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Enhancing the performance of photovoltaic panels by water cooling

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Abstract The objective of the research is to minimize the amount of water and electrical energy needed for cooling of the solar panels, especially in hot arid regions, e.g., desert areas in Egypt. A cooling system has been developed based on water spraying of PV panels. A mathematical model has been used to determine when to start cooling of the PV panels as the temperature of the panels reaches the maximum allowable temperature (MAT). A cooling model has been developed to determine how long it takes to cool down the PV panels to its normal operating temperature, i.e., 35 °C, based on the proposed cooling system. Both models, the heating rate model and the cooling rate model, are validated experimentally. Based on the heating and cooling rate models, it is found that the PV panels yield the highest output energy if cooling of the panels starts when the temperature of the PV panels reaches a maximum allowable temperature (MAT) of 45 °C. The MAT is a compromise temperature between the output energy from the PV panels and the energy needed for cooling.

1. Introduction

1.1. Overheating effect on PV efficiency

One of the main obstacles that face the operation of photovoltaic panels (PV) is overheating due to excessive solar radiation and high ambient temperatures. Overheating reduces the efficiency of the panels dramatically [1]. The ideal P–V characteristics of a solar cell for a temperature variation between 0 °C and 75 °C are shown in Fig. 1, which is adopted from Rodrigues et al. [2]. The P–V characteristic is the relation between the electrical power output P of the solar cell and the output voltage, V, while the solar irradiance, E, and module temperature, T_m, are kept constant. If any of those two factors, namely T_m and E, are changed the whole characteristics change. The

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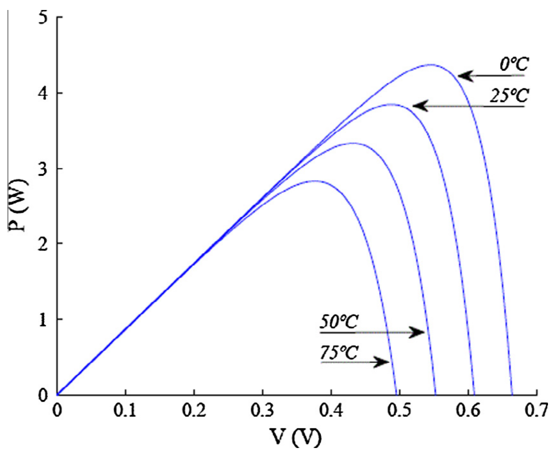

Figure 1 P–V characteristics as a function of the module temperature T_m, adopted from [2]. The module temperature varies between 0 °C and 75 °C.

maximum power output from the solar cells decreases as the cell temperature increases, as can be seen in Fig. 1. The temperature coefficient of the PV panels used in this research [3] is −0.5%/°C, which indicates that every 1 °C of temperature rise corresponds to a drop in the efficiency by 0.5%. This indicates that heating of the PV panels can affect the output of the panels significantly.

1.2. Cooling techniques

Hybrid Photovoltaic/Thermal (PV/T) solar system is one of the most popular methods for cooling the photovoltaic panels nowadays [4]. The hybrid system consists of a solar photovoltaic panels combined with a cooling system. The cooling agent, i.e., water or air, is circulated around the PV panels for cooling the solar cells, such that the warm water or air leaving the panels may be used for domestic applications such as domestic heating. Akbarzadeh and Wadowski [1] designed a hybrid PV/T solar system and found that cooling the solar photovoltaic panel with water increases the solar cells output power by almost 50%. They also found that cooling the solar photovoltaic panel does not allow the solar cells surface temperature to rise above 46 °C when exposed to solar radiation for a period of 4 h. Chaniotakis [4] designed a hybrid PV/T solar system where water and air were both investigated in the combined system as cooling agents. The water-based cooling system was found to increase the solar cells performance higher than the air based cooling system. Dubey and Tiwari [5] designed an integrated combined system of a photovoltaic (PV) panel with a thermal (T) solar water heater. The hybrid PV/T solar system has been designed and tested in outdoor condition of New Delhi. They measured the efficiency of the solar PV panels under three different cases, namely Case A – the absorber of the solar collector is fully covered by the PV module, Case B – the absorber is 50% covered by the PV module, and Case C – the absorber is partially covered by PV module, i.e., 30%. Dubey and Tiwari [5] found that there is a significant increase in the instantaneous efficiency of the solar collector from 33% to 64% as we go from Case A to Case C, simultaneously. The increase in the efficiency is due to increase in glazing area. Batoul [6] studied the influence of air flow on the performance of PV panels using Computational Fluid Dynamics (CFD). The module was constructed such that the air can flow under the panels in order to maximize cooling by natural convection. It was found that the geometry and construction of the solar energy system can have a major impact on how effectively the panels are cooled. Tonui and Tripanagnostopoulos [7] designed PVT/Air system to study the cooling effect on the PV module with either forced or natural convection. Under natural convection, the PV module temperature could reach up to 12 °C in the early afternoon during sunny days. For the forced convection, the experiments were done under three different cases, i.e., Case A – PVT/Air with fins, Case B – PVT/Air with thin metallic sheet, and Case C – PVT/Air normal, the use of fins yields an efficiency of 30%, followed by the thin metallic sheet with 28%, and the normal PVT/Air system with 25%. It was found that the PVT/Air with fins gives the highest thermal output. Kluth [8] studied water as a coolant to increase the solar panel efficiency. Two small solar panel prototypes were designed for this purpose. One prototype was left without cooling and the other was cooled by spraying water using a fan. It was found that the solar panel with water cooling generates more energy than the one without cooling. However, cooling by spraying water using a fan is not an efficient method, since the water will not be sprayed over the whole panel, and therefore, some parts of the PV panels will not be cooled, as well as this method results in a very high water loss.

