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https://doi.org/10.5109/6782151

出版情報：Evergreen. 10 (1), pp.480-488, 2023-03. 九州大学グリーンテクノロジー研究教育センター
バージョン：

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(Received September 6, 2022; Revised March 24, 2023; accepted March 24, 2023).

Abstract. Temperature increases in photovoltaic (PV) cause reduction of PV efficiency. Some cooling technologies were proposed by researchers, both active and passive method. However, until recently, there is no implementation of PV passive cooling technology intended toward Floating PV (FPV) application. The objective of this study is to determine the performance of the thermosiphon passive cooling system for FPV array. Experiment results shows that floating PV array fitted with thermosiphon passive cooling system has lower module temperature of 41.11°C compared to floating PV array without thermosiphon cooling system, i.e. 49.57°C, and PV on ground temperature of 51.61°C. The lower PV temperature improves electric efficiency of floating PV array with thermosiphon by 27% compared to floating PV array without thermosiphon by 8.18%, both relative to ground PV array efficiency.

Keywords: Photovoltaic; Floating PV; Efficiency; Passive cooling; Thermosiphon

1. Introduction

Renewable energy plays a vital role in energy transition[1)] and self-sufficiency in energy[2)] as decarbonization are starting to become long term goal for many nations[3)]. Solar energy is virtually available anywhere, thus utilization of PV will reduce geographical limitation to supply electricity for rural area[4)5)6)].

A PV module suffers from reduced performance along with the increase in module temperature. Elevated temperature has a significant impact to PV module by decreasing its open circuit voltage, thereby lowering the power output and efficiency. Floating PV (FPV) is an emerging concept to take advantage of lower temperature environment thus more desirable for PV operating condition. Cooling effects are expected to reduce PV temperature by 3.5°C and improved efficiency by 1.58%[7)]. FPV is also potential for coordinated operation with hydropower plant which could reduce intermittency and preserve water level during drought periods[8)].

The cooling techniques are then studied and developed to prevent further PV module temperature rise. The PV module cooling techniques are divided into two main techniques, namely active cooling, and passive cooling. Either active or passive cooling method, usually utilize air or water as a heat transfer fluid.

An active cooling method is distinguished by forced cooling fluid flow or circulation by fluid machinery. Several experimental studies about active cooling have been carried out. An active water-cooling method is evaluated experimentally. A water stream was applied on front surface of the PV module through twelve nozzles. The PV module temperature was decreased from 60°C to 38°C and reported efficiency gain was from 10.5% up to 12.0%[9)].

Active cooling technique based on water was applied to PV system comprised of six monocrystalline PV modules each rated at 185 W, while cooling water is stored in 0.3 m^3 water tank. Test location for the PV system was Cairo with the range of solar irradiation is 600 W/m^2 to 800 W/m^2. The cooling system is activated only when PV system overall temperature is reached 45°C. Cooling system will remain active until PV system target temperature is achieved, which is at 38°C. The cooling water will flow on the top surface of PV system at the controlled flow rate of 29 L/min. According to report, applying the cooling system was able to maintain PV systems efficiency at elevated PV module temperature. PV system efficiency was 12.5% at 45°C and 7.5 % at 65°C, while reference efficiency was 12% at 35°C[10].

Another active cooling technique is water spray cooling on the PV panel. It reduced their temperature, increase the power generation, and enhance the system efficiency by approximately 12.5%[11]. Double active cooling techniques was applied to 20 W polycrystalline PV module. The cooling techniques are comprised of water spray on the front surface of PV module and direct water flow on the back side of PV module. The experiment was done at UAE (Sharjah) with solar irradiation ranged from 849 W/m^2 to 863 W/m^2. The PV module temperature was decreased by 0.7°C to 7.7°C, and efficiency was also increased by 2.1% to 4.0%[12]. Cooling technique with a water spray was developed for 50 W monocrystalline PV module. The experimental set up was comprised of water nozzles mounted on the front and back side of PV module. The cooling system was tested at Mediterranean with solar irradiation ranging from 810 W/m^2 to 850 W/m^2. The best result was obtained when front side and back side of the PV module is cooled simultaneously. PV module temperature was reduced by 30°C, and efficiency was improved by 14.3 %[13].

