J Ther Eng, Vol. 8, No. 6, pp. 711–718, November 2022

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.1195570

Journal of Thermal Engineering

Research Article

Experimental investigation and validation of solar PV cooling for enhanced energy conversion efficiency for Indian climatic conditions

Pritam BHAT[1,*], Ananth S. IYENGAR[1], Abhilash N.[1], Pavan KUMAR REDDY[1]

[1]*Faculty of Engineering and Technology, M. S. Ramaiah University of Applied Sciences, Bengaluru, 560058, India*

ARTICLE INFO

Article history
Received: 07 January 2021
Accepted: 19 April 2021

Keywords:
Solar PV Cooling; Performance Enhancement; PV Efficiency; Thermal Collector; Front Water Cooling

ABSTRACT

Solar Photovoltaic (PV) cells convert an average of 10 to 15% of the incident solar radiation into electricity and remaining energy is wasted as unused heat energy. The performance of solar PV is largely dependent on its operating temperature, which is again dependent on solar irradiation. The efficiency of solar PV reduces the higher PV temperature due to charge carrier recombination. The solar PV efficiency drops considerably with increasing temperature. Dust deposition on the surface of solar PV cells reduce incident energy and no technology is commercially available to mitigate the problem. The objective of the present work is to enhance the energy conversion efficiency of solar PV by adopting Front Water (FW) cooling technique. The FW cooling technique maintains the cell temperature at Standard Test Conditions (STC) irrespective of ambient air conditions and also washes away dust deposits, thereby providing maximum energy conversion efficiency specified by the cell manufacturer during the operation with increased lifecycle of solar cells. The experiment was carried out on a 100 W solar panel for a period of 2 weeks and data acquisition system with Arduino controller was used to analyze and maintain STC of the panel to obtain maximum power. The mathematical model of the system was analyzed and obtained results were in good agreement with the experimental measurements. The solar PV panel with FW cooling yielded an efficiency improvement of 9% with 17 W of increased power output at Maximum Power Point (MPP). MATLAB Simulink software is used to model the FW cooling technique. The model is able to predict the power generated by the solar PV cells for the given irradiance with and without cooling. The developed model can now be utilized to design cooling systems for larger installation of solar PV systems.

Cite this article as: Bhat P, Iyengar AS, Abhilash N, Kumar Reddy P. Experimental investigation and validation of solar PV cooling for enhanced energy conversion efficiency for Indian climatic conditions. J Ther Eng 2022;8(6):711–718.

*Corresponding author.
*E-mail address: pritam.bhat9@gmail.com

This paper was recommended for publication in revised form by Regional Editor Tolga Taner

Published by Yıldız Technical University Press, İstanbul, Turkey

INTRODUCTION

Solar energy is one of the abundantly available form of renewable energy especially in the tropical and sub-tropical regions of the world. Solar energy is the most promising technology that can lead developing economies to prosperity. Solar PV cells convert a part of the incident irradiation into electrical energy, the rest of the energy is absorbed that heats up the solar cells. The rise in solar PV cell temperature causes a significant adverse effect on the power generation capacity of PV module. The most important factors affecting efficiency of PV cells are the intensity of incident radiation, quality of the semiconductor device and the operating temperature of the PV cells. The cost and efficiency of the PV cells per watt of power generation is considerably higher than the conventional mode of electricity generation. Therefore, solar PV efficiency plays a major role in its installation and wide spread adoption regardless of the freely available input solar energy to mankind [1]. The testing of solar cells are done for a wide range of temperatures, but high theoretical conversion efficiency is of 15 % is reached at room temperature of 25 0C [2]. The techniques to improve the conversion efficiency in silicon-based PV cells can be categorized into two broad areas: improving the solar PV cell materials and their thermal characteristics, which is much experimentally involved and time consuming. The other method is by optimizing the parameters affecting the efficiency of silicon based existing commercial solar PV. Thus a lot of attention is required to improve the performance of PV cells by optimizing the affecting parameters [3].It has been established that the solar conversion efficiency significantly drops with the increase in panel surface temperature [4]. The temperature coefficient of the solar cells exhibit a linear relationship between cell temperature and electrical energy efficiency. The adverse effect of increased panel surface temperature leads to less solar energy being absorbed, reduces the PV life and also leads to increased heat loss. The solar PV panel temperature can rise to as high as 50 0C in low altitude tropical climates, where the ambient air temperatures during mid-day to late afternoon are on average 35 0C or above. The drop in conversion efficiency is about ~0.45% (also known as temperature coefficient) for every degree rise in temperature from 25 0C [5]. Research has been carried out to improve the efficiency of the solar PV module by providing an efficient cooling system to remove the excess heat from the panel surface and thus maintaining constant operating temperature to reach the theoretical maximum power output. The cooling systems are broadly classified into active and passive cooling system. Passive cooling system refers to technologies that provides cooling effect without requiring any external power. Active cooling systems comprises of heat extraction mechanism using parasitic power consumption devices such as fans or pumps to carry away the heat. Although an active system consumes power, they are used in situations where the improved efficiency is significantly higher in comparison with the additional power required to run the cooling system[6], [7].

