Experimental study of water cooling effect on heat transfer to increase output power of 180 watt peak photovoltaic module

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Abstract. Photovoltaic (PV) modules require solar radiation to generate electricity. This study aims to determine the effect of water cooling PV modules on heat transfer, output power, and electrical efficiency of PV modules. The experiments carried out in this study were to vary the heights of flooded water (with and without cooling water replacement control) and cooling water flow. Variations in the height of flooded water are 0,5 cm, 1 cm, 2 cm, and 4 cm. While the flow rate variations are 2 L/min, 4 L/min, and 8 L/min. The flooded water replacement control will be active when the PV surface temperature reached 45°C. When the temperature dropped to 35°C, the cooler is disabled to let more photon to reach PV surface. The results showed that the lowest heat transfer occurred in the variation of 4 cm flooded water height without water replacement control, i.e. 28.53 Watt, with an average PV surface temperature of 32.92°C. The highest average electric efficiency occurred in the variation of 0,5 cm flooded water height with water replacement control, i.e. 13.12%. The use of cooling water replacement control is better due to being able to skip more photons reach PV surface with low PV temperature.

1 Introduction

The photovoltaic (PV) module is one of the most popular renewable energy products today. PV can convert solar radiation to electrical energy directly. However, only 15% of solar radiation can be converted into electrical energy, while the rest is heat on the PV surface. The electrical efficiency of the PV module will continue to decrease with increasing PV surface temperature [1]. So it can be said that the surface temperature of PV has a vital role in the conversion process, electrical efficiency and output power [2]. Photons in solar radiation cannot be converted entirely into electrical power. In the previous experiments, glass was used as a solar radiation filter to keep the surface PV temperature [3]. However, the amount of solar radiation that passes through the glass filter drops significantly due to the low glass transmissivity of 70%. In this experiment, the water filter is used to keep the surface temperature and keep passing the radiation waves required by PV. For silicon PV cells, only photons with wavelengths below 1.1 μm can produce a photovoltaic effect, the rest will be converted to heat (phonon) and increase the surface temperature of PV cells [4]. Therefore, in this study, water will be used as a cooling fluid, heat transfer will also be conducted to calculate its effect. So it is expected that PV surface temperature can be kept low and electrical efficiency and output power in the PV module can increase.

2 Methodology

2.1 Heat transfer in PV module

The heat transfer occurs when there is a temperature difference. There are three forms of heat transfer processes that occur in this PV cooler module, namely conduction, convection, and radiation. The heat transfer occurring in the PV module is calculated under steady conditions and at one dimension i.e. the y-axis direction. The heat transfer in the form of conduction in the PV module is assumed to be perfect because of the thin plate. The following equations are used in the calculation of heat transfer that occurs in each variation of PV module coolant [4].

In a PV module without a cooling system, the heat transfer occurring to the environment is shown in equation (1),

$$Q_{pv-a} = A\left[h_w\left(T_{pv} - T_a\right) + \sigma\varepsilon_{pv}\left(T_{pv}{}^4 - T_a{}^4\right)\right] \quad (1)$$

$$h_{c,pv-a} = h_w = 8.55 + 2.56v \quad (2)$$

Where A is the area of the PV module (m^2), $h_{c,pv-a}$ is the convection heat transfer coefficient from PV to ambient air (W/m^2K). $h_{r,pv-a}$, is the coefficient of radiant heat transfer from PV to ambient air (W/m^2K). T_{pv} is the temperature of PV, whereas T_a is the ambient air

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temperature (all in Kelvin units). The coefficient of heat transfers by PV to the surrounding wind speed, h_w (W/m^2K) can be calculated using equation (2), with wind velocity range, v, 0 to 5 m/s. Where the wind measurement point is performed at 1 meter above the PV surface [5]

In a PV module with a cooling system using flooded water, the heat transfer that occurs can be calculated using equation (3),

$$Q_{flooded} = Q_{w-a} + Q_{cond,pv-w} + Q_{pv-a} \quad (3)$$

Where the value of heat transfers from above of the flooded water to the surrounding environment can be calculated by equation (4) and equation (5),

$$Q_{w-a} = Ah_{c,w-a}(T_w - T_a) + Ah_{r,w-a}(T_w - T_a) \quad (4)$$

$$Q_{w-a} = A(h_w(T_w - T_a))$$
$$+ A(\sigma\varepsilon_w(T_w - T_a)(T_w{}^2 - T_a{}^2)(T_w - T_a)) \quad (5)$$

Where $h_{c,w-a}$, is the coefficient of convection heat transfer from water to ambient air (Wm^2K), $h_{r,w-a}$ is the coefficient of radiant heat transfer from water to ambient air (W/m^2K). T_w is the water temperature (Kelvin). ε_{pv} is the emissivity of PV of 0.8 [6], and σ is the Stefan-Boltzman constant, of 5,67x10-8 W/m^2K^4.

$$Q_{cond,pv-w} = \frac{k\Delta T}{L} \quad (6)$$

The heat transfers between the flooded water and the upper surface of PV takes place in the form of conduction, due to static flooded water. The value of its conduction can be calculated using equation (6). Where k is the conductivity of water, which value depends on the cooling water temperature [7], ΔT is the temperature difference between PV and the flooded water (Kelvin), L is the thickness of the flooded water layer (meter).