Compared to active cooling technique, the passive cooling technique is less appealing for PV application since its cooling performance was generally lower than active cooling. Despite the difficulty of applying passive cooling for PV application, several researchers have overcome the challenge and were able to develop solutions. The use of phase changing material (PCM) is studied as PV module passive cooling method. The PCM was based on yellow petroleum jelly (vaselinum flavum) which was packed inside a rectangular aluminum tube and then fitted on the backside of the PV module. Two PV modules were used during the study, one PV module used PCM, the other module was kept unmodified as a reference. The experiment was done under tropical climate condition (Bandung, Indonesia) with recorded peak solar irradiation was 1049.5 W/m^2. Reported average power and efficiency gain were 7.3 % and 6% respectively[14].

Photovoltaic thermal (PV/T) hybrid system is developed to improve PV module performance and domestic hot water production. The experiment was done at Tehran, Iran with maximum irradiation of around 920 W/m^2. The PV/T system works by flowing a stream of water on back side of PV module. The idea of the cooling technique is to decrease PV module's temperature while also reduce energy required to provide hot water because the water is already preheated while passing through backside of the PV module. This cooling technique yields in PV module's efficiency improvement from 10.9% to 12.3% and thermal efficiency of PV/T of 49.4%[15].

Air based passive cooling method is investigated by attaching aluminum fins on the back side of a PV module. Two 250 W PV modules were used during the experiment, one of the modules were incorporated with aluminum fins. An intermittent water stream also introduced to provide additional cooling effect for PV module with fins. The other PV module is remained unmodified and receive no additional cooling effect. A 3% efficiency gain is achieved by PV module with multi technique cooling method[16].

A PCM based on crude palm oil (CPO) was tested to reduce PV module temperature. The PCM was packed inside rectangular aluminum tube which then fitted on the backside of a 50 Wp PV module. Two PV module were used during the study, one of which were kept unmodified as a reference. Experiment was conducted under tropical climate condition with recorded peak solar irradiation was 1037 W/m^2. The addition of PCM was able to improve PV module performance, average electrical efficiency was increased from 6.42% to 7.72%, and average power was increased from 14.78 W to 17.87 W[17].

The utilization of PCM is proven to be able to improve PV module performance by preventing further temperature rise, however PCM addition to a PV module result in weight addition. A heavier PV module requires stronger fixtures for installation, hence hindered utilization of PCM as a passive cooling technique for larger scale PV installation.

Novel PV passive cooling concept. Is studied with the aim to investigate whether the passive cooling system, which work based on water circulation driven by thermosiphon effect is applicable for floating PV application. A transient condition with fluid's properties as a function of temperature (piecewise-linear) was simulated to analyze the fluid-flow driven by buoyancy effect in thermosiphon system. The temperature distribution of PV module was also observed in this work. Simulation results showed that water circulation driven by thermosiphon effect can be applied as passive cooling for PV[18].

Additionally, the potential application of nano fluid as a cooling fluid in thermosiphon passive cooling technology. Al_2O_3-water nanofluid was numerically investigated by using two-phase mixture model approach. A laminar flow condition was selected to present the benefit of nanoparticle addition particularly at low velocity favorable for engineering application. The cooling fluid steadily flows in 5 mm channel along 1 m horizontal PV panels. Al_2O_3-water nanofluid mixture was varied by vol.% of 0 (pure water), 0.5, 1 and 2 vol.%. Al_2O_3 nano particles were assumed to have perfect ball shape with uniform and constant properties. According to result, the 2% vol.% Al_2O_3-water nanofluid at Reynold number of 500 yields in PV operating temperature reduction up to 303 K. It is revealed that the volume fraction of nanoparticles has a proportional relationship to thermal conductivity and specific heat of nanofluid[19].

Based on its working principle, the thermosiphon passive cooling system will be suitable for floating PV (FPV) application. The reason is that a water body is available as a heat sink for cooling-fluid circulation driven by thermosiphon effect. According to data from World Bank the world annual installation of FPV shows growth since 2014. The reason behind FPV technology starts to emerge is because of performance gain for PV[20]. Generally, FPV has lower module temperature by 5°C to 10°C compared to conventional ground PV. Overall, performance of Floating PV system is better than PV system on-ground[21].

This research is emphasized on developing and testing the thermosiphon passive cooling system for FPV application with multiple PV module arrangement (PV Array) in real environment condition. The essence of this study is to investigate whether the thermosiphon passive cooling system can deliver performance gain for FPV when up scaled and tested at actual water reservoir.

