INVESTIGATION ON CLOSE-LOOP WATER-COOLED PHOTOVOLTAIC MODULE: EFFECT OF WATER VOLUME ON THE TEMPERATURE PROFILE AND PERFORMANCE ENHANCEMENT OF THE MODULE

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Article History: Received 3 July 2021; Revised 18 October 2021; Accepted 10 January 2022

ABSTRACT: The volume of water in the water reservoir is one of the most important parameters involved in closed-loop water-cooled photovoltaic (PV) systems. However, there are no studies reported on this parameter. Therefore, in this paper, PV modules with different effective surface areas are cooled using different sets of water volumes in a closed-loop system to study the temperature reduction and performance enhancement of water-cooled PV modules. The experimental result indicated that for the 250-W water-cooled module, different sets of water volumes have a significant effect on the surface temperature reduction of PV module and its performance compared to the 10-W and 30-W water-cooled modules. Hence, the preliminary data indicates that the volume of water affects the inlet temperature of the water, which subsequently affects the temperature reduction and performance enhancement of the water-cooled module in the closed-loop system. Besides, the inlet temperature of the water is also affected by the effective surface area of the water-cooled module.

KEYWORDS: *Water-cooled photovoltaic module, temperature reduction, performance*

1.0 INTRODUCTION

Renewable energy has been holding its ground as the best alternative to non-renewable energy sources such as natural gas, coal, and fossil fuels, which make up the non-renewable energy group. In this context, solar radiation from the sun plays a strong role in clean energy compared to non-renewable sources. This elemental source of energy has made it viable for the discovery of photovoltaic modules that convert solar energy to electrical energy. In addition to that, PV technology has increased significantly, with an installed capacity of 97 GW in 2019 alone [1]. Albeit PV technology has grown by leaps and bounds over the decades, the improvement of efficiency of the PV modules is still an expanding aspect. This is due to the fact that one of the major drawbacks of this PV module is its low conversion efficiency, which is mainly contributed by the rise in temperature of the PV module that results in overheating [2]. This is because only 20% of the solar radiation reaching the panel is converted into electrical energy; the remaining 80% is converted into waste heat energy by the PV module, which causes a rise in cell temperature with respect to solar radiation intensity [3]. The power output from the PV module is a function of temperature, in which the current across the solar cells increases slightly with increasing temperature, but the voltage across the solar cells decreases significantly. Consequently, the conversion efficiency decreases [4].

Hence, to overcome this drawback, many researchers have integrated water-cooling systems into closed-loop systems to increase the performance of PV modules while also minimising water consumption. For example, Mah et al. [5] conducted an outdoor experiment to investigate the effect of different water flow rates on the performance of closed-loop water-cooled PV modules under Malaysian conditions. It was found that at an optimum flow rate of 6 l/min, the performance of the PV module increased by 15% at peak irradiation. Besides, Basrawi et al. [6] compared the performance of half-cooled and full-surface water-cooled PV modules in a closed-loop system. The temperatures of the half-surface water-cooled and full-surface water-cooled modules were found to be 22.05% and 51.04% lower, respectively, than the uncooled module. reflecting an increase of 6.10% and 13.50% in power output for half-surface and full-surface cooled PV, respectively. On top of that, it was found that the temperature of the water increased by around 6.9 °C at the end of the experiment. Yong et al. [7] integrated an automated PV water spraying technique into the closed-loop system. The author found that the efficiency of PV module was enhanced by 22.14% compared to that of the uncooled module. Notably, the temperature of the water in the tank increases over time. In addition, Hosseini et al. [8] integrated a heat exchanger as a part of the water-cooled PV module in a closed-loop system. It was found that the inlet temperature of the water was lower than the outlet water temperature with the presence of a heat exchanger. As a result, the efficiency increased in the range of 8- 15% compared to that of the uncooled module. Similarly, Yang et al. [9] integrated a geothermal heat soil exchanger to cool a 0.56 m2 area of PV module in a closed loop system at a lower inlet water temperature as well as to maintain the temperature of the water. It was found that the inlet water temperature in the closed loop system was around 29 °C throughout the cooling process. In other words, the inlet temperature of the water was found to be lower than without a ground soil exchanger, and as a result, the performance of water-cooled PV integrated with a soil heat exchanger was better than without a soil exchanger and an uncooled module. On the other hand, Odeh and Behnia [10] cooled the front surface of a PV module and compared the performance by using underground water and direct tank water as a water source. When compared to direct tank water, it was discovered that using underground water to cool the module achieves the best performance.