At the bottom surface of the PV module, there is convection heat transfer and radiation to the ambient air, which can be calculated using equation (1). The heat transfers to the environment occur in the cooling water flow variation on the upper surface of PV can be calculated using equation (7),

$$Q_{flow} = Q_w + Q_{pv-a} \quad (7)$$

The heat energy absorbed by the cooling water flow (Q_w) can be calculated using equation (8),

$$Q_w = \dot{m}\, C\Delta T = \dot{m}_w\, C_p(T_{w,out} - T_{w,in}) \quad (8)$$

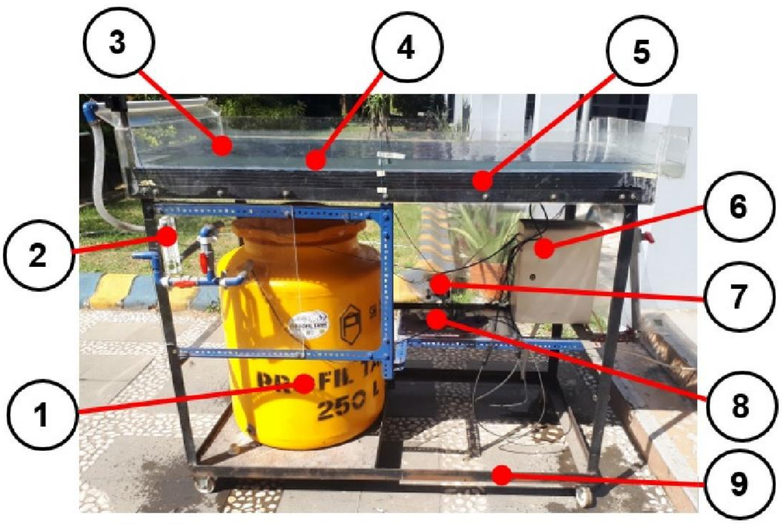
Where $\dot{m}_w$ is the flow rate of cooling water mass (kg/s), C_p is latent heat [7]. $T_{w,out}$ and $T_{w,in}$ are respectively the exit and inlet temperature of the cooling water. While for convection heat transfer and radiation from the bottom surface of PV to the surrounding air, Q_{pv-a} (Watt), can be calculated using equation (1). The electrical performance of PV modules can be determined by calculating electrical efficiency using equation (9),

$$\eta = \frac{V \times I}{A_c \times I_r} \times 100\% = \frac{P}{A_c \times I_r} \times 100\% \quad (9)$$

Where P is the power output of PV, is the product of the voltage (V) and current (I) in a loaded condition. Electrical efficiency is the ratio between output power and input power. Output power is the measured power generated by the PV module during load conditions. While the input power is the energy given by solar radiation (I_r) on a surface area of the PV module (A_c).

2.2 System Design

In this study will be examined the effect of variation of elevation of flooded water and cooling water flow to heat transfer and PV power output. In this study, there are two important methods performed to cool PV.



Information:

1. Reservoir of water
2. Flowmeter
3. Cooling water barrier
4. Cooling water
5. PV module
6. Data logger
7. Display control and sensor readings
8. DC load
9. Support frame

Fig. 1. The result of fabrication of PV cooling system module.

The first method is by using a flooded water, where the method is divided into two, i.e. with and without control. The use of the control is intended to activate the cooling system when the surface temperature of PV has exceeded the specified maximum limit, ie 45°C. The use of the control is also used to remove the flooded water when the PV temperature has dropped to 35°C, and so on this control cycle goes. The heat transfer value is compared to the output power. So it can be seen how temperature and heat transfer affect the electrical performance of PV modules. The module design is adapted to the variations used with varying flooded water heights (with and without control) of 0,5 cm, 1 cm, 2 cm, and 4 cm. The cooling water will also be discharged with discharge variations of 2 L/min, 4 L/min, 8 L/min, on the top surface of the PV module.

2.3 Testing

The test is in the area of Electronics Engineering Polytechnic Institute of Surabaya lat. 7,27 S 112,79 E. Testing and data retrieval is done from 9 a.m. to 3 p.m. starting from 17 June 2017 - 12 July 2017 for all variations. Data was taken using data logger and then processed into several graphs.

Figure 2 shows the test measurement points in this study. Under the IEC 60891 standard and journals [8,9,10], the temperature of the PV module is placed at the geometry center/center of the module's lower surface.

3 Results and Discussion

Testing of PV module with and without cooling variations had conducted on June 17, 2017, to July 12, 2017. So the value of solar radiation intensity received by PV modules in each variation is also different.

Based on the intensity of solar radiation received in variations in Fig. 3 (a), it can be seen that PV without cooling system and without the control of water replacement obtain the greatest solar radiation with an average intensity of 770 W/m^2. Trend graphic shows the amount of solar radiation received is in the form of parabolic.

The peak value is 920 W /m^2, at 12 a. m. While the peak value of solar radiation intensity on the cooling variation is at 12 a. m., with the radiation intensity being approximately the same, about ±800 W/m^2. The weather during testing is average in bright and cloudy conditions. Whereas in the variation of PV module cooling, the highest average radiation intensity occurred in the variation of flooded water without replacement of cooling water was 730 W/m2, at 4 cm flooded water height.

