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Improvement of Photovoltaic Panel Performance Using Cooling Water System

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ABSTRACT

This study examines the impact of water cooling on photovoltaic panel performance under Egypt's harsh summer conditions. Two water flow rates (2.2 L/min and 1.125 L/min) were carefully tested to evaluate their effect on the overall electrical efficiency of the system. Experiments were conducted with voltage (30–35 V), current (0.5–7.8 A), and solar intensity (400–800 W/m²) between 9:00 AM and 1:00 PM. Results clearly show that increasing the water flow rate to 2.2 L/min significantly enhances electrical efficiency compared to uncooled panels. The highest voltage, current, and efficiency were all achieved at 2.2 L/min, while no cooling resulted in significantly lower performance values. Four accurate empirical equations were developed to help predict key performance parameters, with deviations consistently remaining within ±10%. Compared to published data, water cooling improved efficiency at 2.2 L/min, followed by 1.125 L/min, confirming its practical effectiveness in enhancing PV panel performance in extremely hot climates

1. Introduction

The global energy crisis presents a complex challenge that intersects technology, environment, and policy. Rapid industrialization, population growth, and increasing energy demands are straining existing energy infrastructures, which still rely heavily on finite and polluting fossil fuels. This dependence not only accelerates climate change but also raises concerns about long-term energy security and resource availability. For the engineering community, this situation calls for innovative solutions ranging from advanced renewable energy systems and smart grid technologies to enhanced energy efficiency and sustainable design practices to build a more resilient and sustainable energy future. the development of alternative renewable energy sources has become a strategic priority. Renewable energies such as solar, wind, hydro, biomass, and geothermal offer clean, sustainable solutions that can reduce greenhouse gas emissions and diversify the global energy mix. Photovoltaic (PV) panels and solar energy have emerged as vital components in the global shift toward sustainable power solutions. As a clean, renewable, and widely available energy source, solar power offers numerous benefits, including environmental protection, low operational costs, and energy independence. With advancements in technology and growing demand for low carbon alternatives, PV systems are increasingly recognized for their efficiency, scalability, and potential to drive both economic and environmental progress. One of the key challenges affecting the performance of photovoltaic (PV) panels is the rise in back panel temperature during operation. As solar irradiance increases, so does the heat absorbed by the panel, leading to higher operating temperatures especially on the rear surface. This thermal buildup reduces the electrical efficiency of the PV cells, as their performance declines with increasing temperature. Addressing this issue is critical for maintaining energy conversion efficiency, prolonging system lifespan, and ensuring optimal performance in high-temperature environments. Consequently, thermal management strategies, including passive and active cooling techniques, are a growing area of research in PV system design. With the advancement of solar energy applications and the photovoltaic sector, significant efforts have been made to enhance electrical efficiency. One effective approach involves cooling photovoltaic panels with various fluids, such as air and water, to improve performance. Since photovoltaic panels play a crucial role in determining peak efficiency, water-cooling systems have been applied to regulate panel temperature, enhance power generation, and improve electrical conversion efficiency. Several studies have explored different cooling methods. Akio S. et al [1] studied the performance of two hybrid collectors and their characteristics under sunlight, ~~the~~ thermal efficiency of these systems was improved to 72% and 77% using water as a coolant. Two separate one-dimensional analysis have been developed for the prediction of thermal and electrical

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performance of both liquid and air flat plate photovoltaic thermal (PV/T) collectors by Raghuraman P. [2] to record a thermal and electrical efficiencies improvement. Cox III C. H. et al [3] focus on air cooled collector and found that for photovoltaic cell covering more 65% of the total collector area a selective absorber reduces the collector thermal efficiency. Cheap and good thermal efficiency photovoltaic systems using transparent a-Si panels were examined by Lalovic B. [4]. Garg H. P. e t al [5] focusing on design and various operational parameters for two photovoltaic systems to compromise between the cost and efficiency of each system. Al Harbi Y. et al. [6] conducted an experiment on a photovoltaic thermal collector in Saudi Arabia, demonstrating that efficiency increases as panel temperature decreases. Hegazy A. A. [7] compared the performance of four air-cooled PV/T solar collectors. Further studies investigated glazed PV/T air systems for space heating and drying applications Sopian K. et al. [8]. Chow T. T. et al. [9] studied experimentally with computational model an air-cooled photovoltaic panel performance in integrated buildings. Analytical models for electrical efficiency in hybrid photovoltaic collectors constructed by Dubey S. et al. [10]. Teo H. G. et al. [11] studied active air-cooling system for photovoltaic module with efficiency increasing from 9% to 14%. Water cooling has also been explored for minimizing water and energy consumption needed for solar panel, especially in desert regions by Moharram K. A. et al. [12], Khalil A. et al. [13] examined three different position cooling techniques, the highest efficiency improvements were observed when cooling both the front and back of panel. Nanofluid-based cooling using water and Al_2O_3 nanoparticles has been shown to enhance PV performance, with higher concentrations yielding greater improvements by Salem M. R. et al. [14]. Chin Ch. S. et al. [15] studied the performance improvement as a cold plate designs with guided channels which improved efficiency by 2%. A photovoltaic cell cooling technique was studied; results depicts that the increase in electrical efficiency of the system with decrease in thermal resistance by Singh A. [16]. Attached a water-cooling chamber to a back of photovoltaic panel investigated by Muslim N. H. et al [17] the increasing in electrical energy was observed by 17%. Enhancing of photovoltaic panel efficiency by cooling system investigated by Majdi H. Sh. et al. [18] the electrical efficiency improvement was observed. Sultan T. N. et al. [19] presented a two-cooling method air cooled and water-cooled method) to cool a photovoltaic cell, it observed that the water-cooling method increase system efficiency larger than the air-cooled method.

