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EXPERIMENTAL INVESTIGATION OF A CONCENTRATED PHOTOVOLTAIC SYSTEM INTEGRATED WITH WATER SPRINKLER GENERATING ELECTRICITY AND HOT WATER

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ABSTRACT

Power generation through solar photovoltaic (PV) is quite attractive due to direction generation of power from radiation and simplicity in construction. The major concern of the solar PV is 10-15% efficiency, i.e. larger land area requirement per kW of power generation. Concentrated solar PV system is one of the options to enhance the power generation in unit area. But the implication is increase in panel temperature, in turn, reducing the cell efficiency. The researchers proposed cooling of panels using water, air, phase change materials etc. to maintain lower temperature. This paper presents experimental investigation of a concentrating solar PV integrated with water sprinkler to enhance power and generate hot water. The experimentation has been performed in Ahmedabad, Gujarat (23.02°N, 72.57°E). Result analysis of various configurations of solar panels with and without concentrators and water sprinkler has been performed. To make sure the repeatability, each configuration has been experimented for two different days. Performance parameters such as electrical efficiency and overall efficiency have been used to compare the different configurations. The result analysis shows enhancement of power along with the generation of hot water in comparison to conventional solar PV system.

Keywords: Solar Energy, Solar Photovoltaic, Water cooling, Side Reflectors, Hot Water Generation

NOMENCLATURE

parameters

I	Solar Irradiance [W m^{-2}]
V_{oc}	Open-Circuit Voltage [V]
I_{sc}	Saturation current of the solar cell [A]
R_s	Serial Resistance[Ω]
R_{sh}	Shunt Resistance[Ω]
I_{ph}	Photocurrent[A]
I_0	Dark saturation current[A]
I_l	Light Generated Current [A]
I_o	Dark Saturation Current [A]
n	Ideality factor
T	Temperature [K]
FF	Fill Factor (ratio)
I_{sc}	Short Circuit Current [A]
V_{oc}	Open Circuit Voltage [V]
P_{mp}	Maximum Power Point
V_{mp}	Voltage at Maximum Power Point
I_{mp}	Current at Maximum Power Point
CPV	Concentrated Photo Voltaic

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1. INTRODUCTION

With ever increasing population and industrial developments in the last 2-3 decades, the energy demand has increased exponentially. It is estimated that the global energy consumption will increase by 71% between 2003 and 2030 [1]. At present, 80% of the energy on Earth comes from fossil fuel resources [2]. The use of fossil fuel resources negatively impacts the environment, and they are limited in quantity. Solar energy has been one of the most promising sources of clean energy alternatives, mainly because of its abundant presence on the surface of the earth. Solar radiation is used as an energy source in two ways, the first by the use of photovoltaic cells, which convert the solar radiation to usable electricity, and the other in the form of solar thermal energy, which converts radiation into heat energy and the heat is used to generate electricity. Due to simplicity in construction and direct generation of electricity, Solar PVs are quite popular. Solar PVs have a lower efficiency, converting 4–17% of the incoming solar radiation into electricity, depending on the type of solar cells used and the working conditions [3]. Still, the PVs play a huge role in the solar energy work field, as most of the operations require energy in the form of electricity for functioning.

1.1 Techniques used to solve the problem

To increase the efficiency of the solar panel, a setup of concentrating reflectors is used to increase the solar input to the surface of the PV, which sometimes results in overheating of the surface of the PV. The surface temperature of the PV has an inverse relation with the efficiency of the PV cell. The accumulation of excessive heat poses itself as a threat not only to the effective efficiency of the panel, but may also affect the cell's performance with prolonged time. Cooling of the solar cells is hence important, to enhance the efficiency of the photovoltaic cell. This problem can be solved using a wide range of cooling techniques such as active cooling, passive cooling and phase change material cooling with or without additives[4]. This paper focuses on the top cooling of PV using a sprinkler, which falls under the category of active cooling [5].

