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Bi-fluid cooling effect on electrical characteristics of flexible photovoltaic panel

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Abstract

A photovoltaic (PV) system integrated with a bi-fluid cooling mechanism, which is known as photovoltaic thermal (PVT) system, was investigated. The electrical characteristics of flexible solar panel were evaluated for PV and PV with bi-fluid (air and water) cooling system. The integration of monocrystalline flexible solar panel into both systems was tested under a fixed solar radiation of 800 W/m^2. A total of 0.04 – 0.10 kg/s of air flow was utilized in PV with cooling system with a fixed water mass flow rate of 0.025 kg/s. The efficiencies of flexible panel for PV and PV with cooling system were explored. For PV with bi-fluid flow, the highest obtained efficiency of module was 15.95 % when 0.08 kg/s of air and 0.025 kg/s of water were allowed to flow through the cooling system. Compared with PV without cooling mechanism, the highest efficiency of module was 13.35 % under same solar radiation. Current– voltage and power graphs were also plotted to present the electrical characteristics (current, voltage, and power) generated by both systems.

Keywords: PV efficiency; PV current; PV voltage; PV power; I–V–P curves.

I. Introduction

Solar energy is a renewable energy that can produce heat via a thermal system and generate electricity via photovoltaic (PV) module. A photovoltaic-thermal (PVT) collector is a system which has a PV module combined with a thermal collector system. The system is able to produce electrical energy directly from sunlight by using photoelectric effect. Meanwhile, it also extracts heat from the PV and warms the fluid inside the collector. When a PVT collector is irradiated with solar energy, the cell temperature increases prominently. The greater the temperature difference between ambient temperature and temperature of the cell is the less efficient the electrical efficiency and electrical output of the PV module becomes. In order to enhance the electrical efficiency, this excess heat is extracted by passing a heat extracting fluid (water or air) under the module. This integrated method, where thermal and electrical energy are generated

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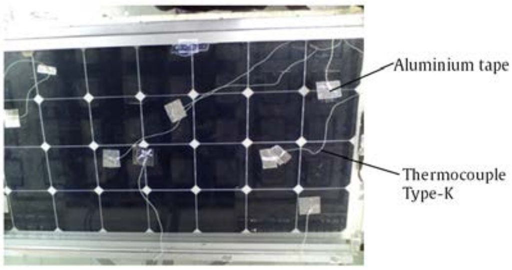

(a)

(b)

Figure 1. (a) Flexible photovoltaic panel (Table 1); (b) integrated with spiral absorber (the water flow channel)

simultaneously, is the basis of PVT collectors [1][2][3][4].

Due to the dual functions of a PVT collector, this type of collector maximizes the use of solar energy resulting in a higher overall solar conversion rate than that of solely PV or solar collector. The PV cells composed of semiconductor material convert high-energy photons of incident solar radiation into electricity. The lower energy photons are absorbed by the PV panel and generate heat within the cells [5]. The generation of heat within the cell reduces the efficiency of the cells. The photovoltaic thermal (PVT) technology extracts a great percent of this heat and utilizes it for practical applications [6]. The removal of heat from the cell and transferring it to the working fluid increases the electrical efficiency of the PV module while simultaneously producing hot fluid which can be used for thermal applications. Since PVT offers an improved method of utilizing solar energy, the overall efficiency of the system is higher [7][8][9].

There are several advantages of PVT collectors over individual PV or thermal collectors discussed in various literatures. One way to enhance the efficiency of the PVT system is by using heat transfer area through the absorber with finned absorber, corrugated surfaces and porous media. The PVT system can be classified into four types based on heat transfer medium, namely the air-based PVT system, water-based PVT system, the combination of water/air-based PVT system and nanofluid-based PVT system [10][11][12][13]. The concept of combining two fluids to cool a PVT collector was firstly introduced in 2007. However, the fluids are applied individually in each time [14]. A design that focuses on the water and air heating component has been proposed to improve bi-fluid PVT system. The results for independent mode operation are concluded as satisfactory. Higher efficiencies on thermal, electrical and overall systems are attained for simultaneous system operation [15]. Recently, a new concept of hybrid PVT was introduced by Othman et al. [16], and this system includes PVT combination with water and air heating. At the chosen optimum mass flow rate throughout the experiment, the total thermal equivalent efficiency is as high as 76 % when the fluids are operated simultaneously.