2.Experimental

An experimental test rig, shown in Figures 1 and 2, was designed to investigate the electrical performance of a water-cooled 350 W photovoltaic panel. The system operates at 35 V and 10 A, with a 0.5 HP pump and a water flow rate of 2.5 liters per minute

The rig includes a water pump, a water flow meter (ranging from 1 to 7 Liters per minute), a 35x45 cm radiator, a 30-watt fan, and a copper sheet heat exchanger with 55 tubes (15.6 mm in diameter and 100 cm in length). The heat exchanger is attached to the back of the photovoltaic panel and circulates cooling water to reduce the back panel temperature. A 70-liter stainless steel water tank serves as both the water supply and a heat sink.

Seven K-type thermocouples, with a temperature range of 5 to 200°C (± 0.5°C), are used to measure the inlet and outlet cooling water temperatures, as well as the back panel temperature of the photovoltaic panel. Three experiments were conducted with different heat-exchanger flow rates: 2.2 Liters per minute, 1.25 Liters per minute, and no cooling.

In this study, a modified photovoltaic panel is used. Normally, when the solar panel is exposed to direct sunlight, it generates direct current, but the panel temperature rises, leading to reduced performance. To mitigate this, the optimum solution is to lower the back panel temperature by using cooling water. The heat exchanger is mounted on the back of the solar panel and connected to the circulating water pump. The thermocouples were calibrated using hot water, with both a standard thermometer and the thermocouples immersed in an insulated vessel. All thermocouples at three locations on the test rig were calibrated from 0 to 100°C using ice and boiling water at atmospheric pressure. The calibration curve relating the measured temperature of the thermocouples to the corresponding temperature from the standard thermometer is shown in Figure 3.

Table 1: Photovoltaic Panel Specification

SI No.	Parameter	Value
1	**Maximum Power,**	**350 W**
2	**Maximum Voltage**	**35 V**
3	**Maximum Current**	**10 Amps**
4	**Cell technology**	**Polycrystalline**
5	**Cell shape**	**Rectangle**
6	**Thickness**	**35 mm**
7	**Length**	**166 cm**
8	**Width**	**100 cm**
9	**Weight**	**18.5 kg**

Table 2: Operating conditions of case studies

	Operating conditions	
1	No cooling	Solar intensity ranged from 400-800 W/m^2 Back-panel temperature ranged from 30.3 and 66 ^oC
2	1.25 Liter per minute volume flow rate cooling water	
3	2.2 Liter per minute volume flow rate cooling water	

Heat Exchanger Calculations

To calculate the heat transferred from the solar panel to the water inside the heat exchanger, two thermocouples were connected to the input and output tube of the heat exchanger, the flow rates were measured after setting up the system, by using a water flowmeter.

$$Q_{H.Ex} = m^{\cdot} \times C_w \times \Delta T_{H.Ex} \quad (1)$$

Where: $Q_{H.Ex}$, heat transferred to Heat exchanger, $m^{\cdot}$ is a water mass flow rate, C_w is water specific heat, and $\Delta T_{H.\,Ex}$ is a temperature difference between inlet and outlet water in a heat exchanger.

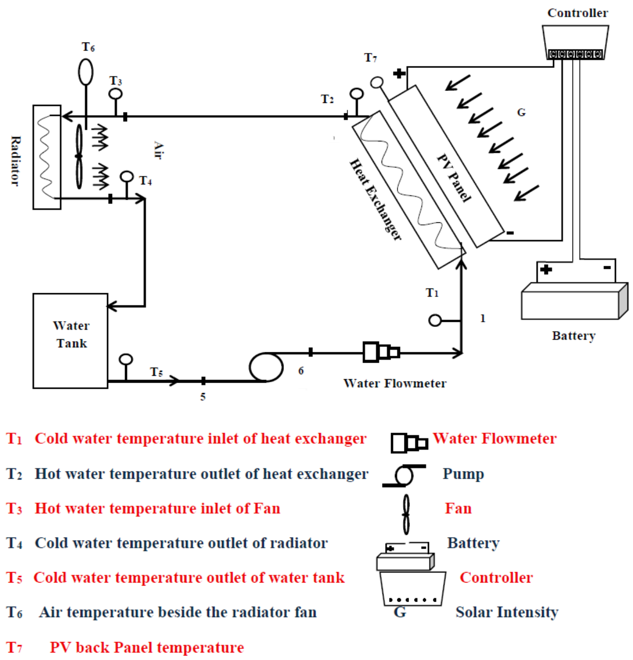

Fig. 1 Experimental setup schematically

Fig. 2. Photography of an experimental set up

Radiator Calculations

To calculate the heat rejected in radiator two thermocouples were connected to the input and output tube of the heat exchanger the flow rates were measured before.