Tang et al. [9] designed a novel micro-heat pipe array for solar panels cooling. The cooling system consists of an evaporator section and a condenser section. The input heat from the sun vaporizes the liquid inside the evaporator section and then the vapor passes through the condenser section, and finally, the condenser section is cooled down using either air or water. Hence, the heat pipe can transfer the heat from solar panel to air or water depending on the system. Using air as a coolant was found to decrease the solar cells temperature by 4.7 °C and increases the solar panel efficiency by 2.6%, while using water as a coolant was found to decrease the solar cells temperature by 8 °C and the panel efficiency by 3%. Therefore, cooling by water was found to be more effective than cooling by air.

It can be concluded from the above literature survey that using water as a coolant is found to be more effective than using air. Thus, the objective of this research is to build a water-based cooling system to solve the solar cells overheating problem with the minimum amount of water and energy. To minimize the amount of water and energy needed for cooling of the PV panels, a heating rate model is used to determine how long it takes to heat up the panels to the maximum allowable temperature limit that can lead to the maximum energy yield. The heating rate model is based on the operating conditions, i.e., solar radiation, ambient temperature, and ambient temperature at sunrise. Based on this model, it can be determined when to start cooling of the PV panels. A mathematical model is developed to determine how long it will take to cool the PV panels to the normal operating temperature. This model will be named as the cooling rate model throughout the paper. The cooling rate model is used to minimize the cooling time needed for the PV panels, as a means of minimizing the amount of water and energy needed for cooling. The heating rate and the cooling rate models are validated experimentally. The MAT is determined based on the heating rate and the cooling rate models, such that it can lead to the maximum energy yield. The mathematical models, i.e., heating rate and cooling rate models and the experimental setup are described in Sections 2 ***and*** 3, respectively. The experimental results and conclusions are presented in Sections 4 ***and*** 5, respectively.

2. Mathematical modeling

2.1. The heating rate model

The cooling frequency of the PV panels is determined by the heating rate of the panels. Thus, by calculating the module temperature as a function of time, the heating rate of the PV panels can be specified, and consequently, the cooling frequency can be specified. The module temperature T_m is calculated using the following well known equation [10–12],

$$T_m = T_{\text{amb}} + (\text{NOCT} - 20)E/800 \tag{1}$$

The module temperature is based on the ambient conditions, i.e., solar irradiance, E, ambient temperature, T_{amb}, and the nominal operating cell temperature, NOCT. The NOCT is conducted from the work of Bharti et al. [13]. The NOCT is a function of the ambient air temperature at the sunrise time T_{rise} as follows:

$$\text{NOCT} = 20\,^{\circ}\text{C} + T_{\text{rise}} \tag{2}$$

It can be concluded from Eq. (1) that the rate of heating of the PV panel, $\frac{dT_m}{dt}$, is dependent on the following: (i) the ambient temperature, (ii) the irradiance, and (iii) the NOCT. The NOCT has a constant value, while the irradiance and the ambient temperature are functions of time. Therefore, the module temperature will be function of time between sunrise and sunset. The solar irradiance, the ambient air temperature, and the module temperature were measured between the sunrise and sunset during 1 day in June 2012. The module temperature T_m has been calculated using Eq. (1), and it is compared to the measured module temperature. The module temperature as calculated and measured is presented in Fig. 2. The difference between the module temperature as measured and calculated does not exceed 5%. Therefore, it can be concluded that Eq. (1) can be used to determine the module temperature as a function of the ambient conditions, such that it can be used to determine when to start cooling of the PV panel as soon as the module temperature reaches the MAT. Linear fitting of the module temperature has been performed to determine the heating rate, $\frac{dT_m}{dt}$, of the PV panel, i.e., the slope of the curve. The heating rate of the solar cells is found to be 6 °C/h or 0.1 °C/min, as shown in Fig. 2.

