Enhancement of Solar Photovoltaic Module Performance by Using a Water-cooling Chamber for Climatic Conditions of Iraq

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Abstract- The cooling of photovoltaic (PV) modules is essential for enhancing electrical efficiency and power obtained. In this paper, a water-cooling chamber is attached to the back of PV module to study the effect of pane orientation, which guides water flow through the chamber, and reverse water flow on the electrical and thermal performance of photovoltaic /thermal (PV/T) system. The installation of PV modules is at a 33°-angle tilted to the south. The type of PV module is FRS-50W with dimensions of 640 mm ×540 mm. Three styles of PV with different pane flow angles of 60°, 30° and 0° are implemented. The modules are simultaneously tested and compared with an uncooled PV (Module 0) under two directions of water flow. The three modules of flow angles (60°, 30° and 0°) are defined as Module I, II and III at up-flow, respectively and Module IV, V and VI at down-flow, respectively. Results show that Module I has a maximum thermal efficiency of 80% at water flowrate 4 l/min and an increment of 54% for a range 1-4 l/min. When flow rate is 4 l/min in cooling chamber of Module I, II, and III, electrical efficiency increases by 17%, 15.3% and 13.6%, respectively compared with Module 0 under the same conditions. Furthermore, its maximum power (Pmax), voltage at maximum power (Vmp) and current at maximum power (Imp) increase with cooling and increasing flow rate for all modules due to decreased PV temperature.

Keywords renewable energy, PV modules, water cooling, thermal efficiency, electrical efficiency.

1. Introduction

Electricity and cooling are the main energy requirements in the residential sector and public and commercial services sector. At present, most of the world's energy (80%) is produced from fossil fuels [1,2]. Massive exploitation depletes these resources and poses a real threat to the environment, which is manifested mainly through global warming and water cycle acidification. The sun provides heat, light and electricity for domestic and industrial applications using solar technologies [3,4]. Photovoltaic (PV) cell is a solar technology that has grown rapidly by 24% between 2010 and 2017 in PV installations worldwide [5-7]. It produces electricity using semiconductors that transform solar irradiation into electricity without employing of any thermal engine. The operating temperature of a PV module increases because a large part of solar radiation is not converted into electricity but absorbed by the plate. When module temperature increases, efficiency decreases. Under the standard test condition, conversion efficiency of PV is reduced by about 0.40 % - 0.50 % for every degree increase in temperature [8, 9]. Therefore, PV module should be cooled by an efficient technique.

Many factors such as solar radiation, temperature, wind speed, dust and humidity affect the performance of PV solar system [10-13]. The cooling of a PV can lower the expenses of solar energy when the electrical efficiency of PV cells increases with the decrease of temperature. Cooling of panels also blocks PV cells from reaching temperatures that create irreversible harm [14,15]. Several cooling techniques had been attempted, such as using active air and water cooling, because they are the simplest. Tonui et al. [16] utilized two modulations to enhance heat transfer to air through a channel jointed behind the PV/T solar collector, hanging thin metallic flat plate (TMS) in the middle of the channel to double the heat removal surface and attaching rectangular fins (FIN) to the back wall of the air channel such that it is parallel to the flow direction. Thermal efficiency increased by 20% and 12% for FIN and TMS, respectively. Rahul et al. [17] showed improvements in the power output and efficiencies of a solar PV thermal collector combined with water and air-cooling systems. Also, Ali R. et al. [18] utilized water and air in cooling of the PV system. Power output increased by 2.4% and 6.3% using air cooled solar panel and water cooling, respectively. Qunzhi [19] noted that water efficiently extracts heat from the front surface of the solar panel due to the high heat capacity of water, and the extracted heat increased with the increase of water flow rate. Zeyad A. et al. [20] experimentally examined evaporative cooling to improve the efficiency of panels. The reduction in PV panel temperature exceeded 20 °C, and the increment in electrical power generation efficiency was between 10% and 14%; this method enhanced PV generation, especially during peak load periods. The fin arrangement inside the air-cooling chamber was used by several authors [21-22] to improve the total efficiency of the PV panel with a cooling chamber and increase heat transfer. Odeh S. et al. [23] used a washing system that includes water flowing on the upper surface of the PV panel under gravity. The advantages of this cooling system are the removal of the circulation pump needed for the cooling operation due to flow under gravity, increasing incident on the solar radiation because of refraction in water layer, high cooling efficiency due to direct contact of water with the PV surface and keeping the PV surface free from dust. The result showed an increment in system output of 4% -10% and about 15% at peak radiation conditions. Kiran S. et al. [24] employed a cooling system consisting of an absorber plate connected to a cooling tube, through which water passes, and attached to the back surface of panels. Many authors [25-27] treated the reduction of efficiency due to a raised surface temperature by dissipating heat from the front surface using water spraying over the cells. They found that spraying water over the PV cells highly improves the efficiency. The water immersion cooling technique was utilized by Mehrotra [28]. The PV panel was submerged in water to preserve its surface temperature. Kumar P. et al. [29] experimentally improved the efficiency of solar PV modules by using back water-cooling tubes, where water flows through a rectangular tube fitted at the back surface of the PV module. Al-Waeli et al. [30] mathematically analysed the heat transfer of a PV/T system whose cooling circuit involves various of nanoparticles added to different types of base fluids. The results demonstrated that heat transfer increases when nano-SiC is added to the base-fluids compared with nano-alumina and nano-CuO. Duaa and Ammar [31] carried out experiments to enhance PV panel performance by using metal foam fins that are fixed at the back of the PV module. Power output was improved by about of 4.9%, and surface temperature was reduced around 8.4% by adding 10 longitudinal fins.

