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Experimental Investigation on the Performance of a Photovoltaic Module

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Abstract. : This work presents a field study for the performance of a photovoltaic (PV) module under cooling with pure water or PCM in aluminium channels beneath the PV panel. Two systems each of0.37 m^2commercial poly-crystalline PV panels have been installed at the Faculty of Engineering at *Shoubra, Benha University, Cairo, Egypt* (30.1°N Latitude).One of them is cooled using the water or the PCM with different occupation of each in the channels; 100%water (0%PCM) to 0% water (100%PCM), and compared with the uncooled panel during July 2017.The results showed that the PV temperature decreases as the cooling water flow rate increases in the channels. In addition, compared with the uncooled panel, using 100% water in the channels provides an increase in the electrical efficiency of 33.4% and 45.5% when the flow rate increases from 0.25 to 1.0 L/min, respectively, while with using 100% PCM, the increase in the electrical efficiency is 15.5%. The average thermal efficiency increases from 44.2% to 68.4% for 100% water when the cooling water flow rate was varied from 0.25 to 1.0 L/min. Furthermore, the percentage increase in the PV electrical power for the 100% water cooled PV is higher than that of the PCM-cooled PV. The average percentage increase in the PV electrical power for 100% water augments from about 24.1% to 28% at flow rates of 0.25 to 1 L/min, respectively. Finally, the average percentage increase in the PV electrical power is 12.4% for 100% PCM cooling technique.

Keywords: Photovoltaic, PCM, Passive and active cooling, thermal and electrical efficiencies.

1. INTRODUCTION

A photovoltaic system is one of the extremely electric energy quality and clearness sustainable energy in the world. Neverless, the lower efficiency and higher cost of PV power generation restrict the development of the solar PV industry. The electrical conversion efficiency of commercial PV is of 6~15% and its output power decreases by 0.2~0.5% per 1 K increase in the module temperature [1].Improving the efficiency or utility of the solar energy collection by developing a hybrid photovoltaic/thermal (PVT) solar collector has been investigated by many researchers . Akbarzadeh and Wadowski [2] experimentally tested the effect of integrating a refrigerant heat pipe to the back surface of a solar cell to be passively cooled. It was indicated that the suggested cooling system has considerably enhanced the electrical output of the solar cells. Tonui and Tripanagnostopoulos [3] numerically examined the cooling of a PV module by a natural air flow. The authors tested the effect of attaching fins to the back side of the air-channel. The authors showed that the developed PVT system could be considered applicable and cost-effective, appropriate for building integration with a considerable contribution to the thermal and electrical demand of it. Anderson et al. [4] experimentally and numerically presented a study in which a passive cooling of a concentrating PV system is done using water heat pipe with aluminium fins. It was illustrated that this cooling system is able to passively reject the heat energy from the concentrating PV cell. Cuce et al. [5] experimentally tested the effects of using an aluminium heat sink as a passive cooling method on the performance of solar cells. The results showed increases in the electrical power by 20%. Hasan et al. [6] experimentally compared the cooling of PV panels by solid-liquid PCM in two countries; Ireland and Pakistan. The results demonstrated that such systems are monetarily feasible in higher temperature and higher solar radiation environment. It was shown that using the PCM as a cooling strategy, enhanced the electrical efficiency by about 8.5%. Rajaram and Sivakumar [7] showed experimentally that the employment of the PCM under the PV panel has reduced the average temperature of the PV module during the continuous operation by 4°C. Hasan et al. [8] experimentally monitored the effect of employing a PCM of melting temperature range of 38–43°C on the performance of a PV module. It was observed less cooling of the PV cell in peak cool and hot months with conducting the PCM. The authors indicated an enhancement of 5.9% in the electrical efficiency in the hot conditions.