2.2. The cooling rate model

The rate of cooling of the PV cells is an important factor that highly affects their performance. Therefore, by determining the cooling rate of the PV cells, the cooling period can be specified. The cooling period is determined based on an energy balance [14], such that the heat energy gained by the cooling water $Q_{\text{gained by cooling water}}$ is equal to the heat energy dissipated from the PV panels $Q_{\text{dissipated from PV panels}}$. The cooling time t is determined from the following energy balance,

$$\begin{aligned} &Q_{\text{gained by cooling water}} = Q_{\text{dissipated from PV panels}} \\ &\dot{m}_w \times t \times c_w \times \Delta T_w = m_g \times c_g \times \Delta T_g \\ &\therefore\ t = \frac{m_g \times c_g \times \Delta T_g}{\dot{m}_w \times c_w \times \Delta T_w} \end{aligned} \tag{3}$$

Since the solar cells are manufactured from silicon which is almost glass and covered by glass, therefore, the glass physical properties are taken to be the physical properties of the PV panels. Where $\dot{m}_w$ is the mass flow rate of water, m_g is the mass of glass, c_w is the specific heat capacity of water, c_g is the heat capacity of glass, ΔT_w is the water temperature rise, ΔT_g is the glass temperature change due to water cooling, and t is the time taken to cool the solar PV panel to a moderate temperature of 35 °C. The mass flow rate of water $\dot{m}_w$ is calculated from the equation: $\dot{m}_w = \rho_w \dot{V}$, where ρ_w is the water density and $\dot{V}$ is the volume flow rate. The mass of glass m_g is calculated from the equation: $m_g = \rho_g A_g x_g$, where ρ_g is the density of tempered glass, A_g is the surface area of the PV panel, and the x_g is the thickness of the glass covering the PV panel. The heat capacity of water, c_w, and the heat capacity of glass, c_g, are assumed to be constant since the variation in the water and the PV panel temperature is not large. The temperature of the PV panel before and after cooling is 45 °C and 35 °C, respectively. It is assumed that the maximum allowable temperature of the PV panel is 45 °C, beyond which cooling of the PV panel should start by water spraying of the panels till its temperature goes down to 35 °C. ΔT_w is the change in the temperature of the cooling water before and after cooling of

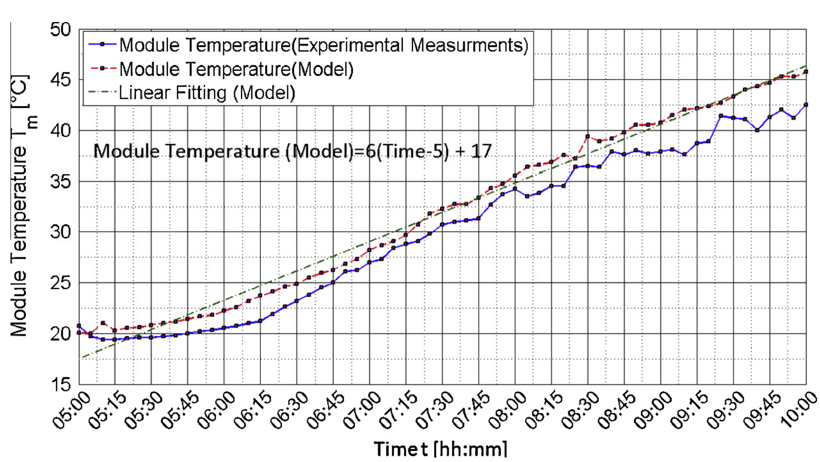

Figure 2 The module temperature as calculated and measured during June 2012.

