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Conference paper

# Performance Analysis of Photovoltaic Solar Cells with Passive Cooling Under Controlled Uniform Radiation Heat Source

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**ABSTRACT**

Many types and designs of solar photovoltaic cells that harness solar energy, yet their efficiency diminishes greatly with an increase in operating temperature. The study aims to investigate the performance enhancement of PV cells' passive cooling methods under a controlled environment of uniform radiation. An experimental setup was custom-made with a tungsten halogen lamp to simulate solar radiation, with the crucial parameters of temperature and electrical power being monitored by a real-time data acquisition system. The novelty of the paper lies in the integration of a zigzag rectangular water channel at the back of the PV panel, which maintains an ideal thermal condition without requiring any external energy input. When constant radiation was set at 1200 W/m2, the flow rates of cold water were varied from 0.096 to 0.601 lpm. Results showed that the temperature of runoff water on the panel surfaces dropped substantially, while the open-circuit voltage increased from 20.25 V to 21.50 V during cooling on top. Hence, it was confirmed that passive water cooling is an affordable and efficient means of improving PV performance and its thermal control. This current study showcases a series of technologies based on non-electrical cooling designed to cool solar cells.

## 1. INTRODUCTION

Photovoltaic solar cells harness solar energy, and their efficiency decreases significantly with increasing operating temperatures. Recent literature indicates that an electrical conversion efficiency improvement of 3.6 % to 5.5% is achievable using proper water channels and tubing cooling systems (Dubey et al., 2013). Photovoltaic (PV) has grown in popularity as an ultimate agent for sustainable energy generation (Akrouch et al., 2023). Yet, PV cell performances depend on the temperature. By increasing their operating temperature, the PV cells decrease their efficiency, mainly caused by a decrease in voltage at

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open circuit and an increase in intrinsic carrier concentration (Arifin et al., 2021). The efficiency of PV cells varies inversely with the operating temperature (Sharaf et al., 2022). High-temperature conditions reduce the bandgap of semiconductor material, which accounts for lowering the voltage at open circuit.

Additionally, increased temperature contributes to the thermal degradation of materials, leading to performance degradation (Manju et al., 2017). Higher temperatures imply worse heat dissipation in silicon solar cells under on-ground conditions, resulting in a rise of 0.5% in efficiency decrement for every increase in degrees Celsius to the standard test condition of 25°C (Zhu et al., 2018). Active cooling of PV panels may achieve an efficiency increase of approximately. 18% but an effective rise of 5.9% efficiency is achievable (Rokade et al., 2017). Active cooling is immediate and controllable with the expense of energy consumption, but passive cooling is a more sustainable and energy-efficient option (Ahmed et. al., 2024). Taking action for this challenge spurs interest in various cooling techniques, among which passive cooling methods have gained esteem because of their simplicity and cost-effectiveness.

Passive cooling methods do not consume external electrical power; hence, this feature makes the method attractive for enhancing PV performance. Common instances of passive cooling methods include:

Heat Sinks: Fins or heat sinks attached to the back of PV panels allow for a larger surface area for convection heat dissipation (Ebhota et al., 2023). The materials usually used are aluminium and copper due to their high thermal conductivities. An experimental study demonstrated that using copper fins improved electrical efficiency by 4% compared to aluminium fins (Kirpichnikova et al., 2022).

Wick Structures: Incorporating wick structures can enhance heat transfer through capillary action, distributing coolant fluids across the PV surface. This method reduces operating temperatures and improves efficiency effectively (Chandrasekar et al., 2013).

Phase Change Materials (PCMs): PCMs absorb excess heat by undergoing a phase transition at specific temperatures, thereby stabilising the temperature of PV cells. Integrating PCMs with additives like ZnO nanoparticles has further enhanced thermal regulation, improving electrical efficiency (Pandiyan et al., 2020).

Water cooling: Passive water flow cooling over solar panels is an innovative method to improve efficiency by reducing operating temperature. Solar panels typically lose efficiency as their temperature rises, so maintaining a lower operating temperature can significantly improve their performance (Rubaiee et al., 2022).