The recent past has seen development in cooling mechanisms of the photovoltaic cell surface by means of a fluid, either by flowing over, flowing below or by sprinkling [6–8]. The fluid cooling systems help reduce the excess accumulation of heat over the surface of the cells, hence reducing the operating temperatures and, in turn, improving the efficiency of the cells. Such mechanisms are easy to install and maintain and have experimentally proven themselves to be effective. Theory suggests that water sprinkled over the surface of the PV would strike the surface, and the impact would cause a greater heat transfer and provide a better cooling effect than running water down the surface without impact, hence the use of a sprinkler with the system [9].

The main goal of this research is to facilitate a solution for the problem of overheating of the panel surface and provide optimal desired output. It is also to manage the investment-to-return ratio. This paper will present power output comparisons between different configurations of a PV cell, such as a plain PV cell, a PV cell with concentrating reflectors and PV with concentrating reflectors and a sprinkler-based top cooling system and try to prove the points mentioned before.

2. METHODOLOGY

2.1 Experimental Setup

The experimental setup involved integrating a CPV system with a water sprinkler. The CPV utilized solar panels with concentrators to increase power generation efficiency, while the water sprinkler was employed to cool the panels and maintain lower temperatures. The whole system is connected to an Arduino board and pump to effectively record values and pump the water through sprinkler respectively [6, 7] .

2.2 Components

The components used in the experiment were carefully chosen. A high efficiency solar panel with concentrators was selected to maximize power generation, and the concentrators were optimized based on the specific requirements of the Concentrated Photo Voltaics system. A suitable water sprinkler system was integrated to provide cooling and generate hot water.

- Sun Star 1217 Solar Panel
  - Power Rating - 20 Watts
  - Working Voltage - 12 Volts
  - Maximum Rated Efficiency - 18 %
  - Dimensions - 390 mm * 340 mm
- Pump (To regulate the water coming to the sprinkler)
- PVC pipes (To channelise the flowing water)
- K type MAX6675 Thermocouple Module (To measure temperature)
- Arduino Mega (To measure the temperature values)

2.3 Experimental Variables

Several variables were considered during the experimental investigation. These variables included different configurations of solar panels with and without reflectors and the presence or absence of the water sprinkler. By analyzing these configurations, the impact of concentrators and the water sprinkler on power generation and panel temperature could be assessed. All of these variables were taken into consideration for the practical technical issues faced, and hence, only a qualitative analyis of these variables was performed.

- Clouds: The presence of clouds can significantly affect the performance of the CPV system. Cloud cover reduces the amount of direct sunlight reaching the solar panels, resulting in decreased power generation. To account for this variable, the experiments were conducted under varying cloud cover conditions. Data were collected during both clear sky and cloudy sky conditions to analyze the system's performance under different levels of solar irradiance. However, data for the clear sky was taken into consideration while analyzing the data [10] .
- Thermocouple Module Functions: Thermocouples were utilized to measure the temperature of the solar panels and the water being sprayed by the sprinkler system. These temperature measurements were crucial in evaluating the cooling effectiveness of the water sprinkler. The thermocouple module functions, including accuracy, response time, and calibration, were considered to ensure reliable temperature measurements throughout the experimental period.
- Shade: The presence of shade, either from nearby structures, vegetation, or other obstructions, can cast shadows on the solar panels, reducing their exposure to sunlight and, consequently, decreasing power generation. The experiments took into account different shade scenarios by positioning the solar panels in various orientations relative to the source of shade. This allowed for the assessment of the impact of shading on the performance of the Concentrated Photo Voltaic system. By tinkering with the following, we chose the readings which were not affected by shade [11].
- Static Errors: Static errors refer to inaccuracies or deviations in the measurement equipment or setup that can affect the reliability of the collected data. These errors can arise from factors such as calibration errors, sensor drift, or imperfect alignment of components. To minimize static errors, appropriate calibration procedures were carried out prior to the experiments. Additionally, repeated measurements and cross-validation techniques were employed to ensure accurate data collection.