$$Q_{radiator} = m^{\cdot} \times C_w \times \Delta T_{radiator} \quad (2)$$

Where: $Q_{radiator}$, is a heat transferred to the radiator, $m^{\cdot}$ is a water mass flow rate, C_w is water specific heat and $\Delta T_{Radiator}$ is a temperature difference between inlet and outlet water in Radiator.
To calculate the overall heat transfer coefficient (U) for the heat-exchanger,

$$Q_{radiator} = U \times A \times F \times \Delta T_{lm} \quad (3)$$

In Eq. (3) radiator heat transfer rate, $Q_{radiator}$ can be calculated as states in Cengel [30]:

Where: U is the overall heat transfer coefficient, A is a surface area, F is the correction factor and ΔT_{lm} is a Logarithmic mean temperature difference.
Where the surface area (A) is calculated by,

$$A = n \times \pi \times d \times L \quad (4)$$

Where: n is the tube number, π equal to 3.14159, D is the outer diameter of the heat exchanger tube and L is the length of the tube. the correction factor (F) is determined from the heat exchanger chart using the two constant P and R

$$P = \frac{t_2 - t_1}{T_2 - t_1} \quad (5)$$

$$R = \frac{T_1 - T_2}{t_2 - t_1} \quad (6)$$

Where: P and R are constants, t_2 outlet hot water temperature, t_1 intlet hot water temperature, T_1 inlet cold water temperature, and T_2 outlet cold water temperature. The Logarithmic temperature difference is calculated,

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{T_2}} \quad (7)$$

$$\Delta T_1 = T_{w_{in}} - T_{Air_{out}} \quad (8)$$

$$\Delta T_2 = T_{w_{out}} - T_{Air_{in}} \quad (9)$$

Where ΔT_{lm}: Logarithmic mean temperature, $T_{w_{in}}$: inlet water temperature
$T_{w_{out}}$: outlet water temperature, $T_{Air_{in}}$: inlet Air temperature, $T_{Air_{out}}$: outlet Air temperature.

Solar Calculation

Solar insolation is amount of electromagnetic energy or solar radiation received at a point on the earth's surface. Cloud coverage, solar declination angle, zenith angle, and hour angle are necessary variables to consider when determining solar insolation. The units for solar insolation are generally expressed in kWh/m^2/day this represents the amount of daily solar energy in a kilowatt-hour striking a square meter of the earth's surface. Calculate the hour angle (H) using the following formula:

$$H = 15^o \times (time - 12) \qquad (10)$$

Time equals the hour of day,

$$Z = cos^{-1}[(\sin x \times \sin Y) + (\cos x \times \cos Y \times \cos H)] \qquad (11)$$

Where: X: is latitude, Y is the solar declination angle and H is the hour angle

Solar declination angle is the angle between a plane perpendicular to incoming solar radiation and the earth's rotation axis. The solar declination angle varies from +23.5 degrees on the summer solstice to -23.5 degrees on the winter solstice. The solar declination angle is 0 degrees on the vernal equinox and autumnal equinox. Calculate solar insolation, I_{angle}

$$I_{angle} = S \times \cos Z \qquad (12)$$

Where: S is solar constant 1000 W/m^2 depending on the angle and weather conditions, Z is the zenith angle.

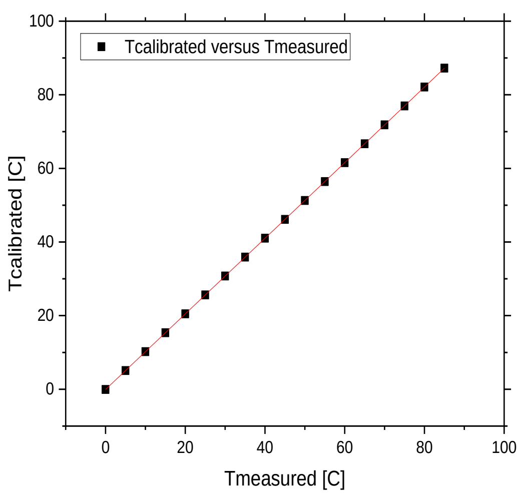

Fig.3 Thermocouples calibration

Figure 3 represents thermocouples calibration made in heat transfer laboratory using a calibration thermometer with accuracy 0.1 ^{o}C to give a linear relation between the calibrated thermometer and entire thermocouples shown on the curve.

4. Results and discussion

The present results show the effect of solar intensity on the panel voltage, power, and back panel temperature also the effect of temperature on the electrical efficiency follows by the governing deduced correlation equations for each case.

4.1 Solar intensity influence the voltage

Figure 4 shows the effect of the solar intensity on the voltage at three cooling water flow rates 2.2 L/min, 1.125 L/min, and no cooling water, it's noticed that the voltage increase with the increase of solar intensity until 600 W/m^2 for all cases, while the 2.2 L/min water flow rate has the highest voltage with 7.7% panel enhancement, then the 1.125 L/min with 5.9% panel enhancement then the no cooling state, the highest voltage gained by the solar intensity at 800 W/m^2 solar intensity while the lowest enhancement 4.1% achieved at 400 W/m^2 solar intensity. It's observed that the voltage increases with the cooling water flow rate increase.