Although extensive research has been conducted on improving performance in water-cooled PV systems, to the best of the author's knowledge, the effect of water volume in the closed-loop water-cooled PV module has been overlooked. The volume of water in the reservoir is an important parameter. This is because as the water cools the front surface module, the temperature of the water will increase significantly if the volume of water is insufficient to compensate for the rise in water temperature. Ultimately, the reduction in PV module temperature and the increase in performance of water-cooled PV will be compromised as less heat will be taken away from the module surface at a higher inlet water temperature [11]. Therefore, the objective of this study is to study the effect of different sets of water volumes in the closed loop system on the water-cooled PV temperature reduction and performance enhancement with different effective surface areas.

2.0 METHODOLOGY

In this experimental work, three PV modules with different effective areas were tested under indoor conditions with the aid of a solar simulator. Four halogen lamps rated at 150 W were used to simulate the solar irradiation for the 30 W PV module, whereas six and 19 halogen lamps were used for the 30 W and 250 W PV modules, respectively. The technical details of the PV modules are presented in Table 1 and Figure 1.

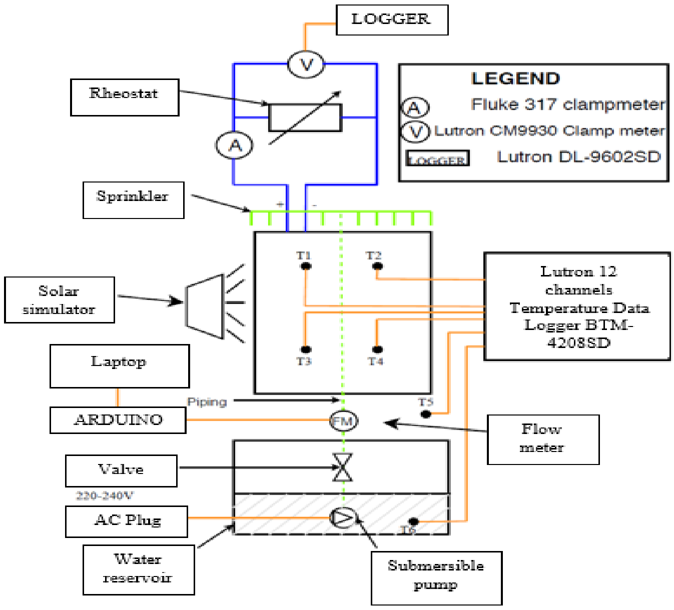

Figure 1: Schematic layout of the experimental setup.

Table 1: Technical specification of PV modules.

Model	Solar TIF-STF-010P6	Venus Solar KL-30W-36P	MYS-60P/B3/CF-250
Pmax [W]	10	30	250
Voc ([V]	21.42	21.6	38.056
Isc [A]	0.66	1.8	9.044
Vmpp [V]	17.28	17.28	29.607
Impp [A]	0.58	1.73	8.563
No.of cells	6	36	60
Effective panel area[m2]	0.068	0.173	1.118

Figure 2 shows the experimental setup for a 10 W, 30 W, and 250 W water-cooled PV module. This study only looked at the effect of different water volume sets on PV module surface temperature reduction and performance enhancement in a closed-loop system. A 10W submersible pump was used in this experiment to lift the water from the water reservoir and force out the water through the sprinkler onto the PV module's front surface. Subsequently, the water is collected underneath the PV module in the water tank after it flows across the PV module surface. Besides, a thin piece of Perspex was attached to the side of the module to prevent the water from spraying out of the PV module.