The increase in efficiency through passive cooling depends on factors like panel material, ambient temperature, water availability, and flow rate. Research studies and practical applications have demonstrated improvements in the 5–15% range, although exact figures may vary (Dwivedi et al., 2020).

Photovoltaics, widely customized for conversion of solar energy into usable energy as a sustainable method of harnessing solar power, however, suffer severely with higher operating temperatures in the range, lowering the output voltage and causing less degradation of efficiency with time. Therefore, the main concerns in the optimization of PV systems are thermal management. On the other hand, some measures have been considered in recent studies for different designs on passive cooling systems: simple, energy-free operation, and cost-effective application. Passive methods are heat sinks, phase change materials (PCMs), wick structures, and natural convection water jackets.

Sharaf et al. (2022) presented a rather thorough analysis of cooling techniques applied to PV systems, stating that passive cooling systems enhance thermal stability, and conversely, power output with ever-varying environmental conditions. Similarly, Farooq et al. (2021) asserted that the water trickling under the panels in a passive configuration yielded efficiency enhancement of up to 6% in high-radiation zones.

The microchannel water-cooling configuration embedded was studied by Zhou et al. (2023), and they found that it reduced temperature by 35% while increasing energy efficiency by 8.7% without demand for any auxiliary power. Hence, the structural channel design proves efficient in supporting natural convection. In another way, the cooling jacket incorporated graphene-enhanced thermal interface materials conceived by Mehmood et al. (2023) showed much better conductivity and a much faster transient thermal response than customary materials.

In such a system operating in extreme situations, systems that act on passive operation designs by way of a travelling mechanism down a wick or a line of capillary action have proved promising. Maqbool et al. (2023) studied new hybrid wick-subjected water methods and found that thermal resistance was brought down by 38%, thereby yielding an electrical gain of 5.2% over conventional panels. In addition, phase change materials are capable of providing thermal buffering with the application of nano-additives, yet durability during thermal cycling remains a challenge (Wahile et al., 2025; Malvika et al., 2022).

Active cooling systems are good systems using forced air or liquid circulation. They require the continuance of power and maintenance and can hardly be administered in smaller or medium-scale plants. In contrast, passive systems are easier to integrate with fewer modifications and thus are a good option for decentralized configurations and rooftops (Alharbi et al., 2024).

Despite these advances, most of the existing studies look at weather conditions outside, where environmental parameters cannot be controlled (Xu et al., 2022). There are few controlled laboratory-based studies performed with uniform radiation, like in this work. Simulating stable solar irradiance and systematically varying water flow conditions in the passive jacket is what this study undertakes, filling an important research gap (Zhang et al., 2024; Murugan et al., 2021). Its originality lies in designing a zigzag rectangular water channel with counter-flow to improve heat extraction and maintain panel efficiency, thus providing a solution that can be scaled and is economical for PV thermal management (Zamanipour et al., 2024).

While these earlier studies looked at direct-contact cooling of PV panels, this study implements a rectangular water channel with a zig-zag pattern integrated directly behind the panel to provide uniform thermal dissipation (Fontenot et al., 2024). Contrary to conventional setups, the design of the compact acrylic system and counter-flow arrangement improves thermal conductivity while simplicity is also maintained, bridging the gap of cheap passive cooling options for small-scale PV installations (Arunkumar et al., 2024).

## 2. METHODS

The in-house experimental setup is built to test the performance of monocrystalline photovoltaic solar cells, which have an effective solar cell area of $380\ mm \times\ 315mm$ under controlled thermal conditions by exposing the cells to a constant heat source. The continuous heat source to the PV panel is supplied using a tungsten halogen lamp that can vary the heat source by changing the distance and inclination. The measurement system measures the temperature of water at the outlet and inlet, the solar panel top temperature, ambient temperature and humidity, and the PV panel-generated current and voltage, which are continuously measured and recorded using a data logging system.

