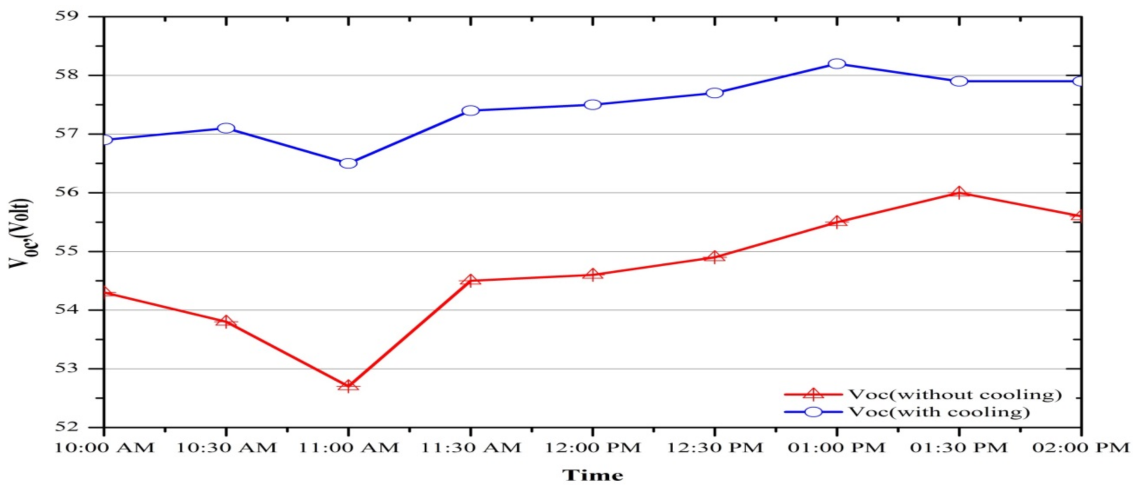


FIG.7. V_{oc} time variation.

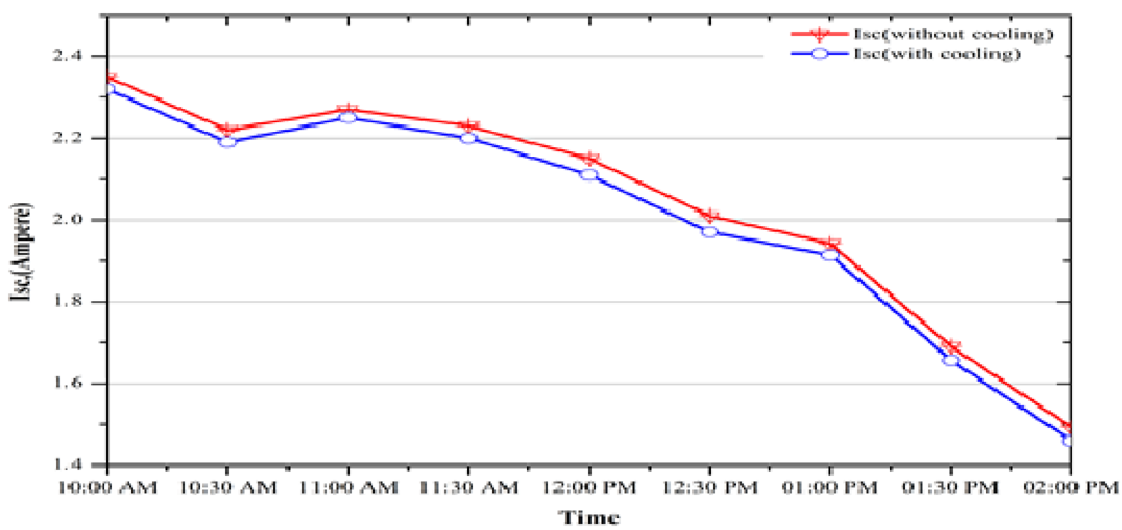


FIG.8. I_{sc} time variation.

Theoretical Results Validation

a) Electrical Model Verification

Fig. 9 indicates I-V characteristics comparison between model and experimental results for both panels at flow rates of 0.06, 0.04, 0.03 l/sec/m^2, respectively. From this figure, one can conclude that there is a good agreement between model and experimental data with a maximum error of 11.6 % and a correlation coefficient of 99.5 %.