For the replacement of flooded water variation (Figure 3 (b)) with the highest average radiation water change of 706 W/m^2 at a variation of 2 cm. For variations of coolant flow discharge above the PV surface, the highest average radiation intensity value is 747 W/m^2 in 4 L/min variation (Figure 3 (c)).

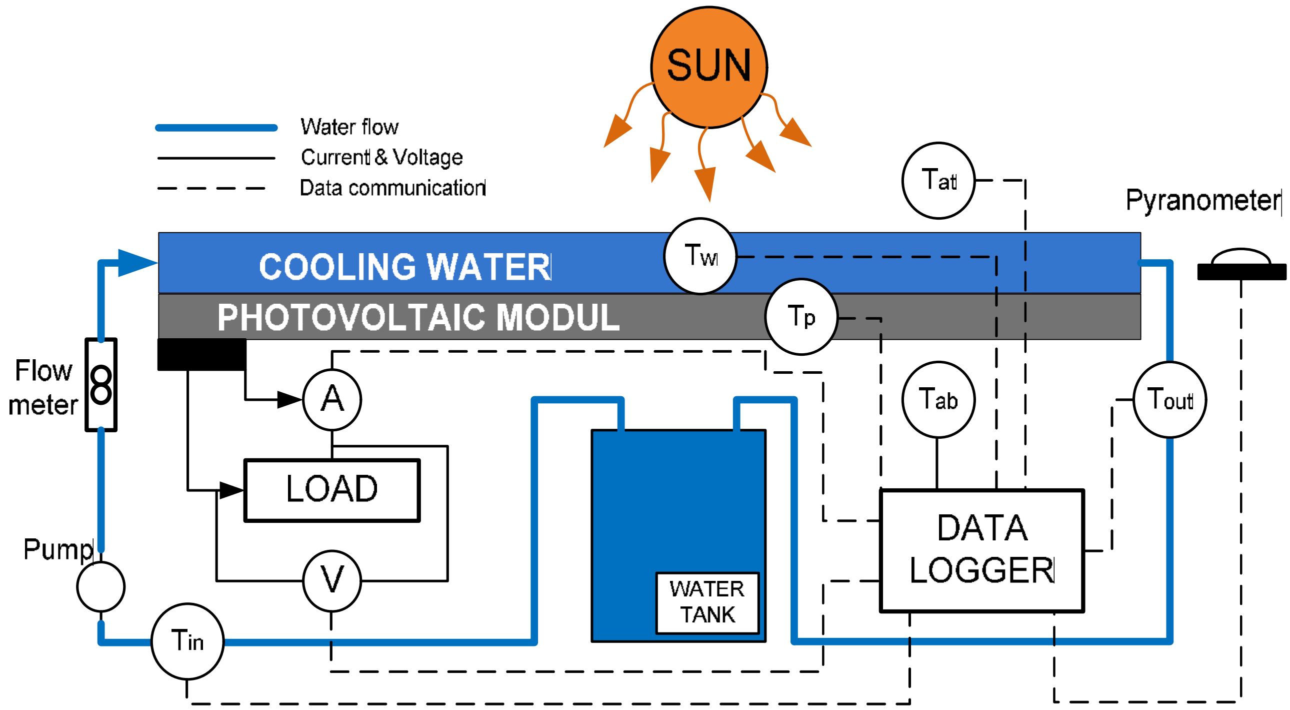


Fig. 2. Testing scheme of PV cooling system module.

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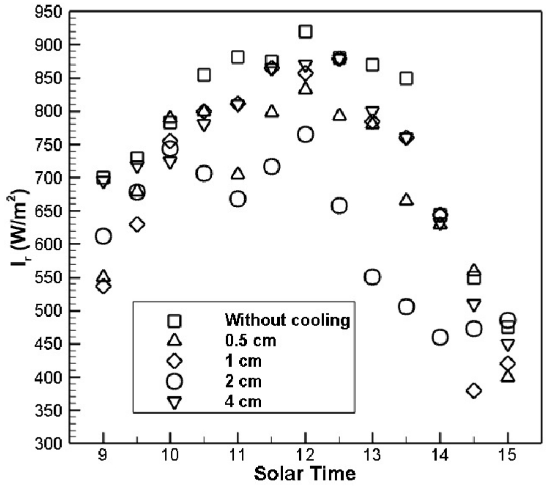
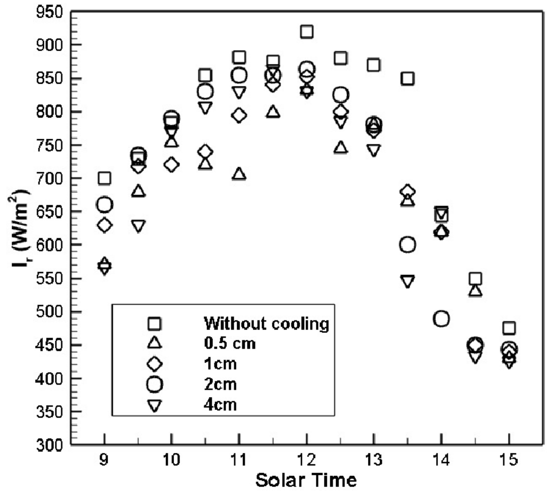
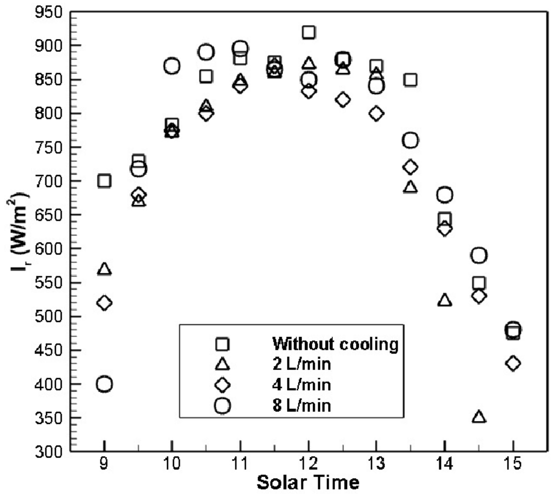