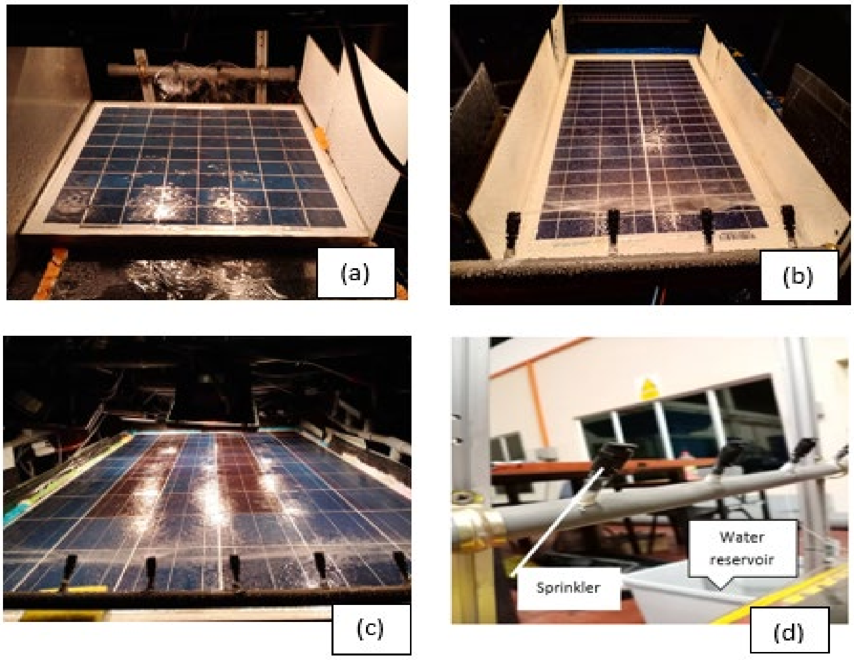

Figure 2:Experimental setup;(a) 10 W water-cooled module, (b) 30 W water-cooled module, (c) 250 W water-cooled PV, (d) Water cooling system.

Table 2 depicts the testing methodology used in this research work for 10, 30, and 250 W PV modules. The 10 W PV module and the 30 W module were tested under 1000 W/m2; however, due to the insufficient number of halogen lamps in the 250 W PV module to simulate 1000 W/m^2, the average solar irradiation falling on the PV module was only 455 W/m^2; as a result, the PV module produces power lower than 250 W for cooled modules and uncooled modules. Despite the limitation, both cooled and uncooled modules were tested under the same value of solar irradiance; therefore, the results can be compared as both have a fair comparison. Furthermore, the flow rates are chosen for 10 W, 30 W, and 250 W are 80, 120, and 400 L/hr, respectively. This is because, at a lower flow rate than the value stated in Table 2, the PV module was not fully established with the water layer, especially at the bottom edge. It is worth remarking that the PV module has to be fully covered with water to produce a significant reduction in temperature.

Table 2:Testing condition of the PV

PV module power [W]	Irradiance[W/m2]	Water flow rate[L/hr]	Volume of water [Litres]
10	1000	80	10,15,20,25
30	1000	120	15,20,25,30
250	455	400	20,40,60,80

Figure 3 shows the measurement setup for all of the testing conditions. The measured parameters in this study are load current, load voltage, the surface temperature of the PV module, water temperature in the tank, solar irradiance, and flow rate. The load current and load voltage were measured by connecting the rheostat of 200 W 4R7J, which has a range of resistance between 1Ω and 200Ω, to the PV modules. The values of voltage and current were recorded using a Fluke 317 clamp metre and a Lutron CM-9930 clamp meter, as shown in Figure 5. The temperature of the PV module and the temperature of the water were measured using K-type thermocouples. The value of temperature was recorded using a Lutron BTM-4208SD 12-channel temperature data logger. All sets of experiments were allowed to run for 30 minutes because, within that time, the PV panel had reached equilibrium. The flow was measured using a YF-S201 flow metre that was connected to an Arduino. The flow rate data was sent from the Arduino to the laptop. On top of that, the water flow rate was controlled using a water valve.