1.1 Temperature effect on photovoltaic efficiency

The efficiency is common parameter to assess the performance of solar cell. Solar cell efficiency is defined as the ratio of energy produced by the solar cell to energy input from solar irradiation. Solar cell efficiency can be given as [22] :

$$P_{Max} = V_{OC} I_{SC} FF \tag{1}$$

$$\eta = \frac{P_{Max}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{I \times A} \tag{2}$$

Where V_{OC} and I_{SC} are open circuit voltage and short circuit current respectively, where I and A are solar irradiance and solar cell area respectively. The PV efficiency is influenced by intensity of the incident sunlight and the temperature of solar cell. Similar with semiconductor, solar cell is strongly influenced by temperature. The open-circuit voltage of solar cell is most affected by an increase in temperature. The open-circuit voltage decreases with temperature, hence reducing power output and efficiency of solar cell. The temperature effect on a PV electrical efficiency is governed by following equation [23] [24]:

$$\eta_C = \eta_{Tref}\left[1 - \beta_{ref}\left(T_C - T_{ref}\right) + \gamma log_{10} I\right] \tag{3}$$

Where h_{ref} is the PV electrical efficiency at the reference temperature T_{ref} and at solar irradiance of 1000 W/m^2. The temperature coefficient (b_{ref}) and the solar radiation coefficient (g) represent PV material characteristic. For crystalline silicon modules, the solar radiation coefficient is usually considered as zero. Hence, Eq. 3 is reduced to Eq. 4 which well known as linear expression for the PV electrical efficiency, Evans and Florschuetz[25].

$$\eta_C = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \tag{4}$$

Crystalline silicon-based PV usually having b_{ref} value of 0.0045[24]. The value of h_{ref} and b_{ref} is usually provided by the PV module manufacturer, however those values can be obtained by quick testing the PV module, in which the electrical output of the module is measured at two different temperatures for a fixed radiation flux. The actual temperature coefficient is not only dependent on PV's material properties but also on reference temperature. The relation is presented by Eq. 5 [26]:

$$\eta = \frac{P_{Max}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{I \times A} \tag{5}$$

T_o is the maximum temperature when electrical efficiency of PV is zero. For crystalline silicon PV, this temperature is 270°C[24].

2. Materials and methods

The experiment has been carried out at Saguling hydro power plant (HPP) facility, West Java, Indonesia (-6.89944°S, 107.37417°E). Area in the perimeter of Saguling HPP water reservoir are free of shading effect and therefore suitable location for testing. The water body is mostly calm with minimum ripple induced by wind. This study utilized two units of PV arrays, one of which will be fitted with thermosiphon passive cooling system and another unit will remain unmodified. The PV module specification is listed in Table 1.

Table 1. Specification of PV module.

Property	**Characteristic**
Cell type	Polycrystalline silicon
Maximum power (PMPP)	125 Wp
Short circuit current (ISC)	7.7 A
Open circuit voltage (VOC)	22.5 V
Efficiency (Max)	14.6 %
Voltage at maximum power point (VMPP)	17.8 V
Current at maximum power point (IMPP)	7.3 A

The unmodified PV array unit is designated as PV array A, whereas the other one which would be fitted with thermosiphon passive cooling system is designated as PV array B. The experiment was conducted under two condition, namely ground test, and floating test. Ground test is aimed towards PV array's characterization and performance measurement. Data obtained from ground test will later act as a baseline performance data, therefore no modifications were applied to both PV arrays during this test.

Floating test is divided into two types of tests, each test is specifically applied for one unit of PV array. The first one is the normal floating test which applied for PV array A. The second test is the thermosiphon floating test which applied for PV array B. A thermosiphon passive cooling system is fitted to PV array B during thermosiphon floating test. During floating test, PV arrays are mounted on a floating platform. Experiment set up is depicted by Fig. 1 and Fig. 2.

The floating platform for PV array A will sustain approximately 104.92 kg of weight load, whereas floating platform for PV array B will sustain approximately 271.91 kg of weight load. The buoy used in this study is a pseudo cube made of high density polyethylene (HDPE), each has a weight load capacity of 87.5 kg. The floating platform structure members are entirely made of SAE 304 Stainless Steel to withstand corrosion at humid environment with RH ≈ 94.9% [27].