There are many researchers that proposed active techniques for PVs cooling. Teo et al. [9] examined practically and numerically the improvement of a PV cell output. The cooling process was achieved by passing air in parallel conduits on the rear of the PV panel. The results indicated that the temperature of the PV module decreased from 68°C to 38°C and the electrical efficiency augmented by 12% to 14%. Ozgoren et al. [10] designed an experimental facility to test the impact of an active water cooling on PV systems. It was found that the conversion efficiency of the PV panels was 8% and 13.6% without and with the cooling system, respectively.Ceylan et al. [11] experimentally estimated the effect of using a simple copper pipe behind the PV module. It was observed that the module average efficiency was 13% and 10% for the cooled and uncooled cell, respectively. Karami and Rahimi [12] experimentally estimated the heat transfer attributes in a PV cell using Boehmite nanofluid with different mass concentrations (0.01-0.5%) as coolants in straight and helical channels. Compared with pure water, the applied nanofluid reduced the electrical efficiency was enhanced to be 20.6% and 37.7% for the straight and helical channel, respectively. Nizetic et al. [13] carried out an experimental investigation on a water spray cooling technique of a PV panel. They observed an augmentation of 16.3% in the electrical efficiency of the PV panel, while the PV temperature dropped to 24°C when compared to 54°C of the uncooled PV panel.

The present research is devoted to experimentally investigate the performance of a PV in Cairo,which isconsidered one of the greatest energy-consumption areas in Egypt where a talented solar intensity is found. The present test rig aims to test the PV output characteristics under operation conditions for cooling system that depends on flowing water in aluminium channels beneath the PV or filling these channels with a paraffin wax as a PCM.Two systems each of 0.37 m^2 commercial poly-crystalline PV cells have been mounted at the faculty of engineering at *Shoubra, Benha university, Cairo, Egypt* (30.1°N Latitude). One of the systems is cooled using the water or the PCM with different occupation of each; 100%water (0%PCM) to 0% water (100%PCM), in channels with dimensions of 25x25 mm^2 and compared with the uncooled panel during July 2017.

2. Experimental Setup

In the experimental work, two identical 50-Watt PV panels were installed on theroof top of at the Faculty of Engineering at *Shoubra, Benha University, Cairo, Egypt* (30.1°N Latitude). The solar panels are being south oriented and fixed at the same tilt angle of 30° with the horizontal plane. The schematic of the experimental work and specifications of PV panelsare presented in Fig. 1 and Table 1, respectively. In the present cooling system, aluminium channels (Fig. 2) are fabricated and used either for passing the cooling water or are filled with the PCM; with varying the occupation ratio of the water/PCM in the channels as shown in Fig. 3. The depth and width of the channels is 25 mm.

Table 1: Solar module specifications.

Cell Type	Poly-Crystalline
Peak power ($Q_{e,p}$)	50 W
Dimension	670*550*35 (±2 mm)
Maximum power voltage (V_{mp})	18 Volts
Maximum power current (I_{mp})	2.78 Amps
Open circuit voltage (V_{oc})	21 Volts
Short circuit current (I_{sc})	3.06 Amps
Maximum system voltage	1000 V
Normal operating cell tem perature	25°C

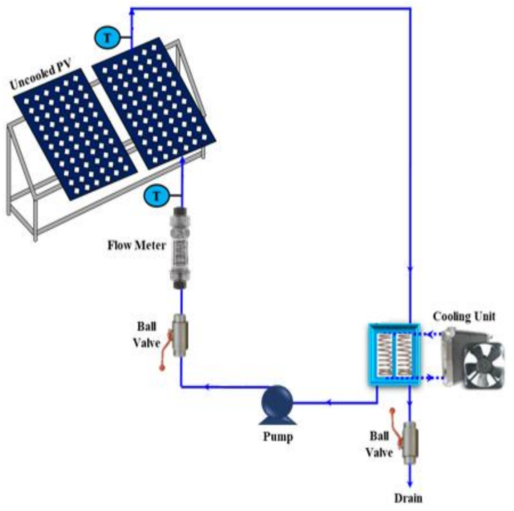

Fig. 1: Schismatic representation of the present experimental facility.