An experimental setup consists of a heating light source with tungsten-halogen lamps that adjust uniform radiation to desired intensities, providing a controlled radiation source. PV modules of 20-watt monocrystalline silicon PV cells. One module is a reference, and another is integrated with passive cooling water jacket systems. Different flow rates were tested, including PV cells with the cooling jacket at the back of the solar panel. A thermistor-based temperature sensor, Solar Power Meter, and current and voltage sensors were employed to monitor temperature, radiation intensity, and electrical output. Fig. 1 shows the entire test setup with the data logging system having a Solar panel, a Radiation heating source, a Data logger circuit, a data recorder and display unit, Water-inlet to the cooling jacket, as well as Water outlet from the cooling jacket.

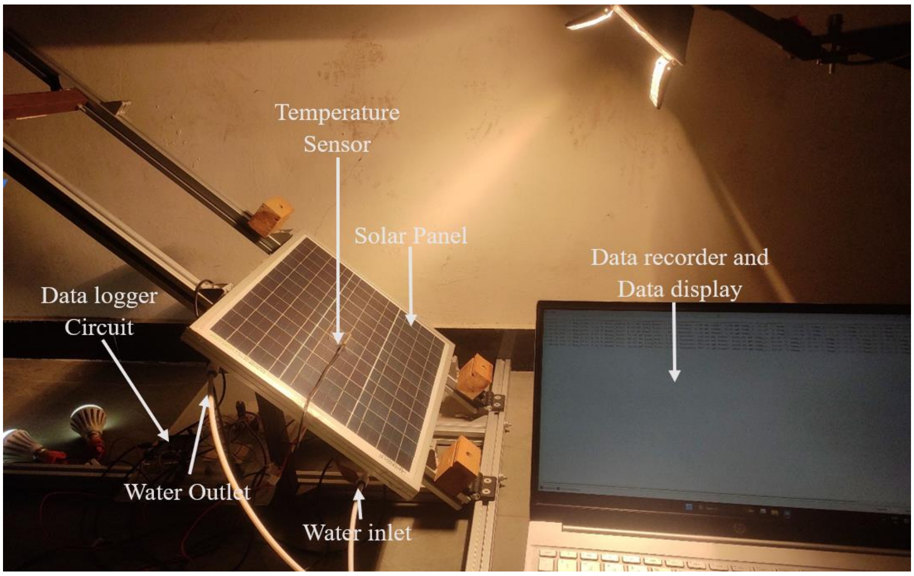


Fig 1. Test setup with the data logging system.

In Fig. 2, the back panel of a setup is shown. The entire area is divided into 8 channels, a water inlet, and an outlet. The channel is made using acrylic material to have 4 × 4-Pass counter arrangements.

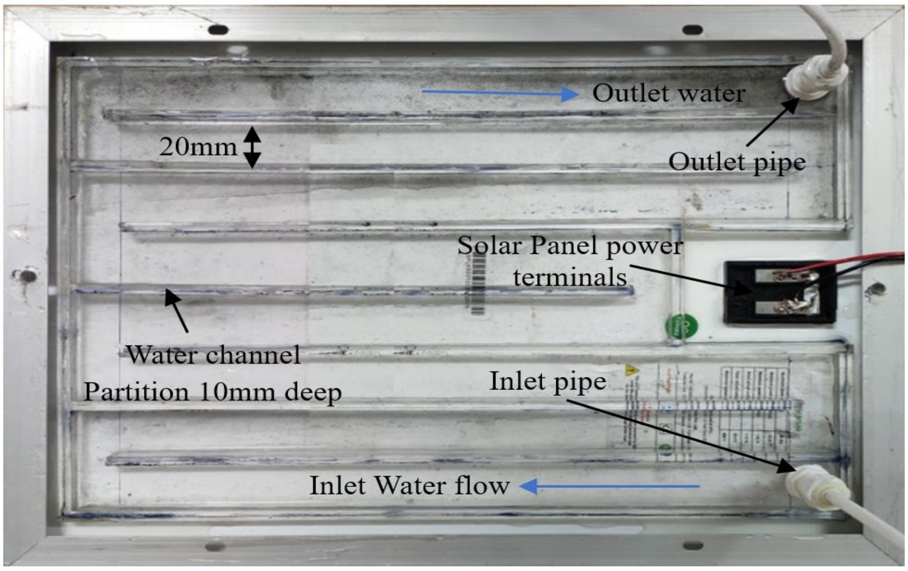


Fig 2. Rectangular channel with a flow pattern with 20 mm partitioned spacing and 10mm depth directly placed at the backside of the PV panel.