Solar energy can be obtained widely in two thirds of Iraq. In the southern and western parts, the solar irradiation period is between 2,800-3,000 hours per year with more than 6.5 - 7 kWh/m² of horizontal radiation per day [32]. Many advantages can be derived from improving module efficiencies; examples include minimization of the space occupied by PV array for same power, reduction of system cost, keeping the modules from higher temperatures and investing thermal energy generated in a PV/T system [33-35]. In the present paper, solar PV modules (Type: FRS-50W) were installed at Renewable Energy and Environment Research Centre, Ministry of Industry and Minerals, Baghdad, Iraq. The installed condition of the PV modules was 33° angle tilted to the south to receive a higher heat flux for the Baghdad condition (33.3° latitude, 44.4° longitude) [36, 37]. Many tests of experimental rig were conducted locally to employ the cooling water technique and absorb more heat from four PV modules simultaneously under the same conditions. The water-cooling chamber at the back of each PV module was utilized to study the effect of pane orientation, which guides water flow with angles (60°, 30° and 0°), and reverse water flow on the electrical and thermal performance of PV/T solar module.

2. Experimental Methodology

2.1. Experimental setup

Three solar PV modules with a cooling chamber were proposed in the experimental work for comparison with an uncooled PV module and studying many parameters of the four PV modules that are simultaneously tested under the same conditions. The proposed cooling technique uses water as a working fluid. The cooling chamber was implemented by adding water passages contact with the rear surface of the solar PV module as shown in Fig.1. When water passes through the chamber passages, it touches the module surfaces such that heat can be transferred out. Chamber passages are made up of 2mm-thick acrylic glass sheets panes. The depth of passages is equal to the rear chamber height of the PV module which is 28 mm. The acrylic plate was pasted by using silicon material at the back of the module. Another sheet of acrylic was cut with dimensions of 640 mm× 540 mm that is equal to the PV dimensions. This sheet was drilled with two holes of 11 mm: one at the top right and another at the bottom left of the PV module. Two tubes were inserted into these holes to allow the inflow and out-flow of water. The sheet was assembled with a solar PV module by rivet and silicon to avoid leakage.