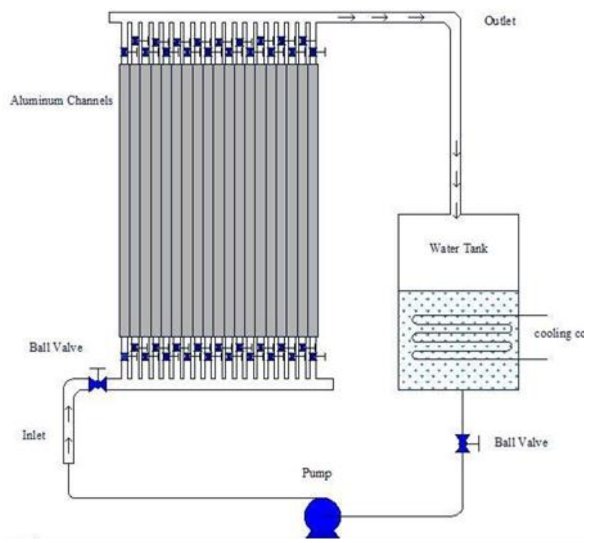

Fig. 2: Schismatic representation of the channels cycle.

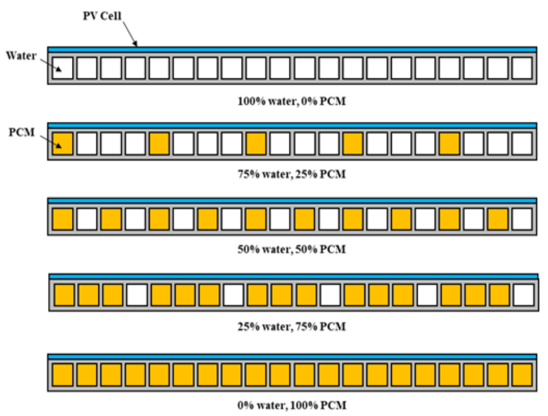

Fig. 3: Schismatic layout of the PCM and cooling water occupation in the channels.

An organic solution PCM type (Calcium chloride hexahydrate; $CaC_{12}H_{12}O_6$) is utilized in the current investigation with technical specifications illustrated in Table 2. Before charging the channels, the PCM is liquefied through a heating process in a water path until reaching its melting point. Then, the selected channel volume is fully charged with the liquid PCM.

Table 2: Characteristic specifications of the used PCM.

Type	Calcium chloride hexahydrate; $CaCl_2H_{12}O_6$
Melting point (°C)	31
Heat of fusion (kJ/kg)	191
Thermal conductivity (W/m·°C)	Solid: 1.08 Liquid: 0.56
Density (kg/m^3)	Solid: 1710 Liquid: 1560
Specific heat capacity (kJ/kg·°C)	Solid: 1.4 Liquid: 1.08
Kinematic viscosity (m^2/s)	Liquid: 0.00184
Thermal expansion coefficient (K^{-1})	Liquid: 0.0005

A DC pump of 4.2 W maximum power consumptionis installed to feed the PV solar system with the required water flow rate. The flow rate is controlled through a flow meter and the installed valves. Rectangular tank of 20litterscapacity is fabricated and insulated using 1-inch wool glass to store water. A vapour compression refrigeration system is used to obtain a constant water inlet temperature to the PV panel. In the experiments, the current and voltage of PV panel, ambient air,inlet and outlet water temperatures, wind speed and solar irradiation are measured.A flow meter is used to record the flow rate directed to cooling the PV panel. To measure the temperatures at different points on the system, calibrated copper constantan thermocouples are used and connected to a digital thermometer with ±0.1°Cresolution. Eight thermocouples are attached to each PV module to record the temperature of the solar cell. Also, two thermocouples are employed on the inlet and exit of the PV. Table 3 reveals the specifications of main instruments in the experimental setup.An electric circuit shown in Fig.4is used to measure characteristics voltage and current (V, A) of each panel.

Table 3: Specifications of main instruments in the experimental setup.

Measured variable	Instrument	Specifications
Solar intensity	Solar power meter	• Model:TM-206 • Up to 2000 W/m^2 • Accuracy: ±10 W/m^2
Weather conditions	Digital environmental multimeter	• Temperature: −10 to 60°C, accuracy ±1.5% and resolution 0.1°C. • Relative humidity: 0 to 100%, accuracy ±3% and 0.1% resolution. • Air velocity: 0.5 to 20 m/s with accuracy ±3% and 0.1 m/s resolution.
Flow rate	Flow meter	Measuring range of 0.002 – 2 L/min
Pressure drop	Digital differential pressure transducer	Working range of 0–103.4 kPa and accuracy of ±1% of full scale.