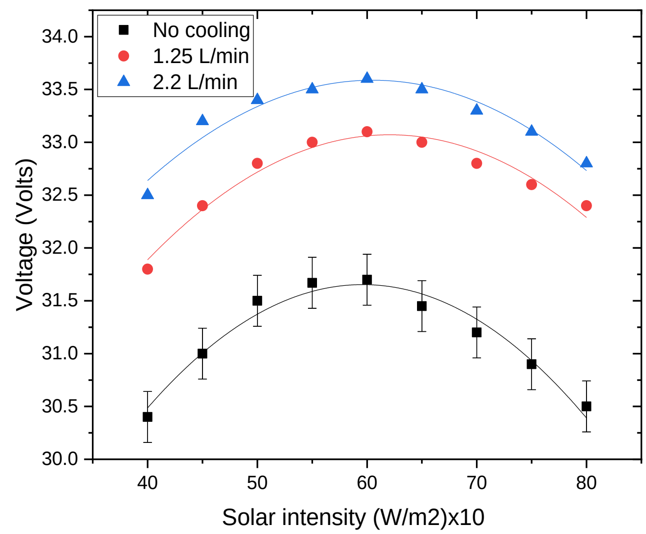

Fig.4 Solar intensity impacts the voltage at different cooling water flow rates

Deduced voltage empirical equation

An empirical correlation equation to calculate the voltage is deduced based on the present experimental measurements. An empirical correlation equation (13) is deduced which is expressed in the following form:

$$V = \{(25.38 + 1.42Q) + ((4.61 \times 10^{-5}) - (3.8 \times 10^{-6}Q))G^2 + ((-1.023\times10-10)+8.2\times10-12Q)G4+((6.744\times10-17)-4.88\times10-18Q)G6 \qquad (13)$$

Where V is voltage [V], G is solar intensity [W/m^2], and Q is a cooling water flow rate L/min. This correlation equation fits the present experimental measurements by Table curve 3D with a maximum deviation of ± 3.4 %. the present correlation equation seems simple and easy to use to calculate the voltage for a wide range of solar intensity and cooling water flow rate. The voltage obtained from the deduced correlation equation of the present study is plotted against the present measurements as shown in figure 5, curve fitting representation of this correlation is shown in figure 6.

Figure 5 depicts a relation between the measured voltage from the present measurements and calculated voltage using equation (13) for water flow rate ranging from 0 to 2.2 L/min solar intensity ranging from 400W/m^2 to 800W/m^2 and back panel temperature range from 42.5 to 66 C^o. This variation is linear between the experimental measurements and those given by the deduced correlation with a maximum deviation of ±3.4%.

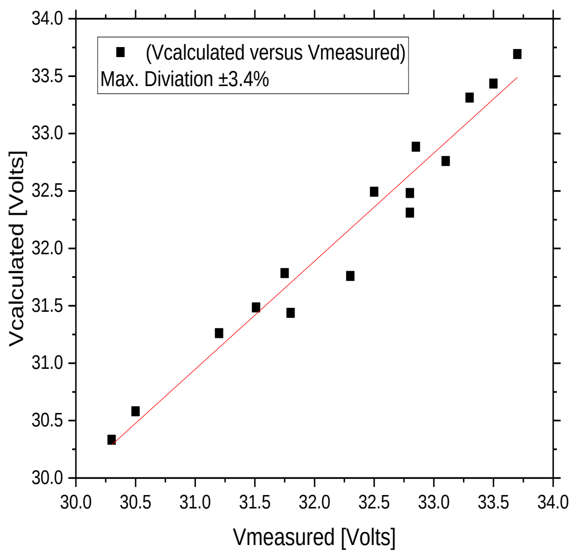

Fig. 5 Calculated voltages versus measured voltage

4.2 Solar intensity impact on Current

Figure 7 presents the effect of the solar intensity on the current at three cooling water flow rates 2.2 L/min, 1.125 L/min, and no cooling water, it's clear that the current increase with the increase of solar intensity to 800 W/m^2 for all cases, achieved the highest current with 9% current enhancement while the lowest enhancement 1.2%. It's observed that the current increases with the cooling water flow rate increase.

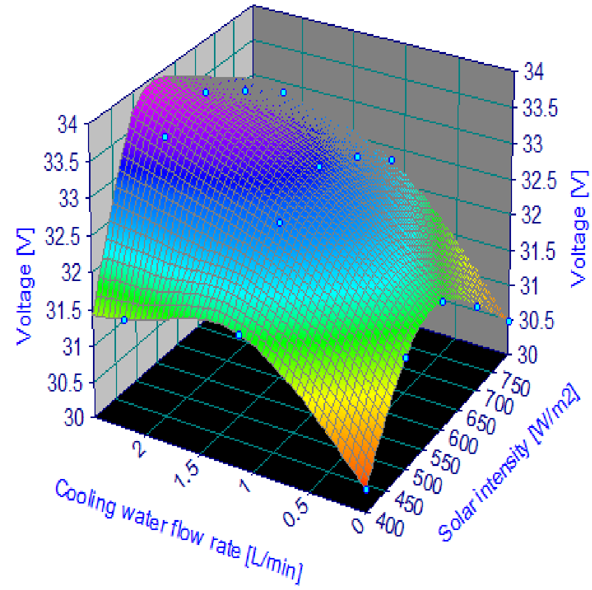

Fig. 6 Curve fitting representation for the voltage as a function of solar intensity and cooling water flow rate

