Experimental Investigation of Photovoltaic Panel Cooling by Uniformly Flowing Water on the Top Surface for Efficiency Improvement

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Abstract The study done in this article furnish the results of an experimental investigation on the cooling of solar photovoltaic (PV) panel with water flowing uniformly over the top surface. An experimental setup was designed, fabricated, and put to testing in real outdoor environment in the geographical region of Chandigarh, India. To overcome non-uniformities in the flow, various trials were made and a cuboidal vessel was designed. About a 50% decrease in temperature was observed. An improvement of about 17% in efficiency was observed by cooling the PV panel, it increased from 11.83% to 13.83%.

1 Introduction

In physics, the quantitative aspect of energy is that it must be conveyed to any matter to perform work on, or to heat, that matter. Indeed, the human race is entirely dependent on energy to stay alive and function. Energy is being derived from various both conventional as well as non-conventional energy resources such as crude oil, coal, solar, hydel, geothermal, etc. The contemporary world is entirely dependent on the capacity of humans to transform energy from one form to another usable form. The countries in the world are categorized as prosperous based on their high energy consumption rate per capita. The biggest challenge that humans are facing is the judicious and efficient use of energy.

1.1 The Energy Scenario

The global human population is increasing by around 1.1% annually. It is estimated to reach up to 8.4 billion by 2030 and 9.6 billion by 2050 in reference to the present

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census of 7 billion people living on earth today [1]. Every one of these individuals will require energy, which is shooting up the worldwide energy demand to the next level high. What's more, the energy utilization per capita is connected to the expectation for the everyday comforts of a nation. The global primary energy consumption had increased by about 2.9% in 2018 which was the maximum growth ever seen since 2010 [2]. In addition to that the carbon emissions from this much use of energy grew by 2% which is also the fastest rise in the past few years. In many nations, the expectation for daily life comforts is quickly increasing like in China and India, where roughly 2.5 billion individuals are living. Both the expanding population and expanding expectations for everyday comforts will build the energy request. What's more, it is normal that the world energy utilization is relied upon to increment by 33% in the period 2010–2030 [3].

To take care of the energy demand there is a weight on the accessible normal assets, which incorporates non-renewable energy sources like crude oil, coal, and gas. Fossil fuels are nothing just solar energy stored in chemical form for million years. The issue lies in the way that people drain these non-renewable energy sources quicker than they are recharged through the photosynthetic procedure in nature [4]. Besides this, in the process of harnessing energy from fossil fuels, these emit greenhouse gases into the environment. These greenhouse gases are solely responsible for the extremities due to climate change all around the globe. The CO_2 concentration in the Earth's environment is drastically increasing. As the pollution level is rising at an alarming rate, the world cannot rely on conventional techniques for harnessing energy from non-renewable sources of energy. Therefore, opting for efficient green technologies, RES (Renewable energy sources) are some of the potential solutions. Harnessing of energy from RES (solar, wind, hydro, etc.) can be done by various processes [5]. However, in any case, the sun is the vitality hotspot for every one of the procedures on the surface of our planet. Indeed, even breeze is a consequence of temperature distinction in the air actuated by sun-oriented illumination, waves are created by the breeze, mists, and rain are at first shaped by the dissipation of water because of daylight. As the sun is the parent source of energy, we have to move back again to a time when we begin to use the sun to fulfill our energy requirements.

1.2 Solar Energy and Solar Photovoltaics

Solar energy, being the biggest source of energy has immense potential to meet the desired energy requirement. To express this lucidly, the solar energy irradiating the earth's surface per hour is equal to the measure of annual energy requirements of the earth. Sun is a radiating black body with an average surface temperature of around 5800K, which prompts 1366 W/m^2 of energy dispersal over the atmosphere [6]. This much energy can be utilized in various ways. Solar energy can be utilized as heat or can be converted to other useful forms of energy. The solar light can directly be converted into electrical energy by using PV panels. Photo represents light and voltaic represents electricity, this is one of the inclusive techniques for solar

energy harnessing, which converts sunlight into usable electrical energy. There are mainly four types of PV panels in the market namely amorphous, mono-crystalline, poly-crystalline, and organic cells. The majority of the solar cells in the market are silicon-based. In this research, the purview is on a typical silicon PV panel consisting of numerous solar cells integrated into groups that are arranged in one plane that constitute a solar PV panel or solar PV module [7, 8]. On account of PV cells, a few scientists have broken down the module conduct and they found out that only 15–20% of the sun's incident illumination can be harnessed in electrical form while the remaining is lost as heat dissipation [9]. In this manner, to improve the electrical efficiency of the PV panel we have to investigate the factors influencing its performance.