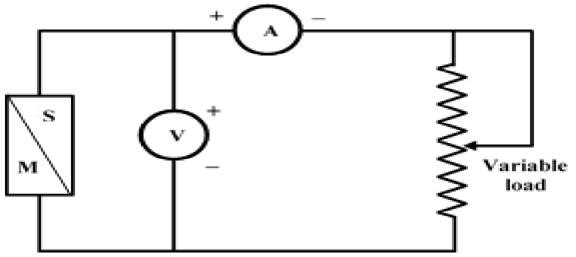

Fig. 4: Measurement circuit for the PV-cell characteristics.

3. Experimental Procedures and Data Reduction

The following procedures were conducted from 8 AM to 5 PM for the two systems;

1- Checking the water level in the tank and ensure that the evaporator is completely submerged in the water.
2- Adjust the control valves at the inlet of the cooled cell to get the required flow rate of cooling water.
3- Close the valves at inlet and exits of the channels, which are occupied with the PCM.
4- Start up the compressor of the refrigeration system to control the inlet temperature to cooled PV panels
5- Record the incident solar radiation, temperatures, voltage and current of the DC pump, and wind speed.
6- Connecting the output from each panel to the variable load circuit to draw the V-I characteristic curve. All measured voltage and current values are entered to Excel program to draw the characteristic curve between current and voltage to obtain the optimum point from the curve as shown in Fig. 5.
7- Repeat these procedures every 30 minutes till sunset.

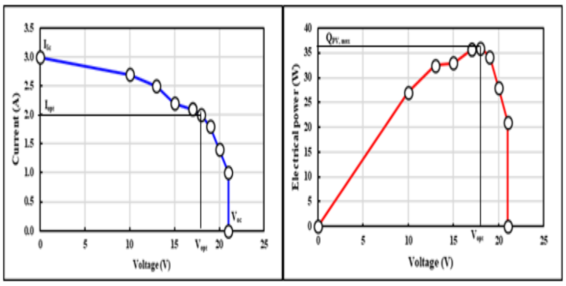

Fig.5: Characteristic curves for the PV cell.

After plotting the characteristic curve at each time and knowing the optimum values of the PV-voltage and current, the following relations are utilized to analyze the characteristics, the electrical and thermal performance of the PV cells.

$$Q_{in} = G_S \times A_{PV} \quad (1)$$

$$Q_{PV} = V \times I \quad (2)$$

$$Q_{PV_{max}} = V_{opt} \times I_{opt} \quad (3)$$

$$\eta_e = \frac{Q_{PV_{max}}}{Q_{in}} \quad (4)$$

$$Q_{th} = \dot{m}_w Cp_w (T_{w,o} - T_{w,i}) \quad (5)$$

$$\eta_{th} = \frac{Q_{th}}{Q_{in}} \quad (6)$$

$$\Delta T_{PV} = T_{PV_{ref}} - T_{PV_c} \quad (7)$$

$$T_{PV} = \frac{T_{PV_f} + T_{PV_b}}{2} \quad (8)$$

$$T_{PV_f} = \frac{\sum T_{PV,s_f}}{N} \quad (9)$$

$$T_{PV_b} = \frac{\sum T_{PV,s_b}}{N} \quad (10)$$

$$\Delta Q_e\,(\%) = \left[\frac{Q_c - Q_{ref} - W_p}{Q_{ref}}\right] x100 \quad (11)$$

4. Results and Discussions

The present measurements are carried out through July 2017. The electric power ofthe PV panels and the heat transfer gained are measured every 30 min from 8 AM to 5 PM. Firstly, the electrical efficiency of the two panels are compared for non-cooling case to test the similarity of two panels. Tiny differences between the two panels shown in Fig. 6 assures that they are identical and can be compared for cooling and non-cooling case.