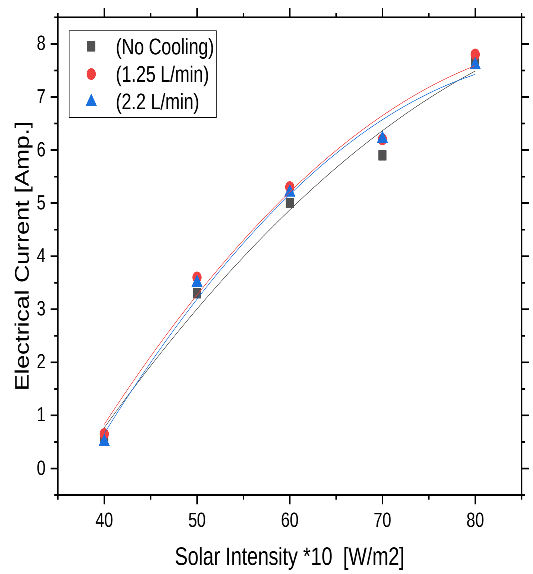

Fig. 7 Solar intensity influences the electrical current at different cooling water flow rates

Deduced current empirical equation

An empirical correlation equation (14) to calculate the current is deduced based on the present experimental measurements in the following form:

$$I = \{(11.38Q^2 - 11.25Q - 59.58) + (-0.0158Q^2 + 0.076Q - 0.057G+6.1\times10-5-5.2\times10-5Q0.5G2+-0.19Q2+0.404Q+2.42N \quad (14)$$

Where I is current [Amp], V is voltage [V], G is solar intensity [W/m^2], and Q is a cooling water flow rate [L/min].

This correlation equation fits the present experimental measurements by Table curve 3D with a maximum deviation of ± 10 %. The present correlation equation seems simple and easy to use to calculate the current for a wide range of solar intensity, voltage, and cooling water flow rate. The current obtained from the deduced correlation equation of the present study is plotted against the present measurements as shown in fig. 8, curve fitting representation of this correlation is shown in fig. 9.

Figure 8 shows a relation between the measured current from the present measurements and calculated current using equation (14) for water flow rate ranging from 0 to 2.2 L/min solar intensity ranging from 400W/m^2 to 800W/m^2 and back panel temperature range from 42.5 to 66 C^o. This variation is linear between the experimental measurements and those given by the deduced correlation with a maximum deviation of ±10%.

4.3 Solar intensity influences power

Figure 10 introduces the influence of the solar intensity on the power at three cooling water flow rates 2.2 L/min, 1.125 L/min, and no cooling water, it's clear that the power increase with the increase of solar intensity for all cases, while the 2.2 L/min water flow rate has the highest wattage with 13.7 % panel enhancement, then the 1.125 L/min with 13.5 % panel enhancement then the no cooling state, while the lowest enhancement 9.2 %. It's observed that the power increases with the cooling water flow rate increases.

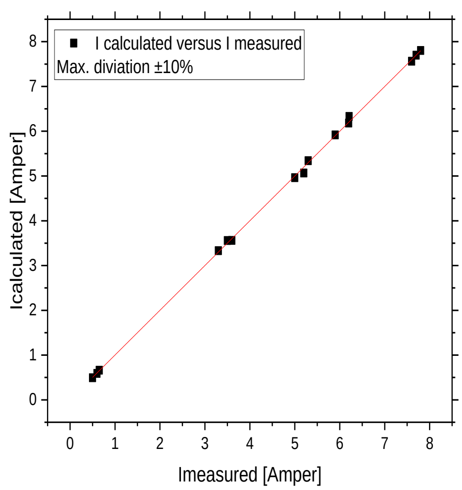

Fig. 8 Calculated current versus measured current

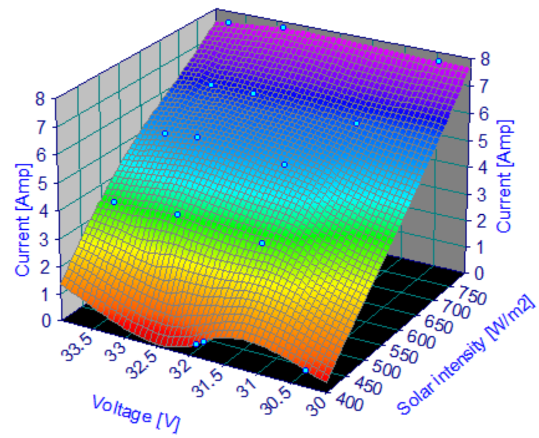

Fig. 9 Curve fitting representation for the current as a function of solar intensity voltage and cooling water flow rate