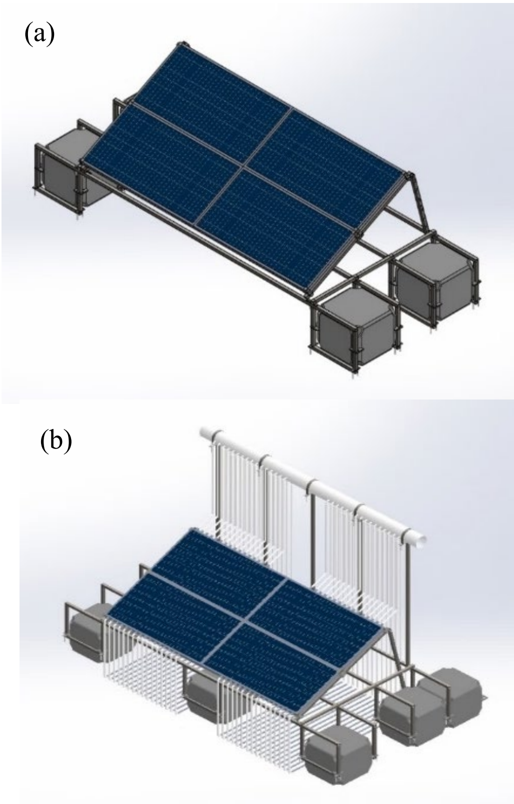


Fig. 1: Floating platform design (a) PV array A (b) PV array B with thermosiphon cooling system attached

The thermosiphon loop assembly is comprised of aluminium profile pipe, polyvinyl chloride (PVC) pipe and the transparent flexible pipe which also made of PVC. Integral with the loop assembly is the cooling water reservoir. The heat from the PV module is extracted via the square profile aluminium pipe attached on the back of the PV module and heat from the cooling system is released to the water body via the circular aluminium pipe submerged under water.

PV array's performance data are recorded using the monitoring system. Monitoring system components include the battery charge controller, the battery, and the DC load. PV array performance data are recorded using battery charge controllers dedicated data logger. The battery charge controller is a Maximum Power Point Tracking (MPPT) type so that PV arrays recorded performance data are always at its optimum point at any time. The DC load, which is a halogen lamps are connected with the monitoring system to avoid battery overcharging by draining its capacity. Several parameters are recorded alongside PV arrays performance, such as solar irradiation, module temperature, water body temperature and cooling water temperature. Solar irradiation data is recorded using solar power meter with 60 seconds interval. Each PV module temperature is measured at two points, one at the top surface and second at the bottom surface. Data retrieval scheme is presented in Fig. 3.

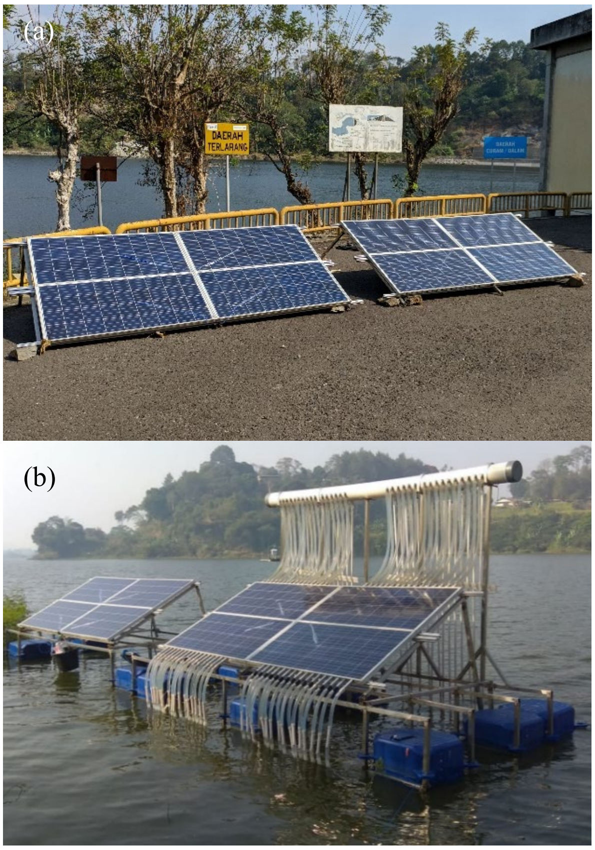


Fig. 2: Experiment set up (a) ground test set up (b) floating test set up

Water body temperature is measured close to the submerged alumunium pipe so the measured temperature is not affected by difference in water depth. Cooling water temperature is measured at two points, which is at the point before it passes PV module and after it passes PV module. K-type thermocouple sensor is utilized at every temperature measuring points and the data is recorded via temperature data logger within 60 seconds interval. Cooling water flow velocity is also measured to ascertain that the cooling system is properly working under thermosiphon effect principle. Flow velocity