Integration of two working fluids in a single PVT system has shown various results in improving the efficiency of PVT or PV with cooling system. The current study aims to investigate the effects of bi-fluid utilisation on the PV module efficiencies and the electrical characteristics generated by PV and PV with cooling systems. In the end of the study, the use of flexible PV as module for indoor test of PV and PV without cooling system is validated.

Table 1.
Specification of flexible PV panel

Model	Symbol	Values
Maximum power	P_{max}	100 W
Voltage at P_{max}	V_{mp}	17.6 V
Current at P_{max}	I_{mp}	5.68 A
Open-circuit voltage	V_{OC}	21.2 W
Short-circuit current	I_{SC}	6.25 A
Irradiance	I	1000 W/m^2
Temperature	T	25 °C

II. Materials and Methods

The PV with cooling system was integrated with glazing, which complemented the duct of air flow in the cooling system, as shown in Figure 1. The setup of PV with cooling system consisted of PV and cooling system in one integrated arrangement and is also known as PVT system. The utilisation of two types of fluids (water and air) for the cooling system required piping arrangement for the water flow and air duct for the air flow to complete the system.

As can be seen in Figure 1, it shows the thermocouples which were used to configure the temperature of each designated part of the system. They were pasted by using aluminium tape which in return affected the exposure area of the panel surface to the solar radiation. A study proved that the shaded area of the panel must be less than 50 % from the total area in order to ensure that the power output is increasing more than 5 % [17].

Figure 2 shows the setup of the system, which was positioned under a solar simulator that acted as the source of solar radiation. The solar simulator acted as the source of the solar energy that radiated upon the system. The simulator consisted of 40 halogen lamps, amongst which nine were arranged in a row. The generated solar radiation was regulated by 9 voltage regulators, amongst which 1 regulated a row of solar simulator.

In the setup, two paths of coolant flow were considered for water and air. Tanks A and B stored the water flow. Tank A was the reservoir tank of water outlet flowing from the water channel. In the meantime, tank B functioned as the cooling tank where the outlet water from tank A was pumped into for cooling. Normal pipe water was loaded, and spiral copper tube was soaked into it to act as the

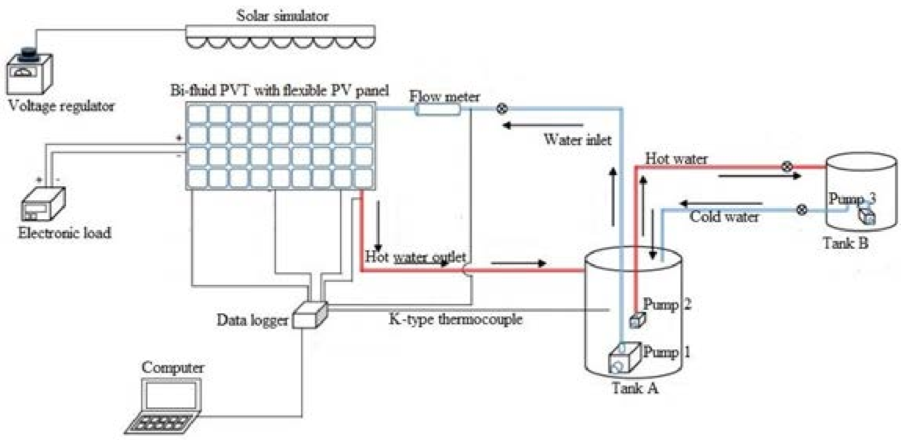

Figure 2. Schematic of experimental setup for PV with cooling system

channel for cooling down the water outlet before being re-used as an inlet and regulated at preferred mass flow.

The air channel was a single path flow of air in which the air input was from the fan installed at the end of collector. The air channel was in between the glass and PV panel and was used to contribute and regulate an evenly distributed heat absorbed by the panel. The speed of the fan was regulated using a dimmer and was then measured by an anemometer. Anemometer readings were used to calculate the mass flow rate of air.