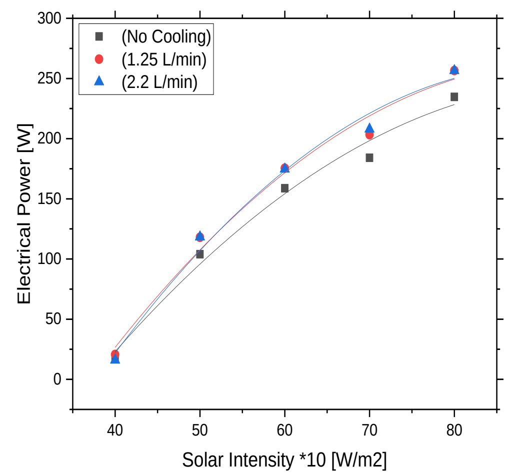

Fig. 10 Solar intensity impacts the power at different cooling water flow rates

4.4 Solar intensity impact on panel temperature

Figure 11 presents the impacts of the solar intensity on the back panel temperature. T_{bp} at three cooling water flow rates of 2.2 L/min, 1.125 L/min, and no cooling water, the temperature is linearly proportional to the solar intensity as displayed with active cooling, the temperature of the PV panel increases 1.9 ^{O}C for every 100 W/m^2 increments of solar intensity. However, if the PV panel is not actively cooled, the increase of temperature will be higher at 5 ^{O}C for every 100 W/m^2. it's noticed that the back panel temperature increases with the increase of solar intensity for all cases and decreases with the increase of cooling water flow rate, while the 2.2 L/min water flow rate has the highest temperature decreasing with 27 % as a temperature panel enhancement, then the 1.125 L/min with 24 % as a temperature panel enhancement then the no cooling state. It's observed that the back panel temperature decreases with the cooling water flow rate increases.

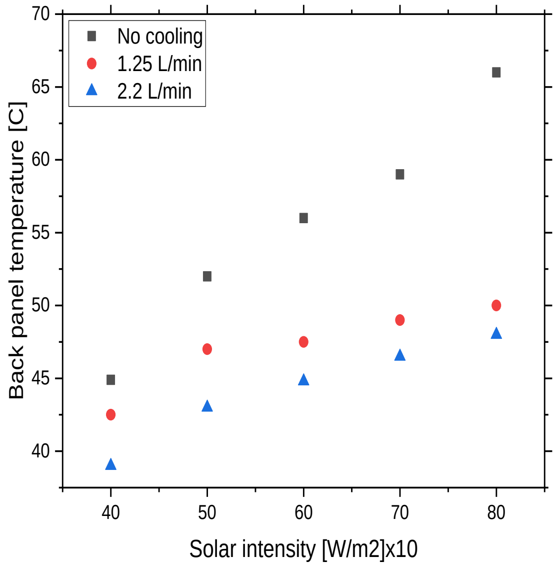

Fig. 11 Solar intensity influences the back panel temperature at different cooling water flow rates

An empirical equation (3) was deduced to calculate the back panel temperature based on the present experimental measurements.

$$T_{bp} = \{(-92.76 + 31.64Q) + (-0.188 + (0.0096Q^3))G + (23.7 - (3.97Q^{1.5}))t\} \qquad (15)$$

Where T_{bp} is back panel temperature [^{O}C], G is solar intensity [W/m^2], Q is colling water flow rate [L/min] and t is time [hours]

Figure 12 depicts a relation between the measured back panel temperature based on the present measurements and calculated back panel temperature using equation (15) for water flow rate ranging from 0 to 2.2 L/min solar intensity ranging from 400W/m^2 to800W/m^2 and back panel temperature range from 42.5 to 66 C^o. this variation is linear between the experimental measurements and those given by the deduced correlation with a maximum deviation of ±3.6%**.** the curve fitting representation of that correlation is shown in figure 13.

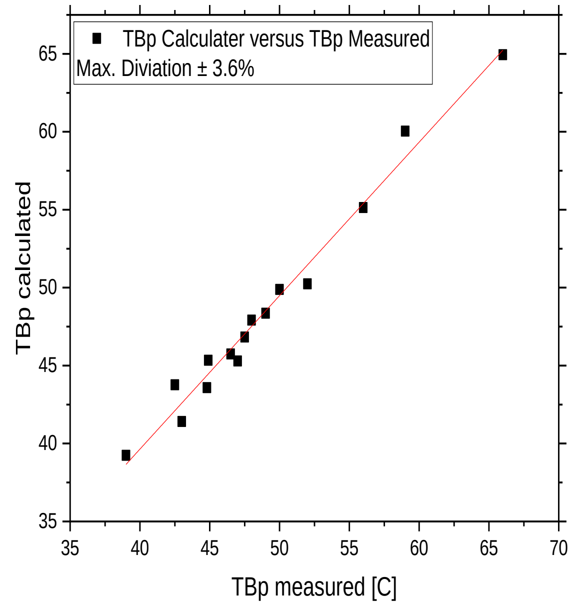

Fig. 12 Calculated back panel temperature versus measured back panel temperature

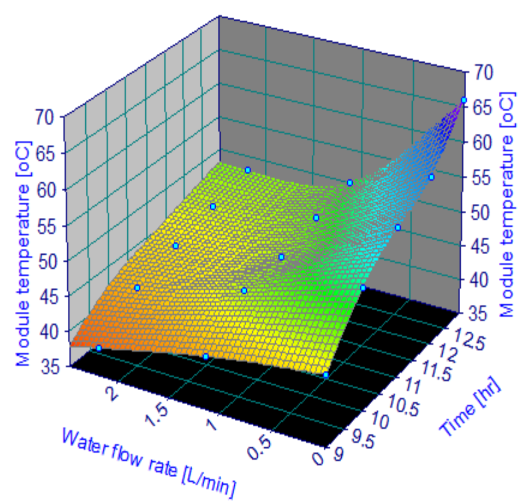

Fig. 13 Curve fitting representation for the module temperature as a function of solar intensity, time and cooling water flow rate