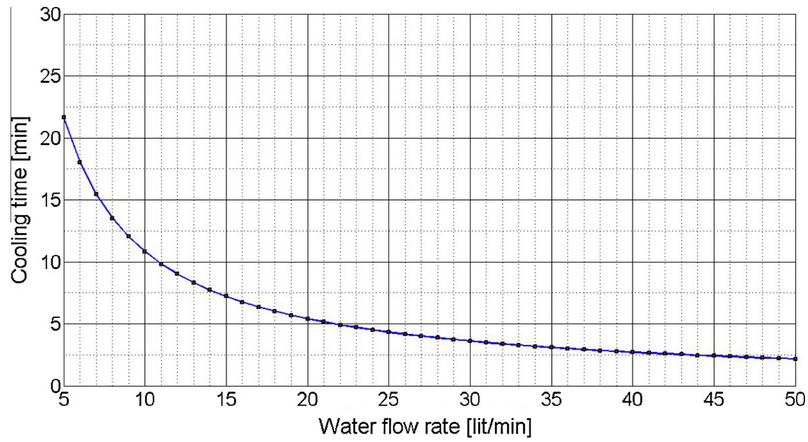

Figure 3 Cooling time t versus water flow rate $\dot{V}$, assuming $\Delta T_w = \Delta T_g = 10$ °C.

the PV panel. The temperature of the water leaving the panel is assumed to be the same as the temperature of the panel after cooling, i.e., 35 °C. ΔT_w is assumed to be equal to the difference between the temperature of hot water coming from the panel toward the tank and the temperature of the water leaving the tank, i.e., 35 °C and 25 °C, respectively. Eq. (3) has been solved to determine the dependence of the cooling time t on the water flow rate, and the results are presented in Fig. 3. It is assumed that $\Delta T_w = \Delta T_g = 10$ °C. It can be concluded from Fig. 3 that as the flow rate increases, the time period needed for cooling the solar PV panel decreases. If the pump is operated such that it sprays water over the PV panels at a flow rate of 29 l/min, this will result in cooling of the PV panels from the MAT of 45 °C to 35 °C in 4.7 min. In this case, it can be concluded that the cooling rate of the PV panels is ~2.0 °C/min, and the water spraying should be stopped after 4.7 min.

Table 1 Electrical and physical characteristics of the PV modules used [3].

Electrical characteristics	
Model no.	BP 7185
Power rating P_{mp}	185 W
Open circuit voltage V_{oc}	44.8 V
Short circuit current I_{sc}	5.5 A
Voltage at maximum power V_{mp}	36.5 V
Current at maximum power I_{mp}	5.10 A
Nominal voltage	24 V
Panel efficiency	14.7%
Fill factor	75.1%
Power tolerance	0.00–2.50%
Maximum system voltage V_{max}	1000 V
Maximum series fuse rating	15 A
Nominal operating cell temperature (air at 20 °C, irradiance 800 W/m^2 and wind 1 m/s)	45 °C
Temperature coefficients	
Temperature coefficient of I_{sc}	0.065%/°C
Temperature coefficient of V_{oc}	−0.36%/°C
Temperature coefficient of P_{mp}	−0.50%/°C
Physical characteristics	
Cell type	Monocrystalline silicon
Cell size (mm × mm)	125 × 125
No of cells per panel	6 × 12
Panel dimensions (mm × mm × mm)	1593 × 790 × 50
Weight	15.4 kg

3. Experimental setup

An experimental setup has been developed to study the effect of cooling by water on the performance of photovoltaic (PV) panels of a PV power plant. The PV power plant is installed in the German University in Cairo (GUC) in Egypt. The total peak power of the plant is 14 kW. The plant has been initiated and directed by the Institute of Physical Electronics (IPEs) in Stuttgart, Germany, and financed by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in Germany. The PV power plant was built to investigate the energy availability and performance of the latest market available PV module technologies under different climatic conditions. Further details about the PV power plant could be found in [15]. Similar stations were also constructed in two other locations that are Stuttgart in Germany [16] and Southern Europe [17]. The experimental setup consists of 6 photovoltaic modules manufactured by Bp Solar [3]. The electrical and physical characteristics of the PV modules are shown in Table 1.

A cooling system has been built up as shown in Fig. 4, and further details can be found in [18]. This cooling system consists of six main parts as follows:

1. Six PV modules of 185 W peak-output each.
2. Aluminum water tank of 0.3 m^3 capacity.
3. Centrifugal pump of 1 hp input power.
4. One stage industrial transparent water filter.
5. 120 water nozzles for spraying water over the panels.
6. Drain pipe for collecting the water and return it back to the tank.