- Ambient Temperatures: The ambient temperature surrounding the Concentrated Photo Voltaic system can influence the overall performance and efficiency of the solar panels. Higher ambient temperatures can increase panel temperatures, potentially reducing power output and decreasing cell efficiency. The experiment was conducted in different time intervals every day in order to check the possible effects of ambient temperature(Before the peak time, after the peak time as well as early evening) [7, 12, 13] .

- Dust : Dust accumulation on the solar panels can reduce their efficiency by blocking sunlight and affecting heat dissipation. Experiments were conducted under varying dust conditions to examine the effect of dust on the system. The solar panels were periodically cleaned to maintain consistent performance, and data were collected before and after cleaning to quantify the impact of dust accumulation [14] .

2.4 Data Collection

A comprehensive data collection process was implemented to gather data and evaluate the integrated system's performance. Various measurements were taken, including solar panel temperature, power output, and water temperature. These measurements were recorded at regular intervals throughout the experimental duration to capture the system's performance under different conditions. All the data sets were recorded on a continuous interval of ten minutes. The time, voltage, current and temperature of the panel are the data that were being noted in all the respective sets. The data collection for the three configurations was carried out during the same time interval from 11:50 a.m. to 2:30 p.m. on three consecutive days, assuming almost the same solar irradiation for consecutive days.

- Configuration 1: Standalone Concentrated Photo Voltaic system.

  Figure 1 with the reflectors in a position parallel to the ground depicts configuration 1. The system is installed with self designed adjustable arms that control the angles of the reflectors. For this configuration the sun rays were incident only on the CPV system. The panel was allowed to reach a temperature of around 55°C at the start of the mentioned time period and the data was recorded.

- Configuration 2: Concentrated Photo Voltaic system with reflectors.

  Figure 1 with the reflectors in a position such that the solar irradiation was focused on the CPV panel depicts configuration 2. Here the reflectors along with the self designed adjustable arms were adjusted constantly qualitatively such that the maximum solar intensity was focused on the PV panel. The panel was allowed to reach a temperature of around 55°C at the start of the mentioned time period and the data was recorded.

- Configuration 3: Concentrated Photo Voltaic system with reflectors and forced water cooling

  Figure 2 depicts configuration 3, with the added implementation of sprinkler water cooling operations. The panel was not allowed to heat up as compared to the other two configurations and was directly kept in the sunlight at the starting time for the data recording. The sprinkler was kept on for 30 minute interval once the panel temperature reached a temperature of 55°C after which the temperature was again allowed to rise till 55°C. This set of experiment aimed to explore active cooling techniques, particularly the use of forced water cooling.