Figure 3 shows other equipment components, namely water tanks, spiral absorber, flowmeter and water pump, were used. The spiral absorber used was made of stainless steel because steel is a good heat conductor. The amount of water allowed to flow was regulated using the flowmeter (1 – 4 G/M) mounted at the inlet of spiral absorber. The water flow absorbed the heat conducted between the PV panel and spiral absorber to maintain optimum temperature for the PV during operation. An 80 W of water pump was applied to tank A to aid the flow process for providing pressure for the water to flow from the outlet tank (tank A) to the cooling tank (tank B) as shown in Figure 2. Copper coil acted as the medium of water cooling as it flowed through. The water outlet was cooled before the fluid entered the inlet system, during which the flow was controlled by the flowmeter as shown in Figure 3.

Previous studies conducted on PVT have integrated different kinds of absorber designs in using fluid as coolant. The performance of water-based PVT with various pattern configurations was compared [18][19]. The outcome with the best performance is achieved using spiral absorber because of the closed-gap between the tubes and large number of areas covered by the PV panel with the absorber attached to it.

Figure 3. The overview of the system set up before it had been placed under the solar simulator

In the present research, the data collected were analysed to determine the electrical characteristics of flexible PV panel for PV and PV with cooling system. The data recorded were listed as follows:

- The data from the logger comprised the readings of each thermocouple pasted on systems, including the temperatures of glass, air inlet and outlet, PV panel, water inlet and outlet and absorber and the ambient temperature of the room.
- The data from the electronic load included those of current and voltage generated by the flexible PV during the experiment.

The data on the temperature of PV panel were mainly discussed due to the concerns of this study. This temperature influenced the electrical energy generated by the PV. The experiment compared the differences when coolants were used or ignored. The temperature difference of coolants (water and air) was briefly explained to justify the effect of coolant use. Furthermore, the performance of PVT bi-fluid system was compared with that of PV system.

The electricity generated was dependent on the temperature of the solar panel throughout the experimental session and the temperature change of the coolants (water and air) in the bi-fluid system. Thermocouple type K was pasted at certain designated parts of the system to detect temperature readings whilst the end of the thermocouples was connected to the ports of data logger. The logger was used to record the data measured by the thermocouple, and the temperature was recorded at each minute for 30 min.

The experiment began with the radiation from solar simulator, which was regulated by the voltage regulator. Pyranometer Epley with a solar constant of 9.13×10^{-6} was used to measure the radiation radiated for matching the radiation that had been supplied to the system to the desired radiation (800 W/m^2). Then, the flow of coolants was started, and the readings were logged onto the logger.

As the data from the temperature readings were automatically recorded, an electronic load was

Table 2.
Electrical characteristics of flexible PV panel without bi-fluid cooling system under fixed solar radiation

Solar radiation, S (W/m^2)	P_{max} (W)	I_{sc} (A)	V_{oc} (V)	Fill Factor	Eletrical efficiency of PV, η_{el} (%)
	18.17	1.726	16.28	0.647	13.63
800	17.34	1.711	16.17	0.627	12.98
	17.17	1.711	16.09	0.643	13.45

connected to the PV panel to obtain its generated electrical energy. The readings were manually measured 15 min before the experiment ended. The obtained data were used to plot the I– V curve graph for determining the maximum power produced by the PV panel.

The data for current and voltage obtained were plotted on the I– V curve graph. Then, Equation 1 was used to find the maximum power output. In this equation, P_m is the maximum power output and I_m and V_m are the maximum generated current and voltage, respectively.

$$P_m = I_m \times V_m \quad (1)$$

The features of a PV solar panel can be removed from the PV solar panel output, which can be explained by the resulting I– V curve nature. The fill factor (FF) of a PV panel was measured from the real I– V characteristic curve. FF is defined as the maximum power produced by the cell against the open circuit voltage (V_{OC}) and the closed-circuit current (I_{SC}). FF can be written as [20]

$$FF = \frac{P_m}{V_{oc} \times I_{sc}} \quad (2)$$

The equation provided was used to calculate the electrical efficiency that was generated by the PV for comparing the effects of cooling fluids to the flexible PV panel for its efficiency. In this equation, η_{el} is the efficiency of the panel and η_{ref} is the efficiency of PV by the manufacturer. Other terms β, T_{PV}, and T_{ref} are the thermal coefficient (0.0045 $°C^{-1}$), mean temperature of PV surface during the operation (°C) and mean reference temperature (25 °C). The third equation was used to attain the electrical efficiencies of both systems and was used to analyse temperature dependence [17][18][19].