The experimental setup was: radiation 1200 W/m$^2$, Ambient temperature 25 °C, Relative Humidity is 73%, Water rate of flow is varying between 0.09 lpm and 0.601 lpm.

A flowchart diagram of the methodology of experimentation is shown in Fig. 3. It outlines a stepwise procedure followed, from system initialization, radiation simulation, and controlled water flow activation, to data logging and performance analysis. This structured approach ensured consistent testing conditions and reproducibility of results.

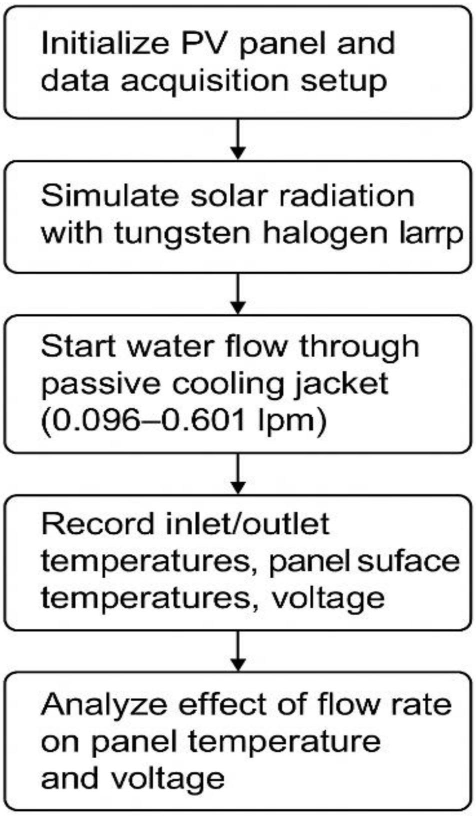


Fig 3. Flowchart of the experimentation.

## 3. RESULTS AND DISCUSSIONS

The front panel's temperature with a constant heat source, i.e., 1200 W/m$^2$ against time, with the varying flow rate of 0.096 lpm to 0.601 lpm, is observed and recorded.

### 3.1 Effect of varying the rate of flow on the temperature of the front of the panel

The result of varying front panel temperatures for different flow rates, i.e., cooling, is compared with the no-cooling condition. The temperature variation is shown in Fig. 4.

Observations indicate that the front panel temperature is more uniform in cooling conditions compared to no cooling. In no cooling condition, the panel takes around 2400 seconds to reach a near steady state, and the panel temperature is around 75°C. With different flow rates, higher flow rates lead to early reaching steady conditions within 600 seconds, and the temperature stabilized earlier at a lower temperature of 40 °C compared to lower flow rates.