(a)



(b)



(c)

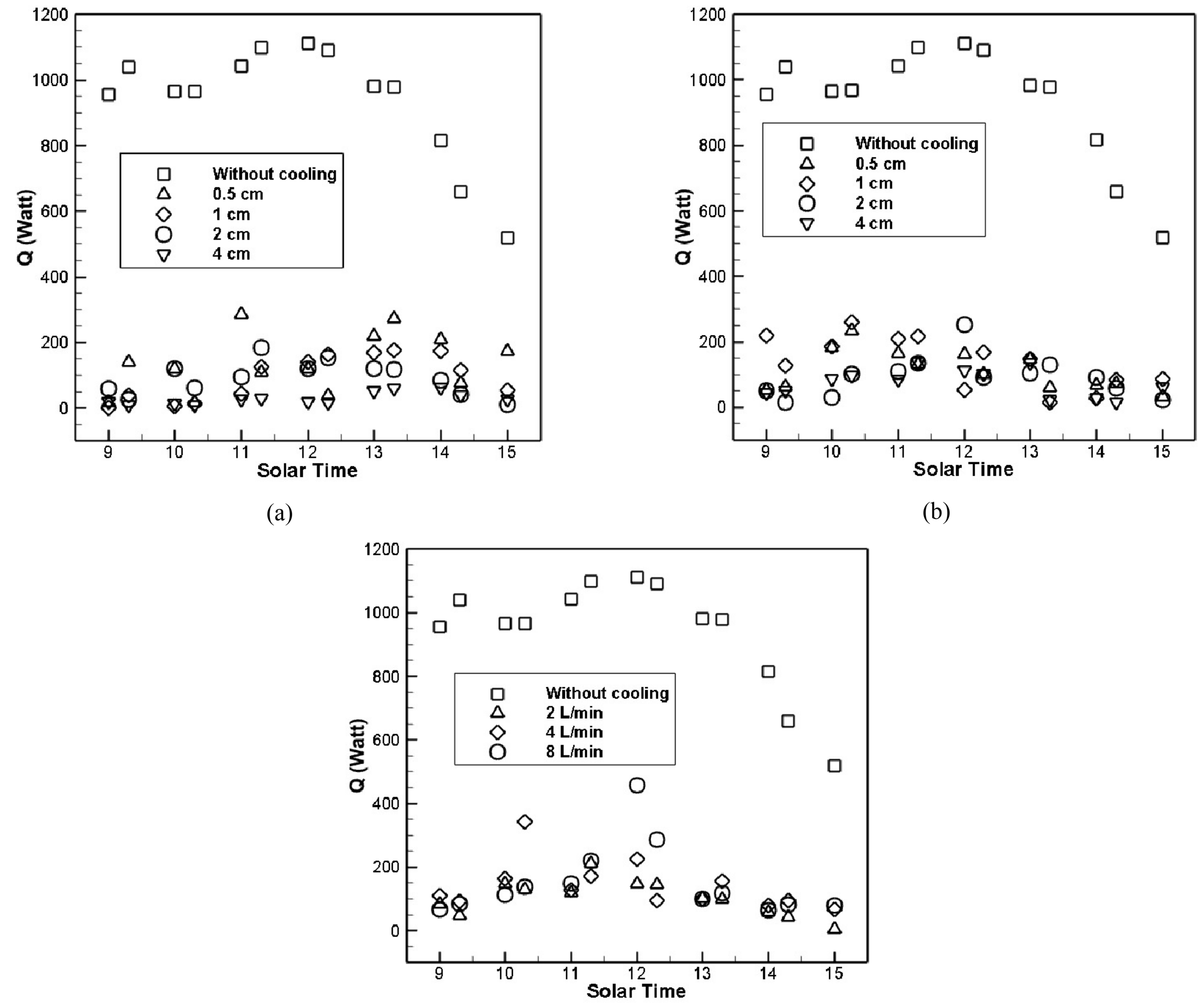
Fig. 3. Intensity of solar radiation over time variation (a) flooded water without replacement of cooling water, (b) flooded water with activation control, (c) water flow.

The heat transfer that occurs in each variation shows the amount of heat energy released by the PV module into the environment. The heat transfer value (Q) in each cooling variation is shown in Figure 4. It can be seen that the largest average thermal energy value dumped into the ambient air under conditions without a cooling system is 940 Watt. Whereas in the variations of flooded water without water replacement control, it can be seen that the value of heat transfer from system to the environment has decreased drastically (Figure 4 (a)).