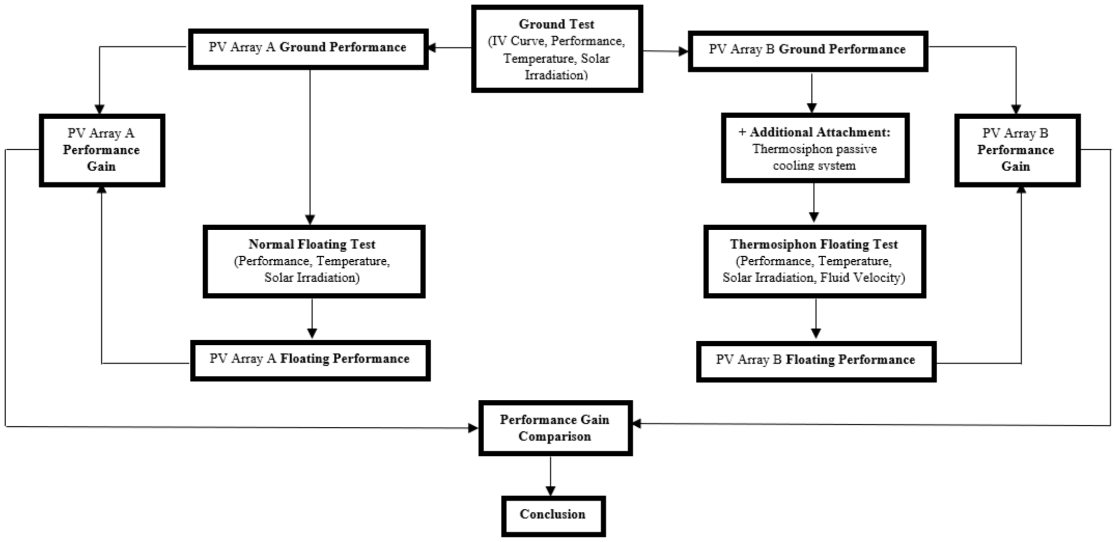


Fig. 3: Data Retrieval Scheme

measurement is done by injecting dye into loop channel. The dye movement is observed through transparent hose.

3. Experimental result

It is important to check ambient temperature on water and on ground, since those temperature strongly influence PV temperature, hence affect the conversion efficiency [21]. The ambient air temperature is monitored at minute intervals to compare the operating environment on water and on ground. Fig. 4 shows temperature profile of ambient air at Saguling dam. It can be seen from measurement result that on water ambient temperature is lower with average value of 27.43 °C, while on ground ambient temperature was higher with average value of 31.52 °C. The benefit of lower average ambient temperature will later be presented in experiment result. The average water body temperature is in the range of 27.68°C - 29.06°C.

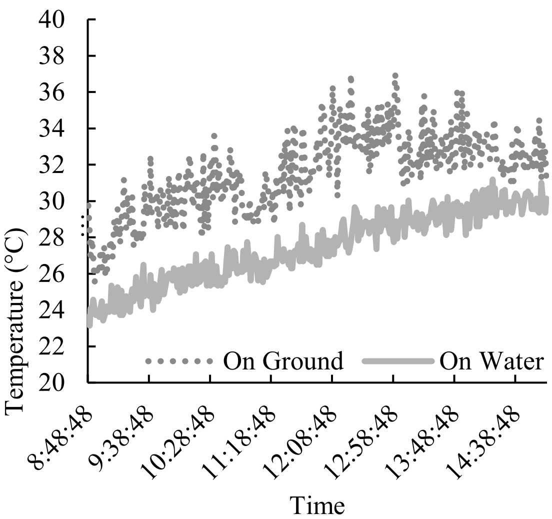


Fig. 4: Ambient temperature measurement result

Initial assessment during experiment is focused toward PV arrays current and voltage (I-V) characteristic identification. The I-V characteristic identification is intended to ascertain and quantify any dissimilarities between two PV arrays. Obtained result shows that the two PV arrays were not identical. Therefore, later in the study, the performance gain experienced by these two PV arrays cannot be compared directly. The PV array's I-V characteristic is presented by Fig. 5. The figure shows that PV array A has better performance than PV array B. I-V curve is recorded at closest possible value to STC solar Irradiation ≈1000W/m2.