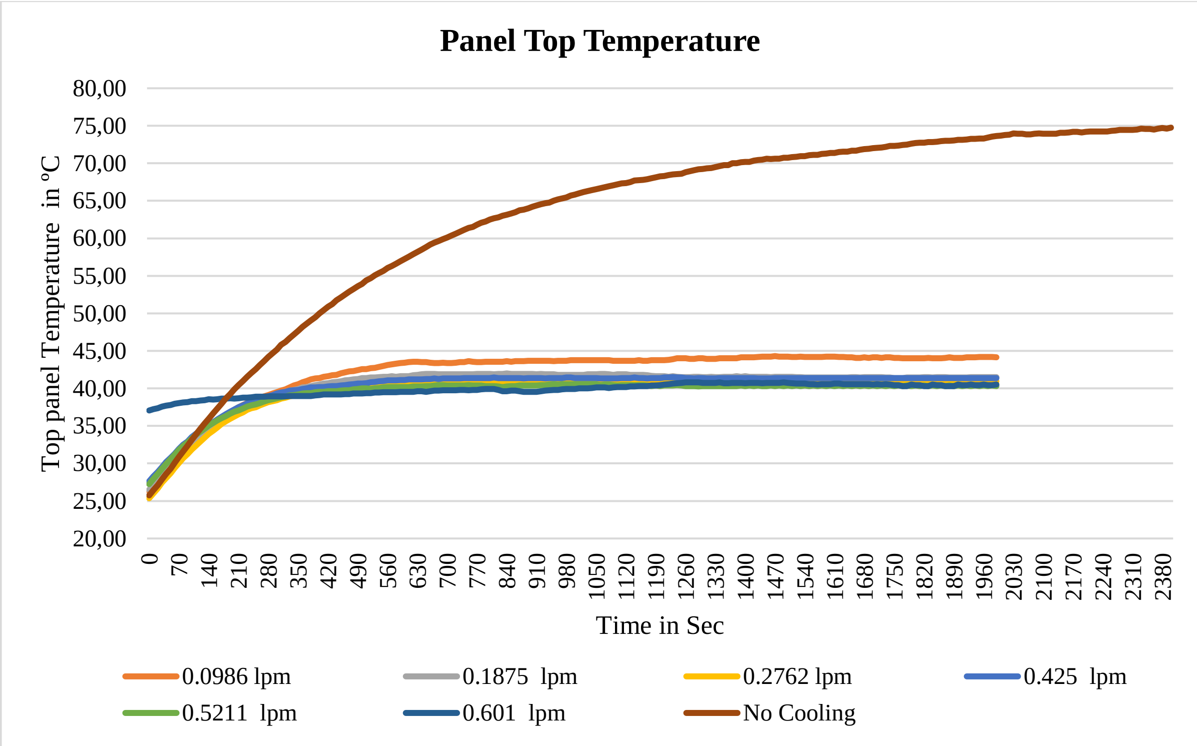


Fig 4. The top surface temperature response to time with the cooling and without cooling.

### 3.2 Effect of varying rate of flow on the temperature of the back panel

The result of varying front panel temperatures for different flow rates, i.e., cooling, is compared with the no-cooling condition. The variation of temperature is given in Fig. 5.