Where the largest decrease occurred in the variation of 4 cm flooded water height, with the average heat transfer value in this variation is 28,53 Watt. In this test, the heat transfer is affected by the wind speed, ambient temperature, and PV module temperature. The value of heat transfer to the environment in the variation of 4 cm has the highest decrease compared to PV without a cooling system. This is because the temperature difference between the surface of the PV module and the environment is getting smaller due to the cooling process. Cooling process with flooded water is strongly influenced by the thickness of the water layer which uses the principle of conduction to absorb heat energy.

In Figure 4(b), we can see the value of heat energy discharged into the surrounding air and the environment in the use of variations in the height of the cooling water inundation with the control of water replacement. The principle of heat transfer that occurs is the same as variation. Whereas when the cooling system is not active, there will be heat transfer by natural convection and radiation to the environment. The average value of heat transfers at variations in height 0,5 cm, 1 cm, 2 cm, 4 cm respectively is 114,03 Watts; 138,48 Watts; 91,47 Watts and 74,92 Watts. The highest mean heat transfer value in the variation of the replacement control of flooded water height 1 cm i.e. 138,48 Watt.

Heat transfer in the variation of the cooling flow discharge above the PV surface is affected by the mass flow rate of the cooling flow above the PV surface shows in Figure 4(c). The greater the discharge flowing, the greater the mass flow rate.



(a) (b)

(c)

Fig. 4. Heat Transfer over time variation (a) flooded water without replacement of cooling water, (b) flooded water with activation control, (c) water flow.

The greater the mass flow rate, the heat energy absorbed from the PV surface will also become larger. The greatest value of heat energy discharged in succession is the discharge variation of 8 Liters/minute of 150,82 Watts, 4 Liters/minute of 140,32 Watts, and 2 Liters/minute of 103.78 Watts.

Heat transfer in the variation of the cooling flow discharge above the PV surface is affected by the mass flow rate of the cooling flow above the PV surface shows in Figure 4(c). The greater the discharge flowing, the greater the mass flow rate. The greater the mass flow rate, the heat energy absorbed from the PV surface will also become larger. The greatest value of heat energy discharged in succession is the discharge variation of 8 Liters/minute of 150,82 Watts, 4 Liters/minute of 140,32 Watts, and 2 Liters/minute of 103.78 Watts.

The value of heat transfer is proportional to the value of the surface temperature of PV showed in Figure 5. Figure 5(a) shows that the temperature of the PV system without the cooling system is the highest, with an average value of 56.46°C. While the average surface temperature of PV with water use puddles 0,5 cm, 1 cm, 2 cm, 4 cm respectively is 37,72°C; 35,6°C; 35,16°C; and 32,92°C. This reduction in temperature is strongly influenced by the thickness of the cooling water pool. The value of the surface temperature is proportional to the value of the heat transfer that occurs.

The average PV module temperature with the use of a water cooling system with water replacement control (Figure 5(b)) has decreased slightly compared to the variation of cooling water inundation without the water replacement process. Although the PV temperature has increased when the cooling system is inactive. However, this increase is offset by a decrease in temperature when the cooling system is active when the maximum set point of temperature, 45°C is reached. The temperature of the water also did not experience a significant increase in temperature because it would immediately be discharged when the PV temperature reached 35°C. So the value of the inundation temperature becomes not too hot. The average temperature value on the variation of 0,5 cm, 1 cm, 2 cm, 4 cm respectively is 34,13°C; 35,48°C; 34,34°C; and 35,23°C. This decrease in surface temperature is not too much affected by the thickness of the cooling water pool, due to continued replacement. The height of this cooling water puddle affects the cooling duration and cooling activation frequency.

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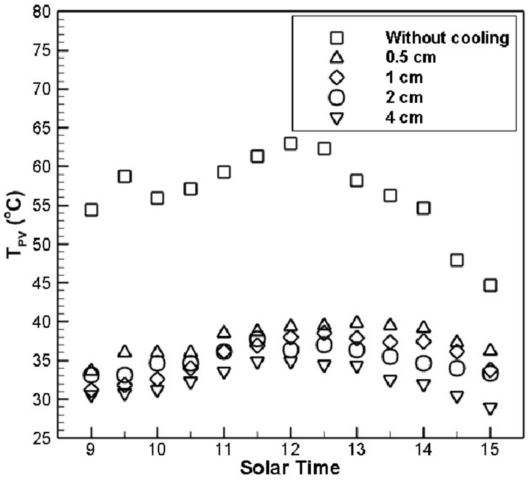
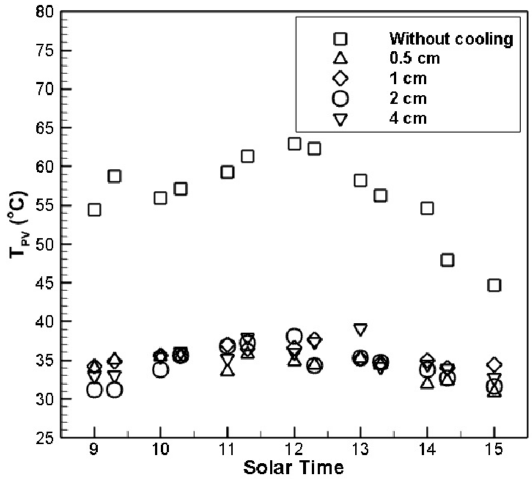