From the literature review of various cooling techniques adopted by different authors, Front Water (FW) cooling has advantages including, simple in design, highest cooling rate and can be controlled easily. This technique is best suited to recover waste heat from solar panel that can be utilized for domestic heating applications especially in Indian climatic conditions. Another FW cooling technique was proposed by [8] in which water is sprayed on the front panel of PV. They found that, the cooling was not uniform as water droplets did not evenly spread across the entire panel surface. It is reported that evaporation loss was considerably high resulting in reduced flow ability of the cooling fluid causing dust accumulation in the dusty areas. This led to reduced solar radiation absorption by the panel surface owing to added thermal resistance caused by the dust particles [9]. Priyabrata Santra [10] integrated solar PV modules with an irrigation system used in rural areas and remote locations where in, a portion of irrigation water is bypassed to flow over the PV modules utilizing the natural water gradient which is later collected in a conduit and supplied for irrigation use.

Researchers have also developed mathematical models to study the improvement of the energy conversion efficiency of the PV modules integrated with various cooling techniques. Kladisios [11] carried out Finite Difference Method (FDM) simulation to investigate the reduction in solar cells surface temperature by using Phase Change Materials (PCM) as cooling medium over PV cells. It was found that PCM effectiveness was dependent on the seasonal weather conditions and the PCM internal temperature. Haidar et al [12] developed a mathematical model to study the effect of evaporative cooling on performance of solar PV. The model considered heat and mass exchange between air, layers of water and solar PV to determine the effectiveness of cooling considering solar radiation intensity, air and water inlet temperatures resulting in 6 0C of reduction in solar PV panel surface temperature. Setiawan et al [13] showed that PV cell characteristics such as open circuit voltage (Voc), short circuit current (Isc), and Maximum Power Point (MPP) are greatly affected by ambient temperatures especially in tropical climates. Thus surface temperature of PV panel plays a major role in output power delivered by the system. Chatta [14] conducted an experimental investigation on monocrystalline and polycrystalline solar PV panel at different tilt angles to study its effect on solar PV performance. It was found that solar panel with tilt angle of around 330 produced optimum power output. It was also found that tilt angle depends on the geographical location, ambient temperature, solar irradiance and panel surface temperature. Akinbowale [15], [16] has showed the various thermal parameters that affects the variation of temperature distribution. Similarly Balotaki

Table 1. Major components and technical specifications of Solar PV panel integrated with FW cooling

Photovoltaic panel specification	**Model**	**ASPV 100**
	Max power (P_{max})	100 ± 5% W
	Voltage at P_{max}	18.4 V
	Current at P_{max}	5.43 A
	Open circuit voltage (V_{oc})	22.2 V
	Short circuit current (I_{sc})	5.76 A
	Panel technology	Poly-crystalline
	Temperature (STC)	29–31°C
	Cell arrangement	4 × 10
Pump	Type	12V DC pump, 300 mA
	Max. pressure	0.48 MPa
	Max. Flow rate	4.1 lpm
Data acquisition	Thermocouple	LM35 (4 in Nos)
	Arduino, multimeters & IR camera	

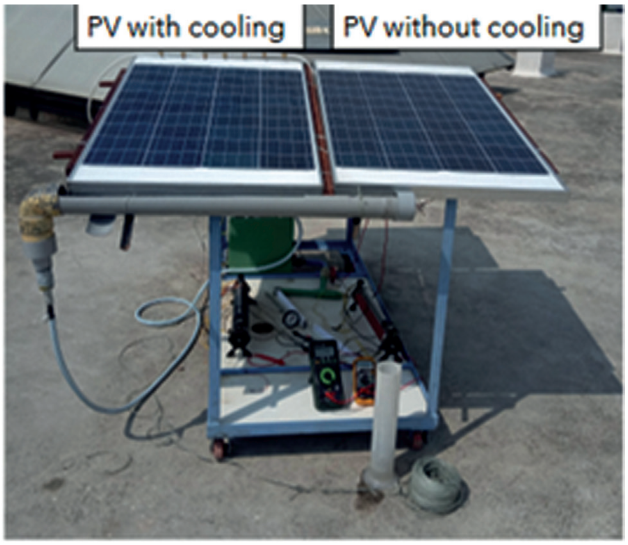

Figure 1. Experimental Test Set-up of Solar PV with and without Cooling.