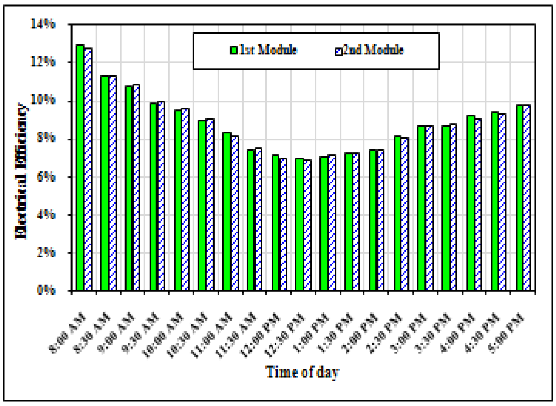

Fig. 6: Comparison between the two panels under the same conditions.

Fig. 7 presents the PV average temperature at different cooling water flow rates and at different occupation ratio of the water/PCM. It is obvious that the PV temperature decreases with increasing the water flow rate and with decreasing the PCM occupation. Compared with the reference panel, it is observed that the PV average temperature is reduced by 12–14.5°C (100% water)and by 7.7°C (100% PCM). In addition, it is illustrated in Fig. 8 that for 100% water, the average increase in the cooling water temperature increased from 2.4°C to 6.1°Cat 1 and 0.25 l/min, respectively. While for 0.25% water, the average increase in the cooling water temperature increased from 1.9°C to 4.5°C at 1 and 0.25 l/min, respectively. The increase in the water temperature is reduced by increasing the PCM occupation due to increasing the heat energy stored in the PCM.

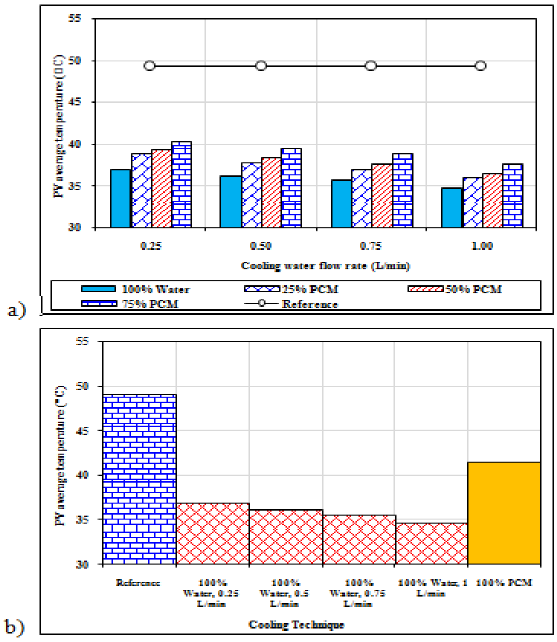

Fig. 7: PV average temperature.

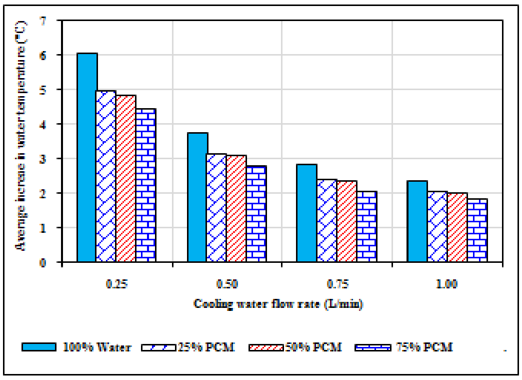

Fig. 8: Average increase in the cooling water outlet temperature.

Fig. 9 presents the variation in the electrical and thermal efficiencies (at selected water flow rates as examples of the results) through the day time. This figure reveals that the electrical efficiency of the cooled panels is always higher than that of the un-cooled cell. It starts high at 8 AM and then decreases to reach its minimum value at 1 PM. This is due to the increase in the panel temperature with increasing the incident solar radiation. As the radiation intensity is going down later, the electrical efficiency is going up gradually due to the decrease in temperature of the solar cells. It can be noticed that the cooled PV panel with 100% water has a noticeable increase in the electrical and thermal efficiencies due to the higher cooling rate. The electrical and thermal efficiencies decrease gradually with increasing the PCM occupation in the channels behind the PV panel.