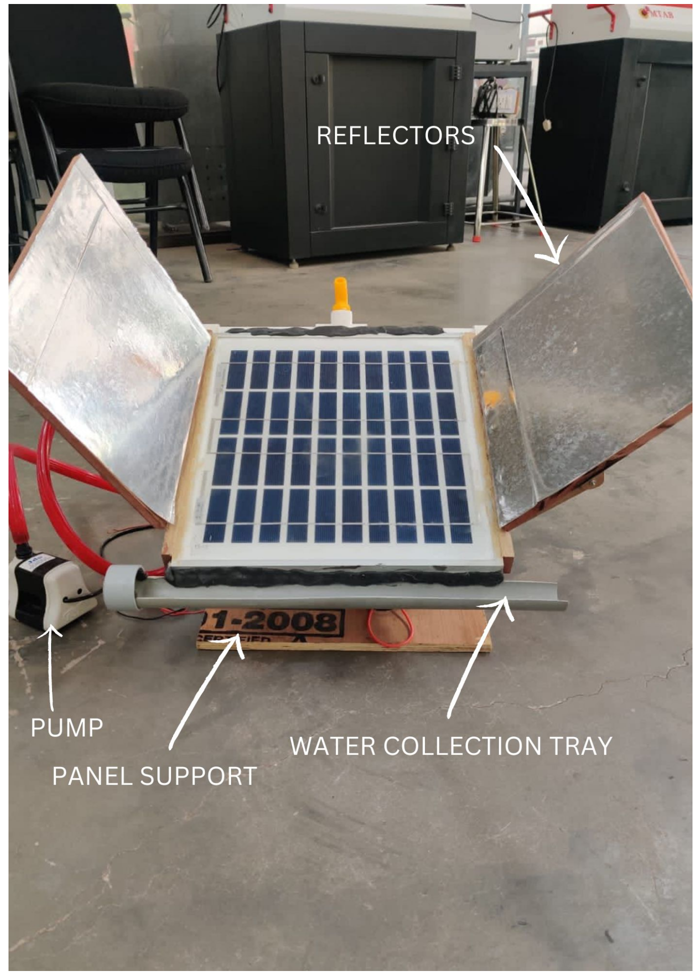

FIGURE 1: SETUP FOR CONFIGURATION 1 & 2

Active cooling was employed as a means to counteract the rise in panel temperature that can occur in CPV systems, which concentrate sunlight onto photovoltaic cells to boost power generation but simultaneously elevate panel temperatures. Forced water cooling, a specific form of active cooling, was applied in this study. It involved circulating or spraying water onto the solar panels to dissipate heat and maintain lower panel temperatures. The setup effectively utilized a sprinkler connected to the system, which received water via a pump connected to an external power source [15]. This cooling method was selected for several reasons, including its capacity to enhance panel performance in high ambient temperatures, prevent hot spots on the panel surface, dissipate heat, reduce temperature-related losses, and offer cost-effectiveness.

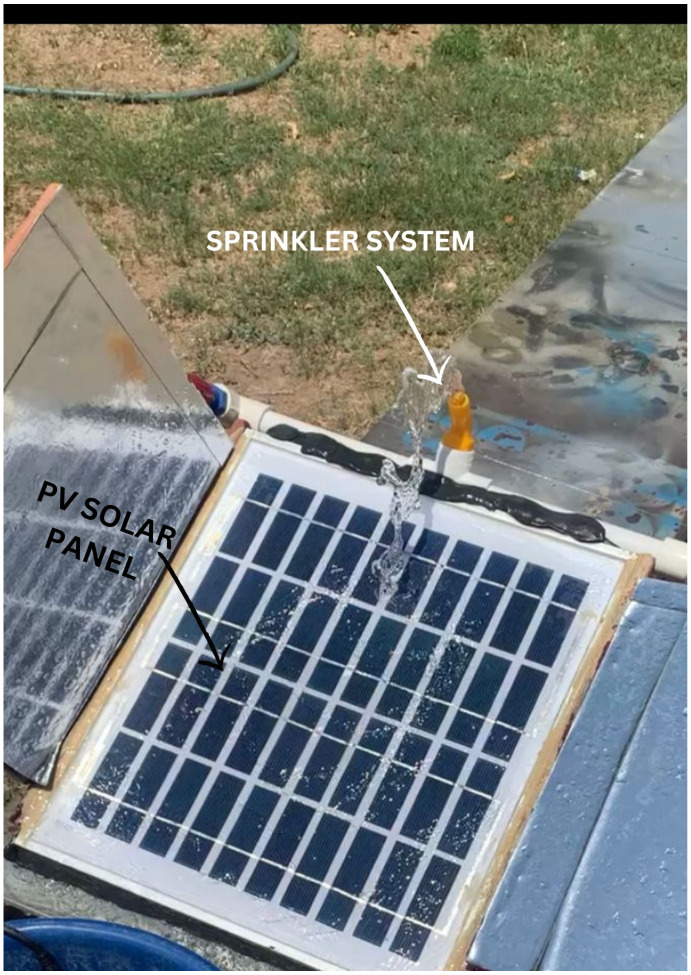

FIGURE 2: SETUP FOR CONFIGURATION 3

2.5 Experimental Procedure

The experimentation has been performed in Ahmedabad, Gujarat (23.02°N, 72.57°E). The experimental procedure consisted of the following steps:

- Before the initiation of recording data, the system was calibrated to ensure accurate measurements. This involved checking and calibrating the sensors used to measure parameters such as solar panel temperature, power output, and water temperature. The necessary adjustments or corrections were made to ensure reliable and precise data collection. These calibrations involved checking for thermocouple sensors in comparison to the ambient temperature. The multimeter outputs were compared with other multimeters and the correct working of the multimeter being used was confirmed. The outputs of the Arduino Mega were checked for correct voltage output and any static or instrumental errors were noted and eliminated.