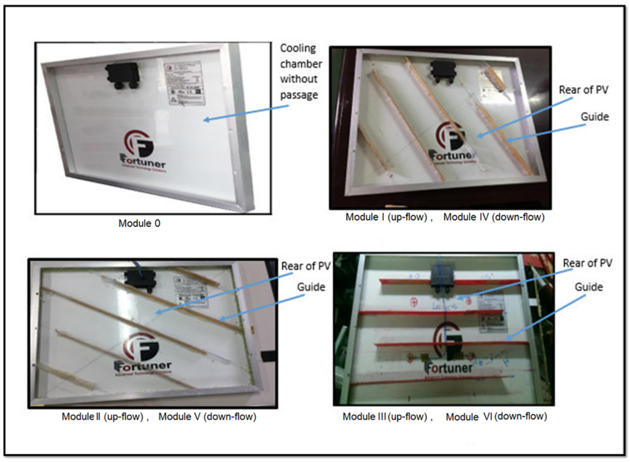

Fig.1. Experimental setup modules

Figure 2 shows the complete combination of the cooling system connected to the four solar modules which were installed on an iron stand at a tilt angle of 33°. The cooling circuit consists of a water tank, a water pump, flow control valves and pipes. The water pump circulates the water from the storage tank to water passages chamber system and returns to the storage tank. The flow valve regulates water flow rate. Schematic diagrams of the experimental rig with measurement devices (flow meters, IR camera, solar analyzer and data logger) and thermocouples locations are shown in Fig.3.

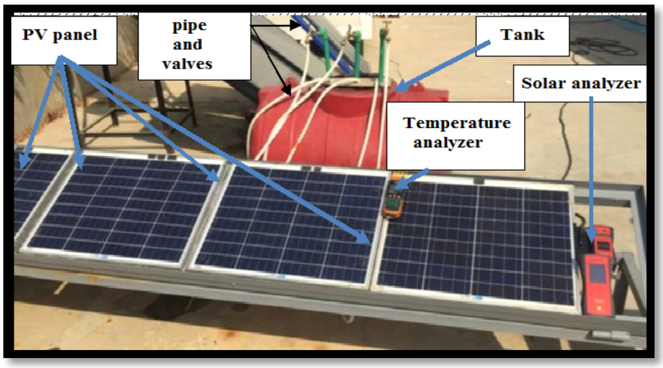

Fig. 2. Experimental setup system with measurement devices

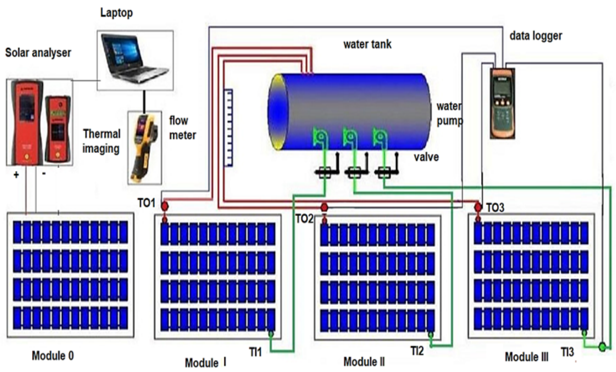

Fig. 3. Schematic of the experimental setup

The type of solar PV module is FRS-50W. It is made from polycrystalline semiconductor and consists of 9× 6 cells. The technical specification of this module is shown in Table 1. The solar PV module dimensions are 640 mm ×540 mm and it faces south at a tilt angle 33°.

Table 1. Electrical characteristics data of solar module at (1,000 W/m2, cell temperature 25 °C.

Specifications of PV Module	
Model	(FRS-50W) polycrystalline
Maximum power (Pmax)	50 W
Voltage at maximum power (Vmp)	18 V
Current at maximum power (Imp)	2.8 A
Open circuit voltage (Voc)	22 V
Short circuit current (Isc)	3.17 A
Efficiency	14.4 %
Total number of cells	36 (4×9)
Module dimensions	(640×540×25) mm

The selected cooling fluid was water because it is a suitable heat–transfer medium, it is low cost and its heat capacity is high. Water was used with four different flow rates (1, 2, 3 and 4) l/min under two directions of flow (up-flow and down-flow).

The portable measurement instrument SOLAR-4000 is one of the most important devices used in the analysis of PV module specifications. The I-V characteristic curve, short circuit current, open circuit voltage, power, irradiance, temperature and inclination angle were recorded by a 16-bit processor attached to the instrument.

This instrument consists of two spilled components: analyzer and sensor. The SOLAR-4000 sensor measures the cell temperature as well as the inclination angle and the irradiation in the solar module level. It is often mounted on the plane of a PV module. The measurement values are transmitted directly to the main instrument (analyzer) by radio signal. The SOLAR-4000 analyzer can determine current characteristic values from individual PV modules as well as module strings. Wireless communication between sensor and analyzer is activated to transfer the measured data from first to second. It can read maximum solar power (P-max), maximum voltage (V-max), maximum current (I-max), voltage at open circuit (V-open), and current at short circuit (I-short) [38].