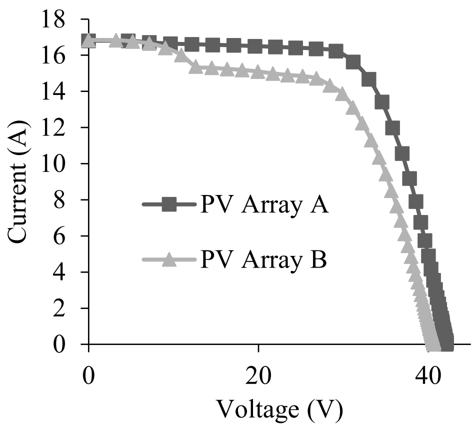


Fig. 5: Characterization result of two PV array's

PV arrays temperature value from three testing condition, i.e. on ground, floating without thermosiphon, and floating with thermosiphon, are plotted against solar irradiance as shown in Fig. 6. It can be observed that PV array situated on the ground has the highest temperature. PV array on the ground has a temperature value ranging from 38.45°C to 56.99°C with average value of 51.61°C. With normal floating test (without thermosiphon), PV array average temperature is reduced to 49.57°C. A lower ambient temperature on water condition helps PV module heat dissipation therefore resulting in lower PV module temperature. During normal floating test, PV arrays temperature was ranging from 38.37°C – 56.80°C.

According to a study conducted by the temperature of the floating solar panel was generally 3.5 °C lower than that of the ground solar panel. In this study the average temperature difference between ground PV array and normal floating PV array was 2.04°C[28]. The difference in the result is influenced by several factors on the field that affecting PV arrays temperature, namely location, humidity, albedo, and ambient temperature which always varies with time[21]. A significant temperature reduction is achieved with thermosiphon floating test.

With thermosiphon-floating test, PV arrays temperature was ranging from 35,64°C to 46,18°C with average temperature of 41,11°C. The result shows that thermosiphon passive cooling reduces PV array temperature. Further measurement is done to ascertain that the thermosiphon cooling system was working as intended.

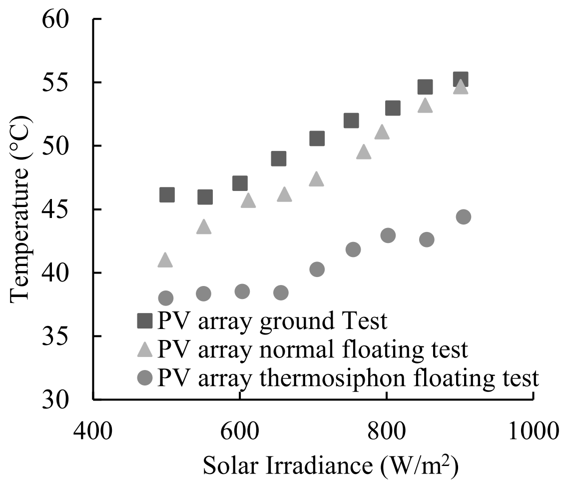


Fig. 6: The value of temperature from three testing condition plotted against solar irradiance

Fig. 7 shows location and result of temperature profile measured at thermosiphon loop and in addition at PV module at PV array B. According to Fig. 8, water temperature measured at point D is higher than the water temperature before passing a PV module which measured at point C. The average temperature of water at point D is 35.72 °C, while average water temperature at point C is 29.43 °C. The temperature difference indicates that the heat was extracted from PV module to cooling fluid effectively. On the other hand, heat is released from cooling fluid to the water body. It can also be observed from Fig. 8 that water temperature measured at point C is close to water reservoir temperature measured at point E with average temperature of 28.85 °C. Inside the thermosiphon loop, the cooling water is flowing with a velocity of around 9 mm/s.