$$\eta_{pv} = \eta_{ref}[1 - \beta(T_{PV} - T_{ref})] \quad (3)$$

III. Results and Discussions

A. Control System Response with Pole Placement Method

The reference efficiency of PV was 17.8 %, and the actual efficiencies of PV were obtained using equation (3). The first to the third repeated experiments for PV system recorded 13.63 %, 12.98 % and 13.45 % of efficiencies, as shown in Table 2. For PV with bi-fluid cooling system, the experimental investigation was performed using water with a mass flow rate of 0.025 kg/s at four different air mass flow rates (0.04, 0.06, 0.08 and 0.1 kg/s). In this experiment, a fixed solar radiation of 800 W/m^2 was radiated upon flexible solar panel, which was integrated at the top of the system.

Table 3.
Efficiencies of PV panel in terms of the temperature of the panel

Type of system	Mass flow rate of fluid (kg/s)		Temperature of flexible PV panel (°C)	Efficiencies of PV panel (%)
	Water	Air		
PV with bi-fluid cooling system	0.025	0.1	47.90	15.97
			47.12	16.03
			49.53	15.84
		0.08	48.92	15.88
			47.21	16.02
			48.31	15.93
		0.06	46.71	16.06
			49.06	15.87
			50.73	15.74
		0.04	48.93	15.88
			50.34	15.77
			51.51	15.68
PV without cooling system	Not available	Not available	77.09	13.63
			85.18	12.98
			79.31	13.45

For each varied parameter of air mass flow rate with constant water mass flow, the experiment was repeated three times. Moreover, the maximum power generated was calculated using equation (2). The electrical efficiencies of PV with bi-fluid cooling system were compared to find the optimum bi-fluid parameter that generated maximum electrical energy. Table 3 shows that the average efficiencies of PV for PV with bi-fluid cooling system were 15.94 %, 15.95 %, 15.89 %, and 15.78 %. The lowest efficiency of 13.95 % was recorded by PV without cooling system.

Therefore, the temperature of the panel influences the efficiencies of the PV module. Specifically, as the temperature of the PV surface increased, the efficiencies of PV decreased. Figures 4 show the I– V– P curve that was graphed for 800 W/m^2 radiated upon bi-fluid PVT with varied mass flow of air (0.04, 0.06, 0.08, and 0.1 kg/s) at a fixed water mass flow rate of 0.025 kg/s. The graphs represent the best result amongst the three repeated experiments for each parameter of varied air mass flow rate. The PV with bi-fluid cooling system should be more efficient in generating energy than stand-alone PV system. In this research, the prediction was proven, and the conclusions were explained.

The experiment with the flow of bi-fluid was repeated three times for each parameter of mass flow rate. The best result amongst the three repeated operations was chosen, as shown in Figure 4 (a) to (d). Table 4 lists the data that had been graphed. As

Table 4.
Maximum power attained by PVT system at constant water mass flow rate with varied air mass flow rate

Mass flow rate (kg/s)		Voltage (V)	Current (A)	Maximum Power (W)
water	air			
0.025	0.04	11	0.55	5.995
0.025	0.06	12	0.59	7.081
0.025	0.08	13	0.57	7.384
0.025	0.1	12	0.55	6.588