The water pump sucks the water from the middle of the water tank via a suction pipe to avoid sucking any dust. The suction pipe consists of a non-return valve and a strainer to avoid sucking of large particles that could damage the water pump. The sucked water passes through the water filter, and then, it is sprayed over the PV modules for cooling. Water is sprayed using water nozzles, which are installed at the upper side of the modules, as shown in Fig. 4. Afterward, the water used for

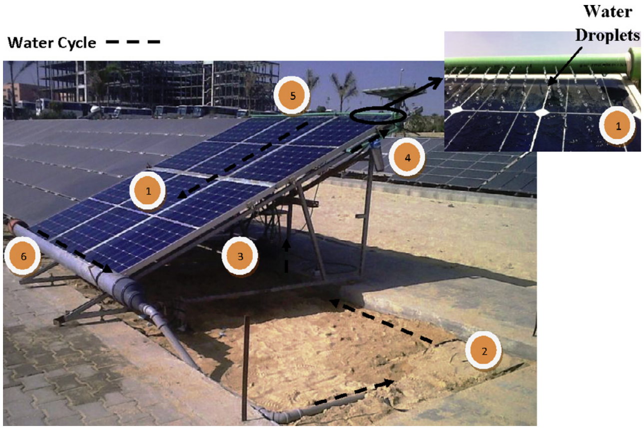

Figure 4 Experimental setup 1 – PV module, 2 – tank, 3 – pump, 4 – filter, 5 – nozzle and 6 – drain pipe.

cooling is collected at the lower part of the PV modules via a drain pipe, and then, it returns back to the water tank such that the water cycle is closed. This design is employed to minimize the consumption of water which is crucial in desert regions. The water tank is buried in the ground to avoid heating by solar radiation and also to cool the water inside the tank by the surrounding ground. The hot water coming from the PV panels is cooled due to mixing with the large amount of cold water inside the tank, i.e., 250 kg of water, and the surrounding ground, and therefore, the temperature of the cooling water was assumed to be constant at 25 °C.

3.1. Experimental procedure

Cooling the solar panels has been performed to determine the influence of cooling and overheating on the performance of the solar cells. Cooling of the solar panels was performed for 1 day in June 2012, and 1 day in July 2012, and the cooling experiment started from 11:00 am till 2:00 pm using a controlled water flow rate of 29 l/min. The performed experiments are done in June and July because it is the hottest period of the year, so succeeding in cooling the solar panels in this period of the year, means that with the proposed cooling system, it will be possible to cool the panels for the rest of the year. The cooling process was repeated each 15 min, approximately, where the cooling period of the photovoltaic cells was 5 min each time. It has been observed that the water loss per month due to evaporation is about 5% of the initial total water volume in the tank. Thus, it can be concluded that this system is suitable for photovoltaic stations installed in deserts.

The efficiency, η, of the PV panels is calculated by,

$$\eta = \frac{P_{\max}}{IA}, \tag{4}$$

where $P_{\max}$ (W) is the maximum power generated from the PV panels, A (m^2) is the surface area of the panels, and I (W/m^2) is the solar irradiance incident on the panels. The maximum power generated is estimated using the perturb and observe (PO) algorithm [19], The solar irradiance is measured using a pyranometer located at the top of the panels. The temperature distribution of the panels is measured using thermocouples located at the back of the panels. The output power, solar irradiance, and temperature are all monitored using a data acquisition system, employing NI LabVIEW [20] system. All measurements are saved to an excel file for further calculation and analysis.

4. Experimental results

Experimental measurements of the efficiency and the module temperature of the PV panel, during June and July 2012, are shown in Fig. 5. The cooling system was operated seven times for 5 min each time, along the day in June 2012, as shown in Fig. 5a. The operating time for the cooling system is specified in Table 2. Moreover, the cooling rate was measured each time when the cooling system is operated, as shown in Table 2. It can be clearly seen from Table 2 that the average cooling rate for the seven times of cooling is 1.9 °C/min. The experiment was then repeated with the same procedures along another day in July 2012, as shown in Fig. 5b, and the average cooling rate was found to be 2.1 °C/min, as shown in Table 3. It has been found previously from the cooling rate model, i.e., Section 2.2, that the cooling rate is 2 °C/min based on the experimental operating conditions, which is almost equal to the experimental measurements made in June and July 2012. Therefore, it is concluded that the developed cooling rate model can accurately predict the cooling rate of the PV panels due to water spraying.