Water mass flow rate was measured using a flowmeter for each PV module of the three installed modules with the range 1–4 l/min. Temperatures were measured using two different techniques in the experiments. The thermocouple and data logger technique were performed using seven thermocouples of type K: three were installed at the inlet of the cooling chambers to measure water inlet temperature, three were placed at the exit water from the chambers and one was used to measure environment temperature. Another technique was the IR camera which is one of the useful techniques for measuring the average surface temperature of the module. Images taken by the IR camera were saved on an SD memory card installed in the camera and analyzed using a computer software called Smart View.

Table 2. Experimental descriptions of module.

Module no.	No. of passages	Flow Angle	Water Flow direction	Flow rate l/min
0	0	---	no cooling	0
I	Six passages	60˚	from bottom to top (up-flow)	1-4
II	Six passages	30˚	from bottom to top (up-flow)	1-4
III	Five passages	0˚	from bottom to top (up-flow)	1-4
IV	Six passages	60˚	from top to bottom (down-flow)	1-4
V	Six passages	30˚	from top to bottom (down-flow)	1-4
VI	Five passages	0˚	from top to bottom (down-flow)	1-4

Many experimental tests were conducted to evaluate the performance of the PV system. The platform was prepared to accommodate four modules that use different cooling systems depending on one tank to study the effects of passage angle, flow direction and flow rate, as detailed in Table 2.

2.2. Formula analysis

The cooling of the solar PV module was investigated to determine its effect on module efficiencies. The performance of the module can by predicted by its electrical efficiency, which is defined as the ratio of actual electrical output to solar irradiation incident on the PV module area [39]:

$$P_{out} = P_{mp} = V_{mp} * I_{mp} , \quad (1)$$

$$P_{in} = G * A , \quad (2)$$

$$\eta_{ele} = \frac{P_{out}}{P_{in}} , \quad (3)$$

Heat transfer rate can be described as follows:

$$Q = \dot{m}. Cp. (To - Ti), \quad (4)$$

where
Q: heat transfer rate (J/s),
Cp: specific heat capacity of working fluid (4,187 J/kg. ˚ C),
$\dot{m}$: mass flow rate of fluid (kg/s) and
Ti and To: inlet & outlet temperatures of fluid in PV/T (˚C), respectively.

Thermal efficiency is determined as a function of solar radiation (G), input temperature of fluid (Ti) and output temperature (To). Thermal efficiency is evaluated by the following equation [40]:

$$\eta_{th} = \frac{Q}{G.\ A} , \quad (5)$$

where η_{th} is the thermal efficiency, and A is the area of PV module.

2.3. Uncertainty Analysis

The accuracy of obtaining experimental results depends on that of measurements, design details of the test system and human error. Experimental errors that may present in the used variables are listed in Table 3 which is taken from measurement devices.

Table 3. Uncertainties of measurement devices.

Parameter	Flow rate	Time	Solar radiation	Current	Voltage
Symbol	∀	T(s)	G(W/m2)	I (A)	V (V)
Accuracy	5×10^{-9}	2 %	10 %	0.012	0.005

Based on the approach of error analysis presented in reference [41], the percentage error of electrical efficiency of a PV module can be evaluated as follows where the electrical efficiency of solar PV modules is a function of:

$$\eta = \eta\ (I, V, G) , \quad (6)$$

$$w_\eta = \left[\left(\frac{\partial\eta}{\partial I} w_I\right)^2 + \left(\frac{\partial\eta}{\partial V} w_V\right)^2 + \left(\frac{\partial\eta}{\partial G} w_G\right)^2\right]^{1/2} , \quad (7)$$

Where w_η is the uncertainty in the result; w_I, w_V and w_G are the uncertainty in current, voltage and solar radiation, respectively.