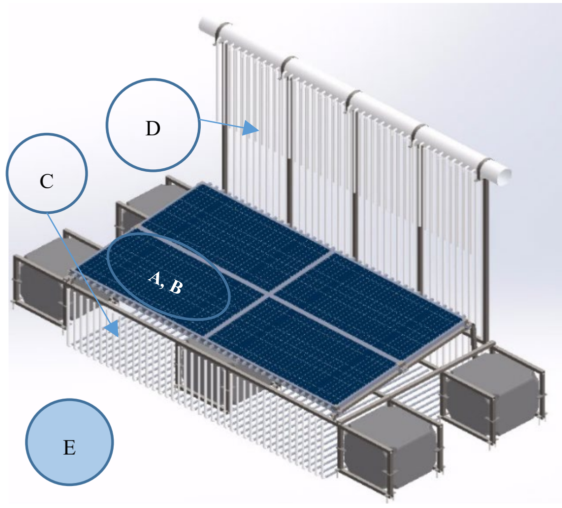


Fig. 7: Temperature measurement point on thermosiphon passive cooling system

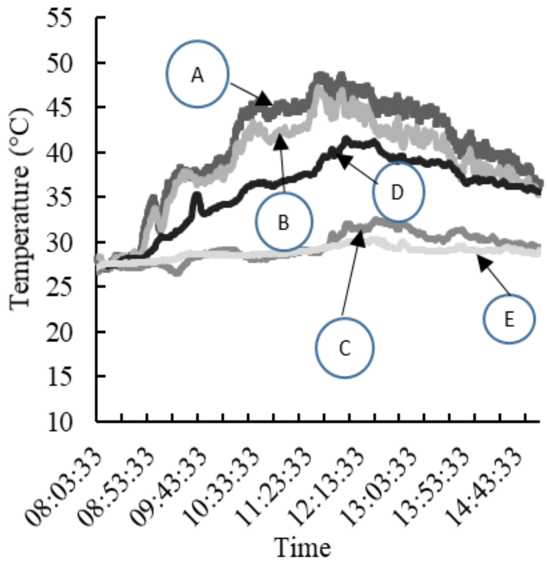
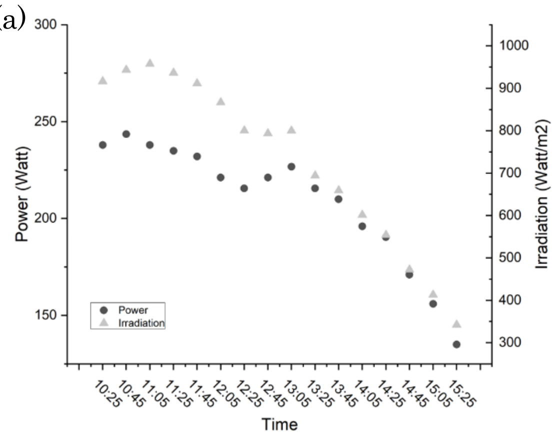


Fig. 8: Temperature measurement result on thermosiphon passive cooling system

From the previous figure, i.e. Fig. 5, it can be seen that performance between PV A & PV B is different. Therefore, when PV A is used as floating PV, and PV B is used as thermosiphon-floating PV, the performance between both PVs cannot be directly compared. In this study, testing of PV A was carried out in ground conditions and floating conditions, while testing of PV B was done in ground conditions and thermosiphon-floating conditions. Result of the tests show each PV improvement.

Fig. 9 represents the test result for PV A. Fig. 9a shows irradiation and power of PV A at ground test, while Fig. 9b shows irradiation and power of PV A at normal floating test. Both experiments were executed at different day.

(a)



(b)

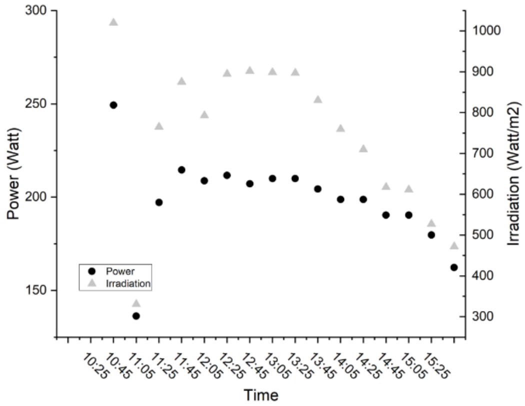
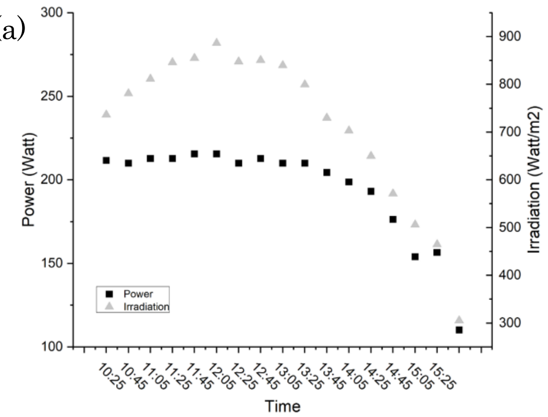


Fig. 9: Test performance for PV array A (a) ground (b) normal floating

Total irradiation and power during test can be calculated by using numerical method. Efficiency of PV A at ground and normal floating test is 7.43% and 8.04%, respectively. Therefore, the efficiency improvement is 8.18%.