1.3 Factors Affecting the Solar PV Performance

Various such factors are classified and sub-classified into operational, economic, and other miscellaneous factors [10]. Considering all the factors, nothing can be done much on the factors, which are mostly governed by nature such as irradiation, soiling, dust accumulation, etc. [11]. Given all the above-stated factors, the panel temperature affects the electrical efficiency of the PV panel the most and it diminishes at a rate of 0.4%–0.65% with every degree rise in the panel temperature [12, 13]. Some researchers observed that PV panel temperature can attain values as high as 353.15 K if installed in hot arid regions [14]. However, to the benefit, the panel temperature can be regulated to a possible extent and utilized the very same to maximize the performance of the PV panel.

1.4 Effect of PV Panel Temperature on Performance

Majorly the rise in panel temperature affects the open-circuit voltage (V_{oc}), which diminishes as directly with the rise in panel temperature. The cell voltage diminishes by about 2.2 mV for every 1 °C rise in the panel temperature and therefore the efficiency descends by around 0.5%–1% for crystalline PV panels [15]. By providing proper cooling to the panel, the electrical efficiency can be enhanced, and it also reduces the rate of deterioration or PV cells with time, bringing about augmentation of the longevity of PV panels [16]. The waste heat extracted by the cooling water may be utilized as in many thermal applications [17]. Figure 1 illustrates some methods being used for cooling PV panels to minimize the consequences of the increased temperature. There are various cooling methods available but the water being assuredly available, the more propitious one is to use a technology where water plays a dominant role in cooling the PV panels [18]. Sensible cooling by air and water is usually applied for the thermal management of various systems such as engines, electronic components, etc. Some of the advantages of this type of cooling are low operating
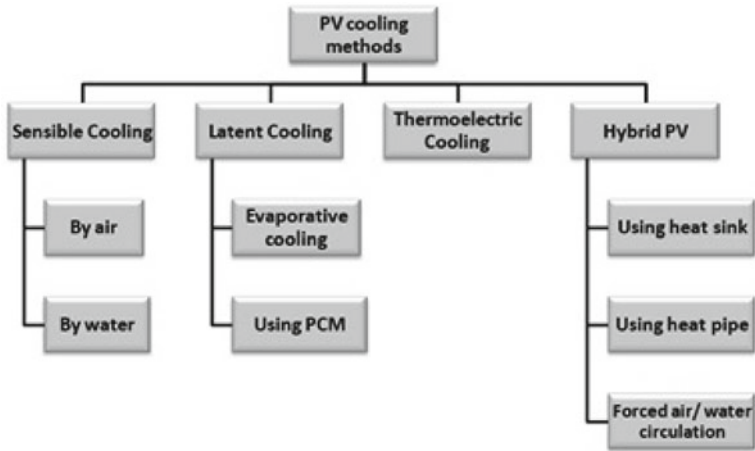
Fig. 1 PV panel cooling methods

costs and low material requirements. A study to improve the performance of PV modules using forced air cooling technique has been presented based on the comparison, it was shown that using the air cooling technique resulted in 7.2% and 6% higher electric output. In a study represented by Kasaeian et al. [19], four fans were used to flow cooling air inside the channels designed for PV cooling.

1.5 Various Top Surface Cooling Frameworks for PV Panels

Some active cooling frameworks used for the PV panel are shown in Fig. 2. These frameworks cannot shower and cover the total surface zone of the PV panel, which implies that some fraction of it is only cooled. There are flow non-uniformity phenomena that were distinguished amid the tuning of the water-spreading framework [20].