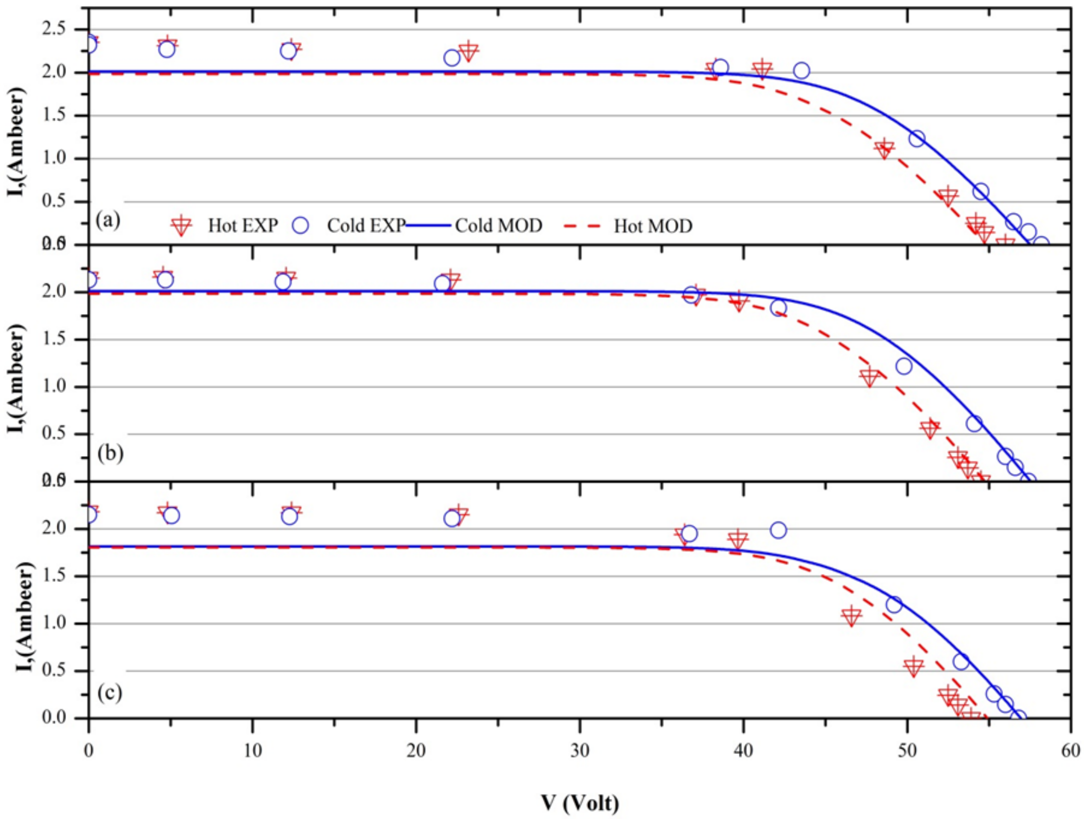


FIG. 9. I-V curve verification for (a) 1 Sept (0.06 l/sec/m^2). (b) 4 Sept(0.04 l/sec/m^2). (c) 11 Sept (0.03 l/sec/m^2).

b) Effect of Ambient Air Temperature on Performance of Different Types of PV Panels

This section investigates the effect of ambient air temperature on performance of three different types of solar cell polycrystalline, monocrystalline and thin film solar cells as predicted by thermal and electrical models. This predicts the characteristic parameters of each panel such as: cell temperature, P_{max} and efficiency for the cases of PV panels with cooling and without cooling. In order to provide a recommendation to the designer and consumers of which type of PV panel is suitable at different locations in Egypt; in Upper Egypt, North of Egypt and Delta, where each region has different meteorological conditions according to efficiency and power output.