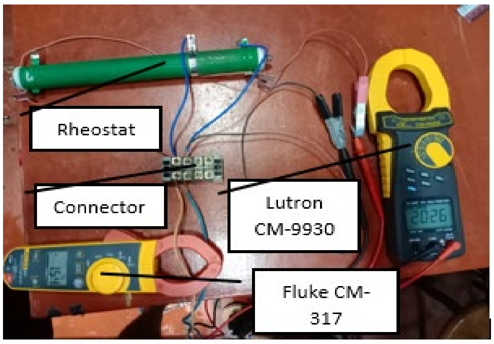

Figure 3: Measurement setup for all testing conditions

The power yield by the uncooled module and the cooled module was calculated using (1). In addition to that (2) was used to calculate the conversion efficiency of the PV module.

$$P = V_{load} \times I_{load} \tag{1}$$

where P is the power output for the PV panel measured in watts [W], V is the measured voltage measured in volts [V], and I is the current measured in Ampere [A].

$$\eta = \frac{P}{G \times A} \times 100\% \tag{2}$$

where P is the power output calculated in watts [W], V is the instantaneous measured voltage [V], I is the instantaneous measured current [A], η is the module efficiency [%], A is the effective module area [m2], and G is the irradiance value [W/m2].

3.0 RESULTS AND DISCUSSION

3.1.1 Relationship between different sets of water volume and the temperature of water

Figure 4 shows the temperature profile for different sets of water volumes used to cool the 10 W, 30 W, and 250 W modules. The colours differentiate the temperature of water for different sets of water volumes. The dotted line, dashed line, and normal line represent the temperatures of the water volumes used to cool the 10 W, 30 W, and 250 W modules, respectively. The initial water temperature for all sets of water volumes was around 28°C–28.2°C. It can be seen that, for 10 W and 30 W water-cooled PV, there was no significant rise in water temperature from the initial temperature for all sets of volumes.