Many investigations had been done on the surface cooling of PV panels using water. Abdolzadeh and Ameri [21] in Iran investigated a cooling framework for cooling PV panels using water spray on its top surface. The effect of spray cooling on electrical efficiency was observed and compared with the conventional non-cooled PV panel. The effect of the water pumping rate was also observed. The results concluded that higher pumping of water was required during the peak sunshine hours since the temperature rise was highest. Hosseini et al. [22] used a thin-film water cooling method for reducing the PV surface temperature and reflection losses. Water was made to flow using a slit of a pipe which was supplied with water with the help of a recirculation pump and a finned water cooler combined in series. A temperature gradient of 1.5 °C was observed across the thickness of the PV panel. A significant reduction in surface temperature and improvements in electrical efficiency
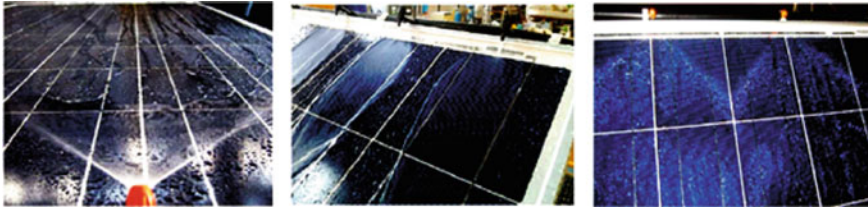
Fig. 2 Details of stream non-uniformity phenomena identified in the water spreading framework

was obtained. Nizetic et al. [23] investigated the water spray cooling technique on both the surfaces of the PV panel. The electrical output raised to a maximum of 16.3% as an effect of cooling of PV panel up to 24 °C. Bahaidarah et al. [24] highlighted the need for water flow uniformity in the cooling of PV panels. The results showed that the consistent water flow cooling increased electrical efficiency and lowered the panel temperature better than the non-uniform water cooling. A lot of other similar studies on Photovoltaic Thermal (PV/T) hybrid systems had been performed by many researchers [18]. These systems are used for simultaneous water heating and PV panel cooling. In such systems, the power generated by the PV panel is used to drive a pump for the circulation of water in the system. PV/T water disinfection systems are also used for thermal or photo-disinfection of water against microbes [25, 26].

This article is aiming to fill the observed gap in the previous research done in the cooling methods for removing the flow non-uniformities. It represents an experimental study on a PV panel cooling arrangement using water with uniform flow over the top surface. The main objective of this investigation is to propose an innovative cooling idea with these advantages: (1) It will not consume any external power to pump water like in the case of spray nozzles, as in the proposed arrangement gravity-assisted flow can be possible. (2) Water is readily available so it is quite a cheap cooling fluid. (3) It also serves another purpose of cleaning the top surface of the PV panel and reducing the reflection losses. (4) This type of arrangement can easily be incorporated in naturally flowing waterfalls, dam spillways, rivers, etc. All this adds up to introduce an effective method to lower the surface temperature of the PV panel and thus enhance its performance. The main aim of this study is to reduce the flow non-uniformities of an active cooling system over PV panels. Moreover, the effect of reduction of flow non-uniformity on efficiency is also investigated. The experiments were conducted in real environmental conditions in Chandigarh, India on summer days. The surface temperature, irradiance, open-circuit voltage, and efficiency were recorded every 15 minutes during the observations which continued for about 3 h.

2 Experimental Setup

An experimental exercise had been directed with the point of examining a PV panel cooling system and the sole aim of the exercise was to decrease the stream non-uniformity. With the assistance of a solar module analyzer, the efficiency of the PV board was estimated and it was additionally contrasted with the non-cooled edition of it.

The panel was inclined to 30° for maximum output, with the help of wooden support for maximum output [27, 28]. The remedies for reducing the flow non-uniformity were tested inside the lab and the experimental setup was then exposed to the real outdoor environment as shown in Fig. 3.