Experimental measurements of the efficiency and the module temperature of the solar PV panel are shown in Fig. 5. It can be clearly seen from Fig. 5 that as the solar module temperature increases, the solar PV panel efficiency decreases gradually. It is found that a rise in the solar cells temperature by 10 °C from 35 °C to 45 °C results in decreasing the efficiency of the cells from 12% to 10.5%, i.e., equivalent to a degradation of the cell efficiency $\Delta\eta$ by 12.5%, which is calculated from $\Delta\eta = \frac{\eta_i - \eta_f}{\eta_i} \times 100$. Where η_i and η_f are the initial and the final efficiency, respectively. Therefore, an increase in the temperature of the PV panels by 30 °C, i.e., heating from 35 °C to 65 °C, will result in degrading the PV panel efficiency by 37.5%. It can be concluded that the increase in temperature has a very bad effect on the solar PV performance. It was also found from the data sheet of the PV panel used in this research [3] that the temperature coefficient at the maximum power operating point is −0.5%/°C, which means that a rise in the solar cells temperature by 10 °C results in a degradation of the solar cell efficiency by 12.5%. The cooling system was operated to solve the overheating problem, where it was observed from Fig. 5 that operating the cooling system for 5 min results in a decrease in the solar cells temperature by 10 °C, and an increase in the solar cell efficiency by 12.5%. Therefore, it is concluded that the proposed cooling system could solve the problem of overheating the PV panels due to excessive solar radiation and maintain the efficiency of the panels at an acceptable level by the least possible amount of water. It has been observed that the PV panels become clean when the cooling system is used compared to the days where the system has not been used. It can be concluded that with the proposed cooling system, it is possible to clean as well as cool the PV panels in hot and sandy regions, e.g., deserts in the middle east and North Africa, where a lot of sand storms can happen and cover the panels with a layer of dust and consequently obscure the solar radiation and deteriorate the efficiency of the panels [21,22].

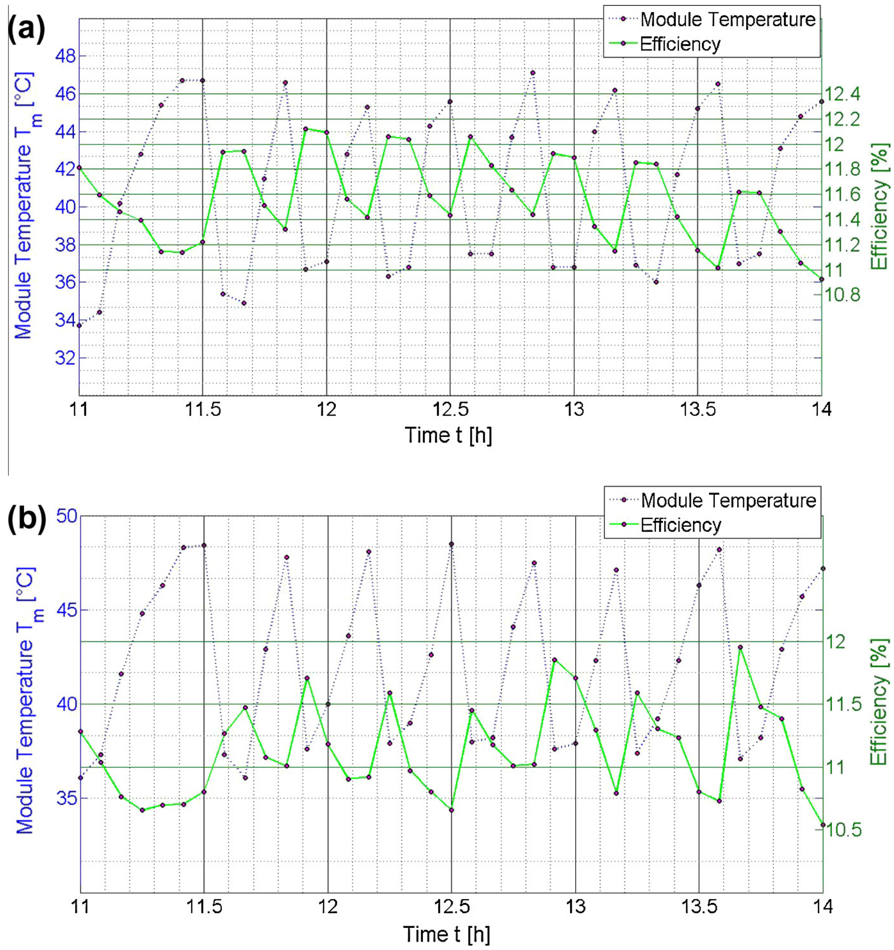

Figure 5 Experimental measurements of the module temperature and efficiency versus time in (a) June and (b) July 2012.

Table 2 Cooling rate along 1 day in June 2012.

Counter	Time	Cooling rate (°C/min)
1	11:30–11:35	2.26
2	11:50–11:55	1.8
3	12:10–12:15	1.8
4	12:30–12:35	1.62
5	12:50–12:55	2.06
6	13:10–13:15	1.86
7	13:35–13:40	1.9
	Average	1.9

Table 3 Cooling rate along 1 day in July 2012.