TABLE 2. Meteorological data for Alexandria, Cairo and Aswan

	Alexandria	Cairo	Aswan
Solar radiation(w/m^2)	730	770	800
Ambient air temperature	30	34	41
Wind speed(m/sec)	3.7	3.7	4.4

c) Electrical Model Results

Fig. 10 indicates that cooling has a significant effect on monocrystalline and polycrystalline photovoltaic panels maximum power output with a maximum power improvement up to 41.84% for Polycrystalline and 30.54 % for monocrystalline panels. On the other hand, thin film has been affected by a percentage of 7.71% at Aswan. This indicates that thin film panels are less affected by temperature rather than the other two types.

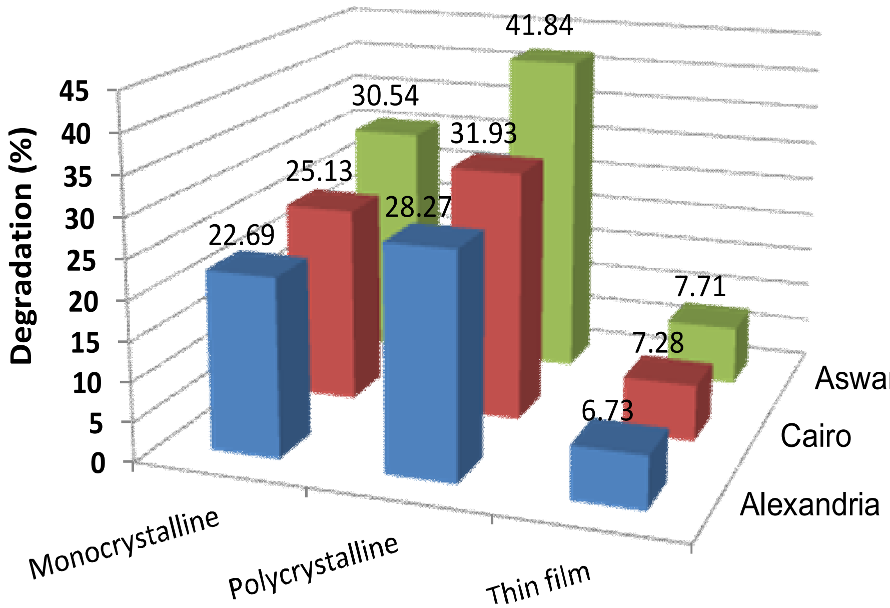


FIG. 10. Maximum power improvement due to cooling effect for three PV panels at different three locations.

Conclusions

This study has investigated experimentally the effects of dust deposition and ambient air temperature on the performance of thin film photovoltaic panels under real outdoor conditions in the humid harsh climate of Borg Al-Arab in Alexandria Egypt. Dust deposition effect has been investigated during a period of remarkable wind activity. The experiments for studying the effect of ambient air temperature on the performance of PV panels have been conducted during the period where there was a remarkable increase in ambient air temperature. Furthermore, two theoretical models were accomplished. The first model is a mathematical one to predict temperature distribution along the photovoltaic panel outer and lower surfaces at various meteorological conditions in different locations in Egypt. The second model is to investigate the PV panel electric characteristics and performance by using PSIM simulation package at different ambient air dry bulb temperatures and incident solar radiation values. Both models output results are verified with experimental results.

The main conclusions from the obtained results in this study are as follow:

- The experimental results show that:
  - Dust deposition has a significant effect on I_{sc} current, with a less effect on V_{oc} voltage.
  - Dust effect becomes more significant on cloudy days than on sunny days.
  - The PV panels must be cleaned regularly every 4 days and directly after a dusty storm in Borg Al-Arab region in the period from 13 of March to 14 of April.
  - The ambient air dry bulb temperature has a significant effect on V_{oc} voltage with a less effect on I_{sc} current.
- The theoretical results have been compared with the experimental results, and good agreement prevailed.
- The theoretical results show that:
  - The crystalline PV panels are more affected by the ambient air dry bulb temperature rather than thin film PV panels.
  - Based on Egypt meteorological conditions as well as the cost performance results, it can be recommended to use crystalline PV panels in Alexandria and Cairo zones, while using thin film PV panels in Aswan area is preferred in case of no cooling for crystalline PV panels. Therefore, in case that of PV panels cooling system is used, the crystalline PV panels become more cost-effective than using thin film PV panels in hot areas.

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