3. Results and Discussions

Experimental tests were conducted on 9 and 12 September 2019 to investigate the effects of cooling style on thermal performance of PV/T module. Seven modules were tested outdoors in cooperation with the Renewable Energy and Environment Research Center, Corporation of Research and Industrial Development, Ministry of Industry and Minerals, Jadiriya, Baghdad, Iraq.

3.1 Thermal experimental analysis

The efficiency of a solar PV module is influenced by several factors: solar radiation, inclination angle and ambient temperature. In this paper, the angle of inclination was fixed at 33° to the south. Thus, the main influencing factors were solar radiation and ambient temperature. The average temperature of the front surface was measured using a thermal camera and the camera software Smart View. The tests included measuring the solar radiation by using a solar meter sensor. The effect of irradiance on the temperature rise was also studied. At the same flow rate, the temperature rise increased with an increase in irradiance.

Figure 4 shows the variation of solar radiation with time in the tests conducted in this paper. The results demonstrate that solar radiation increases gradually with time; the highest solar radiation intensity was recorded between 11:00 and 12:00, reaching about 980 W/m², and started to decrease at 13:00 p.m. Figure 5 shows ambient temperatures during the day. The highest temperature during the day was recorded from 11:00 to 13:00. Ambient temperature rose due to the increase of solar irradiance.

The results show that the maximum reduction rate was 34% for Module I and 32% for Module IV. Two forces influenced on flow through inclined passage, gravity forces affected the vertical way, and buoyancy force influenced the major flow direction and results to appear as a secondary flow in the cross-passage plane.

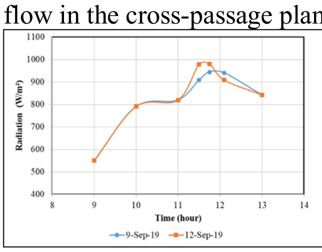

Fig. 4. Solar radiation of different dates

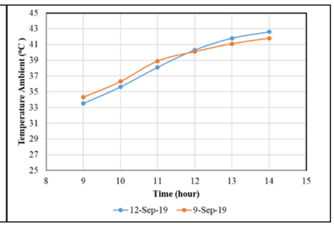

Fig. 5. Ambient temperature of different dates

The secondary flow currents had more arrangements around the passage centerline with the increase of the inclination angle from the horizontal direction and caused an increment in heat transfer from the back solar cells to the water and a reduction in module temperature. When the flow was from bottom to top, the forces caused the convection heat transfer from the module surfaces to the water to be supported with flow direction, but the opposite was observed when the flow from top to bottom. The reduction in the second state was less than that of the first state.as shown in Fig. 6. Heat transfer of the system depend on water flow rate and temperature difference between inlet and outlet water. The water temperature difference increased during the day for different modules at constant flow rate of 1l/min, where ($\Delta T_{water} = T_{out} - T_{in}$). The temperature of the water entering the chamber (Tin) was equal to 32 °C. The general trend of variation shows that ΔT increases as solar radiation and ambient temperature increase until time because water mass flow rate can carry most of the heat absorbed by the PV module from the surrounding and the curve declines afterward as radiation and air temperature decrease.

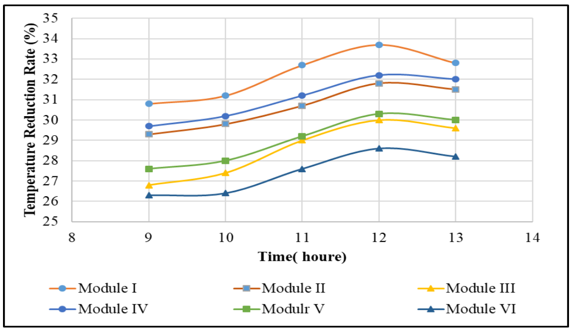

Fig. 6. Variation of temperature reduction with time for mass flow rates (1 l/min).

Figure 7 illustrates the relation between the useful heat transfer and solar radiation with time at the same flow. The results show that heat transfer of Module I (546 W/m²) and Module IV (506 W/m²) were the greatest at up-flow case and down-flow case, respectively.

Figure 8 shows thermal efficiency of all modules. A higher efficiency of about (58 %) was noted for Module I at 12:00 because heat transfer increased with the increase of the length of the liquid path crosses and the increase of the secondary flow arrangement when flowing at an angle 60˚.