[17] demonstrated the effectiveness of using solar collector as heat exchanger in process heat applications. It is found from the literature, that the temperature of the solar PV panel can be maintained constant using FW cooling system.

In the present work, experimental investigation is carried out on a solar PV integrated with FW cooling technique to increase its energy conversion efficiency. The experimental results obtained is validated with MATLAB/ Simulink mathematical model. The MATLAB model can predict power generated by the solar PV cells for the given irradiance with and without cooling. The novelty of the work includes development of a mathematical model that can be utilized to design cooling systems for larger installation of solar PV systems in any climatic conditions.

Experimental Setup of The Solar PV Integrated with Cooling System

The setup of the crystalline solar PV module cooling is shown in figure 1. It consists of 2 solar PV modules of 100 W capacity placed side by side facing the sun at an angle required according to the latitude. One of the modules were cooled using forward water circulation cooling technique while the second solar PV panel was setup without cooling. This facilitated in measuring the uncooled PV module temperature under the same condition. A pump of sufficient capacity was used to circulate water for forward water circulation circuit. Temperatures were measured using LM35 connected to multimeter. A thermal IR camera (FLUKE, VT-04) was used to find any presence of hot spots. Water was sprinkled through nozzles (7 nos.) at the top of the solar PV module. Table 2 lists major components and their specifications. The main advantage of this technique is there is no extra water consumption to cool the panel and dust particles on the panel surface are washed away. No additional power is required for the cooling system in this method as evaporation of water partially cools the circulated water. This technique led to increased solar radiation absorption and an improvement in the electrical efficiency was observed.

The experimental set-up of crystalline solar PV module with and without cooling is as shown in the Figure 1. The solar PV integrated with cooling system consists of water pump, water spray nozzles and data acquisition consisting of micro controller, LM35 temperature sensors, multi meters and IR camera. The water pump (12V, DC) is used to circulate water across the front surface of the solar panel. Figure 2a shows the cross sectional view of the solar PV integrated with FW cooling. Figure 2(a), 2(b) and 2(c) shows the concept of FW cooling applied to solar PV panel in the laboratory. The major components and the technical specifications of the solar PV integrated with FW cooling is given in Table 1. Figure 2d shows an image from thermal IR camera with no hotspots or cold spots indicating proper and sufficient water flow over the solar panel module.

The solar panel output current was modelled as shown in equations (1) to (4). The solar PV cell equivalent circuit is shown in Figure 3a, with a diode, shunt resistance along with a series resistance. The photo – generated current with series and shunt resistances is calculated using eq (1) by the known short circuit current, reference temperature and