- Once the system was ready to run and calibrated, the experimental run for all configurations was initiated. This involved operating the CPV system with reflectors and turning on the water sprinklers to provide cooling and maintain lower panel temperatures.

- During the overall span of the experiment, various measurements were collected at regular intervals. These included the solar panel temperature, the power output of the CPV system, and the temperature of the water being sprayed onto the panels. The data were recorded using appropriate instruments and logged systematically for further analysis.

- Continuous monitoring of the system was carried out to ensure its stable operation. If any anomalies or unexpected variations in the measured parameters were noted. If necessary, adjustments were made to the water flow rate, sprinkler positioning, or any other relevant factors to optimize the performance of the CPV system.

- The experimental run for Configuration 3 was conducted for a specific duration(on the interval of ten minutes the data was being recorded), determined based on the research objectives and requirements. Sufficient time was allocated to collect an adequate amount of data to analyze the performance of the CPV system with reflectors and sprinklers.

By following this methodology, the experimental investigation aims to provide valuable insights into the performance of the concentrated photovoltaic system integrated with a water sprinkler for enhanced electricity generation and hot water production.

3. DATA ANALYSIS AND DISCUSSION

To ensure the repeatability of the data, the experiment was performed twice for each configuration as mentioned in the abstract, out of which the data with more scatter was selected as the analysis data, as it would take the outliers into account as well. The observations for configurations on different days are listed below

3.1 Characteristic IV and PV Curve Analysis

The characteristic PV & IV curves are shown in Fig. 3. The curve shows the variation and characteristics of the short circuit current, open circuit voltage, maximum power, voltage for maximum power, and current for maximum power. The short circuit current(I_{sc}) is the maximum current from a solar cell and happens when the voltage across the panel is zero. Similarly, the Open Circuit Voltage (V_{oc}) is the maximum voltage across the panel and occurs at the time of zero current across the solar panel. The maximum power(P_{mp}) is the point when the maximum power for the panel is reached. The maximum power voltage(V_{mp}) and maximum power current(I_{mp}) reflect the voltage and current at which the maximum power(P_{mp}) is achieved[16, 17]. The Shockley diode equation is used to plot the IV characteristics of the PV panel[18]. The IV characteristics of the PV panel can be plotted using the Shockley diode equation as

$$I = I_{ph} - I_o([exp\frac{q(V + IR_s)}{nKT} - 1] - \frac{V + IR_s}{R_{sh}}) \tag{1}$$

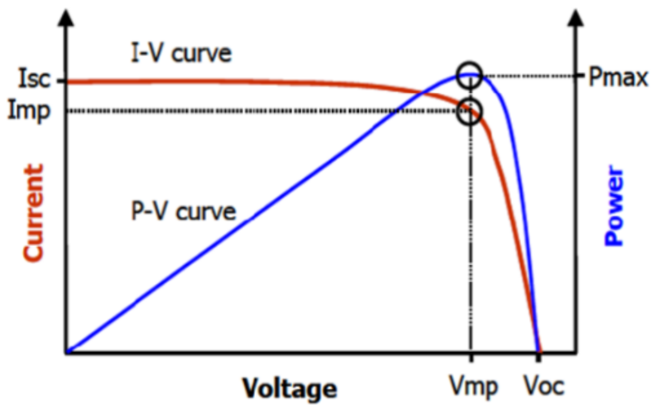

FIGURE 3: PV & IV CHARACTERISTIC CURVE [17]