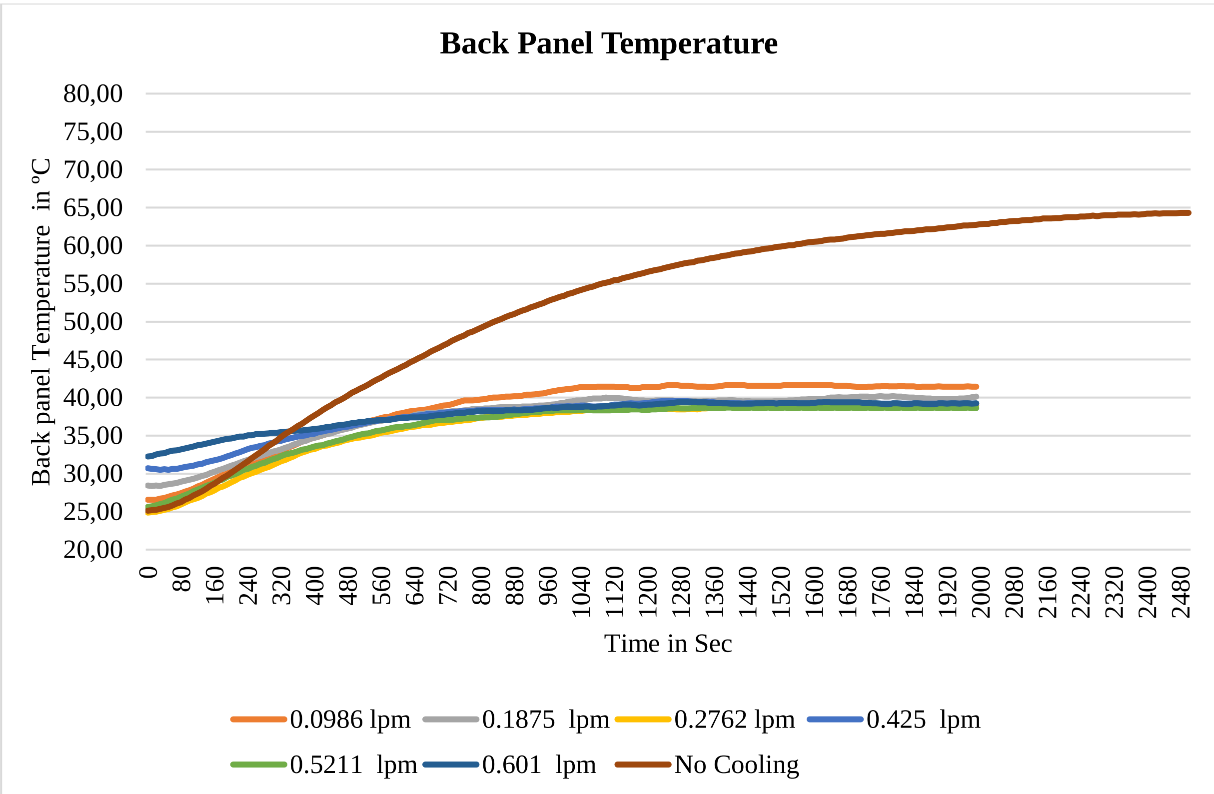


Fig 5. Back surface temperature response to time with the cooling and without cooling.

Observations indicate that the back panel temperature is more uniform in cooling conditions compared to no cooling. In no cooling condition, within the initial 2400 seconds, a considerable temperature rise is observed and reaches nearly 64.5°C. With different flow rates, higher flow rates lead to early reaching steady conditions within approximately 950 seconds, temperature is constant very early at a lower temperature of around 40 °C compared to lower flow rates, and the values vary between 0.0986 to 0.601 lpm.

### 3.3 Effect of the varying flow rate on the open circuit voltage of the solar panel

Fig. 6 shows the voltage response for open circuit, recorded on the data logger over time. At the start of the no-cooling-condition trial run, the ambient and solar panel temperatures were at 25 °C. During the no-cooling-condition trial, the top panel gradually reached nearly 60 °C, and the back panel temperature reached 60°C in the initial 1480 seconds when the measure Open-Circuit Voltage dropped from 21.50 V to 20.25 V is observed.