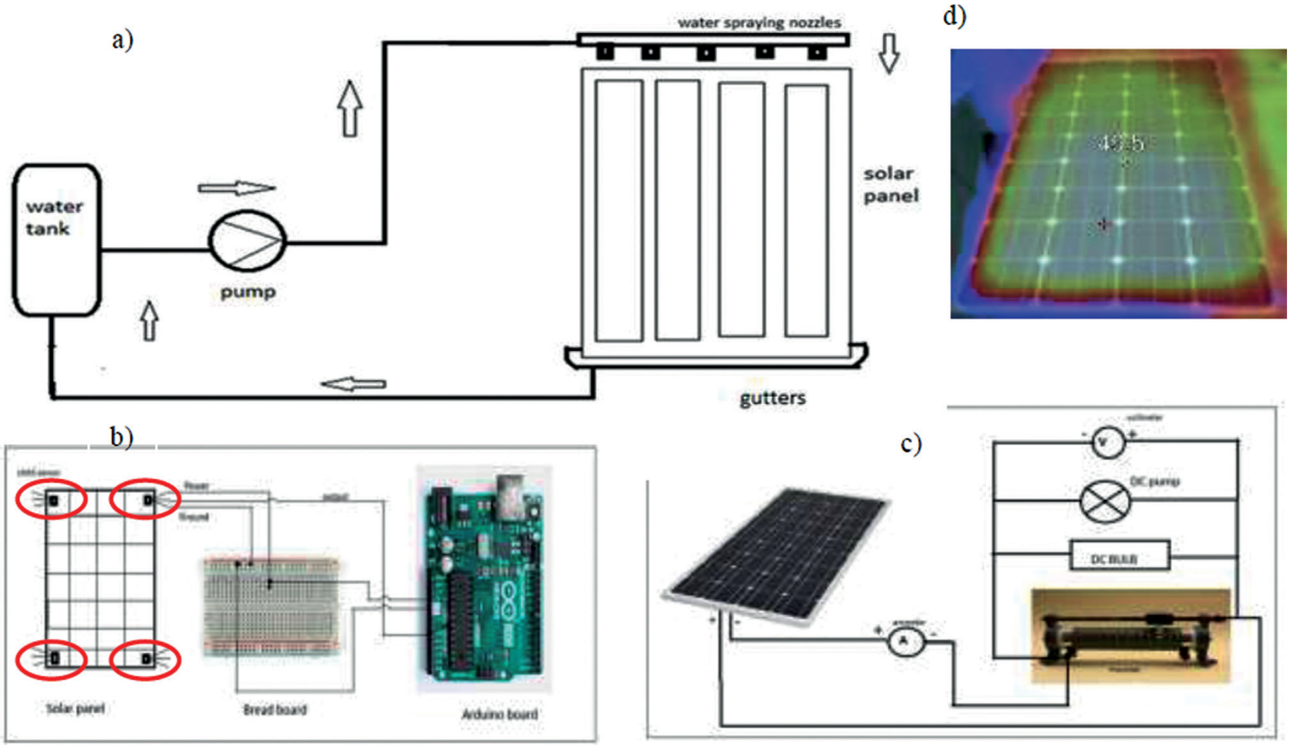

Figure 2. a) Concept of FW cooling technique, b) Temperature sensors connected to data acquisition system, c) PV electrical circuit connection used in FW cooling, d) Thermal IR camera image of PV module.

open circuit voltage. The saturation current is then calculated using equation (2) for the actual temperature. The PV cell current is calculated for the given illumination using eq (3) and the PV module with a Ns and Np PV cells in series and parallel respectively using the equation (4). The model has negative temperature coefficient for the voltage and positive temperature coefficient for the current. Figure 3b shows the schematic of MATLAB / Simulink program coded to simulate the behavior of the solar PV cells. The MATLAB program was developed by referring to thermal model equations given in [18], [19] . The output current is therefore used to produce the I-V and P-V characteristics curves.

$$I_{rr} = I_{scr} \times [e^{((q \times V_{oc}/K \times N_S \times A \times T_r))} - 1] \quad (1)$$

$$I_d = I_{rr} \times (T_a / T_r)^3 \times e^{((E_g \times q/K \times A \times (1/T_r - 1/T_a)))} \quad (2)$$

$$I_{pv} = [I_{scr} + (K_i \times (T_a - T_r))] \times S/1000 \quad (3)$$

$$I_o = N_p \times N_p - I_d \times (e^{[(q/N_S \times A \times K \times T_a) \times (V_O + I_O \times R_S)]} - 1) \quad (4)$$

The Simulink program is shown in the figure as a photovoltaic panel Simulink-mask, the output of the photovoltaic panel is current that is connected to the series RLC circuit to measure the voltage across the polarized capacitor and diode switch. The I-V and Power vs voltage (P-V) characteristics thus produced are plotted and further analyses are carried out.

Uncertainty Analysis of Solar PV Cells

The generated electrical power from a PV module can be expressed as a function of resistances, voltage, current, irradiance and temperature.

$$P = f(R, V, I, G, T) \quad (5)$$

Uncertainty calculation for the generated current is similar to the PV cell literature [20]

$$\frac{\partial f}{\partial P} e_P + \frac{\partial f}{\partial R} e_R + \frac{\partial f}{\partial G} e_G + \frac{\partial f}{\partial T} e_T + \frac{\partial f}{\partial I} e_I + \frac{\partial f}{\partial V} e_V = 0 \quad (6)$$

where, e_R, e_G, e_T, e_I and e_V are the errors in resistance, irradiance, temperature, current and voltage measurement. The total error in the measurement of power e_P is calculated to be ~10% based on the single diode, shunt and series resistance model selected for the PV cells.