4.4 Time influence on solar intensity, G with literature comparison

A comparison of the present results with the published data of Al Harbi Y. [6] is given in Fig. 14 at solar intensity ranging from 400 to 800 W/m^2 and time from 9.00 AM to 1.00 PM where the trend of the present results shows similar behavior as those given by the published data. The present measurements are in fair agreement with published data which shows confidence in the present measurements. while the published data e measured for higher solar intensity at worst summer conditions.

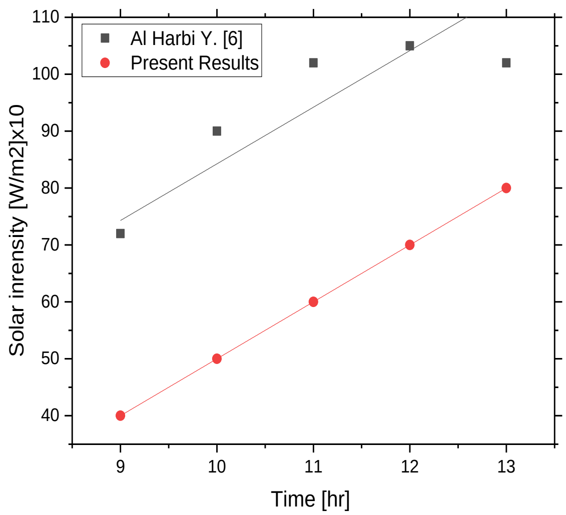

Fig. 14 Time impact on solar intensity comparison between present results and literature

4.5 Back panel temperature impact on electrical efficiency, η_e

The electrical efficiency of the photovoltaic panel can be described as stated in [15] the following equation.

$$\eta_e = \int VI\,dt \,/\, A \int G(t)\,dt \qquad (16)$$

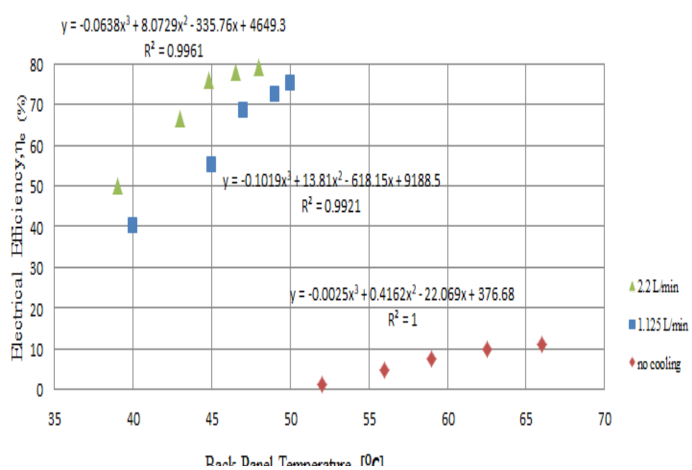

Fig.15 Back panel temperatures, C° effects on the electrical efficiency, % at different cooling water flow rates

Figure 15 express the impacts of the back panel temperature on the electrical efficiency at three cooling water flow rates 2.2 L/min, 1.125 L/min, and no cooling water, it's clear that the electrical efficiency increase with the increase of back panel temperature until 66 C° for no cooling case, 50 C° for 1.125 L/min and 48 C° for 2.2 L/min, while the 2.2 L/min water flow rate has the highest electrical efficiency enhancement to no cooling case, then the 1.125 L/min has electrical efficiency enhancement to no cooling case, the highest electrical efficiency, 79% gained back panel temperature of 48 C° at 2.2 L/min while the lowest electrical efficiency, 1.35% gained back panel temperature of 52 C° at no cooling. An empirical correlation equation (17) is deduced which is expressed in the following form:

$$\eta_e = \{(-aT_{bp}{}^3) + (bT_{bp}{}^2) + (-cT_{bp}) + d\} \qquad (17)$$

Where η_e is Electrical efficiency [%], T_{bp} is back panel temperature [°C], a, b, c, and d constants in the shown equations in figure 15

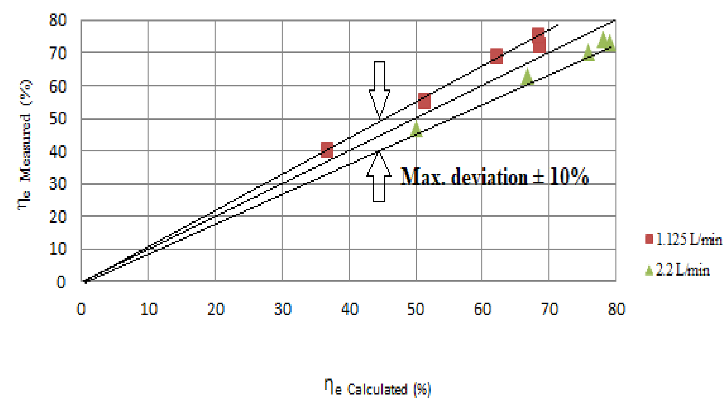

Fig. 16 Measured Electrical Efficiency (%) versus calculated Electrical Efficiency (%)

Figure 16 depicts a relation between the measured electrical efficiency based on the present measurements and calculated electrical efficiency using equation (4) for water flow rate ranging from 0 to 2.2 L/min solar intensity ranging from 400 W/m^2 to 800 W/m^2 and back panel temperature range from 42.5 to 66 °C. This variation is linear between the experimental measurements and those given by the deduced correlation with a maximum deviation of ±10%.