3.2 Open Circuit Voltage Analysis

The main variable of inquiry of the paper is the open circuit voltage as the efficiency of the Concentrated Photo Voltaic Cells is directly dependent on the open circuit voltage of the panel. Each individual single-junction solar cell can generate approximately 0.5 to 0.6 volts. Since our panel has 40 cells connected the maximum output of the open circuit voltage (V_{oc}) should be about 24-25 Volts. The open circuit voltage for each configuration is plotted in Fig. 4. As it is clearly visible from the plot, the open circuit voltage increases with the change from configuration 1 to configuration 2 and from configuration 2 to configuration 3. This shows that the open circuit voltage and in turn the efficiency of the panel increases with the additions of the reflectors and forced water cooling systems. The open circuit voltage reaches its maximum when the forced water cooling and reflectors are attached simultaneously to the Concentrated Photo Voltaic panel. This happens because the open circuit voltage is directly related to the temperature of the panel. Therefore the maximum open circuit voltage is reached when the temperature of the panel is optimum. This also depends on the temperature of the water supply temperature, the lower the water temperature, the cooler the panel becomes which increases the efficiency of the panel.

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3.3 Short Circuit Current Analysis

The second most vital variable of inquiry was the short circuit current of the solar panel. The short circuit panel current depends on the area of the panel, number of photons hitting the surface of the panel, and the spectrum of the light incident on the panel. Thus during peak hours the trend as shown in Fig. 5 is followed.

3.4 Panel Temperatures for Three Configurations

Figure 6 shows the panel temperature variation over the time period for all the three configurations measured through the thermocouple. It was observed that the lowest temperature was observed after starting the Water cooler and implementing the Reflectors at 12:30 pm in the third configuration which proves the vitality of the water cooling system implemented. The temperature for configuration 1 was observed to be higher than that of

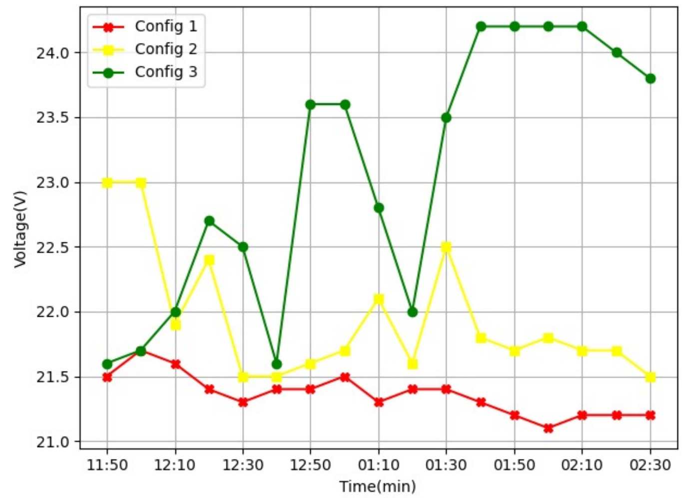

FIGURE 4: VARIATION OF OPEN CIRCUIT VOLTAGE WITH TIME FOR THREE CONFIGURATIONS

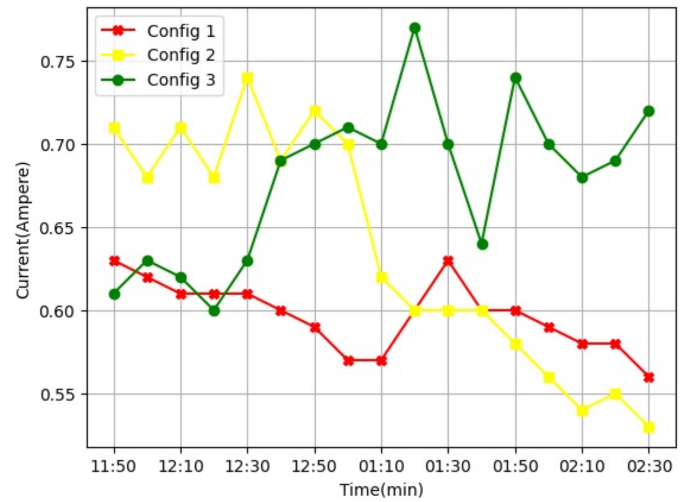

FIGURE 5: VARIATION OF SHORT CIRCUIT CURRENT WITH TIME FOR THREE CONFIGURATIONS

configuration 3 but lower than that of configuration 2 which was the expected result. Since configuration 2 was implemented with reflectors, the highest temperature was recorded in this configuration during the peak hours.