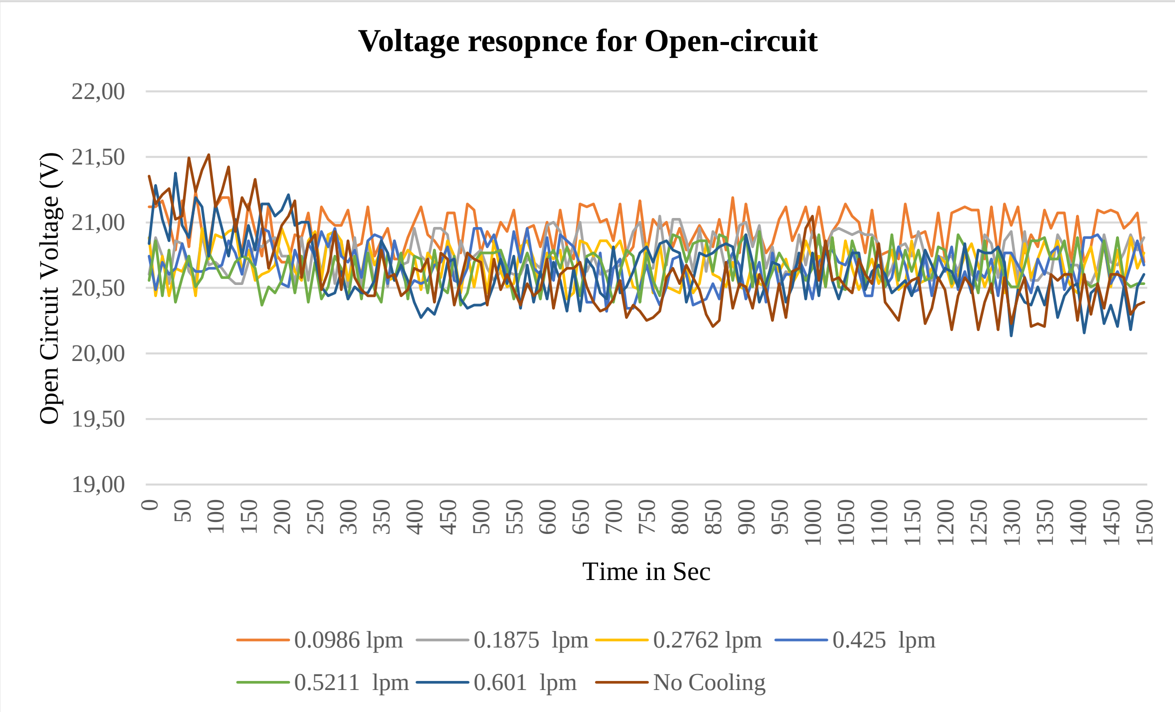


Fig 6. Open Circuit Voltage response over time with cooling and without cooling.

The polynomial trend is indicated in Fig. 7 for better visualization of the OSC voltage variation for 1480-axis time for greater definite knowledge. Observations tell of improving Open-Circuit Voltage with passive cooling methods using water in a zigzag rectangular channel, contradicting discharge flow conditions at the back of the photovoltaic panel at varying flow rates to maintain the best temperature values. The study examines the relationship between incident radiation and electrical output in terms of open circuit voltage affecting PV performance with varying cooling flow conditions. The results reveal that passive cooling techniques can efficiently cool the PV cells and thus enhance electrical outputs. Thus, the study will shed more light upon the importance of thermal management in the applications of PV, leading to a cost-effective as well as energy-efficient cooling setup for PV toward sustainable energy generation.