In the real outdoor environment, the experiments were carried out on six sunny days of summer in Chandigarh (30.7333°N, 76.7794°E), India. A pyranometer was connected with Lab Quest 2 (a computer sensor interface to collect data) to record the solar irradiance.
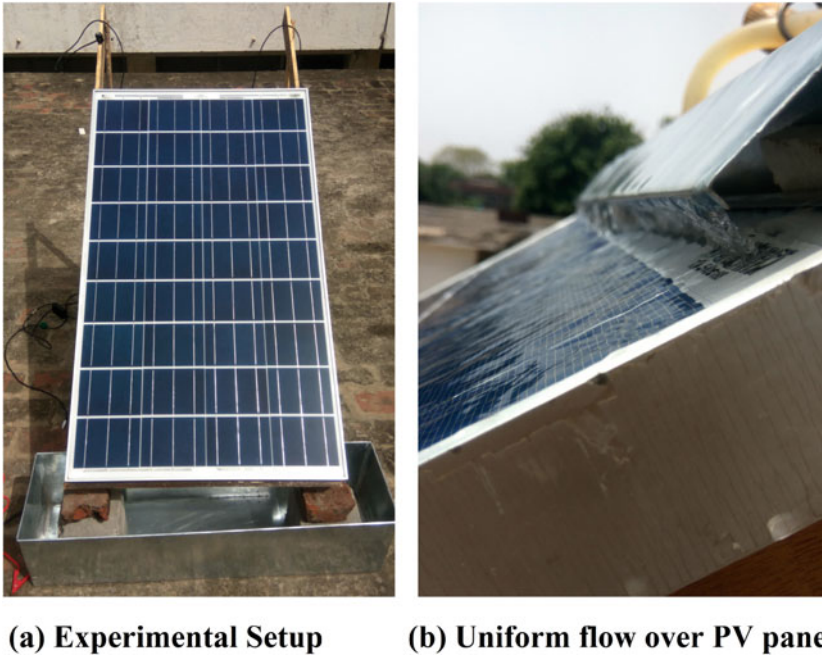

(a) Experimental Setup   **(b) Uniform flow over PV panel**

Fig. 3 Experimental trials to remove flow discontinuities: **a** Trial 1 with a series of nozzles **b** Trial 2 with slitted pipe section **c** Trial 3 Flat spillways with cuboidal catchment vessel

2.1 Experimentation Process

To overcome the non-uniformity in the flow of water various trials were conducted to find the best possible solution.

Trial 1: Initially, water nozzles, commercially available were used along with the breadth of the PV panel. Nozzles were placed at a distance of 5 cm apart over the complete span (66.6 cm) as shown in Fig. 4a. The nozzles were placed on a pipe at a distance of 5 cm away from the panel. While conducting the experiment, it was found that there was flow non-uniformity, water was not able to spread over the whole surface of the panel. A phenomenon of water film breaking was visible as found by the previous researchers.

Trial 2: To solve this problem, a pipe slitted along the length was used. The shape of the pipe was cylindrical and it was maintained throughout the breadth of the panel as shown in Fig. 4b. Again, the problem was not solved. Water was not coming from the edge evenly, only from a certain region. There may be various reasons: (1) the flow rate of the pipe wasn't ample and (2) the edge of the pipe was not finished properly, had it been finished properly still to implement in real life is impractical.

Trial 3: After contemplating the problem and with the help of various suggestions, the concept used in the dam's spillway was incorporated. An open flat spillway with cubical catchment vessel placed with catchment vessel dimension 67 cm x 8 cm x 5 cm, hoping that as soon as the vessel is over-flooded the water would flow uniformly over the panel as shown in Fig. 4c. The problem was still there and water was flowing mainly in the center part owing to the fact that the vessel was buckling; the level of water was not maintained giving rise to the non-uniformity phenomena. To avoid buckling of the vessel, the size was reduced to (67 cm x 6 cm x 4 cm), besides the center was made a little strong. The source of water in all the above cases was a reservoir placed above the PV panel which was supplied to the vessel under the action of gravity.