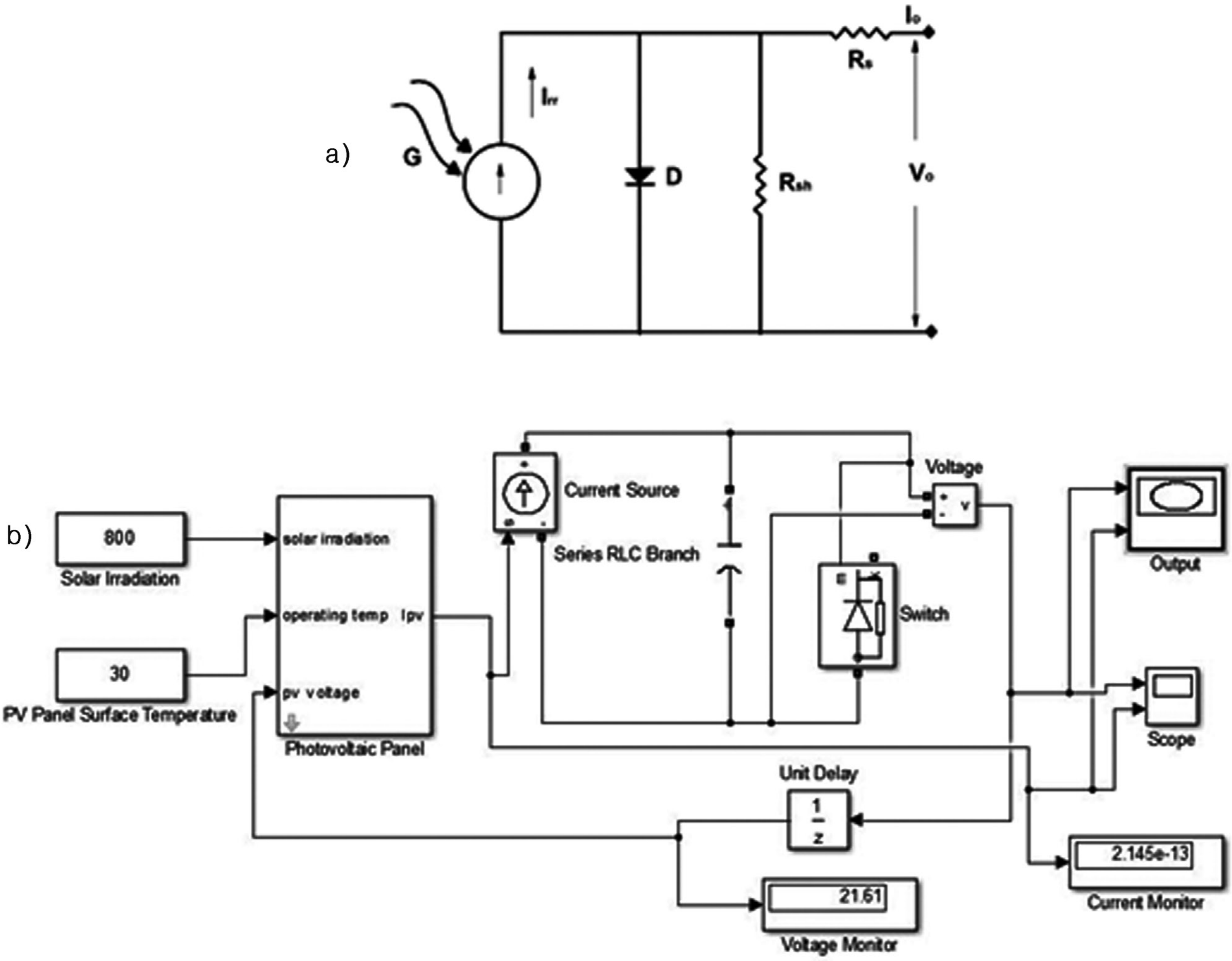

Figure 3. a) Equivalent circuit of a PV cell, b) Mathematical model of PV panel developed in MATLAB/Simulink.

RESULTS AND DISCUSSION

The performance test of the solar PV was carried out at Bengaluru, India (Latitude 13.010 N and longitude 77.510 E) in the month of April for 2 weeks to determine the energy conversion efficiency in the Indian sub-climate conditions. Parameters such as solar irradiation, ambient temperature and wind speed effects on the Maximum Power Point (MPP) in the current – voltage (I-V) curves of the solar panel were investigated. Maximum irradiance of 922 W/m2 was recorded at 12 pm of the day and the average irradiance received throughout the day for the test period is 736.5 W/m2. The water pump capacity of 4 LPM was completely used for cooling one of the solar PV modules. The cooled solar PV module showed no hotspots and was evenly cooled. All the LM35 readings were comparable to each other indicating a minimal localized heating. The panels were cooled within a minute in the FW cooling technique.