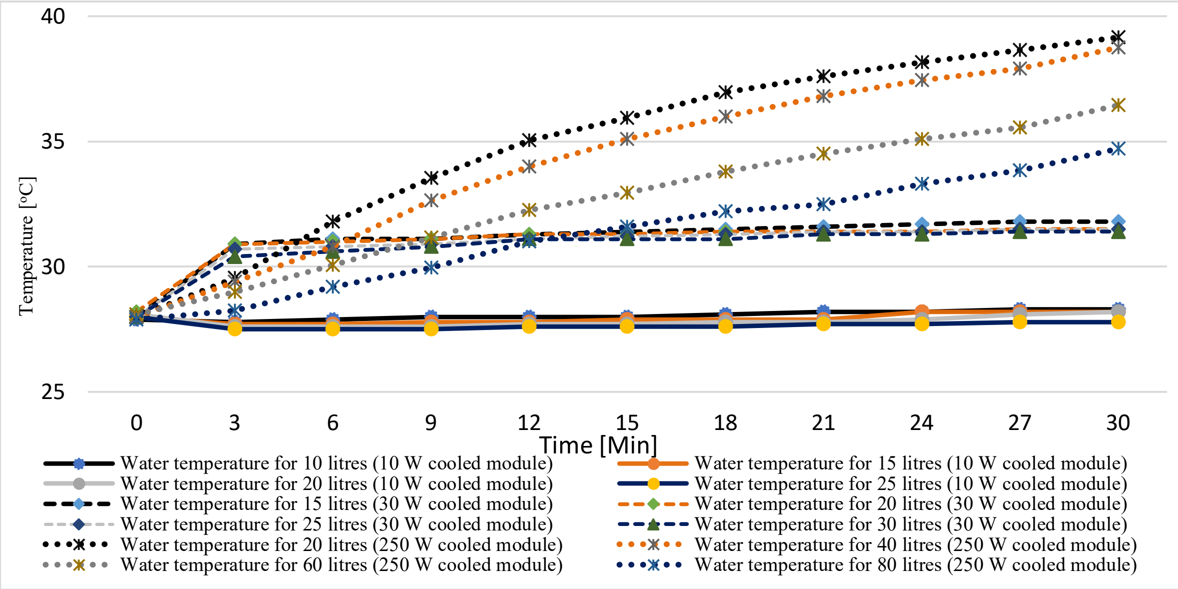

Figure 4: Temperature profile for different sets of water volume

However, when the volume of water is increased, the change in water temperature takes a longer time due to the inverse relationship between the volume of water and the rise in water temperature. Besides, for a 250 W water-cooled module, the rise in water temperature from the initial water temperature was found to be significant for all sets of volumes, where the increment in water temperature decreased significantly from 36% to 25% when the volume of water in the tank was increased from 20 litres to 80 litres. Hence, the trend of the graph indicates that the increase in water temperature is influenced by the volume of water in the reservoir and the effective surface area of water-cooled PV. In other words, the rate of change in water temperature decreases with increasing volume; nevertheless, the rate of change in water temperature increases when the effective surface area of water-cooled PV is greater.

3.1.2 Effect of different sets of water volume on the PV modules surface temperature reduction

The effect of different water volumes on the average temperature of the water and the average surface temperature of modules in a closed-loop system is shown in Figure 5. It can be seen that the uncooled module has the highest temperature in all cases compared to the water-cooled module, where the average temperature of the cooled module at different sets of water volume is suppressed significantly in the range of 53.54-56.81%, 54.46-52.85%, and 49.60-53.47% compared to the uncooled module of 10 W, 30 W, and 250 W, respectively. Besides, the decrement in PV module temperature is highly influenced by the inlet water temperature. For 10 W and 30 W water-cooled PV modules, the increase in water temperature for all sets of water volume from the initial temperature was found to be insignificant due to the smaller surface area of the module, where the heating of water takes a very long period of time, hence the cooling effect of water on the module surface is not compromised. As a result, there were no significant changes in the surface temperature of the PV module when it was cooled using different sets of water volumes. In the case of 250 W, the average increment in temperature of the water has dropped significantly from 25.23%to 11.82% when 80 litres of water are being used to cool the surface of the module compared to 20 litres of water. As a result, the module's average surface temperature was the lowest, at 31.31°C, when compared to other sets of water volumes. In other words, the interpretation of this data indicates that as the temperature of the water increases, the cooling effect of the water on the module decreases as less heat is being absorbed by the water from the module surface. Besides, this data also indicates that there is no need for a heat exchanger to cool the inlet water temperature, but instead a sufficient amount of water according to the effective surface area of water-cooled PV could still maintain the temperature of the water around 29°C as reported in [9], where the cooling effect of the water on the PV module will not be compromised significantly. It should be noted that, under outdoor conditions, there should be enough water in the reservoir based on the effective surface area of a water-cooled PV module to compensate for the rise in water temperature and achieve a better cooling effect.