After the selection of appropriate cooling arrangements, the setup was taken to outdoors for the collection of performance data in the real environment. The uniformity of the water stream was achieved as shown in Fig. 3. To record the data experiments were performed for 6 sunny days, the first 3 days on a non-cooled setup,
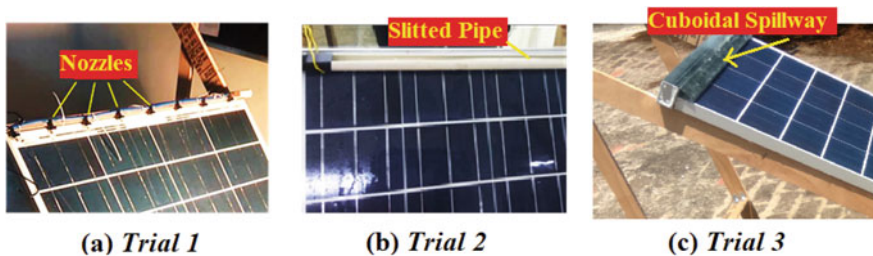

(a) Trial 1 **(b) Trial 2** **(c) Trial 3**

Fig. 4 Experimental trials to remove flow discontinuities: **a** Trial 1 with a series of nozzles **b** Trial 2 with slitted pipe section **c** Trial 3 Flat spillways with cuboidal catchment vessel

and the next three days on a setup with a cooling arrangement. The stipulated schedule for experimenting was 10:45 am–1:45 pm during the peak sunny hours of the day when the maximum temperature of the PV panel was observed. It had been taken care of that the flow uniformity was maintained throughout the process. With the help of the pyranometer, the irradiance level was measured and the input was given at a frequency of 30 minutes to the PV module analyzer. The data of both the setups were collected and efficiency was compared.

3   Uncertainty Analysis

During the experimental analysis, there might be a few errors encountered that need to be identified to ensure the correctness of the results discussed above. So, uncertainty analysis was also carried out for the most important parameter which was the temperature measured on the surface of the PV panel. The total error or uncertainty was calculated as

$$E_t = \sqrt{(E_p)^2 + (E_b)^2} \tag{1}$$

E_b is the biased or systematic error which was specified by the manufacturer and is equal to 1 °C and E_p is the precision or stochastic error which is calculated from the given data in Table 1. by taking five different values of temperature repeatedly measured by the same IR thermometer.

$$E_p = \frac{\sigma}{\sqrt{n}} t_{u, \frac{\phi}{2}} \tag{2}$$

where E_p is the precision error, σ is a standard deviation for n number of measurements taken, $t_{u, \frac{\phi}{2}}$ is the t-distribution corresponding to the degree of freedom $v = n - 1 = 5 - 1 = 4$, at a confidence level of 95% which give $\frac{\phi}{2} = 0.025$, σ of the data is 0.1385. From the t-distribution table, $t_{4,0.025} = 2.776$. Then precision errors are

$$E_p = \frac{0.1385}{\sqrt{5}} 2.776 = 0.172°C \tag{3}$$

Then the total error is calculated as:

$$E_t = \sqrt{1^2 + 0.172^2} = 1.014°C \tag{4}$$

Table 1   Temperature sample for uncertainty analysis

Measurement no.	1	2	3	4	5
Temperature (°C)	85.6	85.72	85.68	86.01	85.76

Since the values of temperature in this study were very large as compared to the total error, it concludes that the results obtained in this study were reliable and correct.

4   Results and Discussion

As the prospect of the experiment was to achieve a condition of uniformity of water stream over the panel, the condition being achieved further provides an opportunity to compare the performance of the cooled and non-cooled setup. Hence, the data was collected for six days, three for non-cooled and three for cooled setup. The first 3 days of experiments were without cooling and the last 3 days were with using the cooling arrangement on the PV panel. The following parameters were measured and compared for the two cases:

4.1   Surface Temperature of PV Panel

The panel surface temperature was measured with the help of an IR thermometer. Figure 5a shows the Irradiance for three hours of peak irradiance. Figure 5b shows the variation of the surface temperature of the panel for the two cases. The first 3 days were for the non-cooled (reference) case and the next 3 days were for the cooled case of the PV panel. The 3 days and 3 hours average temperature of the non-cooling case was recorded at 63.8 °C and that of the cooling case was recorded at 32.5 °C. So, a 31.3 °C (about 50%) decrease in temperature was observed as a result of the cooling arrangement employed in this research.
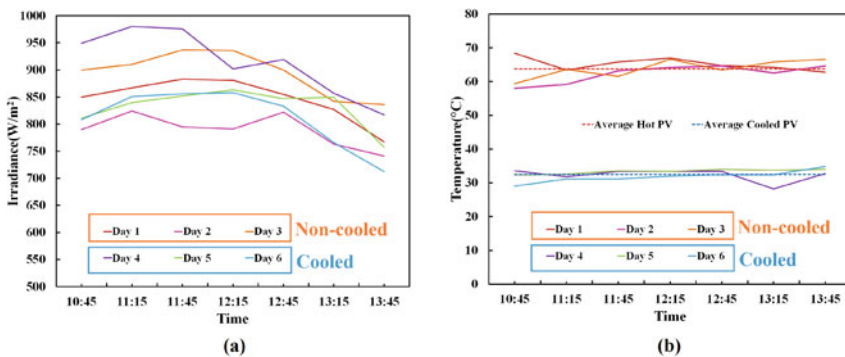

Fig. 5 a Solar irradiance measured during the 6 days of experimentation; **b** Surface temperature of the PV panel during reference case and cooled case for peak radiation hours
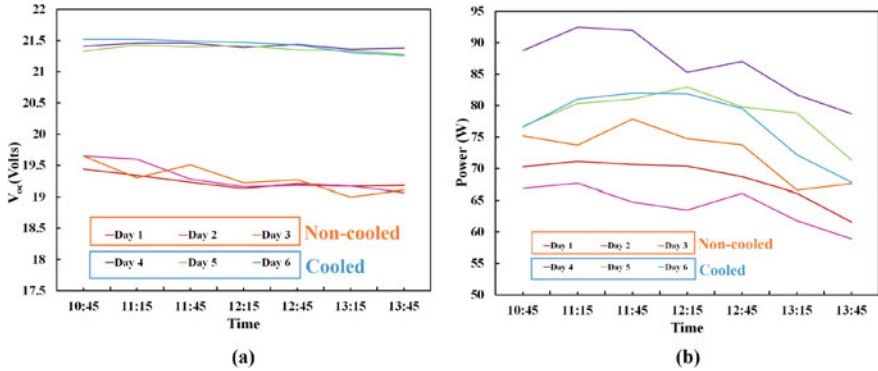
Fig. 6 **a** Open-circuit voltage variation during the peak radiation hours; **b** Power output variation during peak radiation hours

4.2 Electrical Improvements

Clear information is given in the previous section about the decrease in the surface temperature of the PV panel. There must be some improvement in the electrical performance of the PV panel.

4.2.1 Improvement in Open-Circuit Voltage V_{oc}

The electrical performance is quantified in terms of V_{oc}. Figure 6a shows the variation of Voc with time and compares the non-cooling case with the cooling case. The value of V_{oc} increased with a decrease in temperature. An increase of about 2.12 Volts was recorded due to the enhancements imparted by the cooling arrangement. This is about a 0.35% increase in V_{oc} /°C decrease in temperature. The V_{oc} in the cooled case was more uniform as compared to that of the non-cooled case.

4.2.2 Power Improvements

The power output of the PV panel was recorded with the help of a solar module analyzer. Also, it can be calculated by this expression.

$$P_{out} = I_{sc} V_{oc} FF \tag{5}$$

$$P_{ideal} = I_{sc} V_{oc} \tag{6}$$

where I_{sc} denotes the short circuit current, V_{oc} denotes the open-circuit voltage and FF is the fill factor. FF is an important parameter to specify the overall performance

of a PV panel. It is the ratio of the maximum power output given by the panel to the theoretical power output of the panel. Its value varies between 0 and 1. It was also measured with the help of a solar module analyzer and was 0.71 for non-cooled and 0.75 for cooled setups. Figure 6b shows the variation of the power output of the PV panel for both cases. As we can see the blue lines representing the power output of the cooled panel are above the non-cooled. An 18.1 % increase in average power output was observed as a result of the cooling effect.