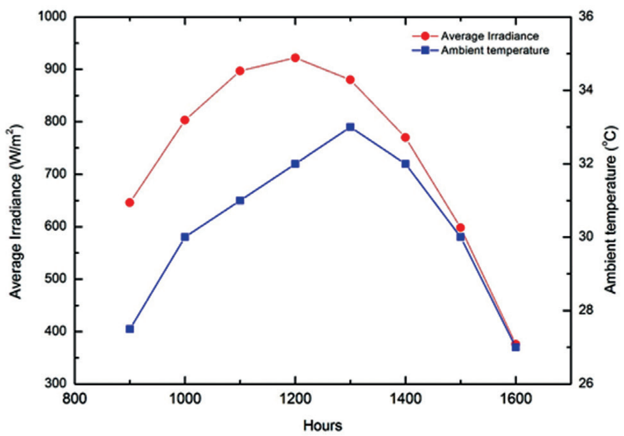

Figure 4. Irradiance and ambient temperature variation during the test period of the day, the time axis is represented in 24 hours format (800 is 08:00 hours).

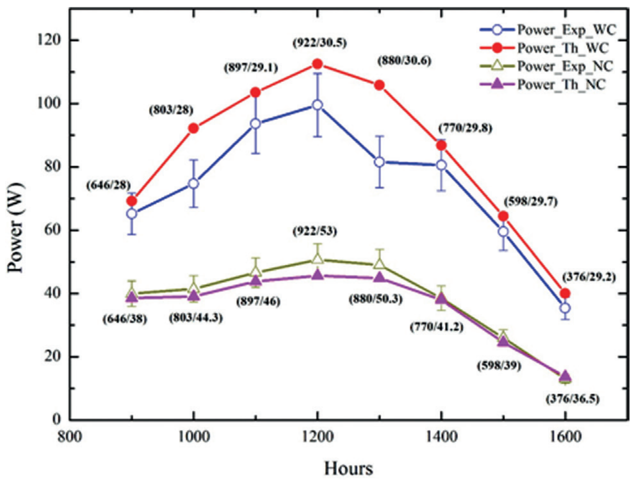

Figure 5. Comparison of PV panel mathematical and experimental power with cooling and no cooling conditions.

[Note: The data labels given in the graph are read as (Irradiation/PV panel surface temperature)]

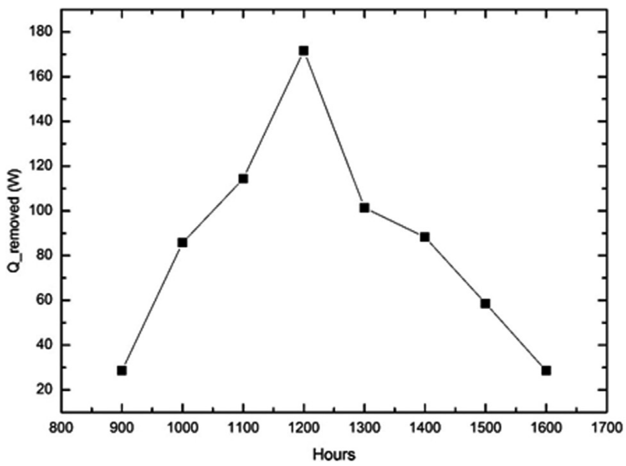

Figure 6. Rate of heat removal from PV panel surface.

Appreciable temperature rise was observed in the water stored in the reservoir of 15 litres capacity at the end of the experiment. Approximately 4% (600 mL) of water was lost due to evaporation during the conduction of experiment. The evaporative heat removal is estimated as 0.07 kW based on the latent heat of vaporization calculation. The remainder of heat removal is due to convection and direct radiative heat transfer to environment.

Figure 4 depicts the diurnal hourly variation of irradiance and the ambient temperature during the test period. The maximum ambient temperature of 35 0C is observed during the noon and average ambient temperature during the test period is 30.5 0C. The panel with and without cooling was kept side by side to nullify the effect of natural convective cooling from the surface of panel. It is evident that the panel surface temperature can be brought closer to ambient temperature with proposed FW-cooling technique as shown in the Figure 5. The average panel temperatures with and without cooling is noted to be 29.8 0C and 45.75 0C respectively. Thus, the cooling technique is able to reduce the panel average temperature by around 16 0C equal to 35 percent of temperature reduction.