Fig. 10 illustrates that increasing the cooling water flow rate enhances both efficiencies which can be returned to the enhancement in heat transfer rate and consequentially decreasing the temperature of PV cells. It is observed that the increase in the electrical efficiency for the cooled PV with 100% water is 33.4% and 45.5% for cooling water flow rates of 0.25 and 1 L/min, respectively. While for PV with 100% PCM, the increase in the electrical efficiency is 15.5%.In addition, the thermal efficiency of the water-cooled PV system follows the solar intensity changes. Furthermore, it is noticed that the average thermal efficiency increases from 44.2% to 68.4% for 100% water (0% PCM) when the cooling water flow rate was varied from 0.25 to 1.0 L/min as shown in Fig. 10. While the average thermal efficiency increases from 31.9% to 52.7% for 25% water (75% PCM) when the cooling water flow rate was varied from 0.25 to 1.0 L/min

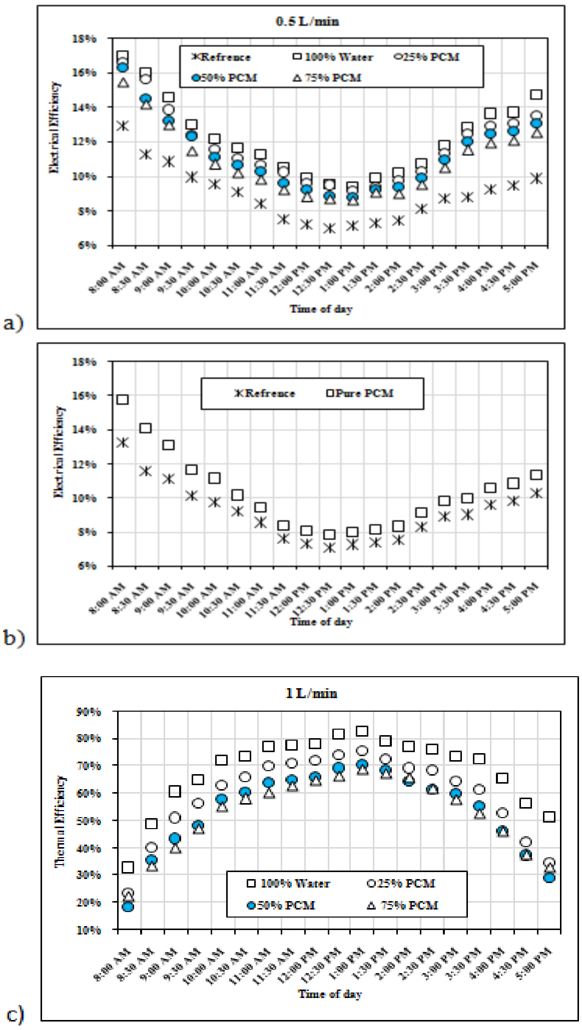

Fig. 9: PV electrical and thermal efficiencies.

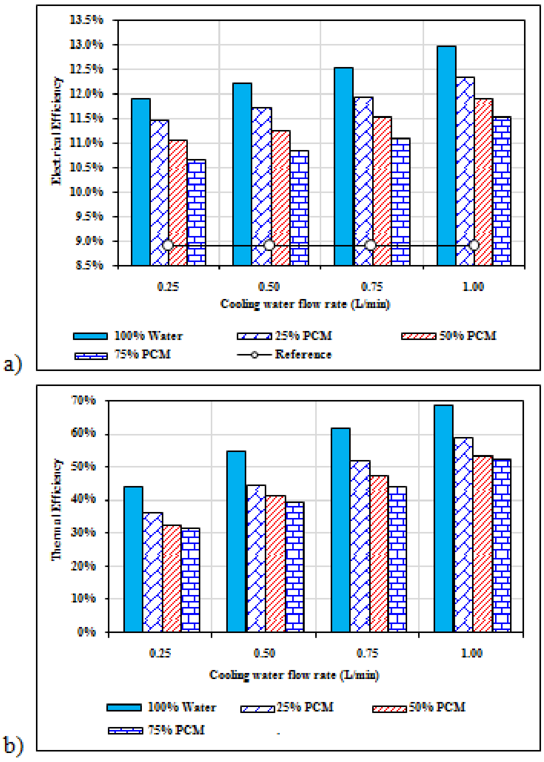

Fig. 10: PV average electrical and thermal efficiencies.