4.2.3 Efficiency Improvements

The improvement in V_{oc} improves the efficiency of the PV panel [29]. Which was calculated by the solar module analyzer by using this empirical formula:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{sc} V_{oc} FF}{G A_s} \qquad (7)$$

where η is the efficiency, I_{sc} is the short circuit current, V_{oc} is the open-circuit voltage, FF is the fill factor, and G is the solar irradiance and A_s is the surface area of the PV panel. All these quantities were measured and calculated with the help of a solar module analyzer. Figure 7a shows the variation of the efficiency of the PV panel with time for the two cases. It is seen that the efficiency of the cooled setup was improved over the non-cooled setup. An improvement of about 17% in efficiency was observed by cooling the PV panel, it increased from 11.83% to 13.83%.

$$Improvement\ in\ efficiency = \frac{\eta_{cooled} - \eta_{non-cooled}}{\eta_{non-cooled}} \times 100 \qquad (8)$$

Table 2 compares the improvements in the efficiency of this work with other studies on the cooling of PV panels using water. Although the design used in this study was
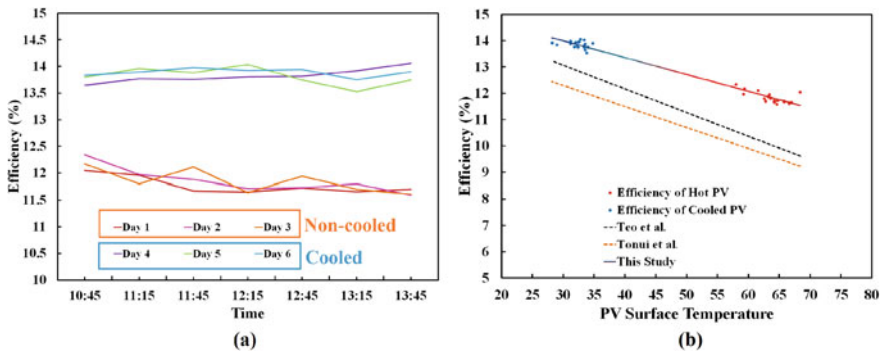

Fig. 7 **a** Efficiency variation during the peak radiation hours; **b** Variation of electrical efficiency with PV surface temperature and validation of this study

Table 2 Comparison of results with the previous studies

Reference	% Improvements
Papadopoulos et al. [31]	7.9
Lucas et al. [32]	10
Haidar et al. [33]	12–14.77
This study	17

simple with cheap material, it helped in the successful removal of flow discontinuity and resulted in effective cooling of the panel. Figure 7b shows the variation of electrical efficiency with the surface temperature of the PV panel and compares the results with previous investigations by Teo et al. [8] and Tonui et al. [30]. A linear correlation of electrical efficiency with surface temperature was observed in the investigation which is in agreement with the previous studies. A mathematical correlation between the electrical efficiency and surface temperature was also established as

$$\eta_{pv} = 15.923 - 0.0641 T_{pv} \tag{9}$$

where η_{pv} is the electrical efficiency of the PV panel. T_{pv} is the surface temperature of the PV panel. The trend lines show that the efficiency of the PV panel decreases with an increase in surface temperature.

5 Conclusions

The electrical performance of a PV panel decreases with an increase in its surface temperature. Out of the different proposed cooling methods, the water cooling system is a cheap and effective method. In this paper, a technique to prevent flow discontinuities in water-based cooling systems is discussed. The results of the experimental investigation enunciate that by maintaining the flow uniformity of an active cooling system over the panel, there was about 50% reduction in the surface temperature of the PV panel, as a result of which there was about 0.35% increase in V_{oc}/°C decrease in temperature and an improvement of about 17% in efficiency was observed by the used cooling technique in this study. It was shown clearly in this study that integrating a water-based cooling system with PV panels and maintaining the continuous flow of cooling water the availability, reliability, and cleanliness of solar power plants can be improved.

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