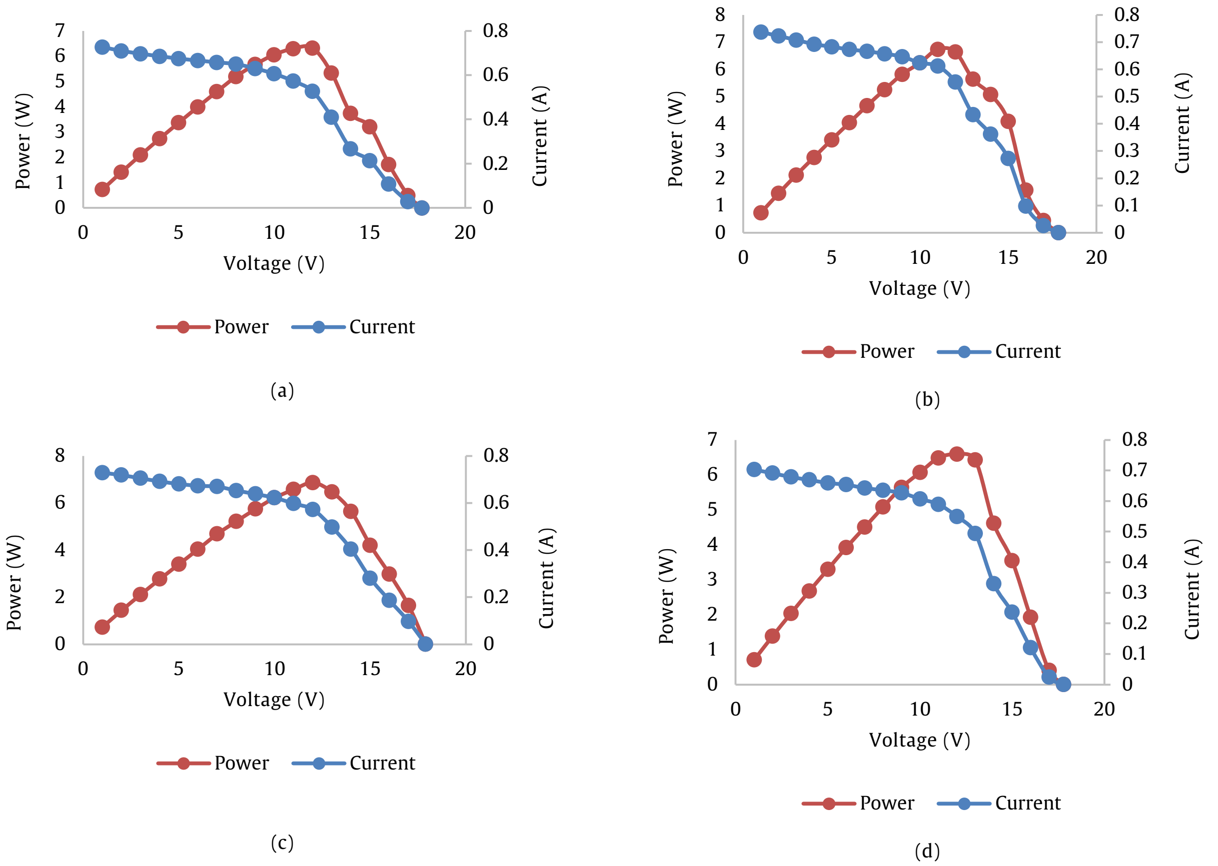

Figure 4. I– V– P curve for the average test conducted at: (a) 0.04 kg/s of air mass flow rate with fixed rate of water mass flow; (b) 0.06 kg/s of air mass flow rate with fixed rate of water mass flow; (c) at 0.08 kg/s of air mass flow rate with fixed rate of water mass flow; (d) at 0.1 kg/s of air mass flow rate with fixed rate of water mass flow

observed, the results insignificantly differed from each other under constant solar radiation and mass flow rate of water with varied air flow rate. The results of maximum power generated showed that it increased from 5.995 W to 7.384 W firstly and then dropped to 6.588 W. The reason was that the module did not withstand the converged radiation from the solar simulator and it can be seen due to a sudden decrease in maximum power produced as has been tabulated in Table 4. One of the reasons that led to this result is due to the high PV cell temperature due to increase in solar radiation which affected the performance of the solar panel [21].

IV. Conclusion

The following conclusions were obtained from the experimental results. The electrical characteristics of bi-fluid PVT system using flexible solar panel were discussed. For PV with bi-fluid flow, the highest efficiency of module obtained was 15.95 % when 0.08 kg/s of air and 0.025 kg/s of water were allowed to flow through the cooling system. Compared with the PV without cooling mechanism, the highest efficiency of module was 13.35 % under same solar radiation. The indoor experiment using flexible design of PV showed that it should be integrated to an outdoor system of PVT. This incapability affected its performance in energy generation.

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Declaration

Author contribution

All authors contributed equally as the main contributor of this study.

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Conflict of interest

The authors declare no known conflict of financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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