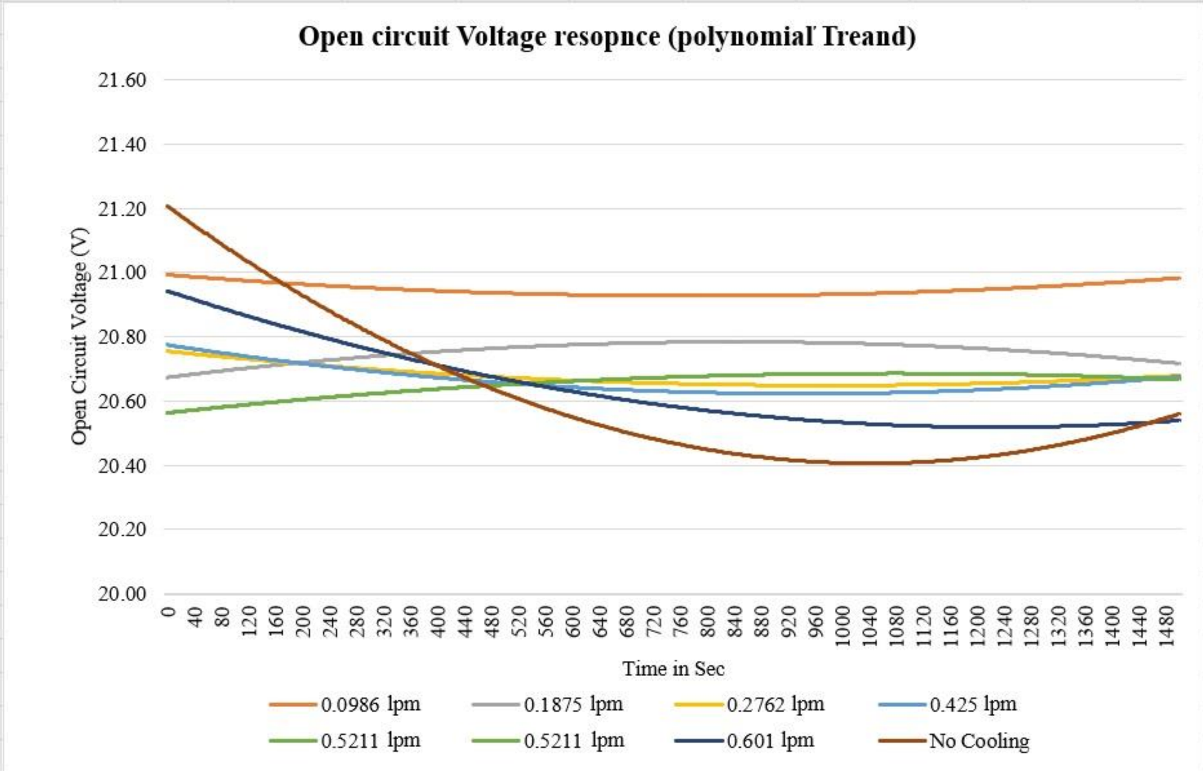


Fig 7. Trend of Open Circuit Voltage over time with the cooling and without cooling.

It was found through a comprehensive study of cooling that the flow rate exerts a strong cumulative influence upon its temperature and electrical performance. The rate rise, ranging between 0.096 and 0.601 lpm, dropped the module front and back surface temperature by 35%-40%. As a result, it considerably lowers thermal stress. Meanwhile, the open-circuit voltage rose by as much as 1.25 V; hence, the electrical power being generated was improved. There occurs a directly proportional relationship between better cooling and stabilized voltage, as passive water cooling fits the bill with a double function. The higher rates of flow also hastened the time to get steady-state thermal conditions and a well-maintained voltage at a high level when radiation input was also kept at a uniform high value. The results therefore come to prove how a properly designed passive cooling system would become a cheap, virtually maintenance-free way of enhancing the operational stability and energy conversion efficiency of PV modules both experimentally and in real life.

It's estimated that with passive cooling, electrical efficiency can go up about 6.17%, which is equivalent to the reported benchmarks and further proves the functionality of the cooling channel design.

The experimental setup used a constant artificial radiation source (tungsten halogen lamp) to simulate solar irradiance, whereas dynamic variations in natural sunlight-from changes in solar angles to cloud covers to convective winds-were not considered. Thus, this analysis does not consider the real-world environmental complexities. Also, as per the design, the cooling jacket was tested for a single small PV panel, and its scaling, mechanical durability, and hydraulic performance remain to be tested for larger-size PV arrays (Reddy et al., 2018).

Further works should attend to systems deployment outdoors, where it can be kept for centuries to observe the performance of this under real-time solar conditions. A study may investigate materials, including highly conductive aluminium alloy or graphene composites, to maximise thermal transfer (Chamsa-ard et al., 2020). Likewise, PCM and nano-additives could be adopted to achieve hybrid passive cooling with thermal energy storage capabilities (Hilarydoss et al., 2021). The use of CFD and thermal simulation tools could optimise channel geometries to maximise velocity uniformity and reduce thermal hot spots. These efforts would help to promote passive cooling in practical applications and make them scale up to cover a diverse range of PV installations (Haque et al., 2022).

## 4. CONCLUSION

The study experimentally confirmed the passive cooling system's effectiveness for water in maintaining safe operational states thermally, in enhancing photovoltaic panels' electrical performance under simulated radiation. The temperature decreases of as much as 40% and the voltage increment of 1.25 volts correspond to a flow, showing a 6.17% increase in efficiency. These findings also demonstrate the thermoelectric dependence and prove that a sufficiently designed passive system can overcome temperature-related power loss without help from auxiliary power. Considering the system's simplicity in design and low-cost fabrication, it becomes an excellent option for rooftop or decentralised solar installations in environments with high temperatures. This work feeds into the ever-growing research on thermal management on PV systems and, in turn, encourages the increased use of energy-efficient and maintenance-free solutions on actual solar applications.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| PV | Photovoltaic | H | Efficiency of the PV panel (%) |
| VOC | Open-circuit voltage [V (Volts)] | $T_{front}$ | Front surface temperature (°C) |
| I | Current generated by PV panel [A] | cp | Specific heat capacity of water |
| P | Electrical power output [W] | t | Time |

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