3.5 Water Supply Temperature Analysis

A thermocouple was placed in the water supply used to supply water to the water sprinkler system. The temperature data for the same is shown in Fig. 7. The observed temperature fluctuations are attributed to variations in water levels resulting from wind-induced losses and the shedding of water from the solar panel's surface during sprinkler operation. It is noteworthy that the water supply temperature showed an increase when recirculated without the addition of fresh water, reaching a maximum increment of approximately 10°C. This observation serves as a compelling evidence of the potential for generating hot water during the experiment. During the use of the water cooling,

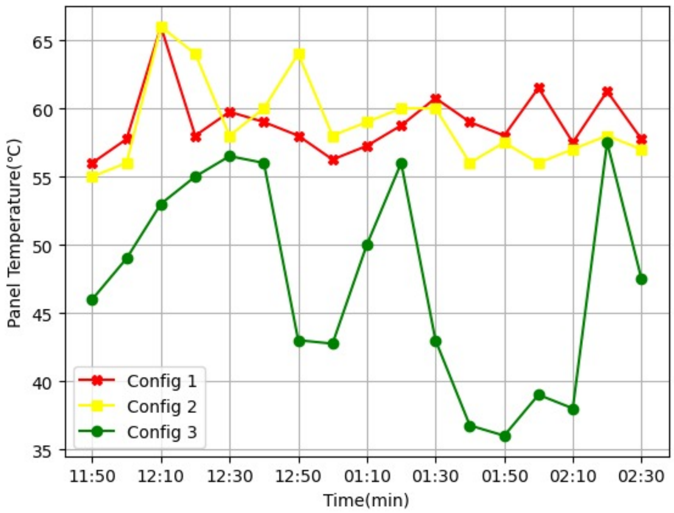

FIGURE 6: VARIATION OF PANEL TEMPERATURE WITH TIME FOR THREE CONFIGURATIONS

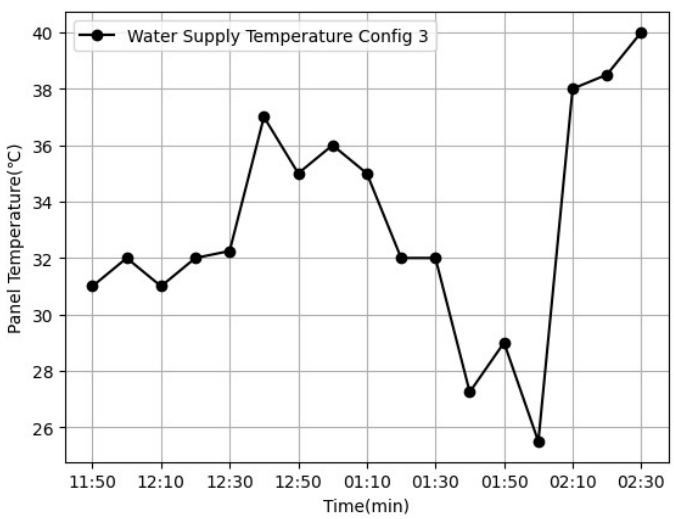

FIGURE 7: VARIATION OF WATER SUPPLY TEMPERATURE WITH TIME FOR THE THIRD CONFIGURATION

the solar panel's temperature was maintained at an approximate level of 39°C, while the water supply temperature stabilized at 36°C through the controlled addition of water as needed. These findings highlight the experiment's capacity to influence water temperature, indicating a valuable aspect of the research.