Fig. 10 represents the test result for PV B. Fig. 10a shows irradiation and power of PV B at ground test, while Fig. 10b shows irradiation and power of PV B at floating-thermosiphon test. Both experiments were done at different day.

(a)



(b)

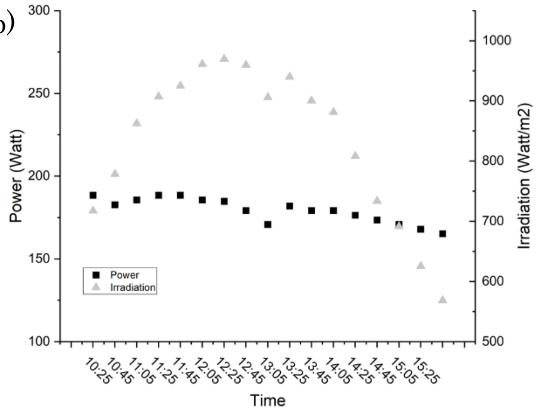


Fig. 10: Test performance for PV array B (a) ground (b) floating-thermosiphon

Similar with previous PV, total irradiation and power of PV B during test can be calculated by using numerical method. Efficiency of PV B at ground and floating-thermosiphon test is 5.98% and 7.6%, respectively. The efficiency improvement is 27%. This result shows that thermosiphon-floating PV is superior than normal floating PV system.

4. Conclusion

Floating PV is an emerging PV technology and gaining popularity among academic and business entity. Floating PV technology has more benefit compared to ground mounted PV in term of performance. In this study, to increase the floating PV performance, circulation of cooling water which is driven by thermosiphon is implemented on floating PV array. Three types of test were conducted, namely ground test for both PV array, normal floating PV test, and test for floating PV fitted with thermosiphon.

From the experimental result, PV array fitted with thermosiphon passive cooling system has the lowest average temperature compared to normal floating PV array without cooling system and conventional ground PV array. As a result, a performance gain for floating PV array with thermosiphon passive cooling system is greater compared to normal floating PV array. A normal floating PV array was able to improve 8.18% in efficiency (it was compared to ground test). While thermosiphon floating PV array achieved higher performance gain with 27% improvement in efficiency (it was compared to ground test). It can be concluded that the thermosiphon passive cooling technology is succefully tested on a PV array system and achieved higher performance gain than the normal floating PV array without cooling system.

To improve thermosiphon cooling system design flexibility on FPV application, future study will need to work on optimizing thermosiphon cooling system application on several PV module arrangement. The effect of various cooling arrangement to cooling performance also needs to be assessed as well.

Acknowledgements

This research is supported by Institut Teknologi Bandung (P3MI scheme and LPIK) and Indonesian Ministry of Research and Technology under World Class University (WCU) program Managed by Institut Teknologi Bandung. Authors of this paper would like to express gratitude toward managements and staffs of PT. Indonesia Power Saguling Hydroelectric Power Plant for their support and assistance at the field.

Nomenclature

PV	Photovoltaic (–)
FPV	Floating Photovoltaic (-)
UAE	United Arab Emirrate (-)
PCM	Phase Change Material (-)
PV/T	Photovoltaic Thermal (-)
CPO	Crude Palm Oil (-)
P	Power (Watt)
V	Voltage (Volt)
I	Current (Ampere)
FF	Fill Factor (-)
T	Temperature
HPP	Hydro Power Plant
A	Surface Area (m^2)
RH	Relative Humidity (%)
PVC	Polyvinyl Chloride
MPPT	Maximum Power Point Tracking
DC	Direct Current
Al	Alluminium
O	Oxygen
HDPE	High Density Polyethylene

Greek symbols

γ	Solar radiation coefficient (–)
η	efficiency (%)
β	Temperature coefficient (-)

Subscripts

OC	Open Circuit
SC	Short Circuit
ref	Reference
MPP	Maximum Power Point
Max	Maximum
in	input

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