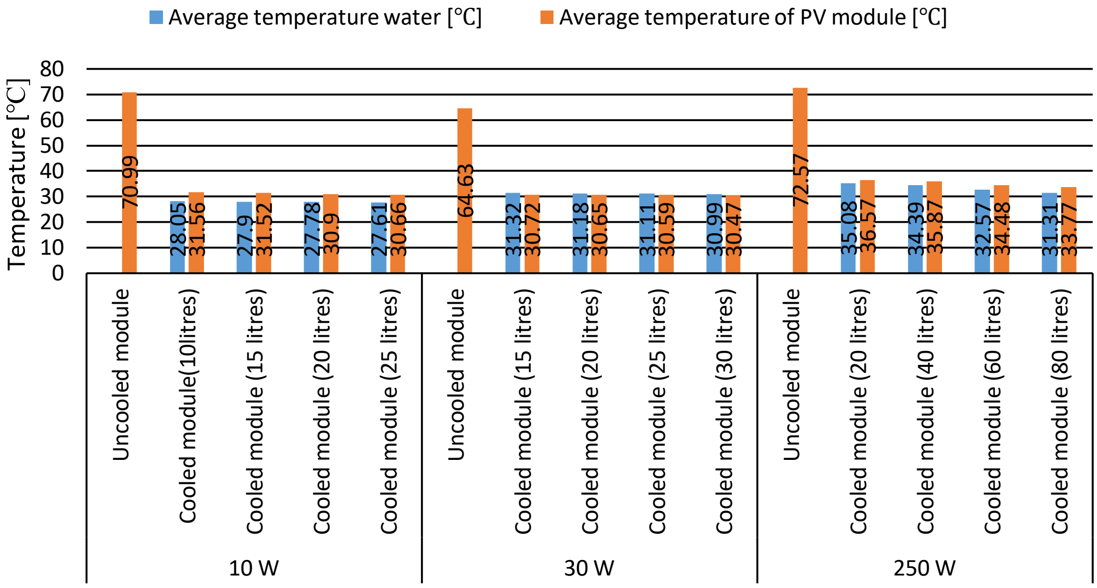

Figure 5: Effects of different sets of water volume on the average temperature of water and average temperature of cooled PV module.

3.1.3 Effect of different sets of water volume on the performance of the PV modules

Figure 6 shows the effect of different water volumes on the average performance of the uncooled and water-cooled modules. The performance of a PV module is a function of its surface temperature. It can be seen that the uncooled module in all cases has the lowest power output and efficiency yield compared to the water-cooled module. For 10 W, 30 W, and 250 W, the average increase in power output is in the range of 27.42–27.68%, 28.27–29.05%, and 33.39–35.32%, respectively, in comparison to an uncooled module. As a result, the electrical efficiency of cooled modules increased in the range of 27.42–27.08%, 28.26–29.03%, and 33.83–35.85% for 10 W, 30 W, and 250 W, respectively. Besides, it can be seen that the increase in performance of the 10 W and 30 W water-cooled modules was found to be insignificant when compared relative to other sets of water volume, as there were no significant changes in the surface temperature of the water-cooled modules. On the other hand, the effect of water volume on the water-cooled 250 W module temperature reduction was found to be significant, where the power gain by the water-cooled PV module increased by around 1.52% when it was cooled using 80 litres of water in a closed loop system compared to that of 20 litres of water. In short, the increasing trend of the performance of water-cooled PV shows that the performance of a 250-watt water-cooled system can be further increased if the volume of water is increased by more than 80 litres, as the rise in water temperature could be further suppressed at a greater volume. Ultimately, a better cooling effect could be achieved.