Counter	Time	Cooling rate (°C/min)
1	11:30–11:35	2.22
2	11:50–11:55	2.04
3	12:10–12:15	2.04
4	12:30–12:35	2.1
5	12:50–12:55	1.98
6	13:10–13:15	1.94
7	13:35–13:40	2.22
	Average	2.1

The selection of the maximum allowable temperature (MAT) is based on maintaining the efficiency of the panels at an acceptable level with the least amount of water and energy usage. Cooling the PV panels by water every 1 °C rise in temperature will lead to the fact that the energy produced from the PV panels will be consumed by the continuous operation of the water pump. Therefore, the objective of this research is to find out analytically when to start cooling, i.e., MAT, in such a way that the efficiency of the PV panels can be preserved without waste of energy. The performed analysis can be used for other PV panels under any different conditions. The output energy is calculated for four cases using different MAT, namely 40 °C, 45 °C, 55 °C, and 65 °C. The solar PV panel is left to overheat till the MAT is reached in each case, and then, the panel was cooled to the normal operating temperature, i.e., 35 °C. This cycle is repeated for 180 min. The temperature variation is calculated based on a cooling rate of −2 °C/min and a heating rate of 0.5 °C/min that is based on the measurements done in June and July 2012, which is shown in Fig. 5. The power variation of the PV panel is calculated based on the temperature variation of the panel and its temperature coefficient [3], i.e., −0.5%/°C, which indicates that for every 1 °C of temperature rise corresponds to a drop in the efficiency and the power output by 0.5%. The power output of the PV panels versus time is calculated for each case by taking into account that the starting output power is 790 W at 35 °C, and