Figure 5 shows the comparison of output power for panel with front water cooling and no cooling. As can be observed, the highest power was obtained at 12 noon for both cooled and uncooled PV panels. The peak power of the cooled PV was a close match to the rated power of 100 W. The uncooled PV panel shows a much lower power output, due to the temperature effects. The parasitic pump load is 3.6 W, which is much lower compared to the difference between the power outputs of uncooled and cooled PV panels. Additionally, figure 5 also shows the predicted power output values from the MATLAB / Simulink simulations.

The mathematical model used in the MATLAB closely predicts the experimental calculations with slight deviation at 1 PM data for the cooled PV panel. The model predicts a lower open circuit voltage and higher photon induced current in line with the literature [20]. It can be observed from figure 5 that the mathematically predicted values are higher for the cooled PV panel and slightly lower for uncooled PV panel. This is due to the temperature dependent resistance used in the mathematical model. Also, the variations of cooling and uncertainties present in the experimental setup produce effects that may not be captured in the mathematical model due to which higher power values are predicted by the mathematical model for FW cooled PV panel compared to experimental power. However, these deviations are well within the experimental errors and uncertainties presented in the paper.

As mentioned before, an appreciable temperature rise in water tank was observed. Figure 6 shows the hourly heat removed from the cooled solar panel. An average of 70 W of heat was recovered from the cooling water. The experiment was performed at rated flow rate of the DC pump. The effect of varying flow rates of water on the heat removal rate from the panel is out of scope in the present work. With further improvements, the present system can be converted to a hybrid PV-thermal solar energy harvesting system.

Figure 7 shows the efficiency improvement of solar PV module with FW cooling system. It can be seen that the best efficiency for an uncooled solar PV module is at 9.00 AM, as the temperature of the module is lower compared to the other parts of the day. As the day progresses, conversion efficiency drops to 7.52% at 10 am and 8.73% at 12 noon and never recovers. However an average of 9.35 % increase in efficiency can be observed for the entire day of testing period for FW cooled PV panel. The FW-cooled PV panels show a much higher efficiency from the early morning times and continues to maintain the higher efficiency throughout the day. The temperature of a FW cooled panel

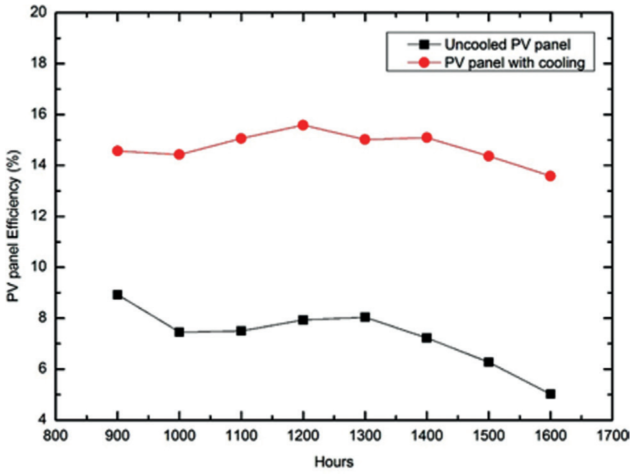

Figure 7. Comparison of PV panel efficiency with cooling and no cooling conditions.

is maintained approximately constant, due to the continuous removal of heat due to circulation of water. This is due to the following reason:

- By energy balance of silicon material of solar cell with flowing water, it can be observed that for a cooled PV, the temperature of solar cell is maintained constant by adjusting the heat carried away by cooling system throughout the test period.
- As the electrical parameters such as resistance, voltage are temperature dependent [20], the efficiency of the FW cooled solar PV remains unchanged throughout the day.

CONCLUSION

A front water (FW) cooling experimental analysis is carried out on a 100 W solar panel for a period of 2 weeks in peak summer season. The FW cooling is found to be very efficient in cooling solar PV panels. The average efficiency increase is found to be 9.35% throughout the day. The peak power was produced at 12 noon and is comparable to the rated power generation of the PV panel at Standard Test Conditions (STC). The FW-cooling shows quick cooling response. The panel reaches the prescribed operating temperature in less than a minute of operation of the cooling system. A mathematical model is developed in MATLAB/ Simulink to predict the behavior of the solar panel and validate experimental results. The model predicts the PV panel output accurately within the limits of experimental uncertainties. The model clearly shows that panel temperature, irradiance are important factors for solar PV panel performance. Several improvements can be suggested for the FW-cooling system, including the utilization of the heat removed. The same system can be used to clean the solar panels of any accumulated dust. The study is an approach to understand the behavior of PV module with FW-cooling technique. The convective cooling effects on PV module is out of scope of this study. Further improvement of the mathematical model will be aimed in the future research.