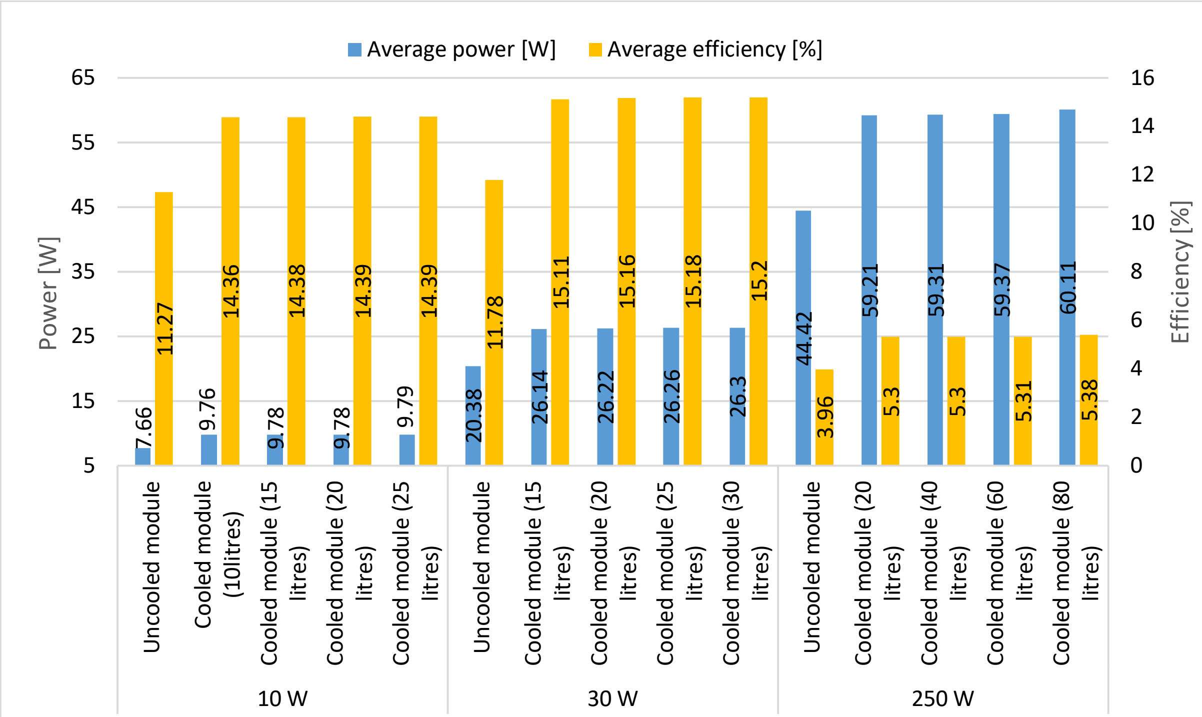

Figure 6: Effects of different water volume on the average performance of water-cooled PV module.

4.0 CONCLUSION

In the present experimental study, photovoltaic modules having different effective surface area was cooled using different sets of water volume in close-loop system to study the temperature reduction and performance enhancement of water-cooled PV module. The highlights of this study are summarized as follows:

- The increase in water temperature is influenced by the volume of water in the water reservoir and the effective surface area of water-cooled PV.
- Different sets of water volume have significant effect on the surface temperature reduction of 250 W water cooled PV module and its performance compared to the 10 W and 30 W water-cooled modules.
- The average temperature of cooled module at different sets of water volume is suppressed significantly in range of 53.54-56.81%, 54.46-52.85 % and 49.60-53.47 % compared to uncooled module of 10 W ,30 W and 250 W respectively.
- The increase in performance of 10 W and 30 W water-cooled module was found to insignificant when it is compared relative to other sets of water volume as there were no significant changes in the surface temperature of water-cooled module due to the smaller surface area of the module, in such the heating of water takes a very long duration in water reservoir, hence the cooling effect of water for all sets of volume on the PV module surface is not compromised.
- The effect of water volume on the water cooled 250 W module temperature reduction were found to be significant as a result the power gain by the water-cooled PV module increased around 1.52 % when it is cooled using 80 litres of water in close loop system compared to that of 20 litres of water.

- Greater the effective surface area of water-cooled module in close loop system, greater the volume of water need in tank is required to suppresses the rise in water temperature to maintain the cooling effect. This suggest there is a unique relationship between volume of water in tank and effective surface area of PV module. Thus, further investigation is needed on this relation.

ACKNOWLEDGEMENTS

The financial support offered by the Universiti Malaysia Pahang under RDU 180313 are gratefully acknowledged.

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