(a)



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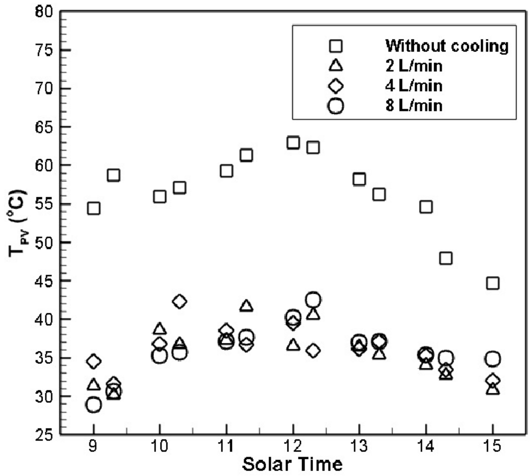

(c)

Fig. 5. PV Temperature over time variation (a) flooded water without replacement of cooling water, (b) flooded water with activation control, (c) water flow.

However, in Figure 5(c) the value of the average surface temperature of PV on the variation of the flow rate of the cooling water flow shows a similar value, ± 36°C. This is because the value of PV temperature depends on the activation of the cooling water flow when the maximum temperature set point, 45°C is reached. Cooling water flow will be inactive when the PV temperature has dropped to 35°C. Variations in the flow rate of this cooling water flow affect the length of the cooling process. PV surface temperature values respectively 56,46°C in PV without cooling system, 35,63°C in variation 2 L / min, 36,17°C in variation 4 L / min, and 35, 97°C at 8 L / min.

The output power of PV modules is very dependent on two parameters, the intensity of solar radiation received and the surface temperature. The greater intensity of solar radiation affects the increase in output electric current of PV. However, with the rising intensity of solar radiation, will be decreasing the output voltage of the PV module, while increasing the current is not too significant. It is the reason why the output power and electrical efficiency decrease. The cooling method used to reduce the surface temperature of PV with the best heat transfer value cannot improve the electrical performance of PV modules. The electrical performance of PV modules still depends on whether the cooling used blocking or reducing the sunlight waves (photons) are received by the PV module.

In Figure 6 (a), it can be seen that the use of a cooling water inundation system along the test on the top surface of PV can increase the output power. Where when without using the cooling system the maximum output power only reaches 106 Watts, at 1:00 p.m. Whereas by using a variation of 4 cm cooling water inundation height, the maximum power that can be produced by PV is 149.3 Watts at 10.30 a.m.

In the variation of the height of the cooling water inundation in Figure 6(b) with the control of cooling water replacement, the results obtained are different from standing water without replacement of water. Cooling is only done when the temperature reaches the maximum set point, 45°C. This allows PV to receive more portions of the sun's intensity without being blocked by coolers at temperatures that remain low. The highest average output power in this method is generated at a variation of 0,5 cm inundation altitude, at 114 Watts. At a variation of 1 cm, 2 cm, and 4 cm height respectively 110,1 Watts; 104,6 Watts and 96,1 Watts.