NOMENCLATURE

Io	PV module output current Amps
Vo	PV module output voltage Volts
S	Illumination W/cm^2
A	photo diode Ideality factor = 1.3
T_a	Actual PV module temperature K
T_r	Reference PV module temperature K
E_g	Silicon material band gap 1.12 eV
N_s	Number of PV cells in series
N_p	Number of PV cells in parallel
K	Boltzmann constant
K_i	short circuit temperature coeff. at I_{scr} 0.0013 A/°C
R_s	Series resistance of PV module ohms
I_{pv}	Actual current generated in PV cells
I_d	PV module saturation current
Irr	Photo – generated current with series and shunt resistances
Iscr	Short circuit current at 25°C and solar irradiance of 1000 W/cm^2

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Abdolzadeh M, Ameri M. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renew Energy 2009;34:91–96. [CrossRef]

[2] Wohlgemuth J, Kurtz S. Photovoltaic Module Qualification Plus Testing. 2014 IEEE 40th Photovolt. Spec. Conf. PVSC 2014, no. December, pp. 3589–3594, 2014. [CrossRef]

[3] Bahaidarah H, Subhan A, Gandhidasan P, Rehman S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 2013;59:445–453. [CrossRef]

[4] Dubey S, Sarvaiya JN, Seshadri B. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world - A review. Energy Proced 2013;33:311–321. [CrossRef]

[5] Sato D, Yamada N. Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method. Renew Sustain Energy Rev 2019;104:151–166. [CrossRef]

[6] Sainthiya H, Beniwal NS. Different types of cooling systems used in photovoltaic module solar system: A review. Proc 2017 Int Conf Wirel Commun Signal Process Networking, WiSPNET 2017, vol. 2018-Janua, pp. 1500–1506, 2018. [CrossRef]

[7] Sainthiya H, Beniwal NS. Efficiency enhancement of photovoltaic/thermal module using front surface cooling technique in winter and summer seasons: An experimental investigation. J Energy Resour Technol Trans ASME 2019;141:1–8. [CrossRef]

[8] Moharram KA, Abd-Elhady MS, Kandil HA, El-Sherif H. Enhancing the performance of photovoltaic panels by water cooling. Ain Shams Eng J 2013;4:869–877. [CrossRef]

[9] Odeh S, Behnia M. Improving photovoltaic module efficiency using water cooling. Heat Transf Eng 2009;30:499–505. [CrossRef]

[10] Santra P. Performance evaluation of solar PV pumping system for providing irrigation through micro-irrigation techniques using surface water resources in hot arid region of India. Agric Water Manag 2021;245:106554. [CrossRef]

[11] Kladisios P, Stegou-Sagia A. Using phase change materials in photovoltaic systems for cell temperature reduction: A finite difference simulation method. J Therm Eng 2016;2:897–906. [CrossRef]

[12] Haidar ZA, Orfi J, Oztop HF, Kaneesamkandi Z. Cooling of solar PV panels using evaporative cooling. J Therm Eng 2016;2:928–933. [CrossRef]

[13] Setiawan EA, Setiawan A, Siregar D. Analysis on solar panel performance and PV-inverter configuration for tropical region. J Therm Eng 2017;3:1259–1270. [CrossRef]

[14] Chatta MB, Ali HM, Ali M, Bashir MA. Experimental investigation of monocrystalline and polycrystalline solar modules at different inclination angles. J Therm Eng 2018;4:2137–2148. [CrossRef]

[15] Akinshilo A. Analytical decomposition solutions for heat transfer on straight fins with temperature dependent thermal conductivity and internal heat generation. J Therm Eng 2019;5:76–92. [CrossRef]

[16] Akinshilo A, Olofinkua J. Variation of Parameters method for thermal analysis of straight convective-radiative fins with temperature dependent thermal conductivity. J Comput Appl Mech 2018;49:125–132.

[17] Balotaki HK, Saidi MH. Experimental investigation of dual-purpose solar collector using with rectangular channels. J Therm Eng 2017;3:1052–1059. [CrossRef]

[18] Tiwari A, Sodha MS. Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study. Renew Energy 2006;31:2460–2474. [CrossRef]

[19] Tiwari A, Sodha MS. Performance evaluation of solar PV/T system: An experimental validation. Sol Energy 2006;80:751–759. [CrossRef]

[20] Attivissimo F, Di Nisio A, Savino M, Spadavecchia M. Uncertainty analysis in photovoltaic cell parameter estimation. IEEE Trans Instrum. Meas 2012;61:1334–1342. [CrossRef]