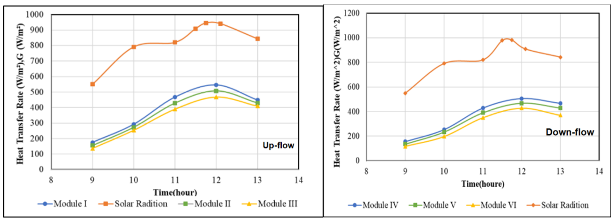

Fig. 7. Variation of heat transfer and solar radiation with time at a constant flow rate (1 l/min).

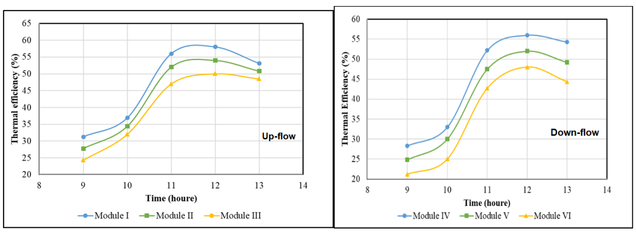

Fig. 8. Variation of the thermal efficiency with time at constant flow rate (1 l/min).

Increasing water flow rate at a range (1-4 l/min) caused a decrease in output temperature of water and a temperature difference between the inlet and outlet. By contrast, decreasing flow rate led to increased outlet temperature because water at low flow rate had long time to absorb heat from the surface of PV module. Thermal efficiency is related directly to heat transfer from the module. Thus, a high thermal efficiency was achieved at a high heat transfer obtained at a flow rate range of (3-4 l/min). Figure 9 shows that Module I had maximum thermal efficiency of 80% at a flow 4 l/min and an increment of 54% for a flow rate range of 1-4 l/min.

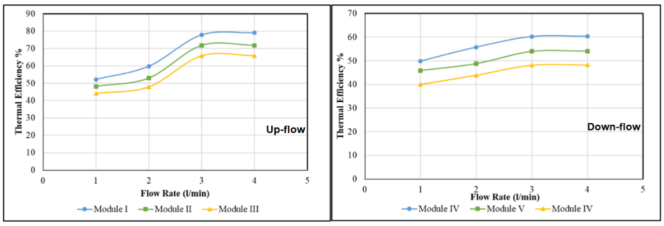

Fig. 9. Variation of thermal efficiency with different flow rate

3.2 Electrical experimental analysis

Characteristics of a solar PV module including power, current and voltage were directly proportional to one another. This relation was affected by the cooling system. Figure10 shows the relations between power-current as well as power-voltage. The Pmax obtained was 44.85 W at Vmp=16.83 V and Imp=2.66 A, open voltage was 21.01 V and short current was 2.821 A for Module I at a flow rate of 4 l/min.

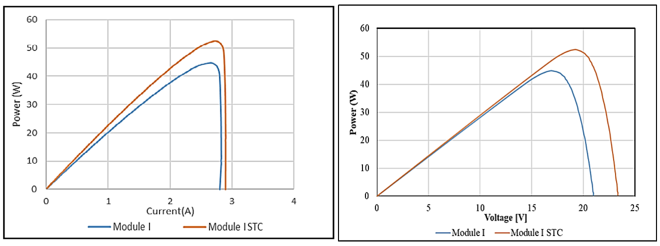

Fig. 10. Characteristics of Module I ([P-I] & [P-V] curves) at $\dot{V}$ = 4 l/min and G= 975 W/m²

Figure 11 illustrates firstly the relation between current and voltage of the tested PV modules that shows the values of Voc and Isc for different modules at a flow rate 3 l/min. The performance of module I was the best due to efficient cooling. Secondly, relations between power-voltage as well as power-current of Module I at different flow rates are presented. Output power increased with increasing flow rate between 1-3 l /min due to decreasing PV temperature that led to increased electrical output. The power at 4 l/min was smaller due to the decrease of the convection heat transfer between water and module surface. This can be attributed to the decrease of coefficient of heat transfer at high velocity of fluid flow.