3.6 Total Power Analysis

The total output power of the panel is given by the factor of Open Circuit Voltage(V_{oc}) into the Short Circuit Current(I_{sc}) of the panel. The Fill Factor(FF) along with V_{oc} and I_{sc} forms the maximum power output of the panel. The fill factor was calculated from the formulas given below [?]. The formulas for calculating maximum power and Fill Factor are given as

$$P_{max} = V_{oc} * I_{sc} * FF \tag{2}$$

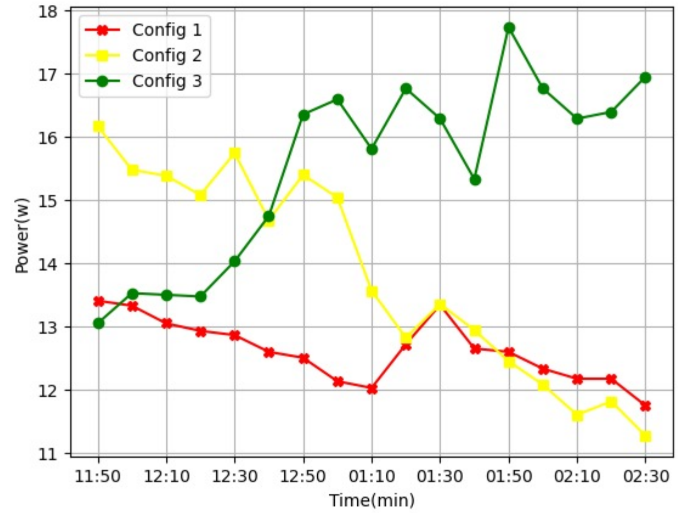

FIGURE 8: VARIATION OF THE POWER WITH TIME FOR THREE CONFIGURATIONS

The Fill Factor was calculated using the following formula -

$$FF = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1} \tag{3}$$

where v_{oc} is "normalised V_{oc}" ,

$$v_{oc} = \frac{qV_{oc}}{nkT} \tag{4}$$

The ideality factor (n) indicates the degree to which a solar cell resembles the characteristic of an ideal diode (for ideal diodes, n=1).

From these formulas the maximum power values for each configuration were calculated and then the power values were plotted as visible in figure Fig. 8. As it is visible that the power increased with addition of reflectors and forced water cooling in configuration 2 and configuration 3 respectively.

Table 1,2,and 3 show the average,maximum and minimum power calculated for the three configurations. The jump in power from configuration 1 to configuration 2 is approximately 10% but not significant as the increased temperature of the panel also causes a fall in the efficiency of the panel. Thus when a forced water cooling is applied to the system in configuration 3 a jump of approximately 12% from configuration 2 and a significant jump of approximately 23% is observed from configuration 1 [19].

TABLE 1: AVERAGE POWER

Configuration	Average Power (W)
Configuration 1	12.62118
Configuration 2	13.81458
Configuration 3	15.5025

4. CONCLUSION

This paper presents an experimental study of a concentrated solar PV system integrated with a water sprinkler to have the top

TABLE 2: MAXIMUM POWER

Configuration	Maximum Power(W)
Configuration 1	13.40586
Configuration 2	16.16394
Configuration 3	17.72862

TABLE 3: MINIMUM POWER

Configuration	Minimum Power(W)
Configuration 1	11.74836
Configuration 2	11.271
Configuration 3	13.04784

cooling of the panel.
The forced water cooling with reflectors can be a promising method to increase the efficiency of the solar panel. The cooling takes care of decreasing the panel temperature, which in turn removes dust and increases the panel's open circuit voltage. The reflectors add solar radiation to the solar panel, increasing the short circuit current to its maximum value. The combined effect of concentration and cooling can be used to bring out the solar panel's maximum efficiency. An added advantage of the system is the generation of hot water.
The current experimentation focus was mainly the qualitative understanding of the proposed sprinkle set-up. The analysis results showed a promising, cost-effective approach to use solar panels for power generation. To have a better understanding of the proposed system, further experimentation with a pyranometer to measure actual solar radiation, incorporating 3-4 temperature sensors on the solar panel to obtain an average panel temperature and arrangement for getting 5-6 hours of real-time data of voltage, current and temperature would be taken up as the future scope.

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