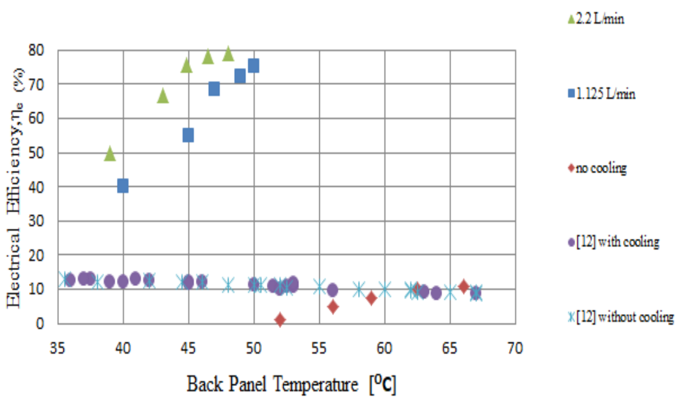

Fig. 17 Back panel temperatures affect electrical efficiency at different cooling water flow rates compared with the literature

A comparison of the present results with the published data of H.G. Teo [12] is given in Fig. 17 at solar intensity ranging from 400 to 800 W/m^2 and time from 9.00 AM to 1.00 PM where the trend of the present results shows similar behavior as those given by the published data. The present measurements are in fair agreement with published data which shows confidence in the present measurements. while the literature measures a lower electrical efficiency and higher panel temperature for lower operating conditions with an air-cooling case.

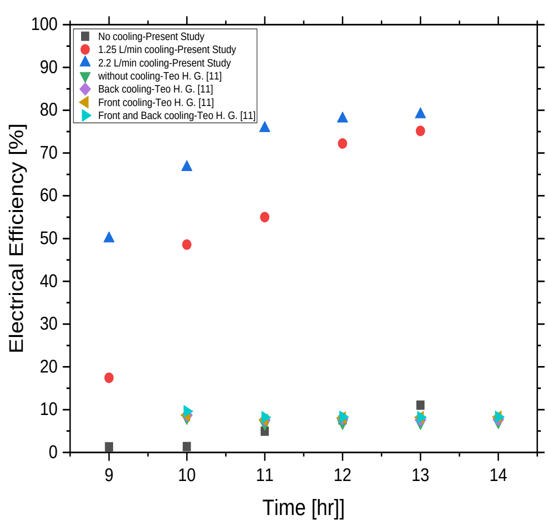

Fig. 18 Time effects on electrical efficiency at different cooling water flow rates compared with literature

Another comparison of the present results with the published data of Teo H. G. et al. [11] is shown in Fig. 18 at solar intensity ranging from 400 to 1100 W/m^2 and time from 9.00 AM to 2.00 PM where the trend of the present results shows similar behavior as those given by the published data. The present measurements are in fair agreement with published data which shows confidence in the present measurements.

Conclusions

1. The highest voltage enhancement of 7.7% was achieved at a cooling water flow rate of 2.2 L/min under 800 W/m² solar intensity, followed by 5.9% at 1.125 L/min and 800 W/m². The lowest enhancement, 4.1%, occurred without cooling at 400 W/m². An empirical equation (13) was developed to predict voltage based on flow rate and solar intensity, showing a strong linear correlation with experimental data and a maximum deviation of ±3.4%.
2. Current increased with solar intensity, reaching up to 9% enhancement at 800 W/m², while the lowest was 1.2%. Higher cooling water flow rates also contributed to increased current. An empirical equation (14) was developed to predict current based on flow rate, solar intensity, and voltage, with a maximum deviation of ±10% from experimental results.
3. Power output increased with solar intensity across all cases. The highest panel enhancement, 13.7%, was observed at a 2.2 L/min flow rate, followed by 13.5% at 1.125 L/min, and 9.2% without cooling.
4. Panel temperature increased linearly with solar intensity. With active cooling, temperature rose by 1.9 °C for every 100 W/m² increase. The greatest temperature reduction (27%) was achieved at 2.2 L/min, followed by 24% at 1.125 L/min, compared to the uncooled state. An empirical equation (15) was developed to estimate panel temperature based on flow rate, solar intensity, and time, with a maximum deviation of ±3.6% from experimental data.
5. Electrical efficiency increased with panel temperature up to specific limits: 66 °C (no cooling), 50 °C (1.125 L/min), and 48 °C (2.2 L/min). The highest efficiency was achieved at 48 °C with 2.2 L/min, while the lowest occurred at 52 °C without cooling. An empirical equation (17) was formulated to predict electrical efficiency based on back panel temperature, with a maximum deviation of ±10% from experimental results.

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