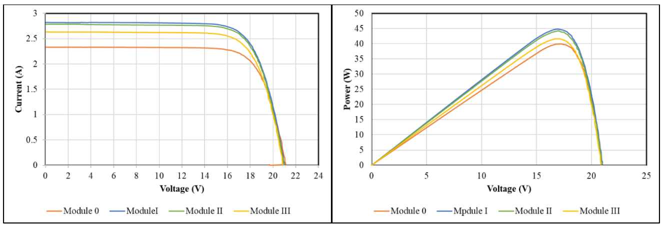

Fig. 11.a Characteristics of PV modules at flow rate 3 l/min

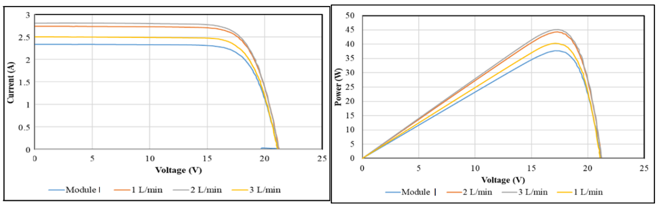

Fig. 11.b Characteristics of PV Module I (P-V) curves at different flow rates

Figure 12 shows that the best electrical efficiency increment was 17% at Module I and a flow rate of 4 l/min, and the lowest value was 7% at Module VI and a flow rate of 1 l/min. As flow varied from 1 l/min to 4 l/min, electrical efficiency increment increased for all modules with the best increment from 13.7% to 17% at Module I.

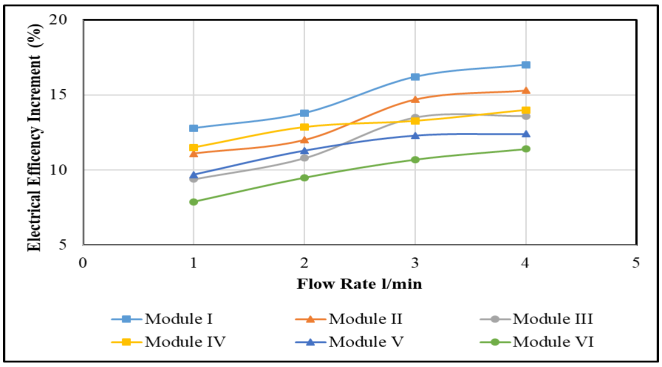

Fig. 12. Comparison of module output electrical efficiency increment (%).

The results of the present work were verified by comparing them with those of previous studies. Figure 13 compares the electrical efficiency increment curve for the PV module in the present study with that of Zeyad[20]. Electrical efficiency of the present work increased (16.6%) for Module I at a flow rate of 4 l/min, whereas the electrical efficiency increment obtained by Zeyad [20] was 14% after cooling in outdoor conditions at a high ambient temperature. This finding can be attributed to the different cooling methods.

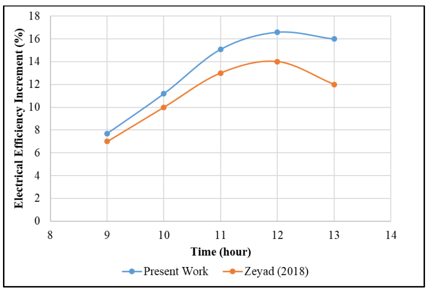

Fig. (13) Comparison with previous results of electrical efficiency increment curve for the PV module.

4. Conclusions

In this work, experimental analysis was carried out in Baghdad, Iraq to study the effect of cooling techniques on the thermal and electrical behavior of PV modules (Type: FRS-50W) installed at a 33° tilt angle. Six types of water flow style through chamber modules [(I, II, III) up-flow and (IV, V and VI) down-flow] were employed and compared with an uncooled Module (Module 0). The results show the effects of passage angle and flow rate on PV performance. Module I (flow angle of 60°) had a maximum thermal efficiency of 80% at a flow rate of 4 l/min and an increment of 54% for a flow rate range of 1-4 l/min. The PV module's electrical efficiency with using Module I, II (flow angle of 30°), and III (flow angle of 0°) with a flow rate of 4 l/min in the cooling chamber increased by 17%, 15.3%, and 13.6%, respectively, compared with Module 0. Therefore, the cooling technique is the best solution to enhance electricity production by maximum reduction of operating temperature of the PV module for efficient use in the hot climate of Iraq.

Acknowledgments

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