To be a successful heat transfer augmentation technique, the rise in the electrical and thermal energy of the active cooled PV panel should be limited in consuming pumping power. Therefore, the consumed pumping power required to flow the cooling water through the channels and piping was measured. Then, the percentage increase in the PV electrical power was calculated through Eq. 11 and illustrated in Fig. 11.

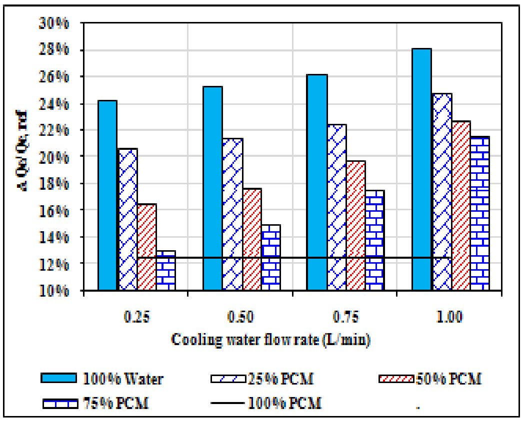

Fig. 11: The average percentage increase in the PV electrical power.

It is well indicated that the percentage increase in the PV electrical power for the 100% water cooled PV is higher than that of the PCM-cooled PV. The average percentage increase in the PV output for 100% water augments is about 24.1% to 28% at flow rates of 0.25 to 1 L/min, respectively .While this percentage is about 12.4% for 100% PCM cooling technique.

5. Conclusions

The results of cooled solar module with cooling water/PCM at numerous occupation ratios for each from 0 to 100% in straight channels beneath the PV were presented and compared with an uncooled reference panel. The panels were installed on Faculty of Engineering at Shoubra, Cairo(at 30.1°N Latitude) and tested during July 2017. The calculated average electrical efficiency of the reference uncooled PV panel was 8.9% with maximum PV cell temperature of 58.3°C at peak time for the mentioned weather conditions. The following conclusions can be expressed;

1. The PV temperature decreases as the cooling water flow rate increases in the channels.
2. Compared with uncooled panel, using 100% water in the channels provides an increase in the electrical efficiency of 33.4% and 45.5% when the flow rate increases from 0.25 to 1.0 L/min, respectively.

3. Compared with uncooled panel, using 100% PCM, the increase in the electrical efficiency is 15.5%.
4. The average thermal efficiency increases from 44.2% to 68.4% for 100% water (0% PCM) when the cooling water flow rate was varied from 0.25 to 1.0 L/min.
5. the percentage increase in the PV electrical power for the 100% water cooled PV is higher than that of the PCM-cooled PV.
6. The average percentage increase in the PV electrical power for 100% water augments from about 24.1% to 28% at flow rates of 0.25 to 1 L/min, respectively.
7. The average percentage increase in the PV electrical power is 12.4% for 100% PCM cooling technique.

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Nomenclatures

A	Area, m^2
Cp	Specific heat, $J/kg.℃$
G	Incident solar intensity(W/m^2)
I	Electrical current, A
$\dot{m}$	Mass flow rate, kg/s
Q_e	Electric power, W
Q_{in}	Incident solar radiation rate, W
Q_{th}	Thermal heat transfer rate, W
T	Temperature, K
t	Time, s
V	Electrical voltage, V

Greek Letters

Δ	Differential
η	Efficiency

Subscripts

a	Ambient
el	Electrical
i	Inlet
in	Incident
MP	Maximum point
o	Outlet
oc	Open circuit
sc	Short circuit
th	Thermal
w	Water

Acronyms and Abbreviations

CPVT	Concentrating photovoltaic and thermal
PCM	Phase change material
PV	Photovoltaic
PVT	Photovoltaic thermal