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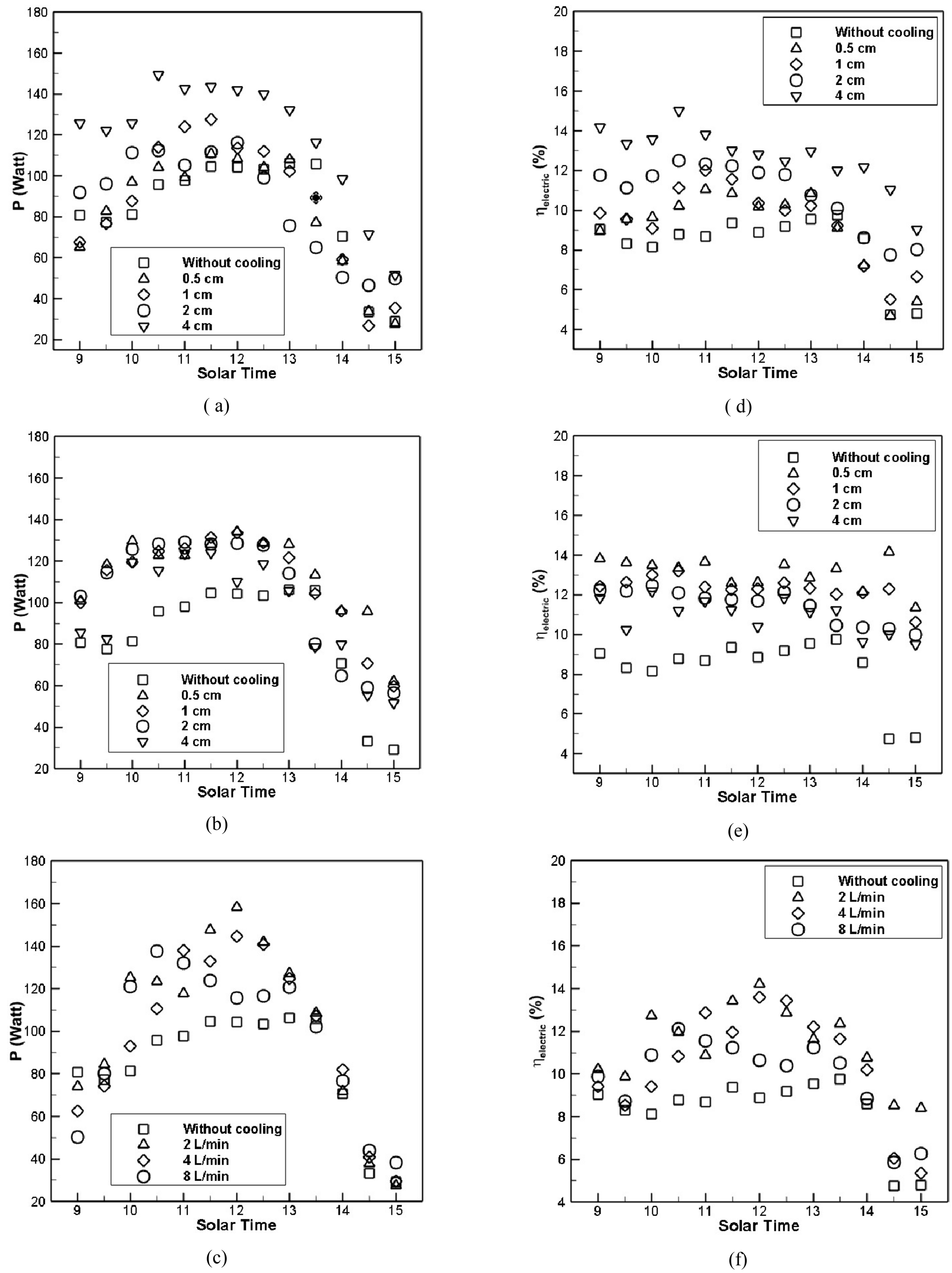

Fig. 6. Output power over time variation (a) flooded water without replacement of cooling water, (b) flooded water with activation control, (c) water flow and electrical efficiency over time variation (d) flooded water without replacement of cooling water, (e) flooded water with activation control, (f) water flow.

While PV without a cooling system, the output power produced is only 83,9 Watts.

Figure 6(c) shows the average output power of PV with a cooling method using flowing water. The highest value produced in the variation of 2 L / min is 103,6 Watt. In the variation of 4 L / min and 8 L / min respectively were 98,55 Watts and 96,85 Watts. While PV without cooling system the output power produced is only 83,9 Watts.

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Based on the picture in Figure 6(d), it can be seen that the higher the pool of cooling water can keep the surface temperature of the PV remains low and increase electrical efficiency. However, the use of cooling water inundation becomes contradictory when cooling water inundation has increased in temperature and causes an increase in the surface temperature of PV, at 0,5 cm variation, starting at 1.30 p.m. until 2.30 p.m. when the cooling water temperature has increased. Cooling water is also not too significant to increase electrical efficiency when the radiation intensity is low and the PV temperature is not too hot. In this condition, the presence inundation of water actually inhibits photons from reaching the surface of PV.

Figure 6(e) shows that the variation of the 0,5 cm inundation control has the highest average electrical efficiency, which is 13,12%. While the lowest electrical efficiency in cooling variation is the use of a 4 cm inundation height, which is 10,92%. Electrical efficiency at 1 cm and 2 cm inundation heights were 12,32% and 11,45% respectively. By looking at the average value of the electrical efficiency obtained, it can be seen that all cooling variations experience an increase in electrical efficiency compared to PV without a cooling system. The magnitude of the increase in efficiency from the lowest inundation heights was 58,07%; 48,43%; 37,95%; and 31,56% respectively. The amount of electrical efficiency in this method is greatly influenced by the process of filling inundated water in each variation.

The higher of water volume, longer the time to pool filling. This filling process is very influential on the photons received by PV because of the influence of wavy puddle water ripples, so it tends to reduce the PV output current.

To determine the improvement in PV performance must consider the input and output energy in the system. The output power produced must consider the input energy it receives, namely the radiation intensity received in the PV area. Electrical efficiency values are used to show the ratio of output energy per input in PV.

So that PV performance can be compared precisely. The average value of electrical efficiency in the variation of flow discharge showed in Figure 6(f) i.e. 2 L / min, 4 L / min, 8 L / min respectively is 11,38%; 10,43%; and 9,86%. In the variation of 2 L / min, 4 L / min, and 8 L / min there was an increase in electrical efficiency compared to PV without a cooling system, with a successive increase of 37%; 25,7%; and 18,8%.