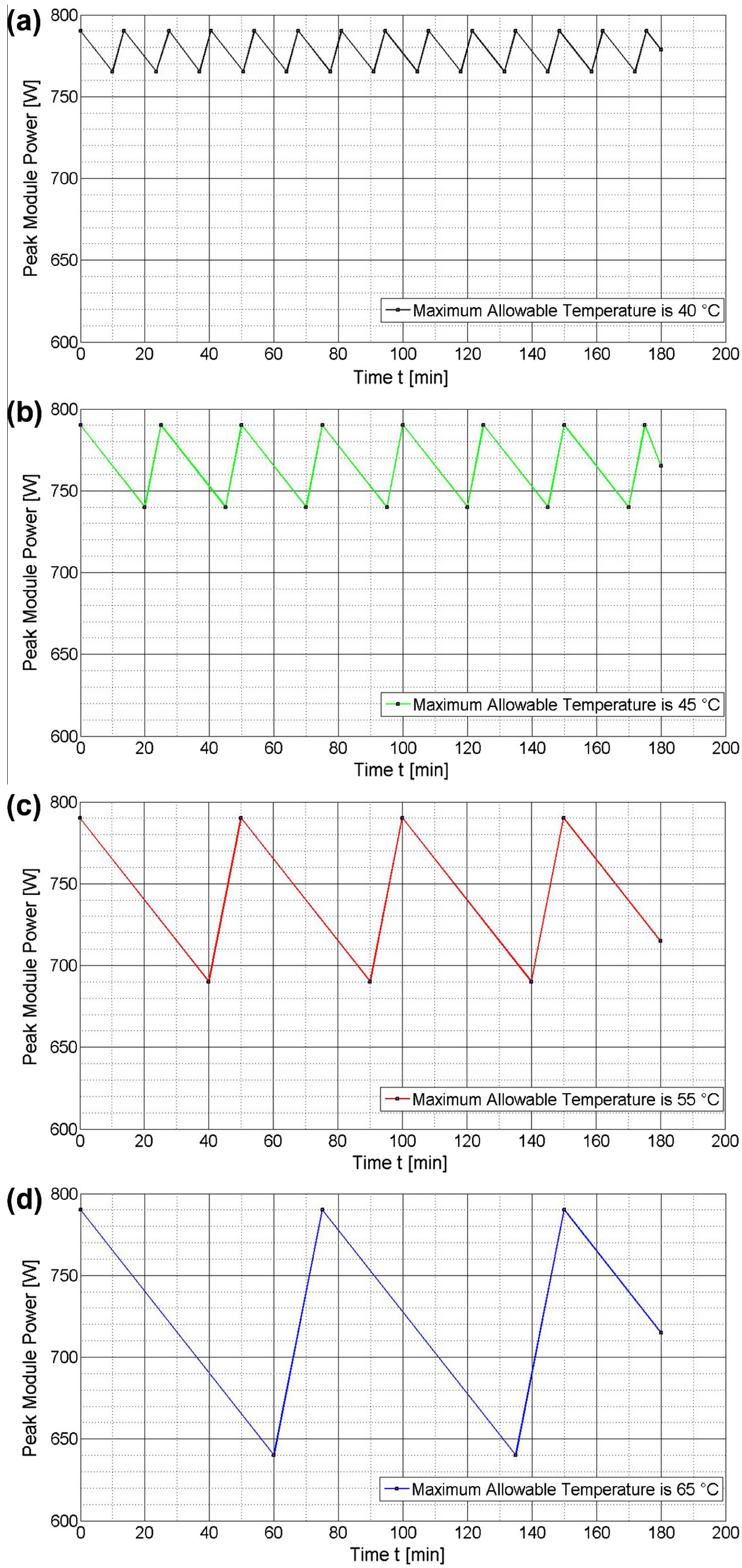

Figure 6 Module output power at different cooling conditions. The maximum allowable temperature is (a) 40 °C, (b) 45 °C, (c) 55 °C, and (d) 65 °C.

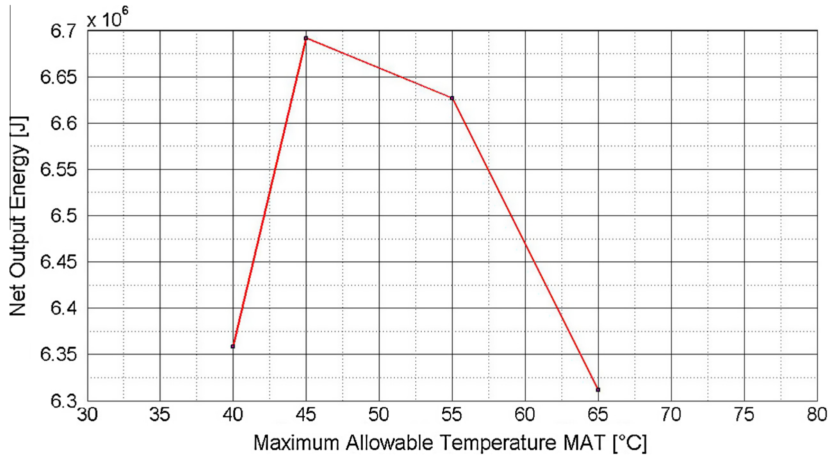

Figure 7 The net output energy of the PV panel as a function of the maximum allowable temperature (MAT).

the results are plotted in Fig. 6. The output energy is then calculated by calculating the area under the power curve shown in Fig. 6. The net output energy from the PV panels is calculated based on subtracting the energy input from the energy output, where the energy input is the electrical energy needed for running the water pump during the cooling period. The net energy output from the PV panel as a function of the MAT is depicted in Fig. 7. It can be concluded that the optimum MAT is 45 °C, which yields the highest output energy. It is also expected that as the MAT value increases, the rate of water evaporation during the cooling operation will increase, and thus, more water consumption will be needed. Therefore, it can be concluded that selecting the MAT to be 45 °C is the optimum value to cool the solar PV panels with the least amount of water and energy usage.

5. Conclusion

The objective of this research is to cool the PV panels using the least amount of water and energy. A non-pressurized cooling system has been developed based on spraying the PV panels by water once in a while. A cooling rate model has been developed to determine how long it will take to cool the PV panels by water spraying to its operating temperature. A mathematical model has been used to determine the heating rate of the PV panels, in order to determine when to start cooling. An experimental setup has been developed to validate both models, i.e., the heating and the cooling rate models, experimentally, and to study the influence of cooling on the performance of PV panels. It can be concluded from the results of this study that;

1. It is possible to cool and clean the PV panels using the proposed cooling system in hot and dusty regions.
2. The cooling rate for the solar cells is 2 °C/min based on the concerned operating conditions, which means that the cooling system will be operated each time for 5 min, in order to decrease the module temperature by 10 °C. The result of the cooling rate model has shown good agreement with the experimental measurements.
3. Both the heating rate and the cooling rate models have been validated experimentally.
4. The PV panels yields the highest output energy if cooling of the panels starts when the temperature of the PV panels reaches the maximum allowable temperature (MAT), i.e., 45 °C. The MAT is a compromise temperature between the output energy from the PV panels and the energy needed for cooling.

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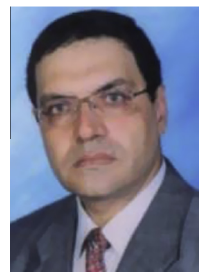

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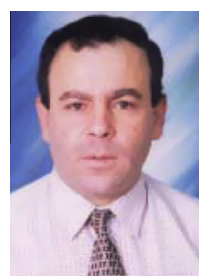

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