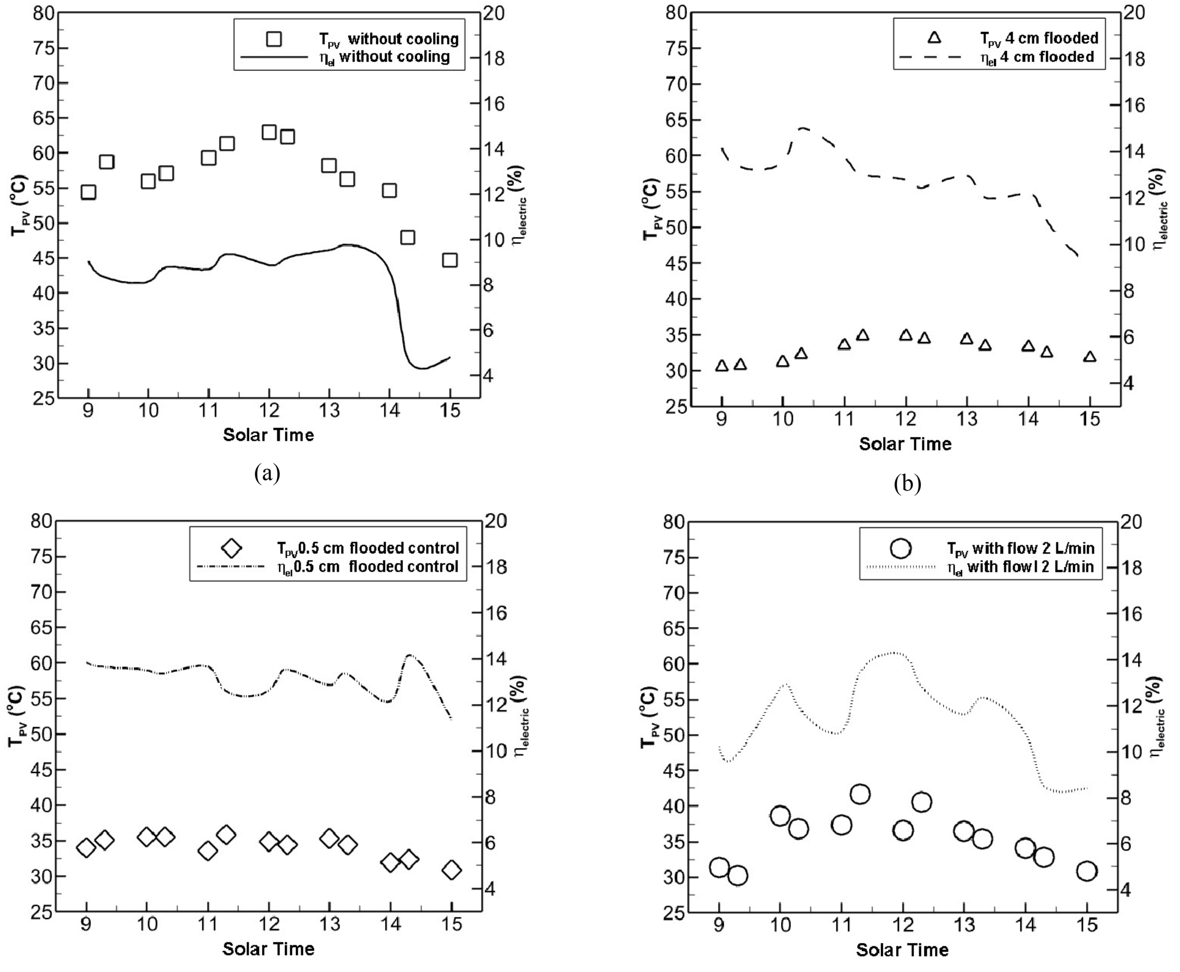

Fig. 7. (a, b, c, d) Relation of surface temperature to PV electrical efficiency to time at the best variation in each cooling method

The increase in electrical efficiency in this variation is quite low compared to the method of cooling water inundation. This can be due to the cooling water flow causing water ripples that have the potential to block or reflect sunlight so that the light intensity received by PV decreases. The increase in electrical efficiency in the Figure 6(d) – 6(f) is affected by the temperature of PV and the intensity of radiation that can be passed to the PV surface. The use of cooling media should also take into account the amount of light that is passed at low temperatures. This is evidenced by the higher electrical efficiency of the cooling system by using 0,5 cm flooded water height when the specified maximum temperature is reached. While the temperature has dropped, the discharge of cooling water allows the higher output power due to the increased voltage, the output current also increases as there is no obstacle above the PV.

In Figure 7 shows an increase in PV surface temperature which is still below 40°C also does not affect the efficiency. This is in accordance with Fig. 5, where in the temperature of 40°C is the maximum PV temperature limit without decreasing electrical efficiency. Under conditions 40°C which is the standard limit which PV begins to depend on temperature, the increase in electrical efficiency is more affected by the intensity of solar radiation received by the PV surface. An increase in temperatures having values below 40°C does not significantly affect electrical efficiency.

4 Conclusion

Based on the results of testing on PV cooling module with variation of flooded height (with and without control) and variation of coolant flow discharge, it can be concluded that:

1. The use of height variation of 4 cm flooded water without water replacement control resulted in smallest average heat transfer value to environment about 28,53 Watt.

2. Variations of 4 cm flooded water without replacement of cooling water produces the highest average output power about 120,1 Watt.

3. Electrical efficiency is affected by heat transfer and solar light intensity received by PV. Variation of 0,5 cm flooded water cooling with water replacement control yielded the highest average electrical efficiency value of 13,12%. This efficiency value in the variation of 0,5 cm flooded water with water replacement control is slightly higher than efficiency value in the variation of 4 cm without water replacement control i.e. 12,71%.

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